Lecture Notes in Intelligent Transportation and Infrastructure
Series Editor: Janusz Kacprzyk

Olegas Prentkovskis ·
Irina Yatskiv (Jackiva) ·
Paulius Skačkauskas · Pavlo Maruschak ·
Mykola Karpenko *Editors*

TRANSBALTICA XIII: Transportation Science and Technology

Proceedings of the 13th International Conference TRANSBALTICA, September 15–16, 2022, Vilnius, Lithuania

Springer

Lecture Notes in Intelligent Transportation and Infrastructure

Series Editor

Janusz Kacprzyk, *Systems Research Institute, Polish Academy of Sciences, Warsaw, Poland*

The series "Lecture Notes in Intelligent Transportation and Infrastructure" (LNITI) publishes new developments and advances in the various areas of intelligent transportation and infrastructure. The intent is to cover the theory, applications, and perspectives on the state-of-the-art and future developments relevant to topics such as intelligent transportation systems, smart mobility, urban logistics, smart grids, critical infrastructure, smart architecture, smart citizens, intelligent governance, smart architecture and construction design, as well as green and sustainable urban structures. The series contains monographs, conference proceedings, edited volumes, lecture notes and textbooks. Of particular value to both the contributors and the readership are the short publication timeframe and the world-wide distribution, which enable wide and rapid dissemination of high-quality research output.

Olegas Prentkovskis · Irina Yatskiv (Jackiva) ·
Paulius Skačkauskas · Pavlo Maruschak ·
Mykola Karpenko
Editors

TRANSBALTICA XIII: Transportation Science and Technology

Proceedings of the 13th International Conference TRANSBALTICA, September 15–16, 2022, Vilnius, Lithuania

Springer

Editors
Olegas Prentkovskis
Vilnius Gediminas Technical University
Vilnius, Lithuania

Paulius Skačkauskas
Vilnius Gediminas Technical University
Vilnius, Lithuania

Mykola Karpenko
Vilnius Gediminas Technical University
Vilnius, Lithuania

Irina Yatskiv (Jackiva)
Transport and Telecommunication Institute
Riga, Latvia

Pavlo Maruschak
Ternopil Ivan Puluj National Technical University
Ternopil, Ukraine

ISSN 2523-3440 ISSN 2523-3459 (electronic)
Lecture Notes in Intelligent Transportation and Infrastructure
ISBN 978-3-031-25862-6 ISBN 978-3-031-25863-3 (eBook)
https://doi.org/10.1007/978-3-031-25863-3

© The Editor(s) (if applicable) and The Author(s), under exclusive license
to Springer Nature Switzerland AG 2023
This work is subject to copyright. All rights are solely and exclusively licensed by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publisher, the authors, and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

The international scientific conference "TRANSBALTICA: Transportation Science and Technology" is a traditional, annual event of the Faculty of Transport Engineering in Vilnius Gediminas Technical University (VILNIUS TECH), organized in cooperation with partners since 2001. The thirteen edition of "TRANSBALTICA XIII: Transportation Science and Technology" was held on September 15–16, 2022, in Vilnius, Lithuania. Authors from 13 countries presented their research, covering a number of scientific problems within the research field of transport engineering, transportation and logistics, as well as other disciplines and interdisciplinary areas related to transport system.

The proceedings of TRANSBALTICA 2022 has been organized into six parts, featuring its main areas of interest:

1) **Intelligent Vehicles and Infrastructure** covers highly automated and autonomous driving and infrastructure for autonomous and connected vehicles.
2) **Combustion in Engines, Alternative Technologies, Energy Management, and Emissions** provides useful information regarding alternative fuels, fuel mixtures, combustion process control methods, and efficient use of energy.
3) **Vehicle Engineering and Dynamics** discusses timely issues in vehicle modeling and simulations, vehicle safety systems and railway transport, and relating technologies and applications
4) **Logistics and Transportation** describes most recent research trends regarding green logistics, supply chain connectivity, computational logistics, as well as new circumstances affecting the carriage of goods and passengers, and possible solutions to them.
5) **Railway Transport** covers various rail-based transport systems, dynamics and mechanics of rail vehicles, rail electrification, rail transport infrastructure, planning and design, and other advanced rail technologies.
6) **Innovations and Development of Aerospace Technologies** considers aircraft design and development, flight operations, and other air vehicle systems and technologies.

The program committee of the international scientific conference "TRANSBALTICA XIII: Transportation Science and Technology", the organizers, and the editors of these proceedings would like to acknowledge all the reviewers who helped evaluate conference submissions and refine contents of this volume. Moreover, our thanks go also to all the program committee members:

- Prof. Olegas Prentkovskis, Vilnius Gediminas Technical University, Lithuania—Chairman
- Dr. Paulius Skačkauskas, Vilnius Gediminas Technical University, Lithuania—Chairman

- Dr. Mykola Karpenko, Vilnius Gediminas Technical University, Lithuania—Co-Chairmen
- Darius Aleksonis, Vilnius Gediminas Technical University, Lithuania—Secretary
- Prof. Darius Bazaras, Vilnius Gediminas Technical University, Lithuania
- Dr. Giedrius Garbinčius, Vilnius Gediminas Technical University, Lithuania
- Dr. Saugirdas Pukalskas, Vilnius Gediminas Technical University, Lithuania
- Prof. Gintautas Bureika, Vilnius Gediminas Technical University, Lithuania
- Prof. Marianna Jacyna, Warsaw University of Technology, Poland
- Prof. Jolanta Janutėnienė, Klaipeda University, Lithuania
- Prof. Raimundas Junevičius, Vilnius Gediminas Technical University, Lithuania
- Prof. Michał Stosiak, Wroclaw university of science and technology, Poland
- Prof. Pavlo Maruschak, Ternopil Ivan Pul'uj National Technical University, Ukraine
- Prof. Dariusz Mazurkiewicz, Lublin University of Technology, Poland
- Prof. Vidas Žuraulis, Vilnius Gediminas Technical University, Lithuania
- Dr. Iyad Alomar, Transport and Telecommunication Institute, Latvia
- Dr. Salvatore Antonio Biancardo, University of Naples Federico II, Italy
- Dr. Metin Mutlu Aydin, Ondokuz Mayıs University, Turkey
- Dr. Kristina Čižiūnienė, Vilnius Gediminas Technical University, Lithuania
- Dr. Olja Čokorilo, University of Belgrade, Serbia
- Dr. Viktoriia Ivannikova, National Aviation University, Ukraine
- Dr. Ilya Jackson, Massachusetts Institute of Technology, USA
- Dr. Viktor Skrickij, Vilnius Gediminas Technical University, Lithuania
- Dr. Tadeusz Szymczak, Motor Transport Institute, Poland
- Dr. Kamil Urbanowicz, West Pomeranian University of Technology, Poland
- Dr. Yonggang Wang, Chang'an University, China

We acknowledge all the authors who have chosen "TRANSBALTICA XIII: Transportation Science and Technology" as the publication platform for their research and would like to express our hope that their papers will foster further developments in the design and analysis of complex transport systems, offering a valuable and timely resource for scientists, researchers, practitioners, and students who work in all the areas mentioned above.

Olegas Prentkovskis
Paulius Skačkauskas
Pavlo Maruschak
Mykola Karpenko

Contents

Intelligent Vehicles and Infrastructure

Comprehensive Vehicle Safety Diagnostics and Management System 3
Maksym Delembovskyi and Svitlana Terenchuk

Validating Adverse Weather Influence on LiDAR with an Outdoor Rain Simulator 12
Michał Brzozowski and Krzysztof Parczewski

Development of a Technology for Monitoring Passenger Traffic in the Context of Intelligent Transport Systems 23
Mykyta Volodarets, Igor Gritsuk, Sergii Pronin, and Alona Yurzhenko

Intelligent Management of Traffic Flows in Large Cities 33
Bohdan Yeremenko, Roman Mazurenko, Oleksii Stetsyk, and Anatolii Buhrov

Conditions of Effective Application of Energy-Saving Programs for the Movement of Heavy Trucks on the Highway 43
Myroslav Oliskevych and Viktor Danchuk

Intelligent Transportation Systems Applications: Safety and Transfer of Big Transport Data 59
Yasin Çelik, Metin Mutlu Aydin, Ioan Petri, and Dimitris Potoglou

Combustion in Engines, Alternative Technologies, Energy Management and Emissions

Artificial Neural Network Model Use for Particulate Matter Evaluation from Ships in Klaipeda Port 77
Paulius Rapalis and Giedrius Šilas

A Case Study for the Development of Environmentally Safe Low-Lead Aviation Gasoline in Ukraine 85
Sergii Boichenko, Anna Yakovlieva, Iryna Shkilniuk, Natalia Gecejova, Olufemi Olaulava Babatunde, and Ihor Kuberskyi

Study on Correlation Between Particulate Matter Emissions and Exhaust Smoke Levels in CI Engines 95
Sai Manoj Rayapureddy and Jonas Matijošius

Comparative Assessment of Organic Rankine Cogeneration Cycle Efficiency with Secondary Heat Sources from Marine Diesel 104
Tomas Čepaitis and Sergejus Lebedevas

Methodological Aspects of Numerical Studies of Ammonia Use in Diesel Cycle 116
Martynas Drazdauskas and Sergejus Lebedevas

Possibilities of Legislative and Economic Support for Electromobility in Slovakia 125
Kristián Čulík, Karol Hrudkay, and Vladimíra Štefancová

Numerical Analysis of Combustion Parameters of a Spark Ignition Engine Fuelled with CNG and Variable Valve Timing 135
Gediminas Mikalkėnas, Alfredas Rimkus, and Saugirdas Pukalskas

Improving the Energy Efficiency of a Vehicle by Implementing an Integrated System for Utilizing the Thermal Energy of the Exhaust Gases of an Internal Combustion Engine 144
Yurii Gutarevych, Jonas Matijošius, Dmitrij Trifonov, Oleksandr Syrota, Alfredas Rimkus, Yevhenii Shuba, and Urtė Radvilaitė

The Comparison and Potential of CO2 Capture Technologies Implementation on the Marine Transport 152
Audrius Malūkas and Sergejus Lebedevas

Scenarios of Accident Events of Electric Vehicles 162
Jozef Kubás, Michal Ballay, and Katarína Zábovská

Vehicle Engineering and Dynamics

The Use of Mineral Powders of Various Nature to form the Structure of Asphalt Concrete 175
Kateryna Krayushkina, Oleksandra Akmaldinova, Kyrylo Fedorenko, and Oleksandra Skrypchenko

Experimental Approach to Water Hammer Phenomenon 189
Michał Stosiak, Kamil Urbanowicz, Krzysztof Towarnicki, Marijonas Bogdevičius, and Mykola Karpenko

Assessment of Hydrogen Assisted Degradation of Stacker Conveyor Boom Steel 200
Olha Zvirko, Oleksandr Tsyrulnyk, and Leonid Polishchuk

Numerical Analysis of Passenger Car Wheel Suspension Models in a Vertical Test of an Axle 208
Miroslav Blatnický, Ján Dižo, and Denis Molnár

Research of Efficiency of Anti-lock Braking System During Emergency Cornering Manoeuver 224
Airidas Staputis and Vidas Žuraulis

Methodology of the Durability Tests of Semi-trailers on the MTS 320 Road Simulator 236
Arkadiusz Czarnuch, Marek Stembalski, Tomasz Szydłowski, and Damian Batory

An Engineering Design of a Frame of an Electric Bicycle 247
Ján Dižo, Miroslav Blatnický, and Denis Molnár

Environmental Problems Associated with Vehicle Braking and Their Solutions 258
Oleksandr Kravchenko, Dalibor Barta, Juraj Gerlici, Kateryna Kravchenko, Iwona Rybicka, and Andrej Zigo

Friction Resistances in a Prototype Internal Gear Pump with Sickle Insert Made of Plastic 268
Krzysztof Towarnicki, Michał Stosiak, Tadeusz Leśniewski, Adam Deptuła, Kamil Urbanowicz, and Paweł Śliwiński

Comparison of Same Aftermarket Monotube Shock Absorbers Manufactured by Different Brands 277
Paulius Skačkauskas, Dominyka Norkūnaitė, Mykola Karpenko, and Vilius Mejeras

Experimental Study of Flow Rate in Hydraulic Satellite Motor with the Rotating Case at a Low Constant Rotational Speed 287
Pawel Sliwinski, Piotr Patrosz, Marcin Bak, Michal Stosiak, Kamil Urbanowicz, and Šarūnas Šukevičius

Determination of the Value of the Energy Equivalent Speed Parameter According to the Residual Deformations of the Finite Element Model 300
Tomas Pasaulis and Robertas Pečeliūnas

Finite Element Analysis of the Tank Semi-trailer‘s Frame on Road Irregularities and Liquid Sloshing Conditions 309
Tomas Smolskas and Romualdas Juknelevičius

Methodology for Calculating the Load of Petroleum Products Emissions on the Soils of the Roadside Space Created by the Operation of Highways 327
Oksana Melnikova, Valentina Iurchenko, and Mykola Mykhalevych

Prospects for the Production of Recycled Hot Mix Asphalt with Plastic Fiber .. 336
Volodymyr Ilchenko, Alla Kariuk, Roman Mishchenko, and Anna Shevchenko

Realtime Measurements of the Relation Between the Acting Force, Unsprung and Sprung Masses on a Road Simulator Test Stand for Large-Size Vehicles 344
Marek Stembalski, Arkadiusz Czarnuch, Tomasz Szydłowski, and Damian Batory

Possibilities of the Using of Drilling Mud in Road Construction 354
Oksana Demchenko, Volodymyr Shulhin, Volodymyr Ilchenko, and Elena Uzhviieva

New Design of Axial Piston Pump with Displaced Swash Plate Axis of Rotation for Hydro-Mechanical Transmissions 365
Paweł Załuski, Piotr Patrosz, and Marcin Bąk

Identification of Specific System Parameter Space in Initial Research Stage 375
Andrius Macutkevičius and Raimundas Junevičius

Comparison of Mathematical Models of Torque Transmitted by Multi-disc Wet Clutch with Experimental Results 383
Marcin Bąk, Piotr Patrosz, Paweł Śliwiński, Paweł Załuski, and Mykola Karpenko

Methodology of Experimental Research on Efficiency of Hydro-Mechanical Automatic Gearbox 393
Piotr Patrosz, Marcin Bąk, Paweł Załuski, Paweł Śliwiński, and Mykola Karpenko

The Use of Simulation Programs in the Traffic Accident Analysis 404
Ján Ondruš, Eduard Kolla, Ľudmila Macurová, and Ján Podhorský

Expert Evidence in the Analysis of the Accident Event – Vehicle, Motorcycle and Pedestrian 415
Ľudmila Macurová, Pavol Kohút, Gustáv Kasanický, and Michal Ballay

Logistics and Transportation

Assessment of Trends in Improving the Performance of Transportation Companies 427
Algimantas Danilevičius and Irena Danilevičienė

Ukrainian High-Speed Normal Gauge Railway: Factors of War and Peace 438
Viktor Myronenko, Valery Samsonkin, Oksana Yurchenko, and Andrii Pozdniakov

Formation of Organizational Principles of Service of Export Cargo Flows in Transport Units 449
Oleksandr Gryshchuk, Anatoliy Petryk, Yaroslav Yerko, and Litus Tetiana

An Application of Driver Behavior Questionnaire: Case Study of Amman 459
Khair Jadaan, Duha Alsarayreh, Qasem Alqasem, and Zaid Alnusairat

Influence of the Bridge's Status on the Military Mobility in the Slovak Republic 470
Ján Jančo and Jaroslav Kompan

A Study for Identifying Fake News in the Information Society: The Case of the Logistics Sector 479
Kristina Čižiūnienė, Artūras Petraška, and Gabrielė Žemaitytė

Engineer Mobility Support on the Territory of the Czech Republic as One of the Host Nation Support Tasks 491
Jindřich Dologa, Ota Rolenec, and Natálie Hanáková

Identification of Problem Areas of Traffic Flow Management and Solutions in Vilnius 502
Aldona Jarašūnienė and Gabrielė Žemaitytė

The Role of East Asia in Current Issues Focus on Value Chain Management of Logistics and Transport Market 510
Veslav Kuranovič

Energy Consumption and Travel Time as Important Factors for Deciding on the Mode of Transport - Case Study from Slovakia 518
Juraj Grencik, Dalibor Barta, Milos Brezani, and Denis Molnar

Optimization of Customs Processes for Improving Cooperation Between Third-Party Logistics Companies 528
Ieva Meidutė-Kavaliauskienė and Renata Činčikaitė

Study of the Dynamics of Railway Passenger Traffic, Identification of Trends 539
Renata Činčikaitė and Ieva Meidute-Kavaliauskiene

Adapting Private Sector Warehousing Services to the Needs of the Lithuanian Armed Forces 548
Aidas Vasilis Vasiliauskas, Ieva Meidutė-Kavaliauskienė, and Edgaras Čerškus

Innovations Development in Intermodal Freight Transport: Polish Practitioners' Viewpoint 556
Ludmiła Filina-Dawidowicz, Tatjana Paulauskiene, Alla Selivanova, Daria Możdrzeń, and Sara Stankiewicz

Investigation of the Possibilities of Optimization of Freight Road Traffic Flows in the Urban Logistics System 566
Šarūnas Šlajus and Nijolė Batarlienė

Streets and Urban Roads Surface Runoff Problems: A Case Study in the Poltava City, Ukraine 576
Iryna Tkachenko, Tetyana Lytvynenko, Lina Hasenko, and Nataliia Sorochuk

Transport Eurointegration of Ukraine (Ways to Revitalize Dnipro Reservoirs) 586
Grygoriy Shariy, Svitlana Nesterenko, Vira Shchepak, and Evgeniya Ugnenko

The Impact of Third-Party Logistics Intermediaries on Supply Chain Responsiveness 598
Aidas Vasilis Vasiliauskas and Olga Navickienė

Method and Results of the Most Efficient Means of Transport Selection for Executing Orders of the Grain Crops Delivery 606
Viktoriia Kotenko

Green Logistics and Marketing Features: Literature Review 618
Margarita Išoraitė

Restriction of Mobility Due to Follow-Up Measures Caused by COVID-19 627
Vladimíra Štefancová, Kristián Čulík, Borna Abramović, and Adriana Pálková

Study of Technological Literacy Competencies of Logistics Specialists of a Transport Company 634
Kristina Vaičiūtė and Irina Yatskiv

Analysis of International Air Hubs: A Competitiveness Review 645
Aya Medany, Ilmars Blumbergs, and Khaled Elsakty

Assessment of the Link Between the Integration of Technological Development of a Transport Company and Marketing in the Supply Chain 655
Kristina Vaičiūtė, Ernestas Vaičius, Liudmila Burinskienė, and Darius Bazaras

Railway Transport

Identification and Classification of Soft Targets in Railway Infrastructure 667
Simona Slivkova and Lenka Michalcova

Assessment of the On-Board Energy Storage Parameters of the Locomotive for Rail Quarry Transport 677
Ievgen Riabov, Liliia Kondratieva, Liliia Overianova, and Sergiy Goolak

Study on Measurement Repeatedness of Vertical Impacts on Rail of Loaded and Empty Wagons 689
Gediminas Vaičiūnas and Stasys Steišūnas

Improving Noise Immunity of Audio Frequency Track Circuits Using Neural Networks and Data Classification 696
Inna Saiapina, Halyna Holub, and Ivan Kulbovskyi

Comparison of Railway Development in the Countries of the World 706
Gediminas Vaičiūnas

Changes in the Passenger Sector in the COVID-19 Era 716
Agata Pomykala

Implementing Intelligent Monitoring of the Technical Condition of Locomotive Hydraulic Transmissions 726
Boris Bondar, Oleksandr Ockasov, Viačeslav Petrenko, and Michail Martishevskij

Methodological Framework for Assessing and Strengthening the Resistance of Railway Critical Infrastructure Elements 737
David Rehak, Lucie Flynnova, and Abdollah Malekjafarian

A Reliable Low-Cost Interlocking System for Regional Railway Lines 746
Petr Šohajek, Martin Šustr, Pavla Šmídová, and Radovan Soušek

Revised Estimation of Public Railway Infrastructure Line Capacity: Lithuanian Case 756
Gintautas Bureika

Innovations and Development of Aerospace Technologies

Influence of the Ground Effect on the Precise Landing of an Unmanned Aircraft 767
Andrius Dubovas and Domantas Bručas

Mathematical Model of Airport Aviation Security 773
Olena Sokolova, Kostiantyn Cherednichenko, and Viktoriia Ivannikova

Scavenging of a Two-Stroke Engine 782
Vytautas Rimša

Optimization of the Special Cargo Delivery by UAV 790
Anna Ayrapetyan and Viktoriia Ivannikova

Crack Open/Close Effect on Impedance Based System of Structural Health Monitoring 797
Vitalis Pavelko and Pavithra Nagaraj

Improvement of Methodology of Calculation and Assessment of Transport and Operational Condition of Airfield Pavement (on the Example of Airport Pavements of Kyiv and Mykolaiv International Airports) 806
Viktor Karpov, Oleksandr Stepanchuk, Oleksandr Dubyk, Oleksandr Rodchenko, and Olegas Prentkovskis

Author Index 825

Intelligent Vehicles and Infrastructure

Comprehensive Vehicle Safety Diagnostics and Management System

Maksym Delembovskyi(✉) and Svitlana Terenchuk

Kyiv National University of Construction and Architecture, Kyiv 03037, Ukraine
delembovskyi.mm@knuba.edu.ua, terenchuksa@ukr.net

Abstract. The main goal of the work is to simulate an integrated system for diagnosing and managing vehicle safety, which will become an alternative to existing analogs and significantly reduce the cost of protecting cars from theft.

To achieve the set goals, the work analyzes the safety indicators of road transport on a global scale. Based on the analysis carried out, the problem of determining the operability of the system, the main purpose of which is remote blocking of the engine in case of theft, is solved.

The scientific work deals with remote blocking of the engine using a GSM module. Thus, the GSM module receives data from the power relay and the OBD-2 vehicle system diagnostic module, this task is assigned to the signal processing subsystem using the built-in Wi-Fi module. This allows you to identify the owner of the car by a unique identifier of the mobile device and determine the location of the car. If there is interference with the Wi-Fi signal to unlock the car, you can integrate the hidden NFC tag into its door card at the same time.

The team of authors has developed an alternative CSDUA system based on the Telegram messenger.

Keywords: Theft · Protection · Remote engine lock

1 Overview of Statistics

Car theft statistics in different countries have their trends and constantly change due to many different factors. And this has been a problem not only for vehicle owners but also for law enforcement agencies for decades.

In each country, car thieves have certain "leading brands", the number of thefts which account for the main share of thefts. The leaders, as a rule, are cars that do not have reliable protection systems. Such cars occupy the middle price segment in the market and form a large demand for components.

According to Eurostat, the annual number of police-registered car thefts in EU (European Union) countries between 2015 and 2017 (see Fig. 1) was 697,000 [8].

On average, from 2015-to 2017, Luxembourg registered the largest number of car thefts registered with the police in the EU – 328 thousand per 100,000 inhabitants. 269 thousand and 257 thousand car thefts per 100,000 people were registered in Greece and Italy, respectively. At the same time, not only cars are used in Italy, but also motorcycles, mopeds, and other two-wheeled vehicles. The priority of Italian hijackers is mainly

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 3–11, 2023.
https://doi.org/10.1007/978-3-031-25863-3_1

such domestic brands as Fiat and Lancia. The lowest level of carjacking in the EU was recorded in Denmark: 4 cars per 100,000 inhabitants [8].

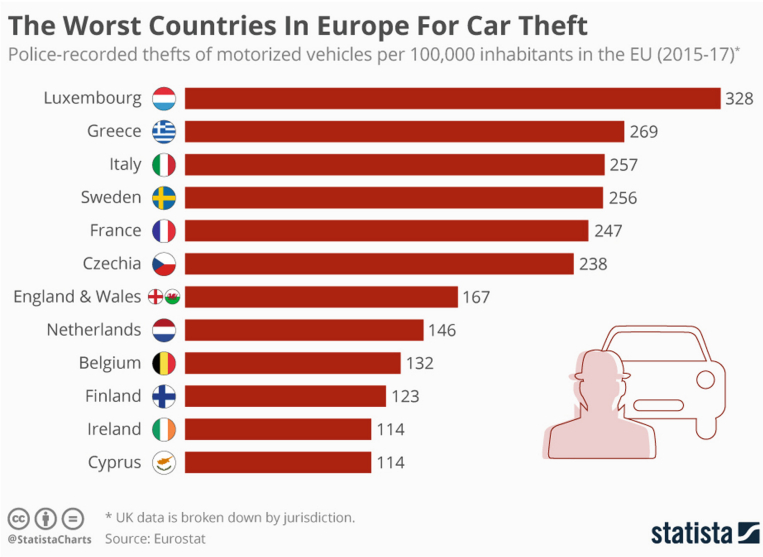


Fig. 1. Car theft statistics in EU countries [8].

The results of a study by the automotive portal TopGear showed that out of 100,000 annual carjackings in Australia, the main share falls on vehicles of the South Korean brand Hyundai. The second place in terms of the number of thefts is occupied by Japanese Toyota cars. The most interesting representatives of the "leading brands" are the Australian brand Holden Commodore and Falcon Forte [8].

The statistics of car theft in England vary significantly. In this country, the majority of crimes are related to Elite Models of transport. At the same time, brands such as BMW, Audi, and Land Rover are in particular demand among hijackers.

In Ukraine, according to the Criminal Investigation Department of the National Police, 5,684 cases of illegal possession of vehicles were recorded in 2017, and in 2018 the agency registered 4,092 cases of illegal possession of vehicles. Only about 30% of cars can be returned to their owners [1].

The National Police notes that V and Daewoo cars are most often stolen. The reason for this choice, first of all, is the large number of such vehicles in the country, which causes a fairly large demand for spare parts for cars of this brand. Therefore, often the theft of VAZ and Daewoo cars is associated with the further sale of their spare parts.

Other reasons that contribute to the theft of these particular car brands are:

– saving owners of inexpensive cars on installing additional protection;
– ability to start the engine in seconds.

Popular Cars of the Toyota, Mercedes, BMW, and HONDA brands in the expensive market segment are usually stolen to order.

In the United States, according to available statistics [8], on average, about 800,000 car thefts occur annually. However, unlike Ukrainian ones, American hijackers are wary of stealing cars of domestic brands and prefer models of manufacturers such as Honda, Toyota, Acura, and Cadillac. The main reason for this choice is considered to be the vulnerability of basic security systems [8].

Thus: a review of car theft statistics shows that such a negative phenomenon as car theft occurs in all countries. However, this may be due to the poor-quality configuration of protection systems during installation or disregard for safety rules by the vehicle owners themselves. Sometimes this can be due to the use of vulnerable "Links" by attackers by security systems, and even advanced security systems offered by luxury car manufacturers do not always guarantee appropriate protection against theft. In any case, the review confirms the relevance of this work.

2 Modern Practice of Using GPS Monitoring, Car Alarm, and Diagnostic Systems to Control Car Safety

2.1 Application of GPS Monitoring Systems

A typical GPS (Global Positioning System) GSM (Global System for Mobile Communications) satellite transport monitoring system consists of such links as the onboard device; server and client (see Fig. 2).

Fig. 2. GPS GSM satellite monitoring system.

Onboard devices [5] are specialized GPS receivers that connect GPS + GSM antennas or separately. Data about the object (location, speed, direction of movement, exact coordinates, status of connected sensors) is recorded by internal memory, the volume of which is 15–70 thousand messages.

Messages from the onboard controller are transmitted to the transport management system using the built-in GSM module that works with the mobile operator's SIM card. Transmission algorithms can take into account the client's wishes but depend on the actual capabilities of the controller since in some cases data can be transmitted with a delay.

There are onboard devices that do not provide the ability to connect additional sensors. Such devices are used when you need to know only the location of the vehicle, the speed of its movement, and compliance with the established route. If you need additional data, such as fuel consumption, time, place and volume of refueling and draining fuel,

refrigerator temperature, and other parameters, then you can't do it without connecting special sensors to the controller. In this case, you need an onboard controller with a sensor board.

The onboard controller of GPS GSM satellite transport monitoring has a built-in battery, which is designed to prevent interference in the operation of the system when the voltage in the onboard network decreases. As a rule, the controller is connected in such a way that its power supply does not depend on the position of the ignition key. As a result, constant monitoring of the vehicle is provided, regardless of whether it is moving or standing still.

A GPS tracker is programmed by the car owner to get information about the location of the car at a certain time every day. This way, your mobile device will receive information about the car's location at the same time. The main advantage of using the device is the minimal probability of its detection, even when using modern frequency scanners since the device can only be detected when transmitting information to the owner's phone. At the same time, messages with data about the location of the car will be transmitted.

2.2 Application of Car Alarm Systems in Cars

One-way car alarm system with standard functions: siren, and central locking, which allows you to control the opening of car doors from the owner's keychain (see Fig. 3).

With this alarm system, the development of modern automotive devices began, the main purpose of which is to generate light and sound signals in cases of unauthorized access to the car. For communication, they use sound and light methods, and the maximum range is up to about 200 m under normal terrain conditions [9].

Today, one-way car alarms are considered outdated and inferior to two-way car alarm systems. The main difference between two-way alarms and one-way models is the use of a pager keychain, which receives information from the main unit of the device.

If there is feedback between the control unit that is installed in the car and the keychain of the car owner, which receives information about the condition of the car, then this gives two-way car alarm systems several indisputable advantages, namely [9]:

- remotely disarm and disarm the car;
- start the engine to warm up in winter;
- notify the owner of events that occur with the car and its environment.

2.3 Application of Diagnostic Systems in Automobiles

Technical diagnostics of a car [10] is a set of goals and tasks related to troubleshooting mechanisms and systems of the car, for their further elimination.

Car diagnostics involves the use of special diagnostic equipment that allows you to determine the technical condition of the mechanisms, systems, and aggregates of the car. Specialized workshops and dealerships are equipped with a wide range of diagnostic equipment. All devices have their characteristics and differ greatly in their capabilities, but all devices can be divided into two main types – motor testers and diagnostic scanners [6].

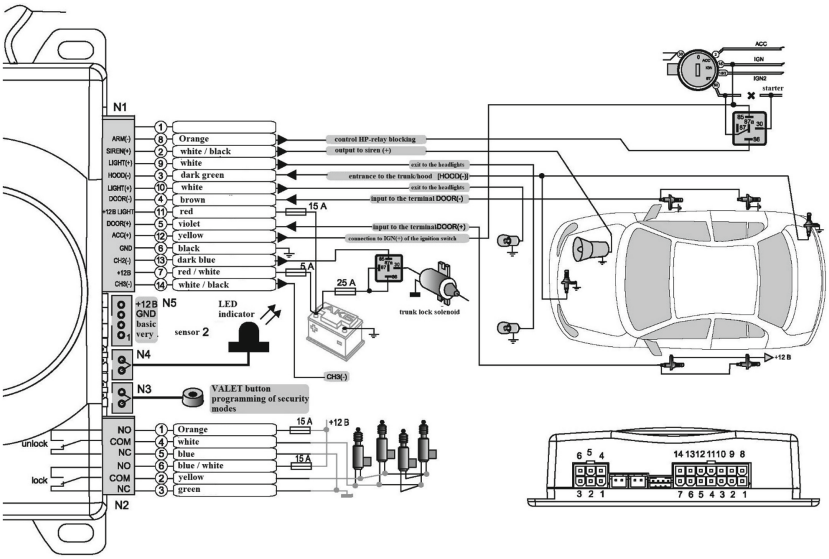


Fig. 3. One-way alarm connection diagram [11] Sheriff APS-2400.

Figure 4 shows a diagnostic scanner, which is a type of equipment used in most service stations and dealerships.

Diagnostic scanners have extensive functionality that allows you to:

- read data from the ECU (Electronic control unit) of cars;
- extract error and fault codes;
- make code decryption;
- change settings in the configuration of the vehicle's electronic systems;
- activate and deactivate functions.

Fig. 4. OBD-2 diagnostic scanner.

3 CSDUA Construction Technology

3.1 Implementation of CSDUA

Figure 5 and Fig. 6 show the implementation algorithm and the scheme for connecting the CSDUA (comprehensive system for diagnostics and management of Auto-Mobile Safety) to the car.

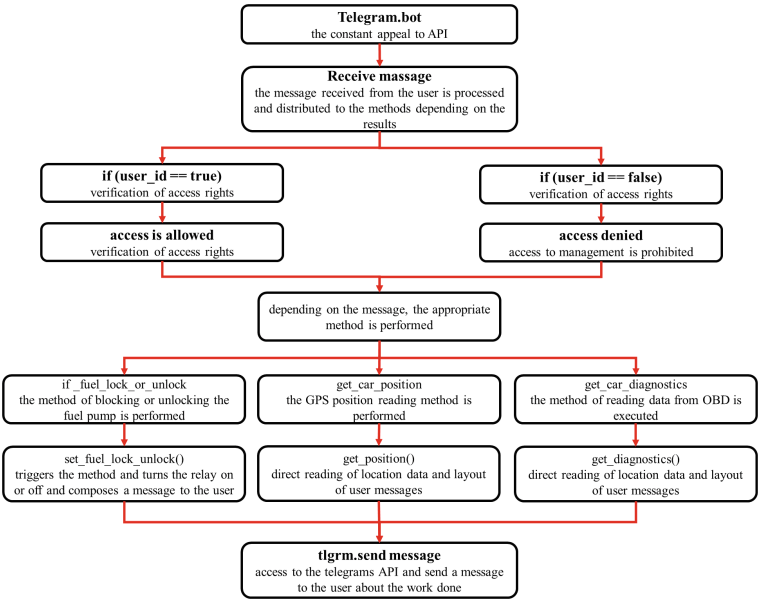


Fig. 5. CSDUA implementation algorithm.

Based on this algorithm and connection scheme, the application code has been developed and tested, and the use of this code makes it possible to create a sensitive interaction between the proposed vehicle systems into one. This approach can simplify the extensive functionality of this system.

3.2 Justification of the Rational Choice of CSDUA

The initial task of developing a CSDUA is to determine the functionality of the vehicle safety system, the main purpose of which is remote engine locking.

GPS tracking of cars, collecting all data from the brain "brain" of car control, and comfortable unlocking of the engine start system depending on the radius of the car alarm signal. It is also important to take into account such criteria as reliability (fault tolerance), the possibility of hacking (security), autonomy, and availability of the system.

To implement a CSDUA with the above criteria, it is necessary to determine the equipment that will provide a rational solution.

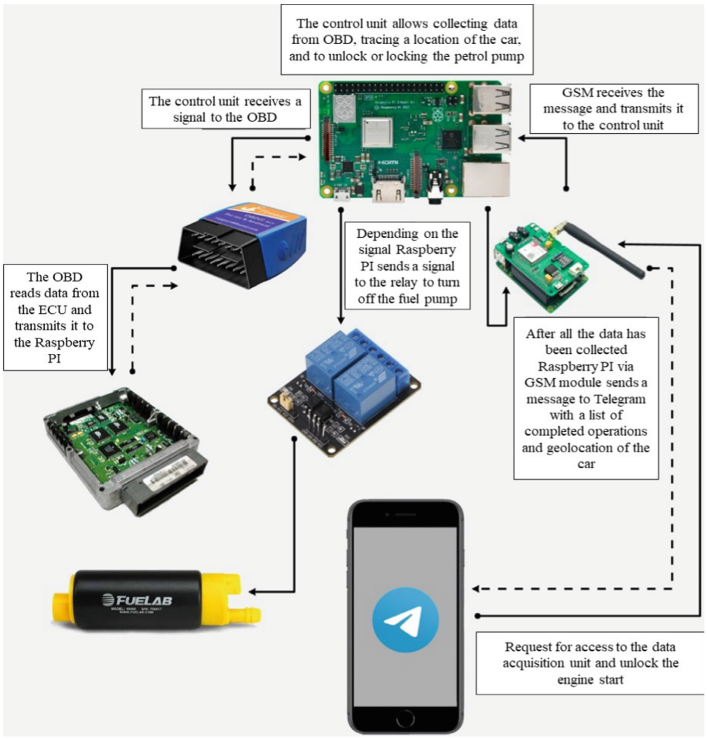


Fig. 6. System connection diagram.

First, you need a control unit that can transmit information via a GSM module from all system components, such as a power relay and a diagnostic module for various vehicle systems OBD-2 (On-Board Diagnostics). to implement this task, you need to create local signal processing using an integrated Wi-Fi module, which in turn additionally provides an opportunity to determine the owner by a unique mobile device identifier and unlock the car. In case of interference with the Wi-Fi signal, it is possible to simultaneously integrate a hidden NFC (Near Field Communication) tag in the car door card to ensure its subsequent unlocking.

Secondly, it is necessary to determine the source of data transmitted from the vehicle protection and diagnostic system unit to the end-user. The system under development is a Telegram messenger running on the MTProto protocol (Media Transfer Protocol). MTProto is based on the original combination of the symmetric AES encryption algorithm. It is a Diffie-Hellman protocol for exchanging 2048-bit RSA keys between two devices and several hash functions. The protocol allows the use of end-to-end encryption with optional key reconciliation. The choice of Telegram is justified by the fact that for 6 years of active work, it has never been hacked, that is, uptime is directed to 100%.

To authorize the user to access the Bot, it is suggested to use a special unique identifier generated by Telegram. This solution increases the guarantee that the Bot can only be operated by the owner of the vehicle's Security System [2].

To get data and control the car alarm system, it is proposed to use Telegram Bot, which can provide an accessible and visual interface for displaying the current state of the car, namely: location and a complete package of information about the state of all car mechanisms with the possibility of remote blocking of engine start by disconnecting the gas pump through the connected additional relay.

The interaction of all components of the security system will take place thanks to the Raspberry Pi mini-computer of the 3rd Generation [3], which is an identical computer equal in functionality to a stationary personal computer, but in size as a basic credit card. Raspberry Pi has integrated Wi-Fi Bluetooth modules, which makes it possible to determine whether there is an owner within the radius of operation of the modules and thereby allow you to unlock the car. As soon as the user leaves the range of operation of the modules, the gas pump is blocked. The user will be determined by the unique MAC address of the mobile device. GSM-GPS and OBD-2 modules and a power relay will be connected to the Raspberry Pi. GSM will host the Telegram Bot, GPS will transmit the location of the car, OBD-2 will collect information from the car's brain, and in the meantime, the power relay will be responsible for locking/unlocking the gas pump.

4 Conclusions

This paper solves an applied problem that helps to increase the efficiency and safety of road transport. The main conclusions are as follows:

1. Based on the analysis, it is established that the effectiveness of existing car safety systems today is insufficient and requires constant improvement and the adoption of appropriate technical decisions.
2. The proposed model for creating a vehicle control and diagnostics system provides opportunities to significantly reduce the cost of more expensive and sometimes questionable analogies.
3. The implementation of this model makes it possible to simultaneously combine several systems into one, which in turn makes it possible to monitor your vehicle more conveniently.
4. Combining a comprehensive system with Telegram messenger significantly increases the level of safety of the car and the system as a whole.

Based on this principle, a real model of this system is developed, followed by its configuration and testing in real operating conditions.

References

1. LNCS Homepage. https://apostrophe.ua/article/society/2019-05-30/pochemu-v-ukraine-protsvetaet-biznes-po-ugonu-avtomobiley/26081
2. Куссуль, М.Э.: Нейросетевой классификатор для систем безопасности автомобиля/ А.С. Сычев, М.Э. Куссуль // Математические машины и системы 2, p. 15–21 (2004)

3. Дегтярьова, Л.М.: Практичні прийоми та керівні принципи розробки комплексів інформаційної безпеки / Л.М. Дегтярьова, В.Г. Ляшевський // Системи управління, навігації та зв'язку. – Полтава: ПолтНТУ, – Вип. 2 (42), p. 94–97 (2017)
4. Chowdhury, M.N., Nooman, M.S., Sarker, S.: Access control of door and home security by raspberry Pi through internet. Int. J. Sci. Eng. Res. **4**(1), 550–558 (2013)
5. LNCS Homepage. https://gps-plus.com.ua/ukr/pitannya-vidpovid/sistemy-gpsmonitoringa
6. LNCS Homepage. https://uk.wikipedia.org/wiki/Автосигналізація
7. LNCS Homepage. https://vagcom.com.ua/ua/clauses/kompyuternaya_diagnostika_sistem_avtomobilya_svoimi_rukami_kak_sdelat_
8. LNCS Homepage. https://www.statista.com/chart/19844/police-recorded-thefts-of-motorized-vehicles/
9. LNCS Homepage. https://alarmspec.ru/signalizacii/sheriff-signalizacii/avtosignalizaciya-sheriff-aps-2400.html
10. LNCS Homepage. https://vse-pro-avtomobili7.webnode.com.ua/news/d%D1%96agnostuvannya-dviguna-avtomob%D1%96lya
11. LNCS Homepage. https://www.manualsdir.ru/manuals/10659/sheriff-aps-2400-sheriff-aps-2400.html?download

Validating Adverse Weather Influence on LiDAR with an Outdoor Rain Simulator

Michał Brzozowski(✉) and Krzysztof Parczewski

Department of Internal Combustion, Engines and Vehicles, University of Bielsko-Biała, Bielsko-Biała, Poland
{mbrzozowski,kparczewski}@ath.bielsko.pl

Abstract. LiDAR is one of the primary sensors used in automated driving. Its task is to provide information about the environment and the obstacles. Adverse weather conditions may affect the effective operation of the LiDAR sensor. The article presents the two most important methods of LiDAR sensor testing. The methodology of building test rigs was described and critically analysed. As part of the work, the construction process from the ground up of the test rig to the study of the impact of rain of varying intensity on the LiDAR sensor works was presented. The method and results of tests carried out with the use of the constructed test rig, showing the influence of rain intensity on the operation of LiDAR sensor, are presented.

Keywords: Automated driving · Autonomous vehicle · LiDAR sensor · ADAS system · Reflectivity testing · LiDAR sensor test rig · Adverse weather conditions

1 Automated Driving and LiDAR Sensor

Autonomous cars are at the forefront of developed automotive technologies. The driver assistance system called ADAS (Advanced Driver Assistance System) is being developed, and its elements are slowly becoming standard equipment for vehicles. Elements of this system, such as active cruise control, lane-keeping assistant, and automatic recognition of road signs, are commonly found in new vehicles. The purpose of introducing these technologies is primarily to increase the level of safety and relieve the driver [2]. Therefore, developing ADAS systems and sensors necessary for their proper operation has become a priority for both car manufacturers and scientists.

The more sophisticated systems in the autonomous vehicle use a range of more advanced sensors such as radar, cameras, and laser scanners (LiDAR). The use of LiDARs (**L**ight **D**etection **a**nd **R**anging) in autonomous cars have become popular because of reducing their cost, size and complexity. They provide reliable and detailed data and have a relatively long effective operating range (even up to 240m).

The general principle of a pulsed LiDAR sensor is to measure the time from the emission to the return of the laser beam reflected from the target and the energy of this beam. This process leads to the generation of data in the form of a point cloud, which contains information about the location and intensity of the given points (which results

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 12–22, 2023.
https://doi.org/10.1007/978-3-031-25863-3_2

from the beam energy) [5]. At a later stage, based on this information, the perception system (using vision algorithms) of the autonomous car locates and creates an image of the surroundings, as well as detects and tracks moving objects. Although LiDAR sensors are considered to be highly reliable and precise, and the data they provide are less disturbed by bad weather conditions than, for example, in the case of a camera, so adverse weather conditions can also significantly reduce the effectiveness of their operation [3, 6, 7].

Due to the widespread use of LiDAR sensors and the fact that it is a very dynamically developing technology, it is necessary to test this type of device and check the capabilities of algorithms and artificial neural networks dedicated to object detection.

Two methods are used to test and validate LiDAR sensor performance:

- simulation,
- tests on test rigs (e.g. in special chambers) [11].

Simulation methods allow large amounts of data to be tested quickly. Suitable software is able to simulate rain or fog by e.g. adding artificial noise to the image. However, without a real test rig on which at least preliminary measurements can be made, validation of such simulations is very difficult because the calculated theoretical range of the LiDAR sensor depends on the coefficients, the values of which should be selected empirically and each time for a specific device. [8, 12]. Computer simulation of LiDAR operation during rain is even more difficult as objects of different intensities generate different drops in detection efficiency. Simulations, on the other hand, can work well in testing various detection algorithms based on data obtained through real experiments at test rigs.

2 The LiDAR Sensor Testing Methods

The test rig must allow for the most credible simulation of road conditions while ensuring the repeatability of these conditions. Another advantage is the ability to add new elements to the examined scene, which makes it possible to extend the scope of research. The construction of the position itself is not an easy task because it requires appropriate knowledge, space, time and financial resources. Many researchers decide to conduct research in a ready, specially prepared chamber, such as the CERMA Climate Chamber in Clermont, France [1, 11]. This chamber allows you to create a stable fog with specific parameters of air transparency (from 5 to 200 m). It also allows you to simulate rain taking into account the size of the droplets (two sizes) and different rainfall intensities. On Fig. 1 is shown the chamber from the Clermont Research Center.

While the Clermont chamber's ability to simulate atmospheric conditions is truly impressive, the chamber is not without some drawbacks. Simulating rain allows producing rain with an intensity of 10 mm/h to 150 mm/h. The classification of precipitation intensity assumes that precipitation above 7.5 mm/h should be considered strong [4]. Thus, even the exceptionally refined chamber in CERMA does not allow simulating light to medium rainfall.

Table 1 shows the basic characteristics of rain intensity. Most rain simulators can only simulate strong rainfall.

Fig. 1. CERNA chamber. Source: [1].

Table 1. Characteristics of rain intensity. Source: [11].

Rain type	Precipitation intensity in mm/h
Very weak	$I < 0.1$
Weak	$0.1 < I < 2.5$
Medium	$2.5 < I < 7.5$
Strong	$I > 7.5$

The Virginia Smart Road could serve as an example of another complex testing rig. It is a 3.5 km long test section of the road that allows you to test many issues in the fields of mechanical (vehicle) and transport engineering. Within this test section of the road, there is a system that simulates rain and produces artificial fog. The test rig allows rainfall simulation with intensity from 2 mm/h to 63 mm/h and reduces visibility from 90 to 3 m. As the entire section is in an area unprotected from wind and sun, the reproducibility of the results is certainly more difficult to obtain than in the case of the tests performed in the test chamber. Still, the possibilities of simulating rain here are much better than in the case of the Clermont chamber [4].

Another solution is to create a test rig from the beginning to the end, designed for a specific experiment. An example of a self-built test rig can be an external rain simulator. It is a simple structure consisting of a frame and water spray nozzles (or pipes) mounted on it. In the presented example, to increase the degree of representation of the real conditions, the researchers introduced separate controls for each of the nozzles. By gradually increasing the number and power of working nozzles, they simulated rain of varying intensity (from 12 to 120 mm/h) and different (but more precisely undefined) droplet sizes. This test rig is shown in the Fig. 2 below [9].

Such a test rig has the main advantages that it is simple and quick to construct, and at the same time, it allows to simulate rain on a similar level as a professional CERNA chamber. In addition, a small outdoor test rig gives great opportunities to change the scene and set up objects.

Fig. 2. Outdoor rain simulator. Source: [9].

To sum up, for research on the operation of LiDAR sensors in adverse weather conditions, it is possible to use both professional chambers successfully, and their research infrastructure, as well as research, test rigs constructed for the needs of a specific experiment. It should be noted that the detailed methodology for both construction and simulation of weather conditions in test rigs has not been developed and rigardised so far. Individual teams of researchers individually undertake various activities aimed at ensuring the highest possible accuracy of measurements. Therefore, it is impossible to distinguish one best method of constructing such a test rig, but there are certain features that such a test rig should have:

- the ability to ensure repeatability of measurements,
- the ability to simulate various weather conditions (e.g. rain of varying intensity).
- the ability to change the location of the tested device,
- size matched to the parameters of the tested device,
- a variety of exposure targets (reflectors with a fixed reflectivity coefficient, road signs, horizontal road signs, road infrastructure elements, mannequins imitating pedestrians, etc.),
- possibility of implementing new illumination targets,
- the ability to change the position of the targets for exposure.

3 Designed Test Rig

When starting the construction of the position, the goal was to fulfil all the criteria listed in the earlier part of the paper. For this purpose, it was decided to build an external test

rig consisting of 3 elements: a rain shower (simulator) with a hydrophore, LiDAR sensor and reflective targets (scene).

The construction of the rain shower is made of a wooden frame equipped with four water pipes. For this purpose, composite pipes with a diameter of one quarter inch were used. Their main advantage lies in the quick and easy assembly and the possibility of attaching measuring devices, e.g., pressure gauges, to them. To ensure even distribution of water, each of the pipes was drilled at 15 points. The pipes, 150 cm long, are each arranged in parallel, with 50 cm intervals. The rig is designed so that it is possible to increase the intensity of rainfall both by filling consecutive pipes with water and by increasing or reducing the water flow separately for each pipe. The adjustment is made independently for each of the pipes. The water pressure in the system was confirmed by the indications of two independent pressure gauges permanently installed in the system. The rig was designed in such a way that its structure enables its easy modification in the event of the necessity to simulate the change of intensification of rainfall. Constructed rain shower and the reflective targets are shown in Fig. 3.

Fig. 3. Constructed rain shower and reflective targets. Source: own research.

An important issue is the need to ensure adequate water pressure. To maintain the accuracy of the measurements and repeatability of the results, it was necessary to ensure that the water was always flowing in the system under sufficiently high pressure.

For this purpose, a 750 W pump was used, and it was connected to a water tank (reservoir) with a nominal capacity of 100 L. The basic parameters of the test rig are presented in the Table 2.

The rain shower allows you to simulate heavy rain in the range of 224 l/h to 568 l/h. Its design enables to change the rain intensity in the future.

The LiDAR LIVOX Horizon was used as the measurement sensor. It is a pulsed solid-state (non-oscillating) LiDAR designed and manufactured as a sensor for use in a

Table 2. Test rig parameters, source: own research.

Dimensions of the test rig	1.5 m x 9 m x 1.7 m
Dimensions of the rain shower	1.5 m x 1.5 m x 1.7 m
Maximum availabe water pressure	7.5 bar
The accuracy of the flow meter	± 10% for pressures from 2 to 8 bar
Number of water distribution pipes	4
The highest measured flow	568 l/h
The lowest measured flow	224 l/h
Tested Lidar	LiDAR Livox Horizon
Dimensions of the largest target	40 cm x 90 cm
Distance from LiDAR to targets	9 m

autonomous car. The basic parameters of the LiDAR sensor used are presented in the table below (Table 3):

Table 3. Livox Horizon Basic Specs, Source: Livox Website.

Livox Horizon sensor	
Wavelength	905 nm
Range	90 m @ 10% reflectivity, 130 m @ 20% reflectivity, 260 m @ 80% reflectivity
Field Of View (FOV)	81.7° vertical x 25.1° horizontal
Number of generated points	240,000 points / second
IP standard	IP 67

The selected LiDAR sensor has a wide FOV, and its effective range is up to 240 m. The targets illuminated by LiDAR were models of road signs and a model of a passenger car, made on a 1:5 scale. Mockups were prepared on a scale because the effective range of LiDAR sensor is much larger than the size of the test rig. The light reflectivity of an object is shown on the screen in colours from blue with low reflectivity to red at its highest values.

The mockups were made of reflective material with a very high coefficient of light reflectivity (Lambert reflection) oscillating around 255.00 (the maximum possible to obtain). As a result, the illuminated targets are shown in red in the image returned by the device. The image of the point cloud generated by the LiDAR sensor, seen in the LivoxViewer program (software provided by the LiDAR manufacturer - Livox), is shown in Fig. 4.

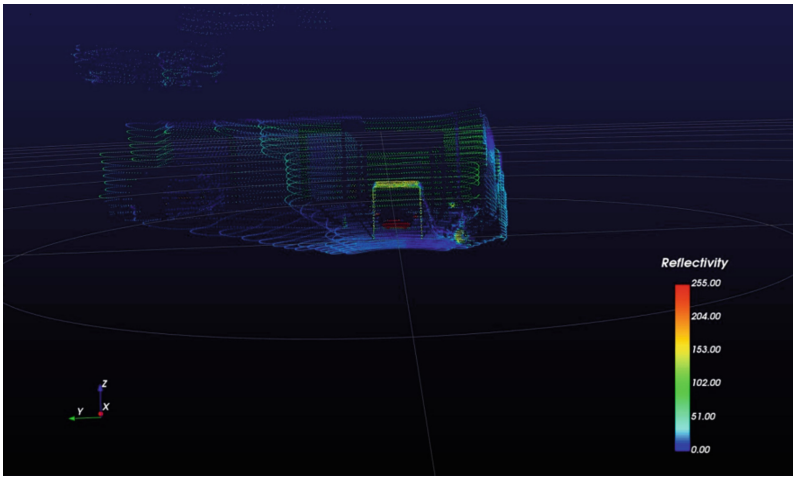


Fig. 4. Point cloud generated by LiDAR displayed in Livox Viewer. Source: own research.

4 Experimental Research

As part of the experiment, rain with three intensity levels was simulated: below16.6 mm/h (<135 l/h) (drops below the effective operating range of the flow meter), 16.6 mm/h (224 l/h) and 25.8 mm/h (348 l/h). Visualisations of the obtained point cloud in the LivoxViewer program (software provided by the LiDAR manufacturer - Livox) are shown in the figures below:

In order to analyse the obtained images, a detection algorithm was used. This algorithm works by recognising the colour of pixels. The first step was to read the searched pixel colour - the algorithm read the RGB colour (76,0,15). A colour selection tolerance of 10% was allowed for all components of the colours. The detection result for the Fig. 5a (without rain) is shown in Fig. 6:

An additional filter based on a mask was used to increase detection accuracy. A mask is an algorithm that analyses groups of pixels in a given area. Without a mask, each pixel is analysed separately, while the mask filter increases the analysed area from one pixel (1x1) to the area of three pixels by three pixels (3x3). A given field is marked if at least half of its pixels meet the given colour criteria. The effect of the filtering algorithm is shown in Fig. 7.

The mask filter allowed for a more accurate marking of the searched object and eliminated the distortions previously visible at the top of the drawing. As the use of a mask filter increases detection accuracy, the analysis of the remaining images was performed using it.

Figure 7a and 7b are almoust the same, while Fig. 7c shows that one of the illuminated targets has not been identified. The exact results of the detection of targets are presented in Table 4:

The total number of pixels in the analysed area was 7,826. For the image without rain, the number of pixels detected was the largest, and objects marked in this way constituted 20.96% of the entire image. In the case of rain below 16.6 mm/h and 16.6 mm/h, the

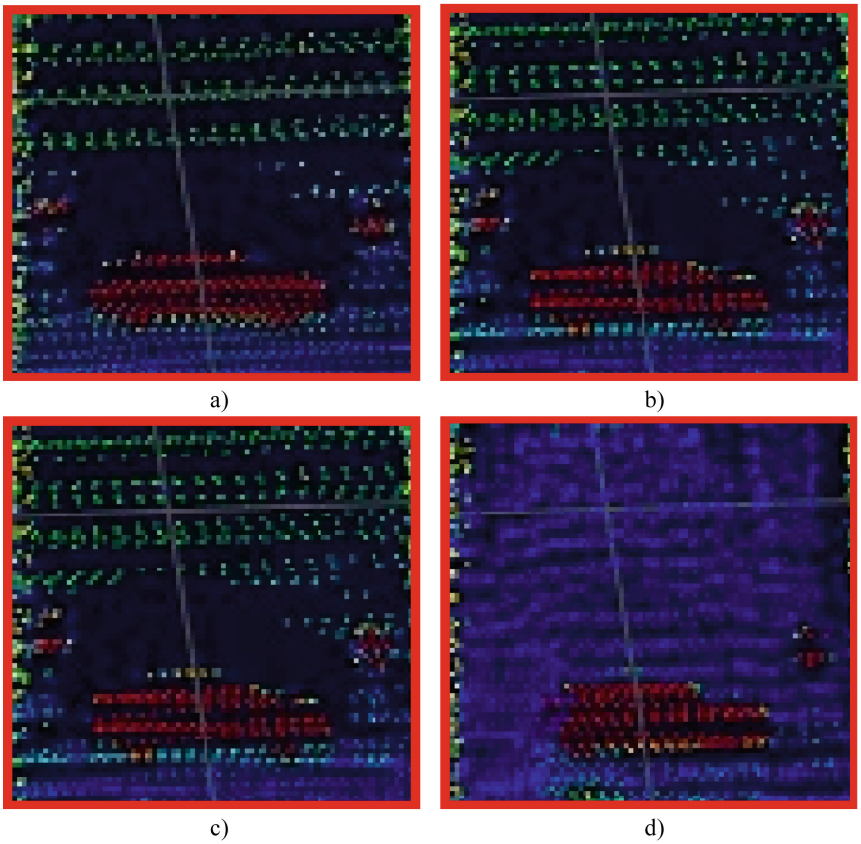


Fig. 5. Comparison of images from LiDAR: a) image without rain b) rain below 16.6 mm/h c) rain 16.6 mm/h, d) rain 25.8 mm/h. Source: own research.

Fig. 6. Detection result for the image without rain. Source: own research.

results were very similar. There was a slight decrease in the number of pixels detected (1,461 and 1,518), while the number of objects detected did not change. The greatest

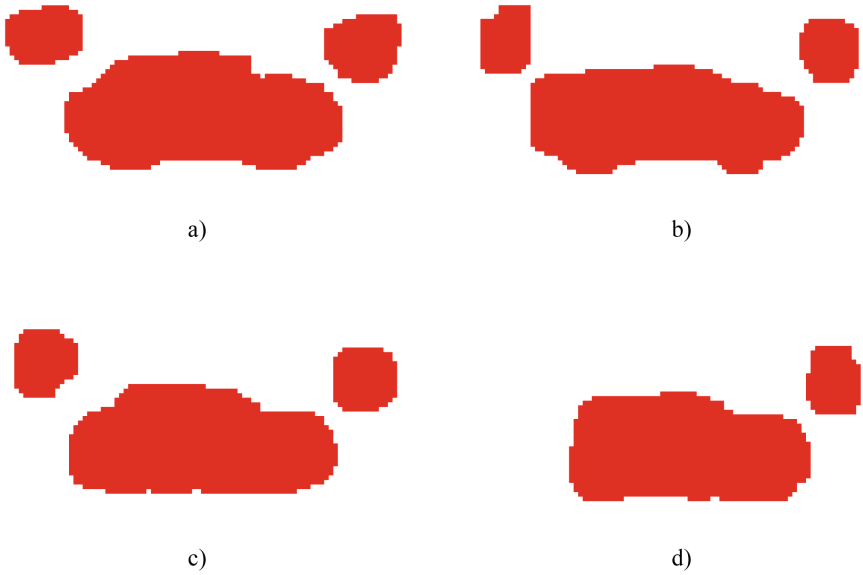


Fig. 7. Detection results for an image using a 3x3 pixel mask. a) no rain, b) rain below 16.6 mm/h, c) rain 16.6 mm/h, d) rain 25.8 mm/h. Source: own research.

Table 4. Detection results for RGB (76,0,15) ± 10% color and 3x3 pixel mask filter.

Image	Total number of pixels	Number of pixels detected	Number of pixels detected as a % of the total	Number of targets detected
No rain	7,826	1,640	20.96%	3
Rain below 16.6 mm/h	7,826	1,461	18.67%	3
Rain 16.6 mm/h	7,826	1,518	19.40%	3
Rain 25.8 mm/h	7,826	1,236	15.79%	2

decrease in the number of pixels detected was for rain with an intensity of 25.8 mm/h (1,236), which corresponds to a decrease in the number of pixels detected in relation to their total number by 5.17%. Moreover, due to the deterioration of the detection quality caused by heavy rain, one of the target objects, a mockup of a road sign, was not recognised.

5 Conclusion

The literature review proves that it is possible to build an effective, external LiDAR sensor test rig. The rigs built outside are much cheaper and easier to build than complex

test chambers, and at the same time, they ensure acceptable quality and repeatability of the performed measurements.

As part of the investigation, an external test rig was built, consisting of a rain shower, LIVOX LiDAR sensor, vehicle models and road signs. The rig provides a constant water pressure of an appropriate value allowing to obtain repeatable pressure values in the pipes responsible for obtaining the required intensity of rainfall. The use of mockups of the car and road signs made in the scale of 1:5 allowed to optimise the dimensions of the rig while maintaining the required accuracy of the analysis of the obtained image. The use of the mask filtering algorithm allowed for the elimination of disturbances and an increase in the accuracy of the analysis.

The preliminary tests allowed for assessing the impact of rainfall intensity on the obtained LIDAR sensor image. The research was conducted for the rain of three different intensity levels. The analysis of materials showed that rain with the intensity (0–16.6 mm/h) is a slight disturbance to the LiDAR sensor operation, and the reduction in the number of pixels detected was from 8.5% to 11%. Neither target ceased to be visible. On the other hand, rain of greater intensity significantly disturbed the operation of the LiDAR sensor, reducing the detected pixels by 24.6%. The disruption of LIDAR sensor operation was so significant that one of the illuminated targets - a road sign mockup, was not detected.

The conducted preliminary research allows for the direction of further research on the operation of LiDAR sensor and image recognition algorithms, improving its performance in the rain.

References

1. Bijelic, M., Gruber, T., Ritter, W.: A benchmark for lidar sensors in fog: is detection breaking down? IEEE Intelligent Vehicles Symposium (IV), pp. 760–767 (2018)
2. Brummelen, J., O'Brien, M., Gruyer, D., Najjaran, H.: Autonomous vehicle perception: the technology of today and tomorrow. Transp. Res. Part C **89**, 384–406 (2018)
3. Brzozowski, M., Parczewski, K.: The influence of adverse weather conditions on the operation of sensors used in autonomous cars. Projektowanie, badania i eksploatacja, University of Bielsko-Biala, pp. 23–37 (2021)
4. Colomb, M., Duthon, P., Laukkanen, S.: Characteristics of Adverse Weather Conditions
5. DENSE. https://www.dense247.eu/fileadmin/user_upload/PDF/DENSE_D2.1_Characteristics_of_Adverse_Weather_Conditions.pdf. Accessed 7 Apr 2022
6. Druml, N., Maksymova, I., Thurner, T., van Lierop, D., Hennecke, M., Foroutan, A.: 1D MEMS micro-scanning LiDAR. In: International Conference on Sensor Device Technologies and Applications, Venice, Italy (2018)
7. Eskandarian, A.: Handbook of Intelligent Vehicles. Springer, London, vol. 2 (2012). https://doi.org/10.1007/978-0-85729-085-4
8. Filgueira, A., González-Jorge, H., Lagüela, S., Díaz-Vilariño, L., Arias, P.: Quantifying the influence of rain in LiDAR performance. Measurement **95**, 143–148 (2017)
9. Goodin, C., Carruth, D., Doude, M., Hudson, C.: Predicting the influence of rain on LIDAR in ADAS. Electronics **8**(1), 89 (2019)
10. Hasirlioglu, S., Kamann, A., Doric, I., Brandmeier, T.: Test methodology for rain influence on automotive surround sensors. In: IEEE 19th International Conference on Intelligent Transportation Systems (ITSC), Rio de Janeiro, Brazil (2016)

11. Jokela, M., Kutila, M., Pyykönen, P.: Testing and validation of automotive point-cloud sensors in adverse weather conditions. Appl. Sci. **9**(11), 2341 (2019)
12. Kutila, M., Pyykönen, P., Holzhüter, H., Colomb, M., Duthon, P.: Automotive LiDAR performance verification in fog and rain. In: 21st International Conference on Intelligent Transportation Systems (ITSC), Maui Hawaii, pp. 1695–1701 (2018)
13. Lewandowski, P.A., Eichinger, W.E., Kruger, A., Krajewski, W.F.: Lidar-based estimation of small-scale rainfall: empirical evidence. J. Atmos. Oceanic Tech. **26**(3), 656–664 (2009)
14. LIVOX LIDAR Specs. https://www.livoxtech.com/horizon/specs. Accessed 04 July 2022

Development of a Technology for Monitoring Passenger Traffic in the Context of Intelligent Transport Systems

Mykyta Volodarets[1](✉), Igor Gritsuk[2], Sergii Pronin[3], and Alona Yurzhenko[2]

[1] Pryazovskyi State Technical University, Universytetska Str., 2, Mariupol 87555, Ukraine
volodarets.nikita@yandex.ru

[2] Kherson State Maritime Academy, Ushakov Ave., 20, Kherson 73000, Ukraine
{gritsuk_iv,sergiy9977}@ukr.net

[3] Kharkiv National Automobile and Highway University, St. Yaroslava Mudrogo, 25, Kharkov 61002, Ukraine
mz@ksma.ks.ua

Abstract. The article shows the results of the analysis of the development of municipal passenger transport. The regulations on the existence and the need to overcome the contradictions between the desired and existing systems for the provision of transport services to the population are formed on the basis of this analysis. The expediency of creating a decision support system for the subjects of the passenger transportation market is shown. It was based on the creation of a single information space for traffic participants in transport systems. A new method for assessing the passenger's choice of travel path based on the MNL (multinomial model) has been developed. The developed method makes it possible to obtain and predict the form of the attractiveness function of urban routes in any city for its further use in models for the formation of rational route networks. A new intelligent technology for monitoring passenger traffic has been proposed. The practical significance of the results obtained lies in the original approach to monitoring passenger traffic, proposed on the basis of the use of information technologies and distributed multidimensional databases. The result of the application of appropriate information and communication technologies for monitoring the movement of passenger transport is useful for the development of transport infrastructure in large cities. This will make it possible to profit from the rational distribution of resources for the maintenance of the route network of cities and regions.

Keywords: Intelligent transport system · Vehicle · Urban passenger transport · Passenger transport monitoring · Data warehouse technology · Automated questionnaire survey

1 Introduction

Monitoring of passenger traffic consists in obtaining information about the state of traffic, tracking and its dynamics forecasting. Monitoring is aimed at improving transport

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 23–32, 2023.
https://doi.org/10.1007/978-3-031-25863-3_3

services for residents of large cities and regions by improving and coordinating the work of transport organizations. The monitoring system has two components: a source of information and a system for storing, evaluating and organizing the information received. The current level of development of the transport infrastructure of cities and regions requires the intellectualization of all components of monitoring, the introduction of new information technologies for monitoring passenger traffic, taking into account the collective opinion of the transportation process participants [1–4].

Monitoring of passenger traffic in a city or region should be considered as an intelligent DSS for the decision maker's choice of alternative options for organizing transport processes, route networks and rolling stock, information development of the transport infrastructure of cities and regions. These systems combine Online Analytical Processing (OLAP) and DataMining. This combination is a new information technology that is focused primarily on users with their actual specific needs.

2 Formation of a Utility Criterion When Choosing a Route

As a result of the analysis of scientific and technical literature [5–18] devoted to the issues of modeling options for the movement of passengers in cities, two main approaches to the choice of a model can be distinguished. The first approach allows determining the probability of a passenger choosing a travel path based on the general characteristics of each route option. Within the framework of this approach, the most widespread are standard or linear models, in which the probability of a passenger choosing a travel path is directly determined by the parameters of the travel path. Another variant of the implementation of this approach is the MNL models, in which the probability of a passenger choosing a travel path is proportional to the exponent of its parameters. The second approach is based on the assumption that each passenger, when choosing a route option, uses the first vehicle from the routes that suit him. In this case, the frequency of route selection is proportional to the traffic intensity, taking into account the level of travel conditions. However, this approach is more consistent with the case of choosing a specific route on a section of the transport network common for several routes than choosing the entire path. Therefore, the models of the first approach were adopted for further development.

Analysis of modeling methods for the procedure for choosing a passenger's route of travel showed the similarity of approaches to solving this issue, but did not answer the question of how to obtain the coefficients of the models. The difference between MNL-models and linear models lies only in the general form of the function of attractiveness or cost of routes, however, the mechanism of their use to determine the probability of a passenger choosing a route of travel is the same in principle.

$$P_i = A_i / \sum_{j}^{n} A_i, \tag{1}$$

where Pi – choice probability of i route; n – number of variants of the route; Ai – calculation function of route attractiveness.

The value of the function A_i is determined depending on the model of distribution of passenger flows. For linear model.

$$A_i = \prod_i, \tag{2}$$

where Π_i – attractiveness function of route.

For MNL – model:

$$A_i = exp(A_i') \tag{3}$$

The problem is that in order to obtain the type of function, the methods of survey of intentions were mainly used, the result of which is just the definition of the attractiveness function. It remains only to obtain the value of the coefficients of the models (most often linear ones) and substitute them in the corresponding expressions.

To do this, firstly, it is necessary to determine the value of the attractiveness function through the probability of the passenger's choice of the movement path. For the general case, one can write down a system of equations with probabilities as coefficients and attractiveness functions as unknowns.

$$\begin{cases} (P_1 - 1) \cdot A_1 + P_1 \cdot A_2 + ... + P_1 \cdot A_n = 0; \\ P_2 \cdot A_1 + (P_2 - 1) \cdot A_2 + ... + P_2 \cdot A_n = 0; \\ ..... \\ P_n \cdot A_1 + P_n \cdot A_2 + ... + (P_n - 1) \cdot A_n = 0. \end{cases} \tag{4}$$

This is a homogeneous system of n linear equations with n unknowns. Possible variant of its solution is a trivial solution, i.e., all values of the attractiveness function are equal to zero or there are many linearly dependent solutions. In the first case, the rank of the coefficient matrix must be equal to the rank of the extended matrix; for a homogeneous system, this means that the coefficient matrix must be unexpressed. Since the trivial solution does not correspond to the problem statement, it is necessary to prove that the determinant of the coefficient matrix is equal to zero. In matrix form, the system looks as follows:

$$\begin{vmatrix} P_1 - 1 & P_1 & ... & P_1 \\ P_2 & P_2 - 1 & ... & P_2 \\ ..... & ..... & ..... & .. \\ P_n & P_n & ... & P_n - 1 \end{vmatrix} * \begin{vmatrix} A_1 \\ A_2 \\ .... \\ A_n \end{vmatrix} = \begin{vmatrix} 0 \\ 0 \\ ... \\ 0 \end{vmatrix} \tag{5}$$

Or alternatively, in matrix form:

$$P \cdot A = Z \tag{6}$$

If we add all n-1 of other rows to the last row of the matrix P, then each column of this matrix will contain the expression.

$$\sum_j^n P_i - 1 = 0. \tag{7}$$

Thus, the nth row will be zero, since such transformations do not change the value of the determinant, which means that $det\ P = 0$, i.e., the solutions of the system are linearly dependent and at least one of them can be specified arbitrarily.

If we specify a value for one attraction from the set $1 \ldots n$, for example A_1, then other values A_i, $i \neq 1$ are determined from the statement.

$$A_i = A_1 \cdot P_i / P_1. \tag{8}$$

Therefore, for each questionnaire it is necessary to set one arbitrary value, however, the best approximation for it may be the value obtained not by calibration, but using the least-square method. That is, the A1 value for each questionnaire should be the variables or factors that determine the A1 value. For each i questionnaire, one can write down n equations of the following type, if a linear description is used.

$$\begin{cases} a_0 + a_1 \cdot F_{11} + a_1 \cdot F_{21} + \ldots + a_m \cdot F_{m1} - 1 \cdot A_i = 0; \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ a_0 + a_1 \cdot F_{1n_i} + a_1 \cdot F_{2n_i} + \ldots + a_m \cdot F_{mn_i} - \dfrac{P_{n_i}}{P_1} \cdot A_i = 0. \end{cases} \tag{9}$$

where a_m is the regression coefficient at m factors that determine the value of attractiveness; F_{kj} is the value of the kth factor in the jth variant of the movement path; A_i is the value of the attractiveness function for the 1st variant of the movement path in the i questionnaire; P_1 is the probability of choosing the first variant of the movement path of the i questionnaire; n_i is the number of movement options in the i questionnaire; m is the number of factors in the regression equation (path parameters).

Thus, each questionnaire adds one variable A_i to the array of factorial features.

The total number of factorial features N_f in the set of information for regression analysis is determined from the expression:

$$N_f = m + N_a, \tag{10}$$

where N_a is the number of questionnaires based on the survey results.

However, the result for all experiments, the number of which N_o is determined from the following expression, is equal to zero.

$$N_0 = \sum_{i}^{N_a} n_i. \tag{11}$$

Most $n_i > 1$, and $N_a >> m$, i.e., the number of experiments significantly exceeds the number of factorial features:

$$N_o >> N_f. \tag{12}$$

One should not expect a linear relationship between parameters or observations, since they are the outcomes of a random selection of the results of the behavior of different people in the transport system. There are quite a lot of motives for such behavior

so that even in the equal conditions different people make different decisions. Therefore, here one should expect not only one result, in accordance with the properties of a homogeneous matrix:

$$\forall a_k = 0,\ k = 1 \ldots m \ldots \tag{13}$$

It is possible to get out of this situation by abandoning the homogeneity of the data set, i.e., setting the value of one base variable. Let it be A = 1.

The search for regression coefficients for such a dataset must be performed with an intercept, since it has a completely definite physical meaning here - this is the attractiveness of a route with zero values of the travel path parameters. For most of the parameters, the regression coefficients should be negative if they characterize the cost of travel of one type or another. It should be borne in mind that these values of the regression coefficients are meaningful only for $m + 1$ of the first factors.

The next consideration concerns the MNL model. Since $A_i = exp(\Pi_i)$, for it, the regression coefficients can be obtained only after transformations based on (10). This expression, taking into account (5), is written as follows.

$$exp(A_1')/P_1 = exp(A_i')/P_i. \tag{14}$$

After taking the logarithm of this equation, by analogy with (15), we can obtain.

$$A_i' = A_1' - -ln(P_1) + ln(Pi). \tag{15}$$

Thus, to obtain the type of the MNL model, it is necessary to first determine the natural logarithms of the probabilities of choosing the options for the travel routes.

Final consideration. For the convenience of using the obtained regression coefficients, it is not necessary to set the value of the base indicator A_1 equal to one. The higher this value is, the higher the value of the regression coefficients.

3 Preparing Data for the Route Selection Model for Further Processing by the Operational Analysis Method

After calculating the parameters of the questionnaires in the processing system, they were transferred to the STATISTICA package to obtain the coefficients of the regression models. Calculations using the linear model gave poor results, the total correlation coefficient did not exceed 0.6 for various parameters. Therefore, it was concluded that it was necessary to use the MNL model with its results which looked successful. The general characteristics of the model are quite high. However, a number of indicators such as path length, coefficient of transport fullness and number of transfers have not confirmed their significance. Therefore, they were not included in the final version of the model. However, the model for determining attractiveness cannot fully characterize the final result of the calculations - probability of selection the route by passengers. Therefore, an additional calculation was carried out in order to determine the accuracy of the resulting model with respect to the probability of selection the route by passengers. Here, theoretical probabilities were compared with probabilities that were obtained from the

survey. Since the maximum accuracy of the results is 0.2 (five days of the survey), in each case the value of the qualitative indicator of the error was found, which is compared to one if the error is greater than 0.2 and exactly zero otherwise. The calculation results indicate a fairly high degree of model accuracy. Only in minor cases there is exceeding the permissible deviation of the probability of selection the route by a passenger. The maximum discrepancy between theoretical and actual values is 0.279.

Such deviations cannot be considered significant. Refinement of the parameters of the model can be carried out by increasing the survey period and increasing the sample size. When using the MNL model, the question arises of determining the options for the route, which should be considered as alternative when calculating the probability of choosing the route, since for any combination of significant parameters, the model will provide a positive value of the probability. The survey results confirmed the conclusions of [18] that it is enough to consider 3 alternatives that have the maximum attractiveness.

4 Implementation of Intelligent Monitoring Technology

Modern information and communication technologies without unnecessary software costs allow monitoring and evaluating the questionnaire, which proves the possibility of introducing such systems on the basis of existing computer networks in a large city. Compliance with the existing computer network and the HTTP protocol is sufficient. On the part of the respondent, it is necessary to have a regular Web browser, which will make it possible to carry out the survey on any modern computer, regardless of the operating system installed. The database server can be commercial solutions based on Microsoft SQL Server 2005/2008 and later, or a free version of MySQL supported by Oracle. An important aspect for solving monitoring problems is the implementation of registration of data provided by respondents in their responses to the electronic form of the questionnaire. Such a questionnaire, as a component of a transport Web portal, can be implemented using the ASP.NET MVC Framework technologies - a framework for creating web applications that implements the Model-View-Controller pattern.

To solve the assigned monitoring tasks and reduce the requirements for the qualifications of system administrators who will maintain the system, one of the optimal solutions will be the use of cloud computing technology - Platform as a Service. This model of providing cloud computing assumes that the entire information technology infrastructure, including computer networks, servers, storage systems, is entirely controlled by the provider, and the consumer is given the opportunity to use the platform to launch applications. The noted features of receiving and transforming monitoring data were used in Kharkiv National Automobile and Highway University (KNAHU) when creating a universal transport portal (Fig. 1).

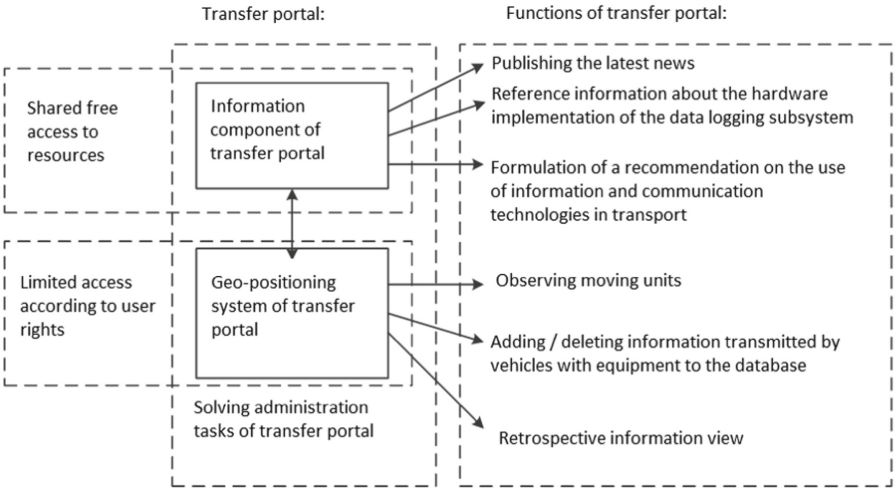


Fig. 1. The structure of the components of the transport portal.

It is universal distribution computer system for monitoring land transport and traffic environment. This is a two-level compute system that provides information and communication technology for the movement of land transport and consists, first of all, of a special website. The transport DBMS technology is proposed to be built on the basis of the "client-server" technology, which will have two parts - a client application (front-end) and a database server (back-end). In general, the developed monitoring system can be found in Fig. 2.

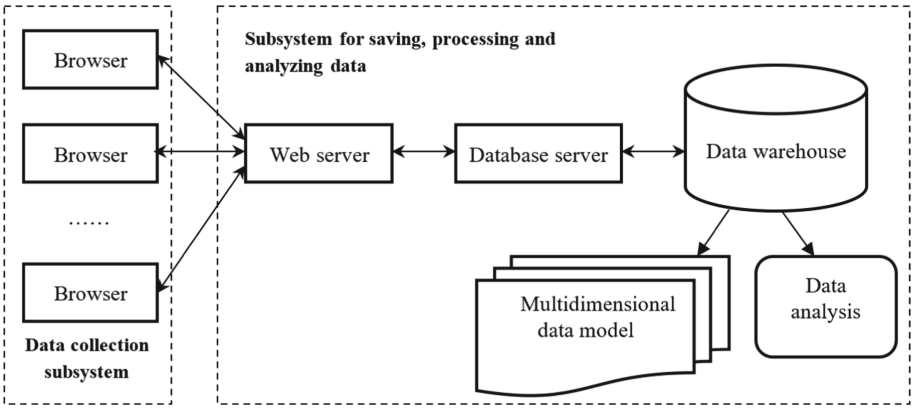


Fig. 2. General diagram of the monitoring system.

5 Technical Efficiency of the Monitoring System

By the technical efficiency of monitoring we mean the definition of the reliability of a given system.

In our case, we have client-server software. The server serves requests from N client programs. In software, errors are evenly distributed over the input domain, among which the most common are:

1. Software failures. If the software is not modified, then the rate of its failures remains constant.
2. Internal failures in the program. Such failures are due to fundamental limitations of the algorithm used in the software (for example, the use of heuristic algorithms can lead to random failures).
3. Failures due to real-time operation restrictions. In the systems under consideration, the environment can change dynamically.

The results of the analysis of the system allowed us to draw preliminary conclusions about the possible load. With the given system characteristics, channels with 10 remain unloaded. Average intensity of servicing requests equals 2.5. The average processing time for one request by the application server is 0.4 s. Comparison of the results of simulation and analytical modeling of the system allows us to draw conclusions about the correctness of the constructed simulation model Average service time of a request – 0.4 and 0.40 s; system load – 4 and 3.8; the average number of requests in the system is 3.9 and 3.8 for analytical and simulation models, respectively. The resulting model is adjusted taking into account the heterogeneity of the flow of requests, different types of input flows. The simulation results are given in Fig. 3.

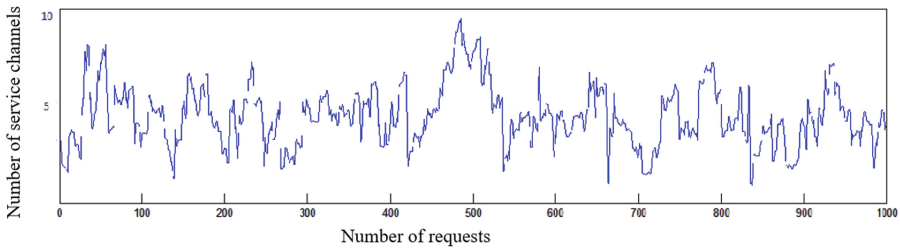


Fig. 3. System load simulation results.

6 Conclusions

The analysis of the development of urban passenger transport showed the existence and need to overcome the contradictions between the desired and the existing system of providing transport services to the population. Their detection and elimination is the key to the successful development of the corresponding transport infrastructure of cities

and regions. The basis for such development is the updating and implementation of the latest information, intelligent and network technologies for monitoring the state of the passenger transportation system.

The expediency of creating a decision support system for the subjects of the passenger transportation market is shown. It is based on the creation of a single information space for traffic participants in transport systems.

A new method for assessing the passenger's choice of route based on the MNL (multinomial model) has been developed. The maximum discrepancy between the theoretical and actual values of the model is 0.279. Refinement of the parameters of the model can be carried out by increasing the survey period and sample size. The developed methodology allows one to obtain and predict the type of the attractiveness function of urban routes in any city for its further use in models of the formation of rational route networks.

The practical significance of the results obtained lies in a new approach to monitoring passenger traffic, proposed to be based on the use of information technologies and distributed multidimensional databases. The result of the application of appropriate information and communication technologies for monitoring the movement of passenger transport is useful for the development of the transport infrastructure of large cities, tested in the conditions of Dnepropetrovsk, Donetsk and Kharkov regions. This provides up to 10–15% of the profit from the rational distribution of resources for the maintenance of the route network of cities and regions. Instead of the usual costs of 10,000–15,000 UAH for the preparation of recommendations to assess the human factor for making one decision on organizing a new route, costs of 1–2,000 UAH are sufficient. In a big city, the savings from the implementation of the proposed monitoring technology are about 10,000 UAH per year. Theoretical regulations on the information development of transport systems have become the basis for teaching the following training courses: "Flexible computerized transport systems", "Modeling of transport machines and processes."

References

1. Gorobchenko, O., et al.: Intelligent locomotive decision support system structure development and operation quality assessment. In: 2018 IEEE 3rd International Conference on Intelligent Energy and Power Systems (IEPS), Kharkiv, pp. 239–243 (2018). https://doi.org/10.1109/IEPS.2018.8559487
2. Prizhibyl, P., Svitek, M.: Telematics in Transport. MADI (STU), Moscow (2003)
3. Volodarets, M., Gritsuk, I., Chygyryk, N., Belousov, E., et al.: Optimization of vehicle operating conditions by using simulation modeling software. SAE Technical Paper 2019–01–0099 (2019). https://doi.org/10.4271/2019-01-0099
4. Vychuzhanin, V.V., et al.: Analysis and structuring diagnostic large volume data of technical condition of complex equipment in transport. In: Machine Modelling and Simulations 2019 (2020). https://doi.org/10.1088/1757-899X/776/1/012049
5. Livshits, V.V.: The system concept of the city and mathematical modeling of the adaptive behavior of the urban population. The use of applied systems analysis in the design and management of urban development, p. 120 – 147. Moscow, Stroyizdat (1974)
6. Rogova, G.L.: Modeling the Choice of Routes for the Movement of Passengers in the Transport Systems of Cities. Moscow (1987)

7. Branovitskaya, S.V.: Economic and Mathematical Models of Forecasting Passenger Traffic in Cities. Kyiv (1971)
8. Vasiliev, V.M.: Investigation of Some Regularities in the Formation of Passenger Traffic on the Urban Route Network of Public Transport. Saratov (1978)
9. Krivosheev, D.P.: Methods of distribution of passenger traffic in transport calculations (review). CSTI on civil engineering and architecture. Moscow (1974)
10. Rickberg, G.S.: On the Method of Modeling Intracity Labor Relations. City and passenger, pp. 48–51. Stroyizdat, London (1975)
11. Soymina, E.Y.: Development of Dynamic Models of Passenger Traffic and their Application to Control Loads on Public Transport Networks. Almaty (1988)
12. Faience, O.G.: Mathematical models of the formation of passenger traffic flows. Mathematical methods in the management of urban transport systems. Institute of Socio-Economic Problems, pp. 621, Nauka (1979)
13. Shaposhnikov, S.V.: Methodology for Calculating Passenger Traffic in Citie. Moscow (1969)
14. Makarov, I.P., Yavorsky, V.V., Tuzovsky, A.F.: Prediction of the distribution of passenger traffic when changing the route network of passenger transport, Modeling of transport systems management processes, pp. 3941. Vladivostok (1977)
15. Ryzhenko, L.I.: Modeling the movement of passengers along the city route network. In: Regional scientific and practical conference "Increasing the efficiency of the transport complex", pp. 1214. Omsk (1989)
16. Sadikhova, O.S.: Choice of the route by passengers. Urban transport and engineering preparation of territories, pp. 3341. LISI (1991)
17. Alekseev, V.O.: Intelligent technology of organizing the movement of vehicles. Automobile transport, Vol.10, pp. 305311. KNAHU, Kharkiv (2002)
18. Kruglov, V., Dli, M.: Intelligent Information Systems: Computer Support for Systems of Fuzzy Logic and Fuzzy Inference. Fizmatlit, Moscow (2002)

Intelligent Management of Traffic Flows in Large Cities

Bohdan Yeremenko[1](✉), Roman Mazurenko[2], Oleksii Stetsyk[2], and Anatolii Buhrov[2]

[1] Taras Shevchenko National University of Kyiv, Kyiv 01033, Ukraine
bohdan.yeremenko@knu.ua
[2] Kyiv National University of Construction and Architecture, Kyiv 03037, Ukraine
mazurenkodev@gmail.com, oleksiy130@gmail.com

Abstract. The study is devoted to solving the problem of traffic jams that arise on the roads of large cities due to various random factors. An overview of the modern systems of automatic control of traffic flows is provided, and the main reasons for the occurrence of traffic anomalies at intersections controlled by traffic lights are considered. The formalisation of input and output data corresponding to stochastic traffic conditions is shown. The research focuses on improving the city's traffic flow management systems by implementing distributed data processing systems. The architecture of the Distributed Data Processing System is proposed, and the scheme of its integration with the Intellectual Traffic Light Control System, which is being developed for automatic situational adjustment of traffic light operation, is shown. The practical significance of such integration lies in the ability to operate with up-to-date information about the situation on the city's roads, which is necessary for the automatic coordination of the city's traffic lights. This possibility can be realised thanks to the ability of distributed data processing systems to process large volumes of stochastic information in real time. In the future, the accumulation of statistical data on the state of traffic will provide an opportunity to form reliable samples for training artificial neural networks capable of processing data from video surveillance cameras.

Keywords: Data processing system · Distributed system · Random process · Traffic light · Urban logistics

1 Introduction

1.1 Basic Concepts

The basic concepts are used in the work:

- The concept "inadequate setting of traffic lights" means the inconsistency of traffic lights within the city.
- The concept of "optimization of the traffic management process" means the situational adaptation of the duration of the relevant traffic light to the traffic conditions around a certain controlled intersection.

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 33–42, 2023.
https://doi.org/10.1007/978-3-031-25863-3_4

1.2 Abbreviations

The abbreviations are used in the work:

- DDPS – Distributed Data Processing System;
- ITLCS – Intellectual Traffic Light Control System;
- GPS – Global Positioning System;
- POI – Point of Interest.

1.3 The Problem of Traffic Jams in Big Cities

According to the Road Traffic Index [1], the number of active cars is growing worldwide. At the same time, the growing number of this type of transport on the roads often exceeds the city's transport infrastructure capacity and leads to traffic jams. That is why the problem of traffic jams from year to year remains relevant for residents of many large cities who need to move quickly by road transport.

This problem is relevant for many large cities, but the causes of traffic jams in different cities can be other, for example [1]:

- An excessive increase in the number of cars exceeds the carrying capacity expected in the construction of urban roads, as in New York.
- The inadequate setting of traffic lights at intersections, as in Paris.

Before the armed aggression of the Russian Federation with the support of the Republic of Belarus, this began on the territory of Ukraine on February 24, 2022, Kyiv ranked third in the world for traffic jams [2].

Now the problem of intelligent management of traffic flows in Kyiv has become even more relevant in connection with the following processes taking place due to the war (see Fig. 1):

- Movement of a large number of vehicles.
- The large-scale destruction of overpasses caused redistribution of the load on city roads.

In addition, in reconstructing destroyed cities and roads, the task of optimising the country's transport infrastructure is relevant and appropriate. This, in turn, involves introducing intelligent systems for the automatic control of car flows.

Studies of modern automatic traffic control systems have shown that these systems can be divided into [3]:

- Systems of interaction with drivers.
- Monitoring and recognising car traffic systems.
- Traffic management systems.

Fig. 1. An example of the destruction of overpasses in Ukraine [4].

2 Overview of Modern Systems of Automatic Control of City Traffic Flows

2.1 Driver Interaction Systems

Driver interaction systems are essentially information systems supporting the driver's decision to choose a route [5, 6]. These systems are mainly based on various types of collected data regarding the current state of the roads that can be used to get from the actual location of the vehicle to the destination.

Rizwan et al. (2016) offered a mobile application for drivers with fairly accurate traffic data. At the same time, each driver independently solves the dynamic multi-criteria task of choosing a route and makes the best decision for him based on the data provided by the application. Big data analysis is performed based on information coming from cheap sensors that are placed every 500 m on certain roads [5].

Xueying et al. (2021) offered an interesting approach to analysing Global Positioning System (GPS) trajectory data and the influence of Point of Interest (POI). Then, based on the user equilibrium theory, they proposed a dynamic traffic flow assignment. It shows how to optimise the road network by making the right traffic assignment decisions [6].

2.2 Monitoring and Recognising Car Traffic Systems

Monitoring and recognising car traffic systems are designed to detect traffic anomalies quickly. Such systems use data obtained from the navigation systems of drivers and means of monitoring the road. These tools can record a car's time in a particular city and its average speed on certain road sections.

Monitoring and recognising car traffic systems are being developed and implemented in many cities [6, 7]. In Kyiv, before the beginning of the military operations of the

Russian Federation, an intelligent transport system was operating on the territory of Ukraine, which included 1,000 cameras connected to an analytical module for predicting traffic congestion and more than 70 "smart" cameras [8]. However, the technologies used in the operation of car traffic monitoring and recognition systems only allow forecasting the number of cars on city roads and do not solve the problem of intelligent management of car flows on a city scale.

2.3 Car Traffic Management Systems

Car traffic management systems are complex systems that are supposed to make decisions to decrease the average travel time.

The analysis of the works in which the problems of traffic organization in modern cities were studied showed that the tools of intellectual support are not sufficiently used in this area [3]. This leads to a loss of flexibility and makes it difficult to automate the process of optimising the process of managing traffic flows in large cities. That is why in this work, the research focus is on the development of an automatic adaptive system. The primary purpose of this is to reduce the trip duration and facilitate the movement of car users due to the situational adaptation of the period of the corresponding traffic light to the traffic conditions around a controlled intersection.

[4] proposes and describes in detail the model of the Intellectual Traffic Light Control System (ITLCS), which is being developed for adaptive traffic management at controlled intersections (see Fig. 2).

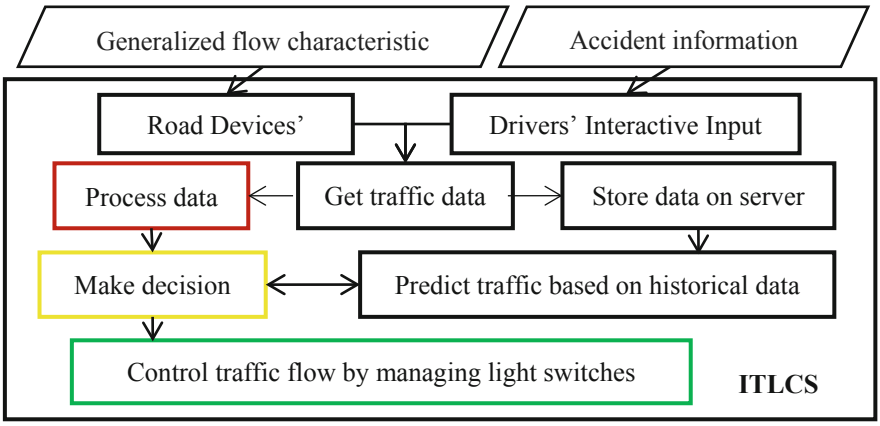


Fig. 2. Model of ITLCS [3].

An essential requirement for ITLCS is a real-time capability to:

- Process stochastic information about a large number of cars.
- Carry out intelligent situational control of traffic lights.

This work is a continuation of [3] and is aimed at developing the "Process Data" module architecture (see Fig. 2).

3 Optimisation of the Process of Managing Traffic Flows

Car traffic management at intersections controlled by traffic lights is carried out following the traffic rules, which ensures the free crossing of the intersection for a certain number of cars.

Figure 3 shows an example of one of the most common types of 4-way intersections.

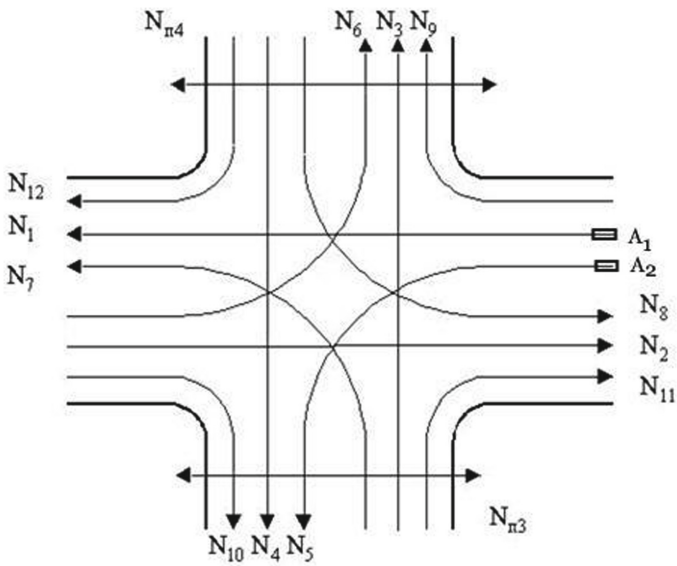


Fig. 3. An example of a 4-way intersection.

Duration $\left(\Delta t_k^j\right)$ of k-th ($k = \overline{1,3}$) traffic light signal, which ensures free crossing of the intersection by the car $A_i(i = 1, I)$ that occupies $N_j(j = \overline{1,J})$ line of the d-th ($d = \overline{1,D}$) section of the road, determined according to:

$$\Delta t_k^j = \sum_{i=1}^{Ij} (\Delta l / \langle v_i \rangle + i \langle \Delta t \rangle) \tag{1}$$

where (see Fig. 3):

- $\langle v_i \rangle$– the average speed of cars at green traffic light ($k = 1$) that cross the road section Δl;
- Δt– the average time interval between cars crossing a road section Δl;
- $J = 12$;
- $i = 1, j = 1$ for car A_1;
- $i = 2, j = 5$ for car A_2;
- d – the section of the road defined by the coordinates $R(t) = (x(t);y(t))$ and speed $v(t)$ of the car in the specified ($t = t_0 + \Delta t$) time.

Free crossing of the intersection by car A_1 implies a red ($k = 3$) traffic light signal for all cars whose trajectories intersect with the trajectory A_1, that is: N_3, N_4, N_6 and N_8 (see Fig. 3). A yellow ($k = 2$) traffic light signal is used to regulate possible traffic deviations from normal traffic by drivers. At the same time, most traffic lights work in automatic mode with predetermined time intervals for each signal. This means that in the event of traffic anomalies at the intersection, the fixed time of traffic signal switching additionally complicates the process of normalizing the situation around the intersection and restoring normal traffic in several directions at once.

Taking into account random factors that can lead to non-standard situations on the road section adjacent to the traffic light, it is assumed that Control traffic flow by managing light switches (see Fig. 3) is carried out in accordance with [4]:

$$\Delta t_k^j = \sum_{i=1}^{Ij} (\Delta l / \langle v_i \rangle + i \langle \Delta t \rangle + \delta\tau(s_1, s_2, s_3, s_4)) \tag{2}$$

where δt – the time of deviation of the duration of the traffic light signal from that expected in the standard situation according to (1).

Herewith among the main factors affecting the duration of the deviation time are:

- The impact of the accident (s_1).
- The influence of weather conditions (s_2).
- The condition of the road surface (s_3).
- The influence of the human factor (s_4).

Random changes in the modes of operation of various traffic lights, as a rule, affect the state of traffic on the sections of the road adjacent to the traffic lights (see Fig. 4).

Figure 4 shows the coordinates R(t) of the car Ai, which with probability (Pij) can occupy one of the lanes Nj of the road in the vicinity of the controlled intersection moving along one of the possible trajectories $\left(T_m^{A_i}, m = \overline{1, M}\right)$ with speed v(t).

Data on the coordinates and speed of the car on a certain section of the road can be determined with Drivers Interactive Input or by the Road Devices, in the field of view of which the car is [8].

If the ITLCS can predict the time of appearance of a given car on a certain section of the road, then a green traffic light signal ($k = 1$) will provide this car with a free intersection crossing. Thus, intelligent management of traffic flows within the city limits with situational control of each traffic light requires coordination of the operation of the traffic lights. This, in turn, involves the ability to automatically process stochastic information about a large number of cars that comes to ITLCS from various sources to determine the mathematical expectation ($M(I, j)$) and variance ($D(I, j)$) of the number of cars at any of the traffic lights.

Solving the task of processing information about the number of cars around the intersection relies on the Process data module (see Fig. 2), which is proposed to be implemented as an integrated Distributed Data Processing System (DDPS).

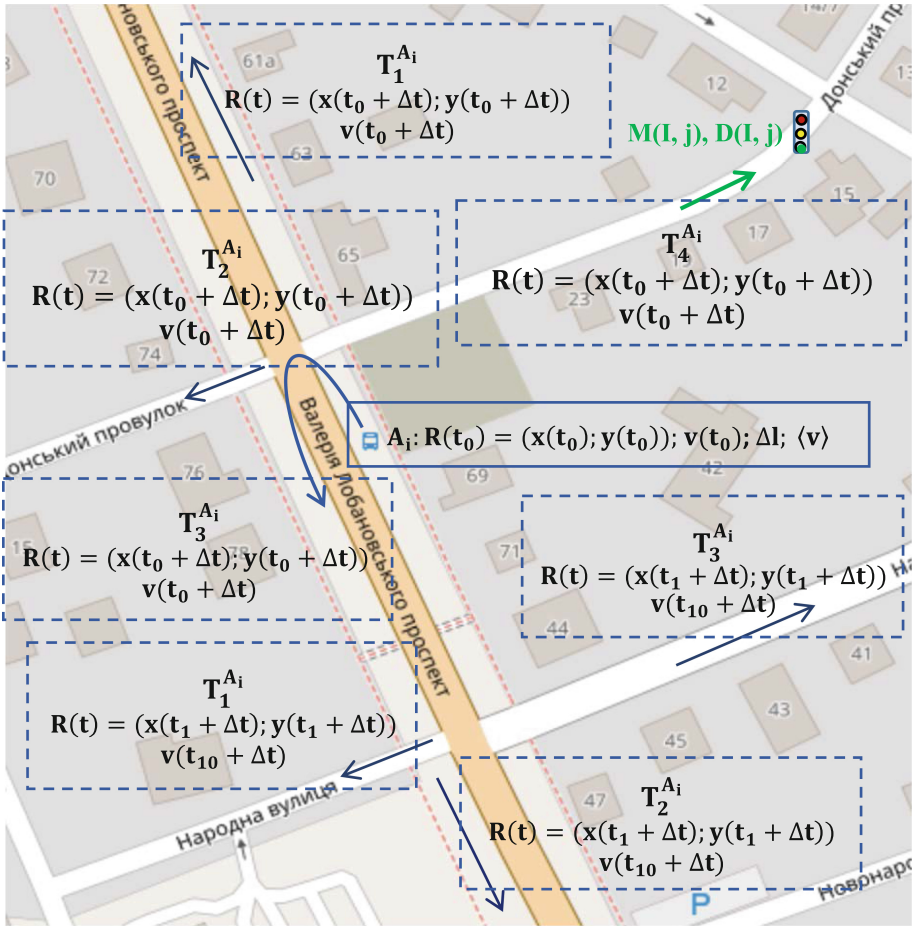


Fig. 4. An example of a road section with adjacent intersections in Kyiv [2].

4 Architecture of Distributed Data Processing System

Figure 5 shows a possible architecture of the integrated DDPS, which is being developed for data processing, on the basis of which "Make decision" (see Fig. 2) will make a decision regarding the activation and duration of the k-th ($k = \overline{1,3}$) traffic light signal.

This model uses data from drivers' navigation systems connected to the Traffic lights controller microservice. Such a connection will ensure a stable connection and continuous transfer of coordinates R(t) of the car (see Fig. 4) to DDPS via Websocket. In addition, Road Devices can be used to determine the coordinates and average speed of vehicles.

Each WebSocket handler will write data to a distributed Kafka message broker and a Cassandra database for further aggregation and analysis. At the same time, the load balancer will allow DDPS to automatically scale when the number of active machines increases, for example, during peak times.

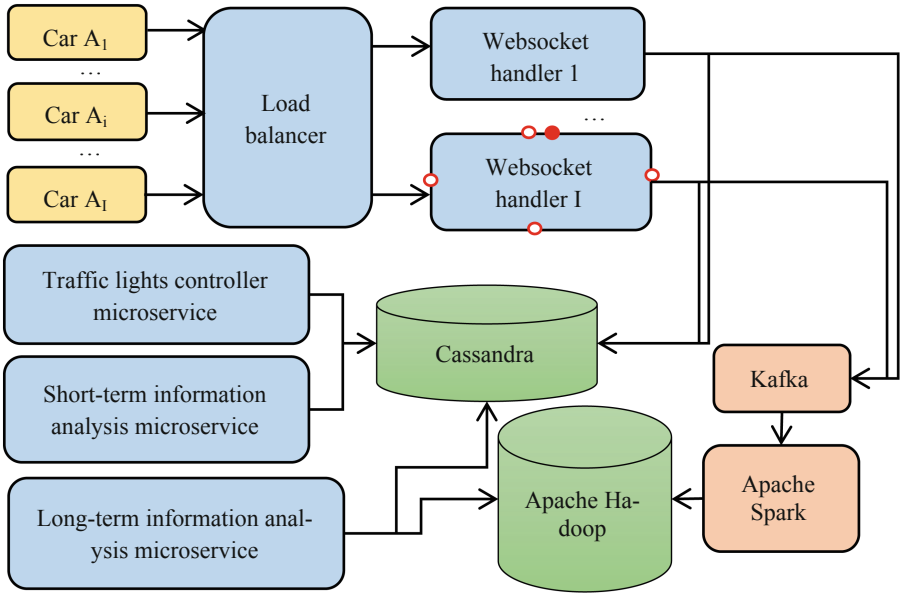


Fig. 5. Model of DDPS.

The Cassandra database is intended to store short-term data. One of the main criteria for choosing this particular database is its decentralised architecture, which provides Cassandra with scalability, reliability and availability [9]. The scalability of Cassandra is ensured by the linear growth of the number of reads and writes operations when adding new servers to the cluster without delay in the addition process. At the same time, data in Cassandra is replicated simultaneously to several servers. This approach ensures that data is not lost if any server fails, as another server can replace it without outages or system interruptions. Also, in Cassandra, you can configure stability due to the number of servers that will respond positively to recording new data. This, in turn, affects the system's availability and provides an opportunity to provide Cassandra with high availability due to the appropriate configuration.

The short-term information analysis service is intended to analyse data contained in the Cassandra database.

The service of long-term information analysis is intended for the analysis of data from the Hadoop database. A Hadoop cluster is intended to store long-term data about the number of cars at traffic lights, the number of cars on different road sections, and the average speed of cars [8, 10, 11].

Aggregated data from both servers are recorded in the Cassandra database for further determination of the mathematical expectation and dispersion of the number of cars at traffic lights around which a car can be after a given time interval.

Using MapReduce technology [12], Hadoop data will be analysed and used to determine the mathematical expectation and variance of the number of cars at a given intersection at a given time.

Figure 6 shows the scheme of integration of DDPS in the process of intelligent management of traffic flows in large cities.

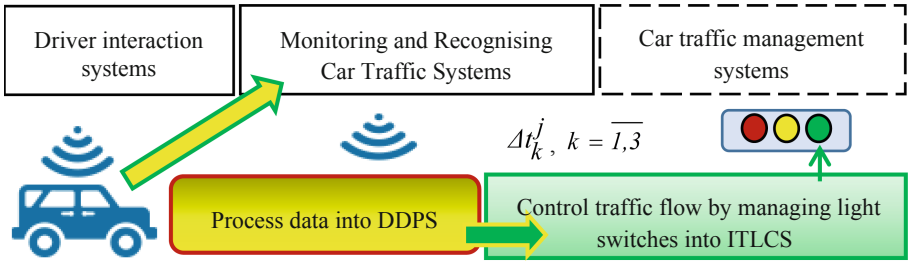


Fig. 6. Scheme of integration of DDPS in the process of intelligent management of traffic flows of large cities.

Further research is planned to analyze the cloud platforms Azure (Microsoft), GCP (Google) and AWS (Amazon) to determine which one is best suited for DDPS implementation in terms of scalability, reliability, sustainability, monitoring and cost.

5 Conclusions

1. In order to solve the scientific and applied problem of intelligent management of traffic flows in large cities, it is proposed to implement the Process data module of the Intellectual Traffic Light Control System in the form of a Distributed Data Processing System.
2. The architecture of the Distributed Data Processing System is proposed and it is shown that the implementation of this system will provide an opportunity to process and transfer data on the number and speed of cars on different road sections in real-time. This, in turn, will increase the reliability of forecasting the number of cars at a given intersection at a given time and coordinate the operation of traffic lights in the event of non-standard situations.
3. The selection of the Cassandra database for data storage, on the basis of which situational adaptation and coordination of traffic light operating modes in stochastic conditions of large cities is justified.

References

1. TOMTOM TRAFFIC INDEX. Ranking 2021. https://www.tomtom.com/en_gb/traffic-index/ranking/
2. Kyiv is Already Third in The World for Traffic Jams. Further It Will Be Even Worse. https://www.epravda.com.ua/publications/2022/02/10/682256/
3. Mazurenko, R., Yeremenko, B., Morozov, V.: Development of intelligent traffic control system project. In: International Conference on Smart Information Systems and Technologies (SIST), pp. 161–164. IEEE, Nur-Sultan, Kazakhstan (2022)

4. A Temporary Bridge from Irpin and Bucha to Kyiv was Opened in Kyiv Region. https://www.dw.com/uk/na-kyivshchyni-vidkryly-tymchasovyi-mist-z-irpenia-ta-buchi-do-kyieva/a-61431028
5. Rizwan, P., Suresh, K., Babu, M.: Real-time smart traffic management system for smart cities by using Internet of Things and big data. In: 13th International Conference on Emerging Technological Trends (ICETT), pp. 1–2. IEEE, Kollam, India (2016)
6. Song, X., Yang, Z., Wang, T., Li, C., Zhang, Y., Chen, G.: Dynamic Traffic Assignment Model Based on GPS Data and Point of Interest (POI) in Shanghai. Sensors **21**(21), 7341 (2021)
7. Kamijo, S., Matsushita, Y., Ikeuchi, K., Sakauchi, M.: Traffic monitoring and accident detection at intersections. Trans. Intelligent Transportation Syst. **1**(2), 108–118 (2000)
8. Rahiman, W., Zainal, Z.: An overview of development gps navigation for autonomous car. In: 8th Conference on Industrial Electronics and Applications (ICIEA), pp. 1112–1118. IEEE, Pulau Pinang, Malaysia (2013)
9. Stetsyk, O., Terenchuk, S.: Comparative analysis of NoSQL databases architecture. Manage. Dev. Complex Syst. **47**, 78–82 (2021)
10. Adnan, M., Sulaiman, N., Zainuddin, N.I., Besar, T.: Vehicle speed measurement technique using various speed detection instrumentation. Business Engineering and Industrial Applications Colloquium (BEIAC), pp. 641–645. IEEE, Langkawi, Malaysia (2013)
11. Ahmed, N., Barczak, A.L.C., Susnjak, T., Rashid, A.: A comprehensive performance analysis of Apache Hadoop and Apache Spark for large scale data sets using HiBench. Journal of Big Data **7**(1), 1–15 (2020)
12. Ghazi, M., Gangodkar, D.: Hadoop, Mapreduce and HDFS: a developers perspective. In: International Conference on Intelligent Computing. Communication & Convergence (ICCC-2015), pp. 45–50. Elsevier, Bhubaneswar, Odisha, India (2015)

Conditions of Effective Application of Energy-Saving Programs for the Movement of Heavy Trucks on the Highway

Myroslav Oliskevych[1](✉) and Viktor Danchuk[2]

[1] L'viv National University of Nature Management, V. Velykogo Str. 1, Dubliany 30831, L'viv Region, Ukraine
oliskevychm@gmail.com

[2] National Transport University, M. Omelianovycha-Pavlenka Str. 1, Kyiv 01010, Ukraine
vdanchuk@ukr.net

Abstract. The study is devoted to the problem of reducing energy consumption by heavy-duty vehicles on autobahns. The task of optimising truck transport cycles, which consist of acceleration, free rolling, and deceleration under the action of external resistance forces, is formulated. At the same time, the truck must complete the transportation task on time, in compliance with the planned schedule and within a safe distance to other objects. Such a problem refers to nonlinear optimal control problems with a fixed left end of the phase trajectory and a free right end. The problem was solved by the method of dynamic programming. A set of optimal phase trajectories and control functions is obtained for different longitudinal profiles of the freeway, different initial speeds and a different number of possible hindrances. The greatest impact on the traffic program is the number and locations of hindrances on the road due to the different densities of the traffic flow. In order to assess the possibility of using optimal cycles, a simulation of truck movement in a traffic flow characterised by mathematical expectation and standard deviation of cruising speed was performed. The prediction horizon of the probable speed of the vehicle was changed in the simulation model. Deviations from the planned movement program measured the quality of driving. It is shown that there is a finite set of numerical values of the prediction horizon on the highway, the control quality for which is the highest. The intelligent information system's conceptual structure for controlling the truck flow to achieve the parameters of the energy saving program is proposed. Experimental studies have been carried out, which indicate an adequate assessment of the theoretical model of the movement program and the possibility of its implementation.

Keywords: Driving cycle · Energy saving · Speed forecasting · Highway · Traffic

1 Introduction

Heavy-duty vehicles (HDV) with hydrocarbon engines are among the largest consumers of energy resources and polluters of the environment. However, there is a reserve of fuel

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 43–58, 2023.
https://doi.org/10.1007/978-3-031-25863-3_5

consumption reducing when driving in long-distance traffic, which consists in the fact that the potential of the road topography (longitudinal profile) is used, energy-saving transport cycles are used, and energy dissipation is reduced to a minimum. In order to use such a reserve, one needs to obtain relevant information about road conditions and transport flows. There are many technical possibilities today to collect and transmit data on road conditions, and expected indicators of traffic flows to the onboard systems of HDV moving along the highway. The transmitted information is obtained directly from onboard HDV sensors and infrastructure elements. Significantly larger volumes of information are received during the interaction of highway traffic objects according to the vehicle-to-vehicle (V2V) and vehicle-to-everything (V2X) formulas [1]. The received information is successfully used to provide cruise control functions. Thanks to telemetry tools, it is possible to plan a route accurately, determine travel time, predict traffic flow delays, and also to carry out the necessary management orders regarding the interaction of a fleet of vehicles on the network within the limits of a given intelligent transport system (ITS). The necessary criterion for evaluating planned actions and the probability of reaching their level is laid down in making decisions. The main indicators of the high efficiency of ITS are the accuracy and reliability of the provided information. However, the known systems of using ITS technical means have not yet reached such a level that, thanks to the received information, it would be possible to use the energy saving resource, particularly hydrocarbon fuel. Most aspects of ITS in forecasting remain unsolved. In particular, the issue of ensuring the accuracy of forecasting large data sets for selecting energy-efficient traffic programs remains unresolved. For example, during the free movement of HDV (without restrictions created by the traffic flow) on hilly terrain, a road train can move in the so-called oscillatory mode, in which acceleration, free rolling, and deceleration under the action of external resistance forces are used alternately in a certain ratio [1]. At the same time, it is possible to save up to 25% compared to movement at a constant speed, which is supported, for example, by traditional cruise control [2]. On flat straight sections of highways, free rolling saves up to 12% of fuel when using oscillating modes. If the parameters of the traffic flow change, the traffic program must be adjusted according to the available information (the forecast of the state of the traffic flow in space and time) [3]. However, this is not always possible due to the unsatisfactory accuracy of the forecast. The change in flow parameters also affects the adherence to the planned trip schedule, especially for commercial trucks. An increase in flow density reduces the truck's average speed and makes it impossible to use the pre-selected, most optimal modes. There is a contradiction in the choice of the traffic program, which consists of the fact that in the absence of sufficient information and proper methods of its collection and processing, the driver of a freight semitrailer can only choose between maximum fuel economy and compliance with the traffic schedule. However, the driver cannot choose the optimal program for this information provided due to the lack of appropriate methodology, considering the subjective factor. Therefore, our research is devoted to improving the organisation of data flow processing on trunk routes, increasing the effectiveness of using available information about road and transport conditions.

2 Literature Review

It is possible to note several works devoted to developing optimal transport cycles of HDV on the highway. It should be noted that the work [4], made a significant contribution to the optimisation of the speed trajectory of an electric truck. First, a new model of the vehicle's speed, acceleration, and battery charge status has been created. Based on this model, energy consumption was optimised, taking into account the topography of the road and the surrounding traffic. For the first time in such studies, the braking force from the truck's standard braking system is not considered. The electric car receives information about traffic and road conditions from the cloud platform. Based on this information and local sensing results (such as the distance of the vehicle in front of it), the electric car's built-in algorithm calculates the optimal speed and travel time within a small number of limited road segments. However, these studies can only be useful for those ITS where only electric vehicles or hybrid vehicles are present since internal combustion engine (ICE) do not have the possibility of energy recovery. The authors discovered a new phenomenon that indicates that an electric vehicle adapts to the road surface more energy-efficiently than a traditional diesel truck. This means that for trucks with ICE, it is necessary to develop algorithms of a different kind. Other approaches to the exchange of information as part of a convoy are needed for HDV also.

The study's cooperative behaviour of accident crews in convoys is most fully investigated [5]. The environment model provides an object list with all surrounding ITS objects. The list of objects is transferred to the prediction module. Objects that support V2X are assigned a plan close to the desired phase motion trajectory. There is no need for them to forecast then. A planned trajectory is provided in the current lane at a constant speed for non-V2X objects. In this way, the authors eliminate the problem of long-term forecasting. However, such a truck convoy management strategy can only be successful on an undisturbed straight road with flat terrain.

The influence of human factors on achieving economic methods of HDV control was studied in works [5–7]. Drivers are reported to have a basic knowledge of green driving, while the question of how to motivate the adoption and practice of such behaviour is ignored, especially in the long term. Given the existing research that focuses on the operational level, a general consensus among researchers on the design of ITS has not yet been achieved.

The theory of energy saving and technologies of ecological driving, assessment of possibilities of ecological driving and practical application of ecological driving are considered in the work [6]. Thanks to the application of big data technology, the evaluation of eco-driving are based on the energy consumption indicators under similar conditions. This can partially exclude the influence of external factors, which makes the prediction results of the motion program more reasonable.

In [8], a complete green driving strategy was developed based on a limited number of HDV driving modes in long-term transportation scenarios to cope with various events on the route and to preview real road profile data. The simulation results showed that the developed methodology is able to provide a phased speed trajectory for the entire route based on the known road events and slope information, while satisfying all the operational constraints of the truck.

The problem of speed planning and monitoring a convoy of trucks on highways is studied in [9]. The speed planning algorithm is developed relative to the average vehicle based on the combined fuel cost and dynamic programming. As a result, the resulting speed profile is much more economical for heterogeneous vehicles with different weights and sizes.

The algorithm for HDV control on the highway, based on the forecast of traffic flow and road conditions in real time, is proposed in the article [10]. It is shown that when the search space is reduced without losing any solutions, this is an obvious advantage.

Methods for evaluating and forecasting traffic information are proposed based on cellular floating vehicle data [11], high-precision sets of vehicle trajectories [8], analytical models [12], statistical and conventional artificial intelligence methods, and quantile forest regression using hyperparameter optimisation, artificial neural networks [13]. In general, it should be noted that thanks to modern forecasting methods, the accuracy of traffic flow parameter forecasting has reached a satisfactory level, but there are very few works that show the effective use of ready-made forecasts.

In the work [14] and other similar, the possibility of achieving energy savings through the use of autonomous vehicles is questioned due to the need to observe driving safety. Instead, adaptive eco-driving strategies are offered, which are based on modified cruise control systems that advise the driver and sometimes correct his actions. All these systems use the prediction of traffic conditions to produce optimal control actions. The objective function is a minimum of dynamic vehicle maneuvers, which, according to researchers, are the causes of overtime fuel consumption.

Of great interest are studies of optimal driving cycles of electric vehicles, in particular [14, 15]. It was proved in the paper [15], that a loaded electric vehicle with serial excitation will move along a horizontal section of the highway, minimizing battery energy consumption, only when the current in its power circuit is formed according to a periodic or quasi-periodic law. However, the models that describe such, the most energy-saving motion, are often those that do not have a solution, or their solution is unstable and strongly depends on the boundary conditions of the model. These models are mainly non-linear. The only successful approach to their identification and solution is dynamic programming. The question of how much the vehicle's driving cycle deviates from the optimal driving cycle when unexpected obstacles are detected and how it is necessary to rebuild the next movement program within the forecasting horizon remains unsolved.

The articles [16] indicate that the main energy consumption of the vehicle is aimed at overcoming rolling resistance and dynamic modes. However, at the same time, the energy expenditure for braking (dissipation) is deliberately included in the vehicle movement model. Thus, the vehicle movement model, built according to the principle of minimum energy consumption, should not include braking force. However, movement without braking is possible when there is sufficient awareness of the driver/crew about the smooth execution of the energy-saving transport cycle. Then the choase of the optimal cycle can be implemented smoothly.

In the paper [17] a complete eco-driving strategy for HDV based on a finite number of driving modes with corresponding gear shifting is developed to cope with different

route events and with road slope data. The problem is formulated as an optimal control problem with respect to fuel consumption and trip duration, and solved using a Pontryagin minimum principle algorithm for a path search problem, such that computations can be carried out online, in real–time. Athors provides a velocity profile and a sequence of driving modes recommendation to the driver. The results of research show that the developed methodology is able to provide a velocity profile for a complete route based on known road events and slope information while satisfying all truck operational constraints. But there were no recommendation of informatiom appliament of optimal velocity profile.

From the performed review of sources it follows that the problem of increasing the efficiency of forecasting the speed of road vehicles in the traffic flow restrains further development and implementation of intelligent systems for controlling the movement of cars, in particular, on highways.

3 Optimisation of the Truck Movement Program on the Hilly Highway Profile

3.1 Theoretical Model and Optimisation Method

The purpose of our research was to ensure the application of such a traffic program of HDV that would meet the safety conditions and maximum energy efficiency of a HDV, subject to compliance with the guaranteed traffic schedule if the road profile is hilly or slightly hilly. As a guaranteed schedule for the performance of a transportation task we accept that one, which provides an average speed of the route movement, not less than the given, economically justified speed. The instantaneous speed of the truck varies from the maximum to the minimum allowed on the highway. We consider the truck as an ITS subject that can exchange information with other moving and stationary objects. The driving program is implemented with the help of an automated onboard system and under the supervision of the driver. If the ITS is based on the V2X system, then the truck's cruise control can be provided with the necessary input data for a sufficiently long distance, comparable to the trip's length.

Positive work can be performed not only by the driving force on the wheels $P_k(t)$, but also by the horizontal component of the gravitational force $P_i(x)$ on the slopes of the highway. Braking of HDV occurs by spending kinetic energy to overcome aerodynamic resistance and rolling forces. In this regard, the content of the optimisation problem is to choose such modes of truck movement on the freeway, which allow arriving from the initial to the final point of the given route with minimal energy consumption, while adhering to the given traffic schedule. A truck must drive the given section of the highway no longer than in the given time.

We consider the length of the trunk route S, so the truck can be considered a material point on it. Such the assumption is quite admissible if we take into account the dimensions of the HDV as an object of traffic flow and the length of the route. On the other hand, in this study we tried to substantiate the conceptual model of energy-saving traffic of a road train as an element of the "highway" system. Therefore, we did not consider the internal

forces that arise in such an object. The problem is optimisation of energy spending. The basic equation of vehicle motion is [3]:

$$m\ddot{x} = P_k(t) - P_o(x) - P_i(x, \dot{x}) - P_w(\dot{x}),\ \text{N}, \tag{1}$$

where m − mass of the vehicle which is concentrated in the centre of mass, kg; x − current location (distance) of the HDV, m; $P_k(t)$ − driving force applied to the drive wheels, N; $P_o(x)$ − rolling resistance associated with the deformation of the roadway, N; $P_i(x)$ − rolling resistance associated with the longitudinal profile of the road, N; P_w − the resistance of air flow, N.

Assuming that the road conditions can be defined some distance S forward by the onboard control system of the car or truck with sufficient accuracy, the Eq. (1) can be written as following:

$$\ddot{x} = u(t) - f_o \pm f_i x - f_v \dot{x} - f_w \dot{x}^2,\ \text{m/s}^2 \tag{2}$$

where $u(t)$ − the driving force per unit of weight of the complete vehicle G_a, which is $(P_k \cdot g)/(\delta \cdot G_a)$, m/s^2; f_o − coefficient of rolling resistance, which takes into account the deformation of the tire and the road and is defined as constant $f_o = P_o/G_a$; f_i, − coefficient of rolling resistance caused by longitudinal profile of road, and is defined as $1/R$, where R − radius of curve of it, 1/m; f_v − additional component of wheels rolling resistance caused by bumpy road and is defined as variable which depends of vehicle velocity and from index of road undulation; f_w – values, which reflect the relative resistance movement depending on the air flow, $N \cdot \text{s}^2/\text{m}^2$.

Vehicle traffic control is optimized after the criterion of minimal energy costs. The optimisation criterion is:

$$E = \int_{t_o}^{T} (P_k(t) - P_i(x))\dot{x}dt \rightarrow \min, \tag{3}$$

where t_o, T is the start and end time of the cycle; x is the coordinate, or the distance travelled by car, m.

The restrictions apply to the left fixed end of the vehicle's phase trajectory (initial coordinate and speed). The right coordinate of the movement program is not limited. The duration of the energy-saving cycle should not be longer than T, which is limited by the permissible traffic schedule. Minimum and maximum speeds are also limited. The initial time, the initial velocity, and the final time are given. Therefore, if a hindrance appears in front of the HDV, then such a cycle must be reviewed and changed. Distance S is much smaller than the length of the route of vehicle S_m on the highway with known conditions, so the final time T cycle is unknown and the integral in expression (3) has a movable right border. Considering the Bellman principle of optimality the route can be divided into sections so that the total traffic on highways program $u(x)$, $x = 0 \ldots S_m$, consisting of partial optimal programs $u(x_j)$, $j = x_{j.\text{o}} \ldots\ S_j$, will be optimal too. One needs to provide such a schedule of an HDV, that at $x_o(t) = 0$, $x_o(T) = S$, where $x = x_o \ldots S$ − distance; T − limiting time of the route performance of length S_m, to arrive at destination point with a minimum energy consumption. Let introduce new variables:

$x_1(t) = x(t),\ x_2(t) = \dot{x}(t).$

Let define $f_x = f_o + f_{i \cdot x}$. Then the function objective becomes:

$$E = \int_{t_o}^{T} (u(t) \pm f_x \cdot x_1) x_2 dt \rightarrow \min, \tag{4}$$

and the system of conjugate equations:

$$\begin{cases} \dot{x}_2(t) = u(t) \pm f_x x_1 - f_v x_2 - f_w x_2^2 \\ x_2(t) = \dot{x}_1(t) \end{cases}, \tag{5}$$

where sign of is f_x taken depending on the profile of the road: on the rise – "-", on the descent – " + ".

It is needed to find a phase trajectory $x_2 = F(x_1(t))$ and program of object control $u(x)$ with such restrictions: $x_1(t_o) = 0$; $x_2(t_o) = V_o$ – left end phase trajectory is fixed; $x_2(t_0) = V_0$; $x_1(T) \geq S$ – follows from the terms of the schedule, that if the limit of time of any part of the passed distance S it is not maintained, a whole schedule is disrupted; $x_2(t) \leq V_{\max}$ – limit of the maximum speed of traffic safety conditions; $u(x) \leq u_{\max}$ – limiting the power of the vehicle [18].

The solution to such a local problem was found using dynamic programming methods. A reduction of the initial optimisation problem to a finite-dimensional problem of mathematical programming was applied:

$$x_2^{i+1} = \left(u^i \pm f_x^i x_1^i - f_w \left(x_2^i \right)^2 \right) (t_{i+1} - t_i) + x_2^i, \tag{6}$$

$$\text{and } x_1^{i+1} = x_2^{i+1} (t_{i+1} - t_i) + x_1^i \tag{7}$$

where f_x, f_w are coefficients reflecting the specific movement resistance, which depends, respectively, on the road profile and air resistance. The new problem relates to mathematical programming, the variables of which are x_{1i}, $i = 1,\ldots N$ and u_i, $i = 0,\ldots N - 1$.

An example of the initial information about the rolling resistance of the main road is given at Fig. 1. The length of the section is 800 m. The coefficient of movement resistance varies in $f_x = 0.015..0.05$, which is due to the presence of hilly terrain. The resistance coefficient assumes a positive value on road slopes in (2). With a known profile and constraints on maximum and minimum speed, as well as time T, the initial conditions differ by the initial speed x_2 at the beginning of the cycle. After optimising the cycle with different input data, we ensured that the initial speed did not affect the type of phase trajectory (Fig. 2).

Thus, for each road profile with known resistance parameters it is possible to build transport cycles fixed in length, which make up the total mileage during the given forecasting horizon and, accordingly, the planned route. Suppose hindrances are foreseen on the forecasting horizon. In that case, the cycle is rebuilt under the imposed restrictions (Fig. 3). At the same time, the energy consumption of HDV remains minimally possible under the given restrictions; that is, problem (3) has a stable, guaranteed solution, despite the nonlinear nature of its formulation. Our results do not apply to specific speed limits that are in effect in many countries. After all, such circumstances are possible when a short-term increase in speed will not only be safe (with the appropriate improvement of the vehicles design), but also energetically beneficial.

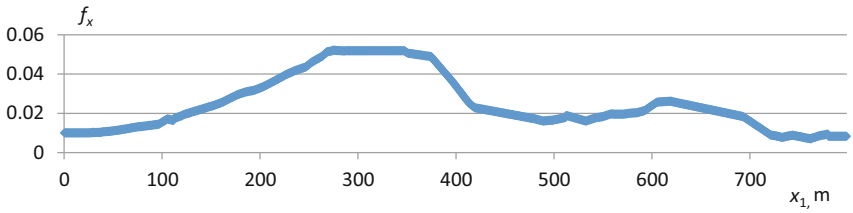


Fig. 1. Sample of road profile.

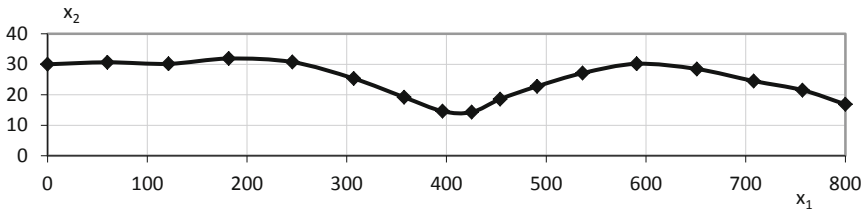


Fig. 2. The optimal phase trajectory of the truck at the start of cycle with $x_2 = 30$ m/s.

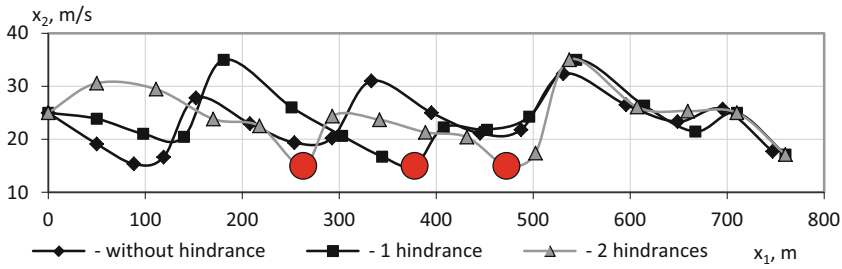


Fig. 3. Optimal phase trajectories of the truck with different number of hindrances on a hilly section of the road: red circles – location of traffic hindrances.

All three, the results are shown in Fig. 3 differ in the number of obstacles, respectively, 0, 1, 2, and do not differ in the average speed of movement 23.75 m/s, which was

programmed according to the movement schedule. However, the total energy consumption calculated under the same initial conditions, namely total truck weight of 36.8 ton is for such the options: without hindrances −85.13 kW; one hindrance −86.21 kW; two hindrances −89.87 kW. However, such costs could be significantly higher if information about transport conditions did not arrive just in time. Thus, energy consumption increases in the absence of information about the presence of one obstacle to 92.74 kW, and about two obstacles to 101.41 kW.

3.2 Study of Incoming Data Flow

Any forecast of traffic conditions is not completely reliable at all. Therefore, unexpected changes may occur in the HDV's traffic program, which should not harm the goal of fulfilling the transport task with minimal consumption of energy resources.

The movement of HDV on trunk roads of the highway route was considered. The starting and ending points of the route are set. The length of the trip L_m is known. The current speed V of HDV varies depending on the road and traffic conditions. It was assumed that the road conditions, that is, the terrain, the plan and profile of the route, the condition of the road surface, are known. Such conditions for a given HDV can be described by the free movement program $V_i(x)$, which is the speed varying along the length of the route $x_1 = [1, S]$. In this case, we will call the traffic program optimal in this case, which provides the greatest energy saving in the absence of obstacles that cause delays, traffic jams and other forced changes in speed. Any deviation from the $x_2(x_1)$ phase trajectory (increase or decrease in speed) leads to an increase in resource consumption. At the same time, there is a limitation on the maximum absolute speed $V_{\max}$. Because there are situations on the highway, in which at some point in time t_{i} it is necessary to reduce the speed to V_i, then, subject to the availability of relevant information at the time $t_{i\text{-}1}$, the onboard control system selects such a movement program that applies to the section of the route $[x_{i\text{-}1}, x_i]$. Such situations are an increase in the density of traffic flow, an increase in the risk of an accident due to weather, natural or other conditions. Thus, the speed V_i is a limitation in the application of the optimal movement program and compliance with the corresponding schedule if $V_{\max}(x) < V_i(x)$. Taking into account the purpose of the research, the speed $V_{\max}(x)$ is taken as the main parameter characterising the transport conditions on the highway. If such information is available, it is possible to identify those sections of the route where $V_{\max}(x) > V_i(x)$. The speed can be increased in such areas from the optimal $V_i(x)$ to the maximum $V_{\max}(x)$. This is a certain time resource that can be used by deviating from the optimal program but keeping to the schedule.

In order to reflect the influence of the flow of information on the choice of an HDV control program in the energy-saving execution mode, we developed a simulation model that reflects the process of executing the optimal energy-saving program under known traffic conditions on a certain length of highway W, on which the presence of obstacles is assumed with probability, no less than 0.9a5. Initial data was prepared that describes the main road on which the speed limit is set. The mathematical expectation $E(V_i)$ and the standard deviation of speed $\sigma(V_i)$ were used to characterise the profile of road conditions. The mathematical expectation of speed $E(V_{\max})$ and the standard deviation $\sigma(V_{\max})$ was used to reflect the trajectory of maximum traffic speeds.

To evaluate the vehicle's driving quality in a dynamic speed forecast, such indicators as the absolute total deviation from the optimal program DV and the deviation from the planned trip schedule ΔT were used.

$$DV = \sum_{x=1}^{L_{\max}} \sqrt{(V(x) - V_i(x))^2}. \tag{8}$$

$$\Delta T = t(L_{\max}) - T_{\max}, \tag{9}$$

where $t(L_{\max})$ is the duration of the last section of the route.

As a result of simulation (SIM), the dependences of $DV(W)$, $\Delta T(W)$ were obtained (Fig. 4). The dependence of DV on W has a clearly defined piecewise continuous character.

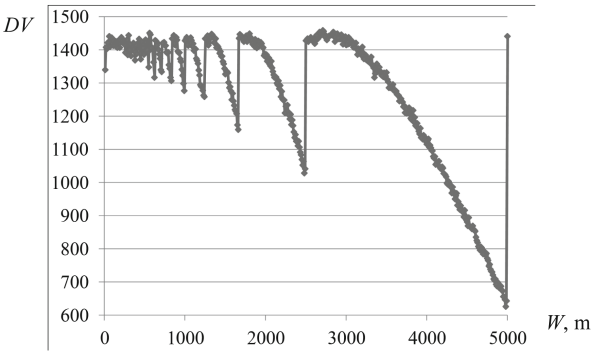


Fig. 4. Dependence of the total deviation from the optimal DV program on the prediction horizon W at $\sigma(V_{\max}) = 0.006$ and $E(V_{\max}) = 0.85$.

The presence of graph jumps is explained not only by the multiplicity of the values of the value W and the length of the route $L_{\max}$, but also by the fact that the dependence $DV(W)$ reflects the phenomenon of the transition of information quantity to quality. Thus, when W increases, the field of variable values V also increases, making it possible to choose a movement program at a distance W closer to the optimal $V_i(x)$. However, the growth of W reduces the probability of the data flow until the amount of information obtained regarding $V_{\max}(x)$ forces us to make a generally inadequate decision. The further growth of the W horizon necessitates the correction of the control system. The quality of control according to the DV indicator is improved at the same time. This happens until the next qualitative change. Thus, the DV(W) function breaks are explained by the growth of the amount of information into the quality, which occurs for certain values of the forecasting horizon.

4 Development of Tools and Strategies for Truck Driving

In order to ensure compliance with the desired traffic programs of the traffic accident population, their onboard control systems must be provided with the necessary optimal

amount of input data. Data flows of road and traffic conditions on highways are cumbersome. Existing telemetry tools can only provide short-term forecasting. Accuracy and volume of data can be increased with V2V, and V2I communications on the highway. Therefore, a comprehensive model of ITS for controlling the modes of movement of the aggregate of HDV, which interact with each other, and the elements of the infrastructure is proposed. The proposed model is supplemented with methods of analysis and processing of the incoming data stream. The motion model was studied on the basis of SIM.

4.1 Justification of the ITS Structure on the Highway

"Internal" and "external" automatic control systems are being developed in order to eliminate subjective factors in road safety, and eco-control of accidents. After all, a person, as the most inertial link in the "driver-car-road-environment" system, should be freed from the need to perform instantaneous actions [11]. However, such systems cannot positively impact traffic conditions on highways. And if traffic jams form on highways, they completely lose their effectiveness. If the strategy of only "external" control is used, then the criterion of energy saving will be fulfilled; that is, the traffic flow will become more uniform in terms of the speed of individual accidents. However, the desired programs and traffic schedules of a certain part of vehicles are not observed. Suppose the flow control function is left only to the "internal" vehicle onboard systems, which do not interact. In that case, the opposite situation will be observed: the vehicles will be closer to their desired program, trying to reach the desired speed under the conditions of compliance with the traffic schedule. However, if these programs differ significantly, acceleration manoeuvres, lane changes, deceleration, and braking cannot be avoided in the flow. As a result, the criterion of energy saving is ignored, emergencies will continue to be created on the highway, energy resource overspending and other negative consequences will occur. Such a contradiction can be resolved if objective conditions are formulated and directions for implementing the complex system are substantiated.

Before the development of the ITS model, it was assumed that HDV moves in the traffic flow only according to an objectively justified movement program. If other subjective reasons are discarded, then the occurrence of accelerations/decelerations can be detected by considering the interaction of two accidents: the one for which the automated traffic control system A_1 is installed and the one that precedes it A_2 and has the same system. After analysing all possible conditions of the application of acceleration/deceleration manoeuvres, a model of the traffic flow control system was developed depending on the following functions:

- disturbance - distances between vehicles – $x(t)$;
- target - desired movement program – $V_{des}(t)$;
- deviation - estimates of one's own speed – $V_i(t)$;
- the objective function – energy consumption of the truck $E(t)$ takes the form:

$$E(t) = F(X,\ V_{des.i},\ V_i,\ t),\ i = 1 \ldots S, \tag{10}$$

where F is a fuzzy, adaptive function.

It was assumed that the system should develop a forecast of its own acceleration/deceleration $j(t)$ while minimising it and adhering to the predetermined motion program, adapting it to the actual traffic conditions. It does not seem possible to directly obtain Vi(t) functions in any traffic flow model with sufficient accuracy. Instead, one can use signals available for measurement, with the help of which one can go to what you are looking for.

Most of the primary signals in the transport flow also have a large measurement and transmission error, so the messages they carry are contradictory, which introduces uncertainty into the automated control process. This applies, for example, to almost all methods of measuring speed and intervals between moving objects. The lack of information to make a decision can be compensated by such messages, which, despite the considerable error of each of them in particular, collectively create a greater entropy. In this regard, the research was conducted in three stages. The first is the analysis of known alternative functional models of the system of controlling the movement of vehicles in traffic and selecting an appropriate one. The second is selecting a set of parameters and synthesising a control algorithm based on SIM. The third is the analysis of the flow of input data for the assessment of the probable error of the automatic control and correction of the initial models under the condition of compliance with the desired motion program.

4.2 Model of the Structure and Functioning of ITS

The ITS model is based on a set of automated onboard systems (BAS) of individual cars, which receive external signals: the vector of distances to moving and stationary traffic obstacles $X(t)$, and their own coordinates and their change over time (GPS navigator); with respect to the rotation frequency of each wheel $\Omega(t)$ and concerning the load distribution on each axis $R(t)$. Based on these input signals, estimates are made:

a) the coefficient of tire adhesion to the road φ – according to the rotation frequencies of the driven wheels w_1–w_2;
b) total coefficient of road resistance Ψ;
c) the current value and forecast of the own speed $V_i(W)$. This is a model of modern cruise control.

BAS has a set motion program $V_{des}(t)$ with the possibility of additional adjustment if the total delays have reached the limit of uncontrollability. Based on the developed optimal program, a decision is made to select the next mode of movement (deceleration/acceleration/uniform). The scheme of the operation of the onboard automated control system according to the first option is shown in Fig. 5.

The concept of the new ITS is proposed based on known ones, with the difference that its objects are, in addition to a group of cars that exchange messages, also immovable objects - highway logs that perceive, remember and transmit information to the next group of vehicles, which approach them (Fig. 6). Logs are placed in those places that correspond to the most effective reception and use of telemetry information. It functions as a complex automated control system (CACS). A group of cars A_1, A_2… A_i, having received a vector of input signals from their own onboard systems, processed them, and selected adequate driving modes with the help of CACS 1, transmits the received

information to the nearest stationary road object – lag *D*. There are as many such lags along the highway as required to ensure the stability of information communication of mobile objects.

At the same time, Lag D transmits to CACS1 the information it acquired from the previous group of cars and determines the instantaneous speed of the accident. Obviously, such situations can arise on the highway when the distance between the HDV is very large, so they do not exchange signals. When a group of cars compares with lag D after such a time gap, it can exchange information with it.

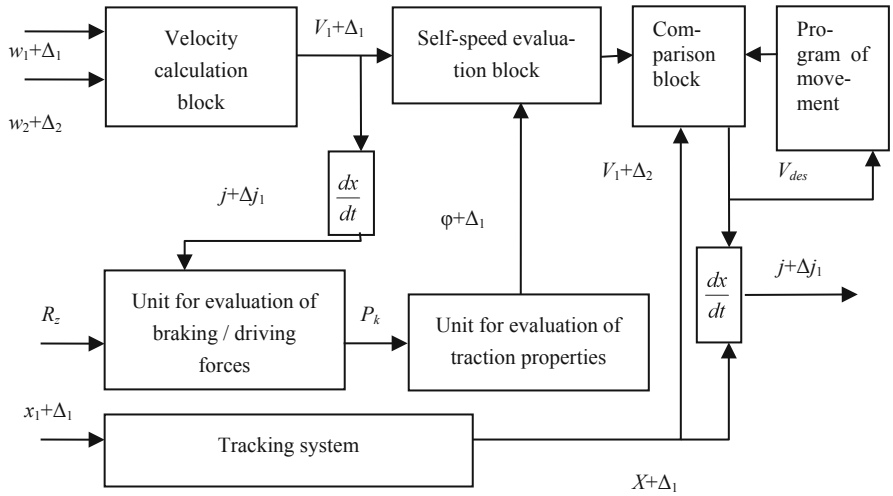


Fig. 5. Basic diagram of BASK: w_1, w_2 – rotation frequency of driving and driven wheels; Δ_1 is the primary parameter estimation error; Δ_2 is the second parameter estimation error.

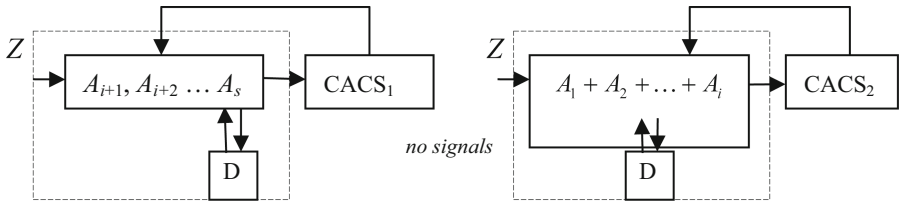


Fig. 6. Scheme of a complex dynamic automated control system: D - stationary road object lag.

Thus, immovable road objects alternately become elements of CACSi, and there is no break in information flows. This means that as such information accumulates, the system becomes more perfect. The quality of CACS management directly depends on the density of the traffic flow.

5 Experimental Studies

In order to test the theoretical claims based on the ITS conceptual model. Experimental studies were carried out on the country road E-471 in the L'viv region (Ukraine) in the

direction of L'viv-Striy, which has a dry flat and hilly road surface that is in good technical condition. The road belongs to the 2nd class. The sections of the road on which the research was conducted were laid on hilly terrain; there are no intersections with other roads, pedestrian crossings, areas with limited visibility, bridges, or narrowings. The research was conducted during the time of the lowest traffic intensity (Sunday, 800–900), which did not reach 5 vehicles/hour. Visibility was good. The research was carried out on a road train as part of a DAF XF 105 truck, engine volume 12.9 l, 2018. With a total mileage of 70,000 km. + semi-trailer Cogel Cargo SN 24. The truck was part of a convoy of two vehicles. The driver was an observer car equipped with devices for recording traffic flow parameters. Changes over time were recorded: road fuel consumption, instantaneous speed of the car, and the frequency of rotation of the crankshaft. Corresponding oscillograms of transport cycles were recorded. The experiments were conducted at different maximum achievable speeds. However, the car's movement length was constant -760 ± 6 m. The data of the recorded oscillogram files were digitised. After that, the tabular data was processed using Excel spreadsheets, and the obtained cycles were compared with homogeneous ones based on the average technical speed on the given section of the road. As a result, it was proved that the best practical results agree with the simulation under the condition of maximum intensive acceleration to the highest possible of the maximum speeds (25 m/s - in this case). The results show that the cyclic oscillating motion of the car is more economical in terms of fuel consumption than the steady motion mode (mode #4). The most significant savings are observed in those oscillating modes where the maximum speed does not significantly exceed the free-rolling speed. However, comparing the acceleration duration/cycle duration ratio, it can be seen that it is the largest for the most economical mode #3. This means that the high acceleration intensity is a negative factor in the car's energy efficiency if we consider the facts from practice (Table 1).

Table 1. Summarised Experimental data on car driving cycles.

No. Experiment	Max. Speed, m/s	Min.speed, km/h	Mileage, m	The ratio of acceleration duration / cycle duration	Total fuel consumption, liters
1	35	15	762	0.31	0.2616
2	30	15	766	0.37	0.2600
3	25	15	758	0.42	0.2693
4	20	20	760	0.0	0.2940

6 Conclusions

The research results open up new opportunities for implementing ITS on trunk roads. This is manifested in the identified phenomena of acceptance and use of information

flows. The main regularity of the HDV control process in the conditions of long-distance transportation is that the optimal amount of forecasted information, which should be provided to the driver, depends on the road and traffic conditions. The study was conducted by evaluating the quality of truck driving in terms of deviations from the optimal energy saving program and the planned schedule. According to such criteria, it is possible to propose several optimal ratios of volume/number of messages about road and transport conditions. It is taken into account that the efforts of modern researchers are aimed at increasing the accuracy of scanning conditions and predicting the speed of the vehicle in the stream. In this regard, the proposed dependence, technique and control algorithm ensures a high level of control efficiency even with the current level of technical and algorithmic forecasting support.

The developed energy-saving cycles can be used in a HDV highway driving, provided that it interacts with telemetry devices. Mandatory conditions for achieving the minimum possible energy consumption for a given HDV are the determined forecasting horizon of road conditions and known traffic hindrances. The energy consumption of cycles on a road with uneven road resistance largely depends on the speed limit of the vehicle, which is set based on the available information about hindrances in the traffic flow. The difference in resource consumption can vary by up to 17%. The greatest positive effect in energy conservation can be achieved when information about the traffic flow arrives at defined fixed points.

References

1. Lai, W.K., Kuo, T.H., Chen, C.H.: Vehicle speed estimation and forecasting methods based on cellular floating vehicle data. Appl. Sci. **6**(2), 47 (2016)
2. Xu, C., et al.: Engine-in-the-loop study of a hierarchical predictive online controller for connected and automated heavy-duty vehicles. Society of Automotive Engineers Technical Paper Series, 1 (2020)
3. Stotsko, Z., Oliskevych, M.: Vehicle driving cycle optimisation on the highway. Transport Problems **11**(2), 123–131 (2016)
4. Zhang, Y., Qu, X., Tong, L.: Optimal eco-driving control of autonomous and electric trucks in adaptation to highway topography: energy minimization and battery life extension. IEEE Trans. Transportation Electrification **8**(2), 2149–2163 (2022)
5. Hauenstein, J., Mertens, J.C., Diermeyer, F., Zimmermann, A.: Cooperative-and eco-driving: impact on fuel consumption for heavy trucks on hills. Electronics **10**(19), 2373 (2021)
6. Xu, N., Li, X., Liu, Q., Zhao, D.: An overview of eco-driving theory, capability evaluation, and training applications. Sensors **21**(19), 6547 (2021)
7. Wang, Y., et al.: A comparative study of speculative retrieval for multi-modal data trails: towards user-friendly human-vehicle interactions. In: Proceedings of the 2020 6th International Conference on Computing and Artificial Intelligence, pp. 99–103 (2020)
8. Borhan, H., Radulescu, R., Lammert, M., Zhang, C., Kelly, K., Vahidi, A.: Advancing Platooning with ADAS (Advanced Driver-Assistance Systems) Control Integration and Assessment (No. DOE-Cummins-EE0008469). Cummins (2022)
9. Guo, G., Wang, Q.: Fuel-efficient en route speed planning and tracking control of truck platoons. IEEE Trans. Intell. Transp. Syst. **20**(8), 3091–3103 (2018)
10. Hellström, E., Ivarsson, M., Åslund, J., Nielsen, L.: Look-ahead control for heavy trucks to minimise trip time and fuel consumption. Control. Eng. Pract. **17**(2), 245–254 (2009)

11. Zhang, L., Liu, W., Qi, B.: Combined prediction for vehicle speed with fixed route. Chinese J. Mechanical Eng. **33**(1), 1–13 (2020)
12. He, Z.: Research based on high-fidelity NGSIM vehicle trajectory datasets: a review. Research Gate, 1–33 (2017)
13. Ayman, A., Wilbur, M., Sivagnanam, A., Pugliese, P., Dubey, A., Laszka, A.: Data-driven prediction of route-level energy use for mixed-vehicle transit fleets. In: 2020 IEEE International Conference on Smart Computing (SMARTCOMP), pp. 41–48. IEEE (2020)
14. Fafoutellis, P., Mantouka, E.G., Vlahogianni, E.I.: Eco-driving and its impacts on fuel efficiency: an overview of technologies and data-driven methods. Sustainability **13**(1), 226 (2020)
15. Мокін, Б. І.: Математичні моделі руху транспортних засобів, оптимальні за критерієм мінімуму витрат енергії, з урахуванням рельєфу. Інформаційні технології та комп'ютерна інженерія. № 3. P. 28–33. (2007). [In Ukrainian: Mokin B. I. Mathematical models of vehicular traffic, optimal criterion for low energy consumption, given the topography. Information technology and computer engineering. 2007]
16. Yoon, D.D., et al.: Predictive kinetic energy management for an add-on driver assistance eco-driving of heavy vehicles. IET Intelligent Transport Syst. **14**(13), 1824–1834 (2020)
17. Da Silva, G.R.G., Lazar, M.: Long hauling eco-driving: heavy-duty trucks operational modes control with integrated road slope preview. arXiv preprint arXiv: 2203. 12378 (2022)
18. Udin, U., Pashentsev, S., Petrov, S.: Using Pontryagin maximum principle for parametrical identification of ship maneuvering mathematical model. Transport Problems **9**(2), 1118 (2014)

Intelligent Transportation Systems Applications: Safety and Transfer of Big Transport Data

Yasin Çelik[1](✉), Metin Mutlu Aydin[2], Ioan Petri[1], and Dimitris Potoglou[3]

[1] Cardiff University, Cardiff CF24 3AA, UK
{celiky,petrii}@cardiff.ac.uk
[2] Ondokuz Mayıs University, Samsun 55139, Turkey
metinmutlu.aydin@omu.edu.tr
[3] Cardiff University, Cardiff, NJ CF10 3AT, UK
potogloud@cardiff.ac.uk

Abstract. The distributed ledger technology (Blockchain) offers a fast, scalable solution for data tracking and authentication. Implementation of Blockchain is expected to emphasize the use of technology to decrease or eliminate third-party costs, better protect devices and systems' data, and enhance transparency and security. Blockchain also offers a highly secure platform that enables quicker operation and payments, and more precise data record of transportation vehicles (in all modes). This feature plays a significant role in the supply chain by providing access to shared information, to decrease or eliminate redundant communication and information, avoiding data transmission errors. Therefore, it becomes feasible to spend less time verifying data and more time analysing and managing data, which can improve the quality of the interaction between participants, control or reduce costs, or both. In the collection, analysis, and secure sharing of big data with relevant parties, technological advances and the efficient use of smart transportation systems in urban and rural transportation take priority. Particularly in recent years, the loss of data from hacker attacks or the inability to determine where data is transported demonstrates that Blockchain technology may be used successfully in this field. This paper examines the "Smart Cities Traffic Safety" project, which is one of the largest Intelligent Transportation Systems (ITS) projects in Turkey and is currently implemented by Samsun Metropolitan Municipality. In these ITS-based transportation applications, Blockchain technology is used to protect against cyber-attacks on the data of intelligent signalised intersections, average speed corridors, parking violation detection, and red-light violation detection systems. Additionally, this research focuses on the secure sharing of the transportation Big Data with third parties based on the step-by-step monitoring of data transfer history. In the context of this project, the first step is to propose a framework that is based on the technology of Blockchain. Then, a platform was developed with the objective to enable the authentication, validation, monitoring, and protection of information and to address the emerging challenges in the field of transportation systems.

Keywords: Blockchain · Intelligent transportation · Data safety · Big data

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 59–73, 2023.
https://doi.org/10.1007/978-3-031-25863-3_6

1 Introduction

Blockchain technology is a very efficient system commonly used to simplify complex processes in transportation-related systems such as mobility as a service (MaaS), data control and transfer, and supply chain management. In the last few years, various transport-related companies have started integrating Blockchain technology to their operation, control and management processes for data tracking and transfer systems [1]. In a Blockchain system, digital ledger records transactions in a series of blocks, and knowledge and data exist in multiple copies spread over multiple users. Thus, Blockchain technology offers accurate tracking of all system records [2]. All these properties of the Blockchain technology make it one of the most promising and popular technologies worldwide [3]. This popularity enables it to support different applications in multiple areas and to propose tracking and transfer systems solutions.

Blockchain technology was originally developed for the cryptography exchange and digital transactions. It has been used in various areas like crypto money, healthcare, financial systems, cybersecurity, smart grid, energy management and intelligent transportation systems [4]. It can distribute a database which is shared among the Blockchain nodes over related partner organisations. In the previous developments, Blockchain technology was effectively used in the finance sector. However, its capacity and current possibilities have proved that Blockchain is a great technology to use in many other areas because of its ability to store data in a distributed database after verification steps [5]. In fact, Blockchain is a reliable technology to record transaction information among trusted partners' data, and it can be used in many legal processes. Therefore, digital assets for the chosen study area can be presented as digital proofs due to the Blockchain's secure, transparent and immutable property [6]. An encountered problem in Blockchain applications is related to the size and safety of storage and transfer of the existing data. It is often not feasible for the data to have a higher number of dimensions and size when transmitting to other parties. Thus, many researchers conduct studies to find solutions to address these data related problems [7–11].

With the rapid increase in accidents, longer travel times and colossal waiting times on roads in the last three decades, and despite notable developments in road infrastructure, the existing transportation solutions that have been developed and applied previously have become insufficient to solve today's traffic problems. Thus, Intelligent Transportation Systems (ITS) have started to find solutions to traffic problems in roads over many cities worldwide [8]. The technological developments and the effectiveness of ITS to reduce traffic chaos, enhance traffic efficiency, and make a positive contribution to the development of smart cities and roads made the utilisation of these systems more popular. IT systems supply valuable information regarding many traffic conditions and systems. Current results on ITS applications have shown that these systems are very effective tools for finding chaos solutions and can supply safety and comfort in urban and rural traffic problems [12]. Thus, ITS can have a significant effect on every aspect of our life with smarter transport facilities and vehicles, as well as safer and more convenient transport services. On the other hand, ITS have shown high social complexity instead of the expected intelligence, leaving many long-standing issues unsolved or even worsened.

Blockchain technology supplies rapid development and has the full potential to revolutionise the increasingly centralised ITS in applications using effective andefficacious

mechanisms to save and keep data as digital proof [5]. ITS also have some critical security problems with data storage and transfer requiring integration with technologies such as Internet-of-Things (IoT) and computing via Artificial Intelligence (IT) for enhanced security. The second issue in ITS systems is the safety of data transfer from these systems to the main server or from operator to third parties. This study aims to contribute with a real-site application case-study on how ITS data storage, control and transmission can be achieved using Blockchain in a real ITS application for Samsun City in Turkey.

The following is the rest of the paper: Sect. 2 includes a number of relevant case studies related to the study's field. Section 3 includes briefing information for Samsun ITS project, while Sect. 4 provides the methodology of the paper. Section 5 presents the implementation procedures and a platform for Blockchain-based data record in ITS systems. The conclusion and future work are provided in Sect. 6.

2 Literature Review

When moved from their original destination to their focus destination, the goods and services in transportation take a product, a carrier, and a middleman who might be irrelevant and disappear. So, Blockchain technology supplies a relevant feature to the transportation system without any involvement of a third party. The current traditional transport systems use electronic data and some developed application program interfaces to provide and record transportation data manually or digitally [13]. This obtained data can be changed, modified and manipulated by a third-party authorised person, which can have critical consequences on the global transportation system.

2.1 Blockchain and Transportation Relation

Blockchain technology excludes the involvement of a third-party authorised person-mitigating the risk with failure of the systems. Blockchain is used for data authentication where the whole network can contribute and validate data to make the system tamper-proof and transparent and to save and transmit the saved data securely. Blockchain technology in transportation systems has many benefits, such as breaking down silos, better traceability, faster payments, easier audits, easier identification of attempted frauds, greater consumer trust, real-time consumer feedback, and better scalability [2]. Blockchain technology can help with improving transportation control, operation and management with benefits such as better accountability, need for more back-office, and access to more information about the transportation system. Integrating Blockchain technology and transportation systems can lead to improvements including transparency, traceability, immutability, trust, distributed gover- nance and cost-saving. All these attributes can be used in the ITS sector effectively, as they have a great potential to improve the operation and maintenance in ITS.

In the last decade, many companies in the world have started using new technologies such as Blockchain, the Internet of Things, and artificial intelligence to develop cyber-physical systems that can help with their competitive environment [14]. The features provided by Blockchain technology make the utilisation of this technology more prominent and efficient. For example, related studies [15] investigated the strategic importance

of the transport sector in creating economic, environmental and social values. They found that Blockchain technology can be a reliable support for supply chain operations. In a different study [16], authors studied the risk of attacker threats to intelligent devices of transportation systems. They explored an example of IoV and proposed a security mechanism for the infrastructure of services of connected autonomous vehicles using Blockchain technology. Blockchain technology allows confidentiality and transparency among customers and taxi drivers by tracking and recording each action of objects relative to vehicles or IoT devices in Blockchain. A Blockchain security study explored how Blockchain can be used as an effective technology for distributed and secured storage of big data obtained by ITS networks. According to the analysis, they reported that Blockchain technology could potentially be a good application for data distribution and secure storage.

In the last years, there is also high interest in electric vehicles. Many researchers have focused on using Blockchain in charging infrastructure. Related studies [17] presented a new and safer e-vehicle charging system based on Blockchain. This new charging system provides some features such as key security, safe mutual authentication, anonymity and direct secrecy for efficient charging. For the testing process of the new system, they compared the proposed system with an old one and demonstrated that the pro- posed system works more effectively than the existing one. Another study [19] proposed an intelligent contract using Blockchain for the e-vehicles' safe charging to maximise the battery performance. To achieve this aim, researchers integrated the Blockchain system between the EV and the vehicle's charging system and obtained optimised battery capacities for e-vehicles. In a similar study [20], authors examined the Blockchain system's contribution to calculating the sale and purchase of electricity in the charger. They found that Blockchain can allow partial or full decentralisation of the process and full automation without involving the intermediate device. It was also observed that Blockchain systems are very effective in modelling the electricity metering system during the charging process.

2.2 Internet of Things (IoT) Combination with Blockchain

The Internet of Things (IoT) is one of the most significant technological developments. It is a logical progression for the Internet (of computers) to evolve into integrated and cyber-physical systems, "things" that, although not computers, contain computers. With a network of inexpensive sensors and networked objects, it is possible to gather information about our planet and environment at a finer resolution. Indeed, such in-depth information will increase efficiency and enable the delivery of sophisticated services across various application fields, including ubiquitous healthcare and smart city services. Nonetheless, the more invisible, dense, and widespread collecting, processing, and distribution of data in the middle of the private lives of individuals give rise to major security and privacy issues [21].

On the one hand, this data may be utilised to deliver various sophisticated and individualised user-beneficial services. In contrast, this data contains information that may be utilised to algorithmically generate a virtual history of our activities, exposing private behaviour and lifestyle trends. The absence of essential security measures in many IoT gadgets of the first generation exacerbates the privacy threats associated with

the Internet of Things. Several security flaws have been discovered in interconnected devices, from smart locks [22] to vehicles [23]. Several inherent characteristics of the Internet of Things exacerbate its security and privacy concerns, including a lack of central management, heterogeneity in device resources, various attack surfaces, situational and context-aware hazards, and scalability.

Various end devices transfer large amounts of data in IoT networks. This means that attacks against the IoT might potentially target either data or devices. Whether it's from a medical IoT system [24] or a national application such as the IoT-based smart grid [25], the sensory data in an IoT system might be private or sensitive [26]. Data privacy and security are indeed important. Security, data integrity, and dependability issues in IoT networks may be solved through Blockchain [27]. In addition to its use in the cryptocurrency industry, Blockchain has attracted significant interest in a wide range of Internet of Things (IoT) applications (including management of supply chains [28] and smart cities [29]). Risks to both sensory input and end devices may be mitigated by using Blockchain technology.

Several major characteristics of Blockchain make it a viable solution for addressing security and privacy issues on the Internet of Things: Security, Anonymity, and Decentralization. This paper proposes a Blockchain-based architecture for the Intelligent Transportation System (ITS) with IoT that delivers lightweight and decentralised security and privacy. The design preserves the advantages of Blockchain while solving the obstacles of integrating Blockchain into IoT (for example, mining blocks is time-consuming, and IoT applications require low latency). An ITS data record example is used to demonstrate the use of these technologies in the field of transportation and smart cities.

Existing literature clearly shows that Blockchain technologies and related systems are developing very fast in various fields of activity. All these systems, such as transport systems, logistics and electric or autonomous vehicles technology, are based on big data processing. Thus, Blockchain utilisation greatly increases many big data and intelligent systems-related sectors. All the previous study results clearly show that Blockchain technology has great potential for safely storing, controlling and transmitting important data to third parties.

3 Smart City Traffic Safety-ITS Project of Samsun City

The increase in the population and the number of vehicles in traffic results in vehicle densities, delays, long vehicle queues, and many traffic accidents on urban and rural roads all over the world. Unfortunately, this chaos in traffic results in an increase in the emission of more CO_2, NO_x, PM2.5, etc. harmful gases to nature from fossil fuel-consuming vehicles and this issue impacts climate change. This uncontrolled increase in traffic may also lead to traffic accidents, aggressive driver behaviours, disobedience to rules, etc., and adversely affecting human health in traffic. To develop a solution to the problem, which is among the top priorities in the United Nations (UN) Action Plan, many cities worldwide are trying to control and manage existing urban and rural roads with innovative IT systems. In addition to using these intelligent and environmentally friendly systems, many cities also aim to initiate and expand the use of e-vehicles, micro-mobility

or mobility as a service (MaaS) systems instead of fossil fuel vehicles in their public transportation systems, commonly. For this purpose, Samsun Metropolitan Municipality of Turkey has started to implement the "Smart City Traffic Safety" project throughout the city in June 2021 with the biggest technology and defence company "ASELSAN" in Turkey and got the best ITS City project awards in Turkey in 2022.

In the scope of the project, a total of 78 "Intelligent Intersection Systems" have started to install at signalised intersections, "Average Speed Detection System" in main corridors, "Parking Violation Detection System" in roadside parking areas, "Red Light Violation Detection System" in sections with signalised lights, and total 20 e-Buses are started to use for the public transport system of the city. Therefore, this ITS project has become one of the biggest projects in Turkey. After the contract was signed, Smart City Traffic Safety-ITS started to be implemented in July 2021 and will be completed in 2023. In the project, firstly, the geometric and technologic infrastructure transformation of a total of 78 intelligent intersections has started, and then many intelligent intersection systems and violation detection systems will be implemented to manage traffic and air pollution throughout Samsun city. For public transport, new e-buses developed by ASELSAN, a partner in the "Smart City Traffic Safety" project, are used in Samsun city instead of fossil fuel buses (Fig. 1).

Fig. 1. New fully electric and supercharged e-Buses in Samsun City [30].

4 Determination of Methodology Steps

Blockchain is a cutting-edge technology that combines various fields, including encryption, IT, economics, and politics. Therefore, there are few application examples and case studies in most industries, including construction and transportation.

A literature review of academic articles, conference proceedings, textbooks, technical documents and reliable online resources was conducted to better understand emerging technologies. In this context, the scope, features and use of Blockchain and other technologies in various industries were determined by analyzing online resources as well as

case studies, whitepapers and other published materials. Critical analysis of the literature and comments by public experts allowed us to identify the most common problems in transportation. Within the scope of the identified problems, a methodology framework was prepared comprehensively on a solution with Blockchain technology for the examined IT systems. For the usability and validation of this framework, smart contracts were prepared and integrated into a frontend web platform. The obtained ITS data was successfully recorded into Blockchain via a frontend web platform. The proposed steps for the study are presented in Fig. 2.

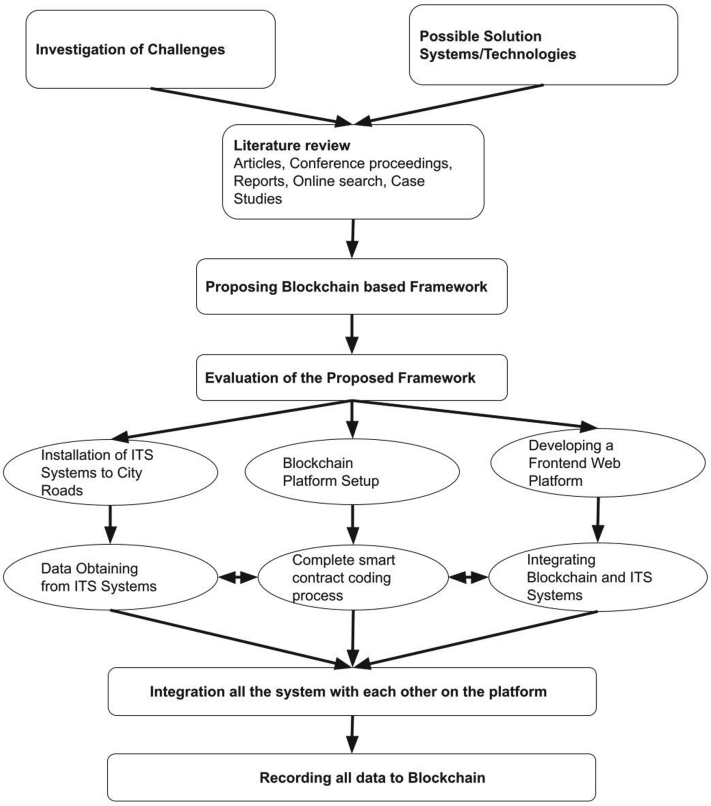


Fig. 2. Methodology diagram of the proposed study.

5 Evaluation of Dealing with Big Data Records of ITS

The evaluation was conducted with datasets from the Smart City Traffic Safety-ITS project of Samsun City, which involves collaborative efforts utilising ITS systems for Blockchain technology integration. The provided structure was used throughout the ITS systems based on smart contracts in Blockchain. The following processes initiated

by ITS systems such as an Intelligent Signalized Intersection System, Park Violation Detection System, Red-Light Violation Detection System, Speed Corridor System and e-Bus system, were recorded in the Blockchain for reporting samples of information. Data from ITS systems are stored on the digital platform when the smart contract was implemented. The user may then register using Blockchain to track if any modifications are made to these initial set of details. Due to the structure provided by the Blockchain, none of the prior records created can be altered or tampered with.

In collaborative work with users, the security and dependability of information are crucial. Inter-disciplinary collaboration, trust, and cooperation are the most significant aspects impacting the design process. The reason for changes or disagreements and any difficulties that arise often result in extra delays and expenses; however, with smart contracts, this process becomes more autonomous. Users can monitor and have confidence in any changes. Consequently, the growth of the process, its roles and duties, as well as inter-disciplinary cooperation can be used more feasible in the digital environment.

Once the data has been coordinated in the first phase, the Blockchain-based solution generates its own documentation, which is then made available to all users. This enables a transparent, automatic process since everyone knows their fundamental duties and remedial methodology, as well as the significance of capturing all actions as trustworthy data records in the Blockchain database. Since each dataset has its own identity, every issue may be identified and linked to the appropriate individual including the author using metadata assigned to the file, reports, and user levels. This develops a complicated filtering mechanism inside the models to discover coordination issues in multiple disciplines and make them visible to the public in order to improve efficiency (Fig. 3). When a user signs into the system, a timestamp is appended to each activity that is logged on the distributed ledger as evidence of registration.

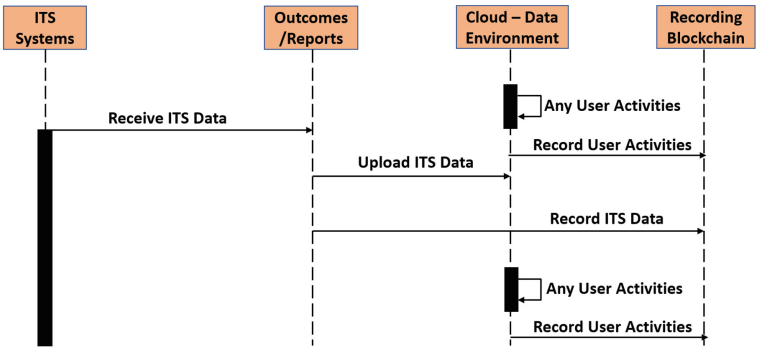


Fig. 3. Working scheme of the system.

Large enterprises and organisations' use of sophisticated analytical tools for storing, visualising, and analysing data has contributed to the exponential growth of big data technology. However, big data safety has become a major concern due to the massive data consumption and transportation. Despite significant security issues, cloud technology has been broadly used for applications involving vast volumes of data. When suitable

security procedures are not used, third-party apps and intruders might readily engage in destructive actions such as stealing sensitive data and crashing the server. Big data has several challenges, including data collection, sharing, storage, and processing. This chapter evaluates the strategies and applications based on Blockchain technology for big data in the transportation domain. Figure 4 illustrates an overview of Blockchain in a transportation environment, including data collection, storage, analytics, and privacy and security.

Reports, images and other data from sensors, cameras and other devices are available to many participants. Many participants share and record the data in an open environment, such as municipalities, control centres and academia. Although the data can be in many forms, all fields are recorded in the system for each vehicle.

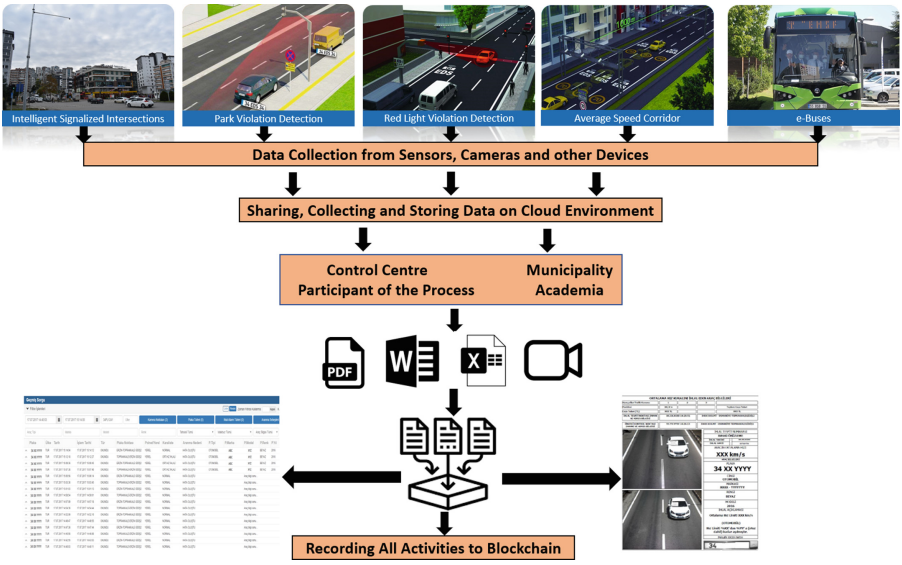


Fig. 4. Overview of Blockchain in a transportation environment, including all process steps.

5.1 Creating Smart Contracts and a Web-Based Platform

The Remix platform is used to compile and deploy smart contracts. Remix is an Ethereum Solidity (ES) development environment that facilitates the development and execution of smart con- tracts. In the data structure to be used in the creation of the smart contract to be recorded, file name, provider, violation (red light, park etc.), location, date and time and timestamp of the data are used as seen in Fig. 5 (i), smart contract structure was designed in Solidity as - `struct ITSDataRecord {address sensorID; string violation; string location; uint32 reportID; uint32 timestamp;}`

Thus, when project data was recorded, metadata about where and how data was recorded can be stored as unalterable evidence. Secondly, digital data can be generated by creating a new smart contract for each vehicle. In this contract, information specific to the vehicle that com- mits violence is registered to the Blockchain by identifying the vehicle's Blockchain ID. In this way, each vehicle-specific data record can be created digitally through the Blockchain as demonstrated in Fig. 5 (ii), smart contract structure for the Vehicle Data Record was designed as – `struct ITSVehicleRecord {address vehicleID; string violation; string location; address senderID; uint32 reportID; uint32 timestamp;}`.

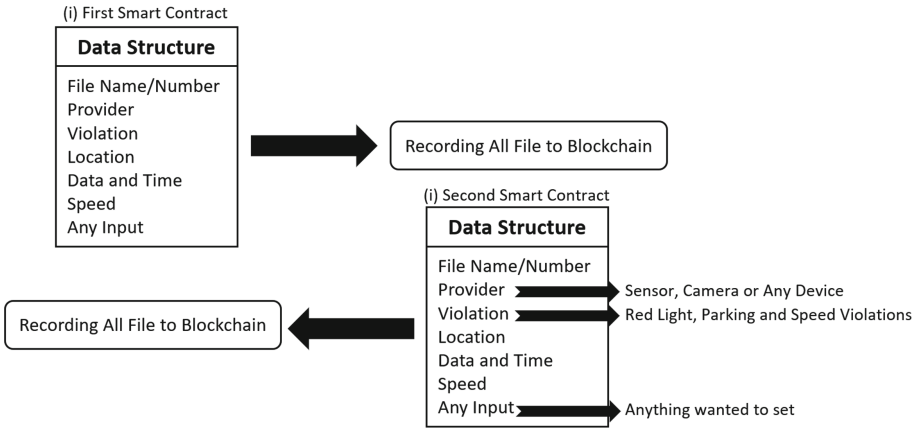


Fig. 5. Smart contract specific data record process of vehicles (ii) or report of systems supplied by ITS.

A platform that enables interaction with smart contracts using front-end websites was created. To generate the interactivity of the front-end website, a front-end JavaScript interface connecting the front-end website to the Blockchain system has been developed. The user interface allows users to engage with contracts, including the deployment of new contracts and contract processes such as recording or retrieving data from Blockchain. Three smart contracts are deployed to implement the outcomes of Blockchain-based ITS systems as evidenced by this research. (i) Smart contract for registering new users/reports/updates: Each contract is identifiable by its unique number, which is stored in the mapping link to the most recent contract address. Using the new user(.) method, the contract is created and updated for each user so that other nodes may see all users' records (see Fig. 6). (ii) Smart contract for the outputs recording of ITS systems: It is a mechanism for recording outputs and seeing all outputs that have been recorded. When additional nodes are registered to the platform, the newData(.) methods may be used to inspect registered data. (iii) Smart contract updates with users: ITS systems are implemented following the original contract. After registering on the Blockchain network, each action should be recorded in the contract. With the updateUser(.) and updateData(.) methods, the end User/Client is able to see the whole transaction history for all data.

Big data applications, in general, gather data in various types from various sources (unstructured data). As documents cannot be processed in their original format the data must be transformed into a structured format from which different application-domain predictions may be derived. With its capacity to efficiently manage large amounts of data, Blockchain offers organised data for generating predictions. Through consensus algorithms, Blockchain protects data integrity, reducing cybersecurity risks. As such,this research focuses on two sub-areas of Blockchain technologies for big data collection: secure big data collection and secure big network infrastructure.

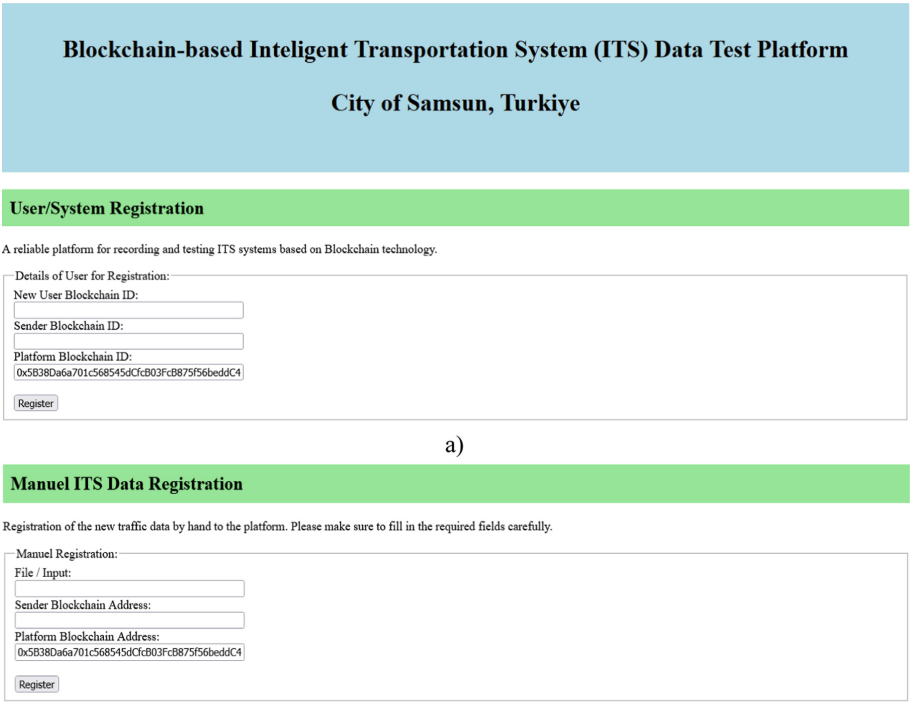


Fig. 6. Data test platform of the proposed system.

With this recorded platform, it is possible to track and monitor when and by which system data is recorded, as illustrated in Fig. 7(a). If desired, records specific to these devices can be viewed separately, as it is seen in Fig. 7(b).

Registered ITS Data

The recorded ITS data selection is a drop-down list to monitor and view all the logs and records:

Choose an Intelligent Signalized Intersection System Number: ISI-1 Submit Query

Choose a Park Violation Detection System Number: PVD-1 Submit Query

Choose a Red Light Violation Detection System Number: RLVD-1 Submit Query

Choose a Speed Corridor System Number: SC-1 Submit Query

Choose an e-Bus Number: e-Bus-1 Submit Query

ID	DataID	Systems	SenderID	TxHash	Timestamp	Contract Address
1	ISI-5515_01.06.2022_Report	ISI-1	0xaEPâ€¦2tf	0xeb...c018	02.06.2022-00:01	0xEFa212...72F10BCdB
2	ISI-5517_01.06.2022_Report	ISI-17	0xc5Yâ€¦43e	0x33...ed45	02.06.2022-00:01	0xPSw12...75F10DFES
3	ISI-5505_01.06.2022_Report	ISI-5	0xID4â€¦e74	0x33...ed45	02.06.2022-00:01	0xPSw12...75F10DFES
4	ISI-5530_01.06.2022_Report	ISI-30	0xaDEâ€¦ef3	0x12...d101	02.06.2022-00:02	0x2D460â€¦4b8B003C99
5	PVD-5502_01.06.2022_Report	PVD-2	0xe24â€¦8fe	0x63...ec55	02.06.2022-00:02	0xRFw12...6wKD86ajC
6	CV-5503_01.06.2022_Report	CV-3	0xsa9â€¦kf5	0xwe3...as6d	02.06.2022-00:02	0xAw1P2...83As8SaEf
7	e-Bus-5504_01.06.2022_Report	e-Bus-4	0x1saâ€¦p09	0x5t...8dha	02.06.2022-00:02	0xe8d4...94Dses87s
8	RLVD-5501_01.06.2022_Report	RLVD-1	0xeDFâ€¦yh3	0x4e...ew32	02.06.2022-00:02	0xSdw2...Ewr4w6rd

a)

Registered ITS Data

The recorded ITS data selection is a drop-down list to monitor and view all the logs and records:

Choose an Intelligent Signalized Intersection System Number: ISI-5 Submit Query

Choose a Park Violation Detection System Number: PVD-1 Submit Query

Choose a Red Light Violation Detection System Number: RLVD-1 Submit Query

Choose a Speed Corridor System Number: SC-1 Submit Query

Choose an e-Bus Number: e-Bus-1 Submit Query

ID	DataID	System	SenderID	TxHash	Timestamp	Contract Address
3	ISI-5505_01.06.2022_Report	ISI-5	0xaEPâ€¦2tf	0xeb...c018	02.06.2022-00:01	0xEa212...72F10BCdB
17	ISI-5505_31.05.2022_Report	ISI-5	0xaEPâ€¦2tf	0xa4...d4e3	01.06.2022-00:01	0x3E4sw...34Ase5a2w3
9	ISI-5505_30.05.2022_Report	ISI-5	0xaEPâ€¦2tf	0x2s...d3sa	31.05.2022-00:01	0x2s36y...2es21ws46
58	ISI-5505_29.05.2022_Report	ISI-5	0xaEPâ€¦2tf	0xa3...ds58	30.05.2022-00:01	0xE3Ds5...57e6da2Ef

b)

Fig. 7. a) Recorded data of all system and b) recorded data of a specific system.

6 Conclusion

Data integrity, privacy, database management, and availability can be achieved through implementing ITS systems combined with Blockchain technology. Users and interactions with a transportation system may be tracked, and conflicts between users in terms of tasks and responsibilities can be eliminated by utilising Blockchain technology. Each participant in the system has a unique user ID, roles and responsibilities, resulting in a

well-coordinated network of requirements. ITS system data may be shared more effectively because of the immutability and traceability provided by Blockchain. As a trustworthy record of all transactions' history, the Blockchain can be relied upon to store proof of every execution in chronological order. It is possible to keep track of any changes to the transaction list using blockchains and to the ITS system's data as a distributed database on a global ledger, including transaction data on the network. To store encrypted data, cryptographic hash techniques incorporate a ledger containing the block header's root. The timestamp feature of the Blockchain platform is ideal as it automates the process, prevents participants from making unwanted changes and is ideal for secure data recording. An additional benefit of an open and decentralised procedure is the reduced time required for secure file sharing and accessibility. With the use of Blockchain, it is possible to follow the registration processes of ITS systems for any vehicle, from the production of the vehicle until it is completely withdrawn from the traffic.

In the digitalisation process, IT systems and Blockchain integration can also transform the requirements and preferences of performers based on coded services. Blockchain applications can connect real-time data and systems throughout the whole lifecycle of devices and participants involved in the process. In terms of limitations, while Blockchain is a novel technology, it should be taken into consideration that additional advancements might have an impact on the findings and converting IT systems to smart contract codes may also be problematic. Blockchain and the Inter- net of Things (IoT) integration will be further explored in future research to create more complex models based on real-world case studies.

In future work, the primary focus will be on the creation of an advanced data record system that will be based on the Blockchain technology for each vehicle and system entity. By using this system, vehicles and traffic services work in integration in order to achieve improved autonomy and real-time monitoring of all the activities and assets.

Acknowledgements. This study was conducted under a research project titled "i-gCar4ITS: Innovative and Green Carrier Development for Intelligent Transportation System Applications" which was supported by British Council. The authors would like to thank British Council for this support. The first author of the paper also would like to thank the Republic of Türkiye Ministry of National Education for the scholarship.

References

1. Cocîrlea, D., Dobre, C., Hîrţan, L.A., Purnichescu-Purtan, R.: Blockchain in intelligent transportation systems. Electronics **9**(10), 1–24 (2020)
2. Aggarwal, S., Kumar, N.: Transportation system applications. In: Aggarwal, S., Kumar, N., Raj, P. (eds.) Advances in Computers, vol. 121, pp. 431–454. Elsevier (2021)
3. Bodkhe, U., et al.: Blockchain for industry 4.0: a comprehensive review. IEEE Access **8**, 79764–79800 (2020)
4. Tanwar, S., Bhatia, Q., Patel, P., Kumari, A., Singh, P.K., Hong, W.C.: Machine learning adoption in blockchain-based smart applications: the challenges, and a way forward. IEEE Access **8**, 474–488 (2019)
5. Balasubramaniam, A., Gul, M.J.J., Menon, V.G., Paul, A.: Blockchain for intelligent transport system. IETE Tech. Rev. **38**(4), 438–449 (2021)

6. Yuan, Y., Wang, F.Y.: Towards blockchain-based intelligent transportation systems. In: 2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC), pp. 2663–2668. IEEE (2016).
7. Lin, I.C., Liao, T.C.: A survey of blockchain security issues and challenges. Int. J. Netw. Secur. **19**(5), 653–659 (2017)
8. Aujla, G.S., Singh, M., Bose, A., Kumar, N., Han, G., Buyya, R.: BlockSDN: blockchain-as-a-service for software defined networking in smart city applications. IEEE Netw. **34**(2), 83–91 (2020)
9. Sayeed, S., Marco-Gisbert, H.: Proof of adjourn (PoAj): a novel approach to mitigate blockchain attacks. Appl. Sci. **10**(18), 1–23 (2020)
10. Hîrţan, L.A., Dobre, C., González-Vélez, H.: Blockchain-based reputation for intelligent transportation systems. Sensors **20**(3), 1–24 (2020)
11. Lamssaggad, A., Benamar, N., Hafid, A.S., Msahli, M.: A survey on the current security landscape of intelligent transportation systems. IEEE Access **9**, 9180–9208 (2021)
12. Jabbar, R., Dhib, E., Ben Said, A., Krichen, M., Fetais, N., Zaidan, E., Barkaoui, K.: Blockchain technology for intelligent transportation systems: a systematic literature review. IEEE Access **10**(2022), 20995–21031 (2022)
13. Bali, R.S., Kumar, N.: Secure clustering for efficient data dissemination in vehicular cyber–physical systems. Future Gener. Comput. Syst. **56**, 476–492 (2016)
14. Narbayeva, S., Bakibayev, T., Abeshev, K., Makarova, I., Shubenkova, K., Pashkevich, A.: Blockchain technology on the way of autonomous vehicles development. Transp. Res. Procedia **44**, 168–175 (2020)
15. Tanga, C.S., Veelenturf, L.P.: The strategic role of logistics in the Industry 4.0 era. Transp. Res. Part E: Logist. Transp. Rev. **129**, 1–11 (2019)
16. Rathee, G., Sharma, A., Iqbal, R., Aloqaily, M., Jaglan, N., Kumar, R.: A blockchain framework for securing connected and autonomous vehicles. Sensors **19**(14), 1–15 (2019)
17. Jiang, T., Fang, H., Wang, H.: Blockchain-based Internet of vehicles: distributed network architecture and performance analysis. IEEE Internet Things J. **6**(3), 4640–4649 (2018)
18. Matthes, C., et al.: The Collaborative virtual reality neurorobotics lab. In: 26th IEEE Conference on Virtual Reality and 3D User Interfaces, VR 2019, pp. 1671–1674, Osaka, Japan (2019)
19. Asfia, U., Kamuni, V., Sheikh, A., Wagh, S., Patel, D.: Energy trading of electric vehicles using Blockchain and smart contracts. In: 18th European Control Conference (ECC) , Naples, Italy, pp. 3958–3963 (2019)
20. Zielińska, A., Skowron, M., Bień, A.: The concept of the blockchain technology model use to settle the charging process of an electric vehicle. In: Applications of Electromagnetics in Modern Engineering and Medicine (PTZE), Janow Podlaski, pp. 271–274, Poland (2019)
21. Das, M.L.: Privacy and security challenges in Internet of Things. In: Natarajan, R., Barua, G., Patra, M.R. (eds.) Distributed Computing and Internet Technology. ICDCIT 2015. Lecture Notes in Computer Science, vol. 8956, pp. 33–48. Springer, Cham (2015). https://doi.org/10.1007/978-3-319-14977-6_3
22. Ho, G., Leung, D., Mishra, P., Hosseini, A., Song, D., Wagner, D.: Smart locks: lessons for securing commodity internet of things devices. In: Proceedings of the 11th ACM on Asia Conference on Computer and Communications Security, pp. 461–472 (2016)
23. Amoozadeh, M., et al.: Security vulnerabilities of connected vehicle streams and their impact on cooperative driving. IEEE Commun. Mag. **53**(6), 126–132 (2015)
24. Yang, Y., Liu, X., Deng, R.H.: Lightweight break-glass access control system for healthcare Internet-of-Things. IEEE Trans. Ind. Inform. **14**(8), 3610–3617 (2017)
25. Chin, W.L., Li, W., Chen, H.H.: Energy big data security threats in IoT-based smart grid communications. IEEE Commun. Mag. **55**(10), 70–75 (2017)

26. Atzori, L., Iera, A., Morabito, G.: The Internet of Things: a survey. Comput. Netw. **54**(15), 2787–2805 (2010)
27. Zha, X., Wang, X., Ni, W., Liu, R.P., Guo, Y.J., Niu, X., Zheng, K.: Blockchain for IoT: the tradeoff between consistency and capacity. Chin. J. Internet of Things **1**(1), 21–33 (2017)
28. Korpela, K., Hallikas, J., Dahlberg, T.: Digital supply chain transformation toward blockchain integration. In: Proceedings of the 50th Hawaii International Conference on System Sciences (2017)
29. Biswas, K., Muthukkumarasamy, V.: Securing smart cities using blockchain technology. In: Proc. 18th IEEE International Conference on High Performance Computing Community; 14th IEEE International Conference Smart City; 2nd IEEE International Conference on Data Science System, HPCC/SmartCity/DSS 2016, pp. 1392–1393 (2016)
30. URL-1 (2022). Samsun Büyükşehir Belediyesi. https://samsun.bel.tr/haberler/akilli-sehir-nedir-samsunda-neler-yapilacak. Accessed 06 May 2022

Combustion in Engines, Alternative Technologies, Energy Management and Emissions

Artificial Neural Network Model Use for Particulate Matter Evaluation from Ships in Klaipeda Port

Paulius Rapalis(✉) and Giedrius Šilas

Klaipėda University, Bijūnų 17, 91225 Klaipėda, Lithuania
{paulius.rapalis,giedrius.silas}@ku.lt

Abstract. This publication deals with the evaluation of forecasting the emissions of ships operating in the port through neural networks. Analyzed particulate matter (PM1, PM2.5, PM10, TSP) emissions from ships at various parts of the port. The research is based on usage of AIS system data, the technical database of the ship, the ambient air measurement data and the ambient air pollution measuring data for the use of neural network training. Results showed that trained neuronal networks could be sufficiently accurate (the correlation coefficient amounted from 0.82 to 0.92 depending on pollutant) to use for ship operating in the port emissions evaluation.

Keywords: Solid particles · Ship air pollution · Neural network · Port pollution

1 Introduction

In port emissions from ships are only small part of global shipping emissions. However, these emissions are very important for the residents and environment of the coastal regions [1, 2]. There is a lot of publications proving that particulate matter (PM) causing negative effects on human health [3–5].

Increasingly focusing on air quality in cities and ports more effective ways to evaluate emissions are sought. Currently, there are two ways to evaluate air quality changes in the city due to the influence of shipping: i) direct air pollutants measurement or ii) usage of air quality evaluation models [6].

Direct emissions measurements on board the ships or emissions plume measurement are complex, time consuming and requires a lot of human resources. Nowadays two most used methods for direct and/or indirect emission data collection and processing are bottom-up, top-down or their combination [7]. Top-down method is cheap and doesn ‘t requires a lot of data [8]. When evaluating ship emissions by using bottom-up methodology in addition to the main engines, the work of auxiliary engines and heat exchangers is also evaluated [9]. However, the calculations of emissions based on ship statistics are characterized by a major error [8, 10].

Neural network models are increasingly chosen to avoid these major calculations errors. The usage of neural networks models is very broad, from ship affecting forces

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 77–84, 2023.
https://doi.org/10.1007/978-3-031-25863-3_7

evaluation or ship fuel consumption optimization to emissions evaluation [11–14]. The results obtained by using these models are almost identical to direct measurements [15].

This article attempts to evaluate the use of the neural network model to evaluate emissions of the solid particles from vessels operating in Klaipeda port.

2 Methodology

The amount of solid particles from the ship power plants depends on many factors, but the main decisive is the engine type, power, and load. The dispersion of solid particles depends on the position of the ship, technical parameters, emissions, and meteorological conditions. These parameters can also be evaluated directly, or through secondary parameters. The relationship between all these parameters is known, but the direct evaluation of each of them is difficult. Using neural networks can simplify the determination of these connections and systematically predict the propagation of ship exhaust, at higher speeds, and using fewer initial data than conventional dispersion programs.

As shown by Zhu et al. [18] artificial neural networks (ANN) can be effectively used in air pollution research and simplify the determination of these connections and systematically predict pollutant propagation at higher speeds and using fewer initial data than conventional dispersion programs. Albeit their approach was to use models' data as inputs and differs from this paper aim to use direct measurements data it shows that ANN's can be used to reduce obstacles which comes with traditional methods.

2.1 Data Used for Neural Network Model

The research is based on usage of AIS system data, the technical database of the ships, the ambient air measurement data, and the ambient air pollution of 1 μm, 2.5 μm, 10 μm and suspended particulate matter (PM1, PM2.5, PM10, TSP) data. The methodology of ships plume evaluation is described in the previous publication [16]. All parameters used for data for neural network training is given in Table 1.

Fig. 1. Location of air pollution measurement station. Ortophoto map layer data: google maps.

To distinguish the ambient air pollutant data from other sources, the data was selected when the wind direction was from 180 to 360 degrees. The following Fig. 1 show location of air pollution measurement station (55.6892, 21.1386) in Klaipeda port.

Table 1. Data used for neuron network model training.

Parameter	Dimension	Parameter	Dimension
Ship speed	km/h	Ship depth	m
Ship course in respect of the bottom	°	The total power of the engines	kW
Ship course	°	Wind speed	m/s
Latitude	°	Wind direction	°
Longitude	°	Relative humidity	%
The distance to the end of the port	m	Ship draft	m
DWT	t	Concentration of PM1	$\mu g/m^3$
Gt	–	Concentration of PM2.5	$\mu g/m^3$
Ship length	m	Concentration of PM10	$\mu g/m^3$
Ship width	m	Concentration of TSP	$\mu g/m^3$

2.2 Neural Network Model Parameters

To create and train neural network model, Neural Designer software were used [17]. Model consists of four perceptron layers with different number of inputs and neurons. Created model consisted of layers typical to approximation models – scaling layer, hidden perceptron layers, unscaling layer and bounding layer. Number of inputs and neurons for each layer is given in Table 2.

Table 2. Neural network model parameters.

Layer	Inputs	Neurons	Activation function
Scaling layer	17	17	-
Perceptron layer 1	17	150	Hyperbolic tangent
Perceptron layer 2	150	80	Hyperbolic tangent
Perceptron layer 3	80	55	Hyperbolic tangent
Perceptron layer 4	55	4	Linear
Unscaling layer	4	4	–
Bounding layer	4	4	–

The training data consisted of real measurements of ambient air pollutant concentrations of particulate matter done in one-minute intervals in port for 3 months. Out of this data, only those measurements when wind direction was such that plume is carried toward the city was used. This data was paired with other parameters describing weather conditions, ship location with regards to measurement stations, mowing direction and speed and technical parameters describing each ship (as presented in Table 1) were used.

This formed a data array describing shipping intensity weather conditions, and pollutant concentration in one-minute intervals. In total data array consisted of 81,949 rows which was divided for neural network training, selection and testing as follows: i) 60% for training, ii) 20% for selection, and iii) 20% for testing. Training samples were used to create and train model while selection samples were used for choosing the neural network with the best generalization properties. Testing samples were used to validate the functioning of the model.

Activation functions for hidden perceptron layers were selected by choosing from available functions selection in software. Functions were tested by trial-and-error method until most suitable function – Hyperbolic tangent – were determined.

Both the inputs' scaling in the data set synchronization with the inputs' scaling in the neural network and the scaling of the targets in the data set synchronization with the unscaling of the outputs in the neural network were done by Neural Designer software without any intervention by the user.

3 Results

The trained neural network, using position, technical and meteorological data, predicted the concentrations of particulate matter at different distances from the vessel. The correlation between experimental data and predicted results were quite high. The correlation coefficient amounted from 0.82 to 0.92 depending on pollutant. Correlation for PM1, PM2.5, PM10 and TSP between direct measurements and predicted results from neural network model are shown in Figs. 2, 3, 4 and 5.

The minimum accuracy is achieved with suspended particulate matter (TSP), and the best correlation is achieved with PM1, the smallest fraction measured solid particulate matter.

As the accuracy increases, as the particulate matter fraction decreases, it is likely to be related to the specificity of solid particulate matter generated from internal combustion engines. Since diesel internal combustion engines generated more of small fraction particulate matter (PM1 and PM2.5), while other industrial and natural sources are more related to PM10 and TSP generation, therefore there is a significant difference between TSP and PM1 forecast accuracy when only the emissions generated by shipping are evaluated.

The capability of neural networks to perform approximation on field measurements with sufficient accuracy expands the possibility of shipping pollution predictions based on remote measurement data, that was previously plagued by significant errors due to limitations of simpler iterative functions and eliminate the need for significant lab scale testing as described in [16].

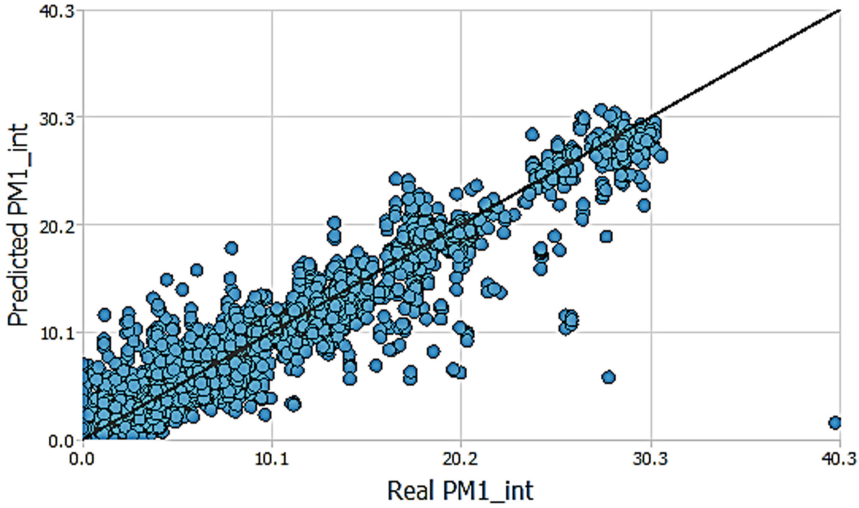


Fig. 2. Correlation for PM1 between direct measurements and predicted results from neural network model.

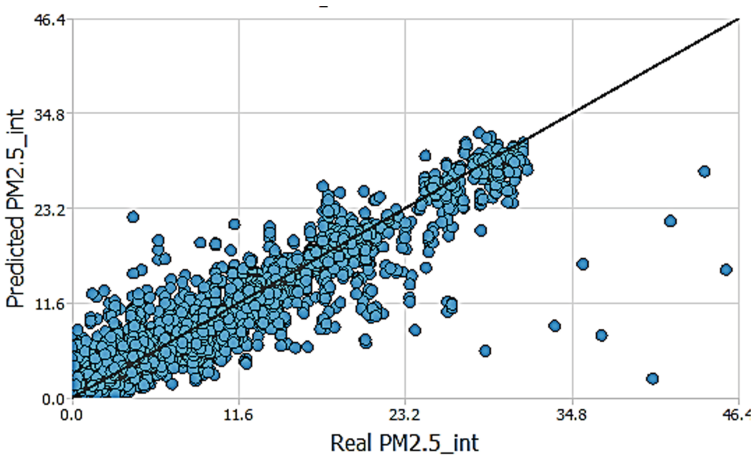


Fig. 3. Correlation for PM2.5 between direct measurements and predicted results from neural network model.

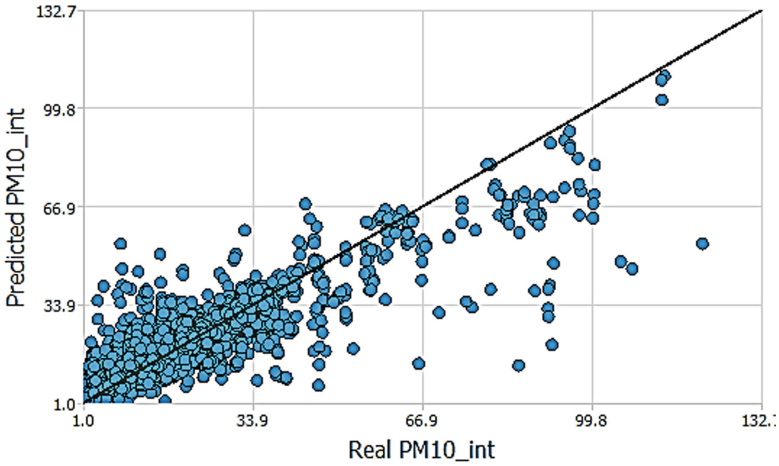


Fig. 4. Correlation for PM10 between direct measurements and predicted results from neural network model.

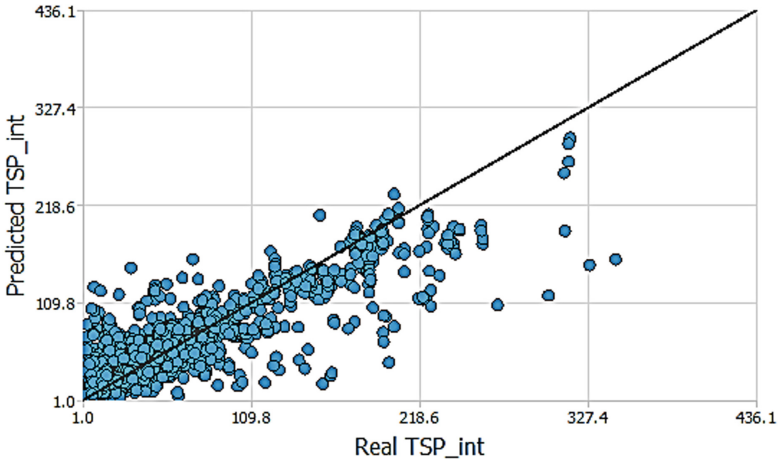


Fig. 5. Correlation for TSP between direct measurements and predicted results from neural network model.

4 Conclusions

Increase in the concentration of solid particles due to the passage of emission plume through measurement site can be easily identified due to the characteristic short-term increase in pollutants concentration. Due to the geographical layout of Klaipeda port, it is easy to distinguish the ambient air pollutants from shipping.

The repeatability of ship traffic and weather data is sufficient to produce data arrays suitable for neural network training. With this data is possible to create a neural network that shown strong correlation with experimental measurements with only limited initial

training data that can accurately predict exhaust gas plume concentration without the need for dispersion modeling and data of emission rates.

References

1. Mamoudou, I., Zhang, F., Chen, Q., Wang, P., Chen, Y.: Characteristics of PM2.5 from ship emissions and their impacts on the ambient air: a case study in Yangshan Harbor, Shanghai. Sci. Total Environ. **640–641**, 207–216 (2018). https://doi.org/10.1016/j.scitotenv.2018.05.261
2. Wen, J., et al.: PM2.5 source profiles and relative heavy metal risk of ship emissions: Source samples from diverse ships, engines, and navigation processes. Atmos. Environ. **191**, 55–63 (2018). https://doi.org/10.1016/j.atmosenv.2018.07.038
3. Mifka, B., Žurga, P., Kontošić, D., Odorčić, D., Mezlar, M., Merico, E., Grasso, F.M., Conte, M., Contini, D., Alebić-Juretić, A.: Characterization of airborne particulate fractions from the port city of Rijeka Croatia. Mar. Pollut. Bull. **166**, 112236 (2021). https://doi.org/10.1016/j.marpolbul.2021.112236
4. Mao, J., Zhang, Y., Yu, F., Chen, J., Sun, J., Wang, S., Zou, Z., Zhou, J., Yu, Q., Ma, W., Chen, L.: Simulating the impacts of ship emissions on coastal air quality: Importance of a high-resolution emission inventory relative to cruise- and land-based observations. Sci. Total Environ. **728**, 138454 (2020). https://doi.org/10.1016/j.scitotenv.2020.138454
5. Wu, S.-P., et al..: Chemical nature of PM2.5 and PM10 in the coastal urban Xiamen, China: insights into the impacts of shipping emissions and health risk. Atmos. Environ. **227**, 117383 (2020). https://doi.org/10.1016/j.atmosenv.2020.117383
6. Toscano, D., Murena, F., Quaranta, F., Mocerino, L.: Assessment of the impact of ship emissions on air quality based on a complete annual emission inventory using AIS data for the port of Naples. Ocean Eng. **232**, 109166 (2021). https://doi.org/10.1016/j.oceaneng.2021.109166
7. Zhou, F., Fan, Y., Zou, J., An, B.: Ship emission monitoring sensor web for research and application. Ocean Eng. **249**, 110980 (2022). https://doi.org/10.1016/j.oceaneng.2022.110980
8. Topic, T., Murphy, A.J., Pazouki, K., Norman, R.: Assessment of ship emissions in coastal waters using spatial projections of ship tracks, ship voyage and engine specification data. Cleaner Eng. Technol. **2**, 100089 (2021). https://doi.org/10.1016/j.clet.2021.100089
9. Huang, L., Wen, Y., Zhang, Y., Zhou, C., Zhang, F., Yang, T.: Dynamic calculation of ship exhaust emissions based on real-time AIS data. Transp. Res. Part D: Transp. Environ. **80**, 102277 (2020). https://doi.org/10.1016/j.trd.2020.102277
10. Trozzi, C., Vaccaro, R.: Methodologies for estimating air pollutant emissions from ships: a 2006 update. 9
11. Namgung, H., Kim, J.-S.: Vessel trajectory analysis in designated harbor route considering the influence of external forces. J. Mar. Sci. Eng. **8**, 860 (2020). https://doi.org/10.3390/jmse8110860
12. Karagiannidis, P., Themelis, N.: Data-driven modelling of ship propulsion and the effect of data pre-processing on the prediction of ship fuel consumption and speed loss. Ocean Eng. **222**, 108616 (2021). https://doi.org/10.1016/j.oceaneng.2021.108616
13. Yuan, Z., Liu, J., Zhang, Q., Liu, Y., Yuan, Y., Li, Z.: Prediction and optimisation of fuel consumption for inland ships considering real-time status and environmental factors. Ocean Eng. **221**, 108530 (2021). https://doi.org/10.1016/j.oceaneng.2020.108530
14. Cao, K., Zhang, Z., Li, Y., Xie, M., Zheng, W.: Surveillance of ship emissions and fuel sulfur content based on imaging detection and multi-task deep learning. Environ. Pollut. **288**, 117698 (2021). https://doi.org/10.1016/j.envpol.2021.117698

15. Schaub, M., Baldauf, M., Hassel, E.: Prediction of PM emissions during transient operation of marine diesel engines using artificial neural networks. In: Proceedings ASIM SST 2020, pp. 167–174. ARGESIM Publisher Vienna (2020)
16. Rapalis, P., Žemgulis, M., Jonika, L.: Emisijų iš laivų Klaipėdos uoste nustatymo nuotoliniu būdu galimybių apžvalga (2018).
17. Explainable AI Platform—Neural Designer. https://www.neuraldesigner.com/. Accessed 10 June 2022
18. Zhu, G., Zhang, P., Tshukudu, T., Yin, J., Fan, G., Zheng, X.: Forecasting traffic-related nitrogen oxides within a street canyon by combining a genetic algorithm-back propagation artificial neural network and parametric models. Atmos. Pollut. Res. **6**, 1087–1097 (2015). https://doi.org/10.1016/j.apr.2015.06.006

A Case Study for the Development of Environmentally Safe Low-Lead Aviation Gasoline in Ukraine

Sergii Boichenko[1], Anna Yakovlieva[2](✉), Iryna Shkilniuk[1], Natalia Gecejova[3], Olufemi Olaulava Babatunde[4], and Ihor Kuberskyi[1]

[1] National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Borshchahivska Str. 115, Kyiv 03056, Ukraine
{chemmotology,i_shkilniuk,kio2773230}@ukr.net
[2] National Aviation University, Liubomyr Huzar Ave.1, Kyiv 03058, Ukraine
anna.yakovlieva@nau.edu.ua
[3] Technical University of Kosice, Rampova Str. 7, 04121 Kosice, Slovakia
natalia.gecejova@tuke.sk
[4] Scientific-Technical Union of Chemmotologists, Artema Str. 21, Kyiv 04053, Ukraine
rotorukr@gmail.com

Abstract. The paper is devoted to the development of environmentally safe avgas compositions with low content of tetraethyl lead. Modern trends in global avgas production and consumption are shown, along with tendencies in restriction of tetraethyl lead use for anti-knock properties improvement. The main methods of avgas octane number rising are shown, among which are introduction of high-octane hydrocarbons, oxygenated compounds and anti-knock additives. The influence of individual hydrocarbons on octane number is studied. It is found that blending alkylate, isopentane, isooctane and benzene with based improves octane number by 2–4 units. Similar tendency is found for blending base gasoline with anti-knock additives. Combination of high-octane hydrocarbons and anti-knock additives has allowed to improve octane number of avgas up to 6 units. Basing on these components new compositions of avgas were developed.

Keywords: Aviation gasoline · Piston engine · Anti-knock properties · Octane number · Anti-knock additives · Ecological properties · Operation properties

1 Introduction

The reduction of the impact of aviation on the environment and increasing fuel efficiency of aircraft engines through the introduction of alternative motor fuels has become the objective. At the same time, the issue of ensuring the safe transition of aircraft equipped with piston engines to unleaded aviation gasoline (avgas) is not unsolved. Today, there is a tendency for prohibiting the use of leaded avgas [1, 2]. The world's leading organizations in the field of civil aviation develop pathways to completely replace leaded avgas with its unleaded alternative. At the same time, one of the main trends and requirements

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 85–94, 2023.
https://doi.org/10.1007/978-3-031-25863-3_8

is environmentally safe energy-efficient development of air transport within the global strategy for sustainable development [3, 4].

Ukraine, traditionally being the country with a well-developed aviation sector, is now faced with a number of problems connected to the use of Avgas. Since 2003 in Ukraine production, import, sale, and use of gasoline, which contains tetraethyl lead (TEL), is prohibited [5, 6]. As the result, aircraft, equipped with piston engines, are fueled with unleaded automobile gasoline. This leads to early deterioration of engines, rising the number of failures – all these threaten the flight safety. Operation of these aircraft on any other fuel is a violation of technical conditions. In accordance with international standards in the field of civil aviation further operation of these aircrafts is banned, including the arrival of foreign aircraft using leaded gasoline into Ukraine [6].

Therefore, one of the urgent scientific and practical tasks is to develop new alternative environmentally safe Avgas that will have sufficient operational and environmental characteristics. Taking into account the abovementioned, the *aim of the study* is to develop the compositions of low-lead avgas for improving its anti-knock properties.

Object of the study – production of low-lead avgas with better anti-knock properties.

Subject of the study – anti-knock properties of low-lead avgas compositions.

2 Literature Overview

Avgas, is a gasoline fuel for aircraft equipped with piston engines. Such aircraft are mainly used for private needs, business aviation, flight training and harvesting, cultivation of agricultural fields, tourism, sport activities, etc. (Fig. 1) [7]. With the development of unmanned aerial vehicles (UAV) avgas is actively used to power them. Aircraft piston engines operate on the same principles as engines found in motor vehicles [8].

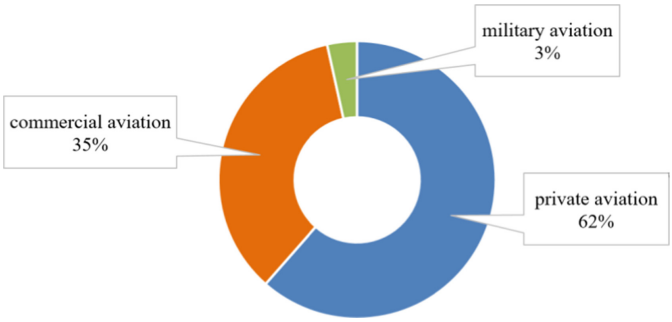


Fig. 1. Global Avgas market share, by end-users in 2020 [7].

Avgas consumption has increased due to the development of business aviation. The use of small aircraft provides high mobility, efficiency and productivity of business aviation [7, 9]. The global demand for small aircraft has grown. Various air sports are also actively developing. Modern aircraft have become cheaper, faster, more reliable, and more environmentally friendly. These encourage an increase in demand for avgas.

The presence of TEL is a limiting factor in the development of small aircraft [10]. TEL is an anti-knock additive that improves octane number (ON) of avgas. It reduces the tendency of the avgas to ignite suddenly and instantaneously during the combustion that

leads to catastrophic failure of the engine. However, LED has negative impact on human health and environment. The largest source of TEL exposure is from the evaporative emissions associated with fuel technological processes. Lead is classified as carcinogen. It causes neurological, hematological, immune and cardiovascular effects for humans. Lead from aircraft exhausts is consumed by flora and fauna, having cumulative negative effect on animals and finally on human [11].

However, attempts to replace conventional leaded avgas with its unleaded alternatives have not satisfied the safety and operational requirements of the aircraft [8]. It is obvious that transition from leaded avgas has performance issues with possible serious consequences for the flight safety. Thus, there is a need to create an unleaded high octane avgas with required physical-chemical and operation properties to provide long-term and reliable operation of aircraft with minimal negative impact on environment.

2.1 Methods of Improvement of Anti-Knocking Properties of Avgas

There are several approaches to improve operation properties of avgas, in particular, anti-knock characteristics: addition of high-octane components; blending with oxygen-containing compounds; use of anti-knock additives [19].

Among *high-octane components* of avgas it necessary to consider isoparaffin and aromatic hydrocarbons. The most effective among them are isopentane and alkylbenzin [5, 8]. Pyrobenzene and alkylbenzene are used as aromatic high-octane components. Other high-octane hydrocarbons may be also used as components of avgas [10].

The use of *oxygen-containing compounds (oxygenates)* for improvement operation characteristics of avgas is also studied. Oxygenates are low molecular weight aliphatic alcohols and their ethers (e.g. methanol, ethanol, methyl tert-butyl ether (MTBE), ethyl tert-butyl ether (ETBE), etc.). Also oxygenates are used for expanding of feedstock for fuel production. Oxygenates naturally have high ON [5, 6].

One of the most effective method of improving octane rating of avgas is use of *anti-knock additives* [10, 11]. Depending on the type of high-octane components, its origin, and mechanism of action, they may be grouped into:

- aromatic amines;
- manganese-based anti-knock additives;
- ferrum-based anti-knock additives;
- lead-based anti-knock additives.

The principle of action of anti-knock additives is the elimination of active hydrocarbon peroxides or radicals during combustion and prevention of detonation [6, 9]. The most effective compounds are: TEL, metallocenes based on iron and manganese, alkali metal compounds and aromatic amines. Susceptibility of gasolines to the anti-knock additives depends on the group composition and anti-knock characteristics of gasoline. The lower the ON of gasoline, the greater will be the effect of the additive [8]. Additives have some disadvantages, which limits its use. Amine additives lead to accumulation of resins in fuel system and formation of deposits in the combustion chamber. Manganese additives lead to formation of metal deposits on spark plugs. Ferrum additives lead to

increased fuel consumption and NO_x emissions. Concentrations of all additives in gasoline are limited and the maximum increase in ON is also limited. The dependence of the ON rise on the concentration of the additive is nonlinear [10].

2.2 Nomenclature and Specification for Avgas

Avgas grades are distinguished according to their ON. Today the number of grades of Avgas are used. *Avgas 100* is the most popular high-octane gasoline for aircraft with a high content of TEL. *Avgas 100LL* is a low lead version of Avgas 100 (LL – low lead). Specifications ASTM D910 [12] and DEF STAN 91–090 [13] determine quality requirements to these kinds of fuel. *Avgas 82UL and Avgas 87UL* – are new grades of Avgas with no TEL additive (UL – unleaded). It is a low-octane grade and may be used in engines with low compression rate. Aircraft, which are allowed to used motor gasoline are allowed to use this kind of fuel. Quality requirements are set in the specification ASTM D6227 [14]. *Avgas UL91* and *Avgas UL94* – are also unleaded Avgas modifications. Both are similar to Avgas 100LL, but absence of TEL leads to lower ON. Quality requirements to these grades are set in the specification ASTM D7547 [15].

3 Materials and Methods of the Study

Within the study a set of avgas blends with different ratios of basic components and the content of different anti-knock additives was developed and studied. The ON of avgas blends was determined in order to select the optimal composition and ratio of components. The following components were used to prepare avgas blends for testing:

- base gasoline, produced by the oil processing plant JSC "Ukrtatnafta" in Kremenchuk city, Ukraine;
- individual high-octane hydrocarbons: alkylate, isooctane, isopentane, and benzene, produced by the oil processing plant JSC "Ukrtatnafta";
- industrially produced ethyl alcohol (96%);
- anti-knock additives: Octaburn TM 8000, Octamar FK, PLUTOcen GS 2300i, ADA-TF C8 and TEL.

A sampling of avgas, components and additives was done using an automatic bottle dispenser, analytical scales and pipette samplers. Avgas blends were prepared by mechanical blending and stored in borosilicate glass bottles at room temperature without access to light. The volume of blends was 1000 ml. The ON was measured at the UIT-65 unit by the research method [16]. The studies were done at the Interactive Laboratory "Aviatest" of the National Aviation university.

The influence of high-octane components on the avgas ON was studied. For this the avgas blends of base gasoline with 5% (vol.) and 15% (vol.) of high-octane components were prepared. Ethanol was added to in quantity 3% (vol.) and 7% (vol.). Next, the influence of anti-knock additives on avgas ON was studied. For this the additives were added to the base gasoline in different concentrations. Finally, the anti-knock properties of avgas compositions were studied. The compositions were prepared by blending base gasoline with different amounts of high-octane components, ethanol and anti-knock-additives.

4 Results and Discussion

4.1 Study of the Influence of Individual High-Octane Components on the Octane Number of Gasoline

At the first stage the base gasoline was blended with high-octane components; the dependence of ON of base aviation gasoline on individual high-octane components was studied. Base gasoline was blended with certain components – alkylate, isooctane, isopentane, and benzene in quantities 5% (vol.) and 15% (vol.). Ethanol results was added to gasoline in quantity 3% (vol.) and 7% (vol.). Results of the research are shown at Fig. 2 (a-e). It is seen that high-octane hydrocarbons allow rising ON of gasoline on 2–4 units. Addition

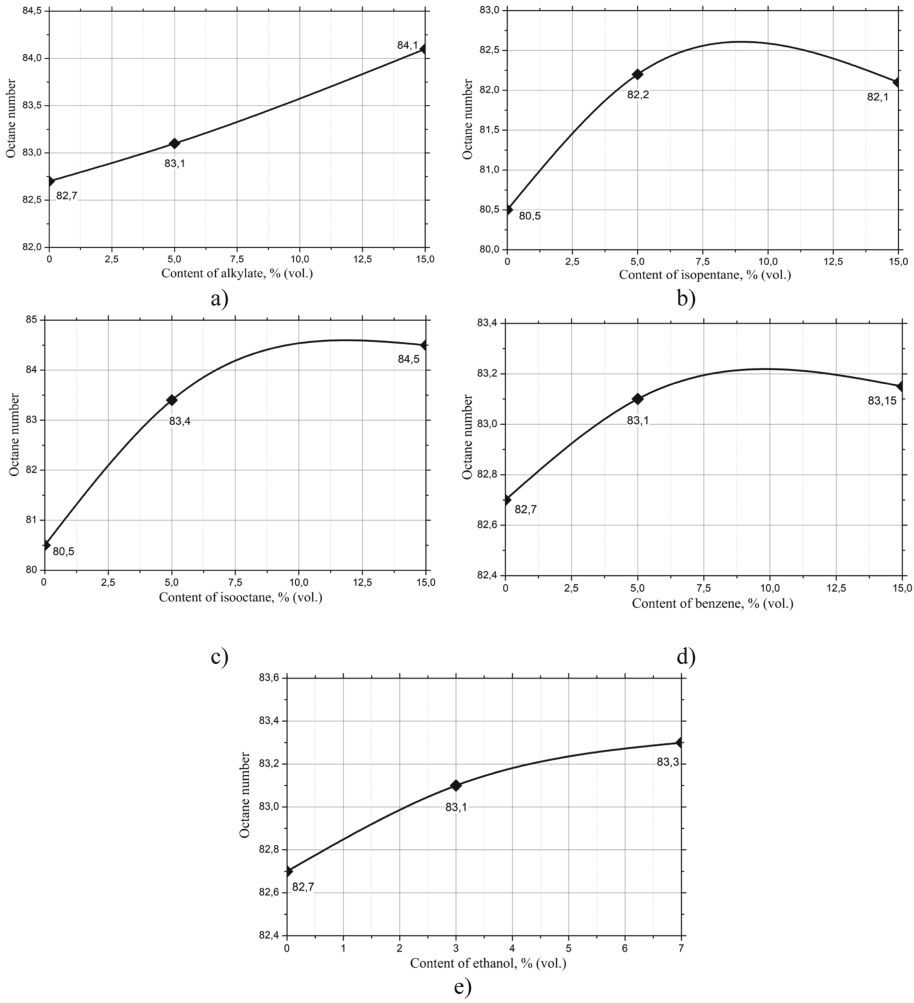


Fig. 2. Dependence of the ON of base gasoline on the content of individual high-octane components: a) – alkylate, b) – isopentane, c) – isooctane, d) – benzene, e) – ethanol.

of 5% (vol.) of components results in more intensive rise of ON. It proves theoretical data that improvement of ON may be easily reached for gasoline with low initial ON and that fact, that ON dependence on the content of high-octane components is not linear. The highest rise of ON is provided by addition of isooctane.

(Fig. 2b) and less isopentane (Fig. 2c). It correlates to that fact that isoparaffins usually have the highest ONs comparing to other types of hydrocarbons and considered to be the most effective for rising ON of gasolines. The isoparaffins have a low freezing point (below minus 60 °C), low hygroscopicity and high sensitivity to TEL [13].

Aromatics are less effective for detonation resistance improvement that is proved by the experiment (Fig. 2d).Use of aromatics has some disadvantages, mainly high freezing point, reduced sensitivity to TEL, and high hygroscopicity, which limit it content in avgas. It may be concluded that addition of 15% (vol.) of components do not result in extensive change in ON. It may be predicted that adding higher concentration of high-octane components is not effective. The use of the ethanol doesn't show any significant effect on rising of the ON of gasoline (Fig. 2e). However, it may be used for replacing some amount of crude oil components. Also it will positively affect the completeness of fuel combustion in the piston engine and quality of exhaust gases.

4.2 Study of the Influence of Anti-Knock Additives on the Octane Number of Gasoline

Next, the anti-knock additives were introduced into the base gasoline; the dependence of ON of base gasoline on anti-knock additives was studied. The additives were added in the following concentrations: Octaburn TM 8000 – 8 mg/l and 18 mg/l, Octamar FK – 22.5 mg/kg and 45 mg/kg, PLUTOcen GS 2300i – 22.5 mg/kg and 45 mg/kg, ADA-TF C8 – 1% and 3% and TEL – 0.0013 g/kg and 3.1 g/kg. Results are shown at Fig. 3 (a-e). Anti-knock additives allow rising ON of gasoline by 0.5–3 units. The highest rise of ON is provided by additive ADA-TF C8 – 3 units (Fig. 3d) and Octamar FK – 2 units (Fig. 3b). The dependence of the ON on the concentration of additives is non-liner. It is seen that the lower the ON of gasoline, the greater is the anti-knock effect of the additive. This proves the theoretical data presented in the literature overview section. It is known that different types of hydrocarbons typically have different level of susceptibility to anti-knock additives. Susceptibility decrease as the following: Paraffins → naphthenes → olefins → aromatics [6, 13]. Therefore, it is necessary to study the effect of the anti-knock additives on gasoline blended with high-octane components.

4.3 Study of the Anti-Knock Properties of Compositions of Aviation Gasolines

At the last stage the compositions of avgas were prepared and their ON was studied. Avgas compositions were prepared by blending base gasoline, high-octane components in different amounts, ethanol and anti-knock additives. The effect of TEL addition to compositions was also studied. Figure 4 presents results of the ON determination in composition with different content of high-octane components, ethanol and ADA-TF C8 additive. Similar to the previous avgas compositions, adding smaller amounts of components improve ON by 2.6 units and adding bigger compositions by 4.4. However,

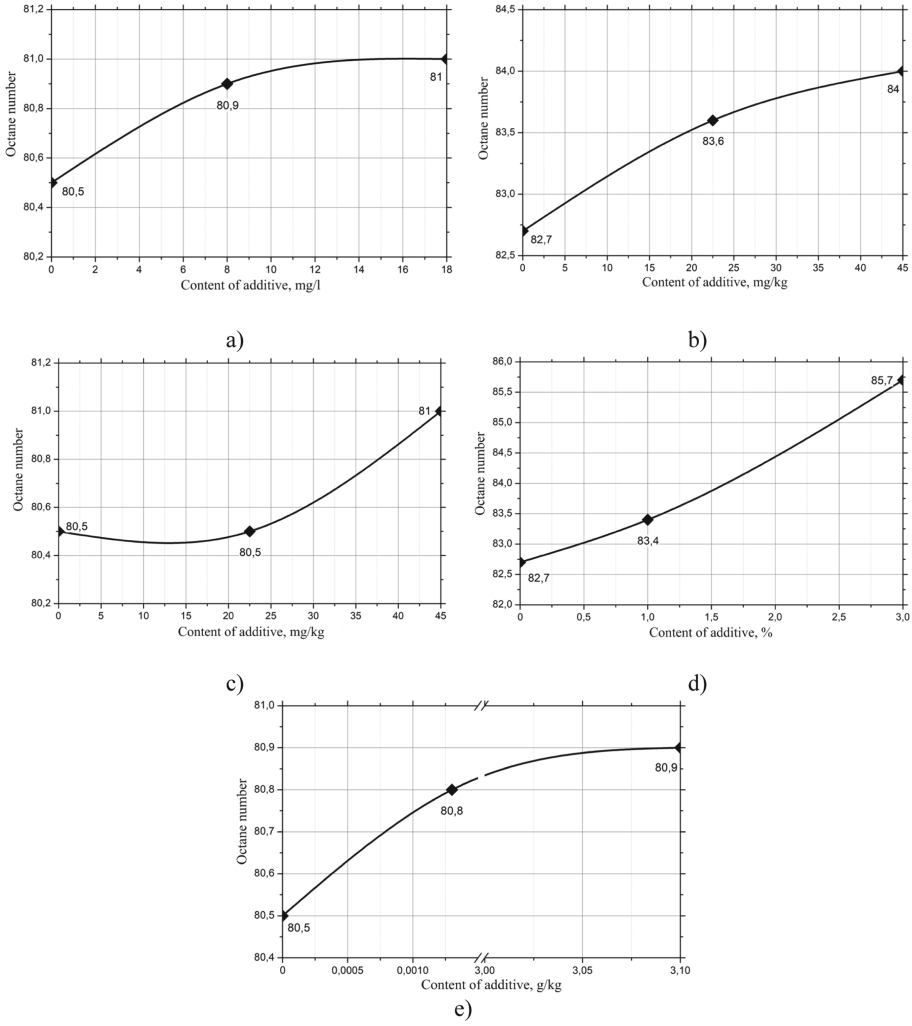


Fig. 3. Dependence of the ON of base gasoline on the content of anti-knock additives: a) – Octaburn TM 8000, b) – Octamar FK, c) – PLUTOcen GS 2300i, d) – ADA-TF C8, e) – TEL.

there is almost no effect of ADA-TF C8 additive, as the values of ON of the compositions are close to ON of compositions without anti-knock additives.

The avgas compositions containing high-octane components, ethanol and Octamar FK additive were studied (Fig. 5). Additionally, the effect of the combination of Octamar FK and TEL additives was studied.

Adding 5% of high-octane components, 3% of ethanol and low concentration of additive increases ON only by 1.6 units. Adding higher amounts of high-octane components, ethanol, and additive provide higher rise of ON (88.3). Combination of high-octane components and additive in high concentrations can be effective. Combination of TEL and Octamar FK additives doesn't result in any changes in ON.

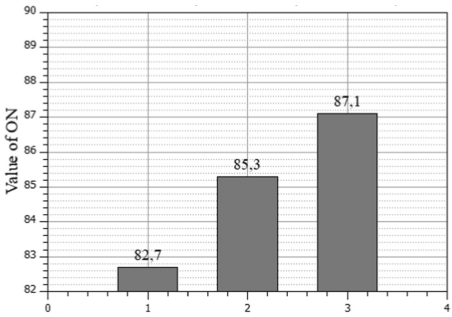


Fig. 4 ON of avgas composition with different content of high-octane component, ethanol and ADA-TF C8: 1 – base gasoline; 2 – base gasoline (77%) + alkylate (5%) + isooctane (5%) + isopentane (5%) + benzene (5%) + ethanol (3%) + ADA-TF C8 (1%); 3 – base gasoline (33%) + alkylate (15%) + isooctane (15%) + isopentane (15%) + benzene (15%) + ethanol (7%) + ADA-TF C8 (1%)

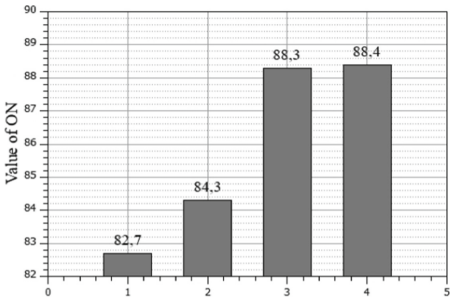


Fig. 5. ON of avgas composition with different content of high-octane component, ethanol and Octamar FK: 1 – base gasoline; 2 – base gasoline (77%) + alkylate (5%) + isooctane (5%) + isopentane (5%) + benzene (5%) + ethanol (3%) + Octamar FK (22.5 mg/kg); 3 – base gasoline (33%) + alkylate (15%) + isooctane (15%) + isopentane (15%) + benzene (15%) + ethanol (7%) + Octamar FK (45 mg/kg); 4 – base gasoline (33%) + alkylate (15%) + isooctane (15%) + isopentane (15%) + benzene (15%) + ethanol (7%) + Octamar FK (45 mg/kg) + TEL (3.1 g/kg).

Next, the avgas compositions containing high-octane components, ethanol and Octaburn TM 8000 additive were studied (Fig. 6). The effect of the combination of Octaburn TM 8000 and TEL additives was also studied. Adding 5% of high-octane components, 3% of ethanol and low concentration of additive increases ON by 2.5 units. But, adding higher amounts of high-octane components, ethanol, and additive provide significant increase of ON – by 5.9 units. The combination of high-octane components and anti-knock additive in high concentrations showed its effectiveness. The cumulative action of high-octane hydrocarbons and Octaburn TM 8000 additive is seen. Combination of TEL and Octaburn TM 8000 additives doesn't result in significant change in ON. Therefore, the use of TEL is not effective.

Basing on the results it may be concluded that combination of high-octane hydrocarbons, ethanol and some anti-knock additives allows obtaining avgas compositions

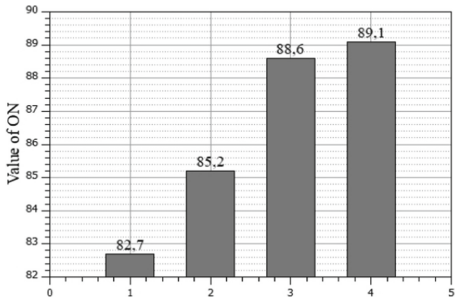


Fig. 6. ON of avgas composition with different content of high-octane component, ethanol and Octamar FK: 1 – base gasoline; 2 – base gasoline (77%) + alkylate (5%) + isooctane (5%) + isopentane (5%) + benzene (5%) + ethanol (3%) + Octaburn TM 8000 (8 mg/kg); 3 – base gasoline (33%) + alkylate (15%) + isooctane (15%) + isopentane (15%) + benzene (15%) + ethanol (7%) + Octaburn TM 8000 (18 mg/kg); 4 – base gasoline (33%) + alkylate (15%) + isooctane (15%) + isopentane (15%) + benzene (15%) + ethanol (7%) + Octaburn TM 8000 (18 mg/kg) + TEL (3.1 g/kg)

with sufficient anti-knock properties. The use of high-octane components provides balanced composition and properties of avgas. Using alkylate provides proper fractional composition, saturated vapor pressure and rise of ON. Isooctane and isopentane provide sufficient fractional composition and freezing point of avgas. Aromatics balance its fractional composition. Ethanol positively affects the combustion process and reduce amounts of unburned hydrocarbons in exhausts. Octaburn TM 8000 and Octamar FK additives in combination with high-octane hydrocarbons increase the ON of avgas by about 5 units compared to base gasoline. They do not contain TEL, so are not toxic.

5 Conclusions

The influence of high-octane hydrocarbons on ON of gasoline was studied. It was found that blending alkylate, isopentane, isooctane, and benzene may improve ON of gasoline by 2–4 units. Addition of ethanol doesn't have a significant effect on ON rise. The influence of anti-knock additives on ON of gasoline was studied. The ON of base gasoline was improved by 0.5–4 units. ON dependence on the concentration of additives is non-linear and it is easier to rise the ON of fuel with initially lower ON.

The new compositions of avgas were developed and ON number was studied. The compositions were produced from base gasoline fraction, alkylate, isopentane, isooctane, and benzene, ethanol and different anti-knock additives. Combination of high-octane hydrocarbons and anti-knock additives has cumulative effect and improves ON of compositions up to 6 units. Octaburn TM 8000 and Octamar FK additives have shown the greatest effect. Both additives do not contain TEL and considered non-toxic.

At the same time results create the basis for further research aimed at the development and implementation of new environmentally safe avgas. The next researches will be devoted to studies of physical–chemical properties of new Avgas, operation properties, bench tests on model piston engines, and assessment of its emission characteristics.

References

1. Europe moves to ban lead in avgas. Flyer Homepage. https://flyer.co.uk/europe-moves-to-ban-lead-in-avgas/. Accessed 12 Mar 2022
2. EPA commits to regulating lead in aviation gasoline. Earth justice Homepage. https://earthjustice.org/news/press/2022/epa-commits-to-regulating-lead-in-aviation-gasoline. Accessed 20 Mar 2022
3. Yakovlieva, A., Boichenko, S., Zaremba, J.: Improvement of air transport environmental safety by implementing alternative jet fuels. In: 2019 Modern Safety Technologies in Transportation (MOSATT), 28–29 November 2019, Kosice, Slovakia, pp. 146–151 (2019)
4. Yakovlieva, A., Boichenko, S., Leida, K., Vovk, O., Kuszewski, H.: Influence of rapeseed oil ester additives on fuel quality index for air jet engines. Chem. Technol. Fuels Oils **53**(3), 308–317 (2017)
5. Kondakova, O., Boichenko, S.: Environmentally clean reformulated aviation gasoline. In: Karakoç, T., Colpan, C., Şöhret, Y. (eds.) Advances in Sustainable Aviation, pp. 3–14. Springer, Cham. (2018). https://doi.org/10.1007/978-3-319-67134-5_1
6. Fortune business insights Homepage. https://www.fortunebusinessinsights.com/aviation-gasoline-avgas-market-103446. Accessed 28 Mar 2022
7. Sedlackova, A.N., Kurdel, P., Labun, J.: simulation of unmanned aircraft vehicle flight precision. In: International Scientific Conference on LOGI - Horizons of Autonomous Mobility in Europe, vol. 44, pp. 313–320 (2020).
8. Sarkar, C.G.: Tetraethyllead (TEL) in gasoline as a case of contentious science and delayed regulation: a short review. Orient. J. Chem. **36**(1) (2020)
9. Kumar, T., Mohsin, R., Ghafir, M.F.A., Kumar, I., Wash, A.M.: Concerns over use of leaded aviation gasoline (AVGAS) fuel. Chem. Eng. Trans. **63**, 181–186 (2018)
10. Klimov, N.: Research and development of perspective low- and nonleaded aviation gasolines. Ph.D. degree dissertation. Moscow (2019)
11. Aviation Fuels. Technical Review. Chevron Products Company. https://www.chevron.com/-/media/chevron/operations/documents/aviation-tech-review.pdf. Accessed 10 Apr 2022
12. ASTM D910–20a Standard Specification for Leaded Aviation Gasolines
13. DEF STAN 91–90, Revision I5, December 14, 2019 - Gasoline, Aviation, Grades UL91, 100/130 and 100/130 Low Lead. JSD: AVGAS UL91, AVGAS 100 and AVGAS 100LL
14. ASTM D6227–18 Standard Specification for Unleaded Aviation Gasoline Containing a Non-hydrocarbon Component
15. ASTM D7547–18a Standard Specification for Hydrocarbon Unleaded Aviation Gasoline.
16. DSTU 8737:2017. Fuel for engines. Research method for determination of octane number (2018)

Study on Correlation Between Particulate Matter Emissions and Exhaust Smoke Levels in CI Engines

Sai Manoj Rayapureddy and Jonas Matijošius(✉)

Department of Automobile Engineering, Faculty of Transport Engineering, Vilnius Gediminas Technical University, J. Basanavičiaus Str., 28, 03224 Vilnius, Lithuania
{sai-manoj.rayapureddy,jonas.matijosius}@vilniustech.lt

Abstract. Particulate Matter is one of the harmful exhaust emissions that effect both environment and human health. Various universities and research centers often estimate the level of Particulate Matter through the smoke levels. For more than 3 decades, researchers are trying to validate the existing correlation between Particulate Matter emissions and exhaust smoke levels. While the measuring principles of both pollutants follow similar principles, the cost and operation associated with them are widely different. Instruments that measure Particulate emissions that are released from the engine exhaust are very valuable because of their high cost, unavailability of skilled technicians and maintenance of equipment. While some proposed that dark substance from the exhaust and on smoke filter is because of the presence of the primary component of the particulate matter, soot, others proved it with results of their experiments. In this article, we will study the research results that prove the existing correlation between the both. It is observed that the particulate matter and smoke opacity follow a linear relationship.

Keywords: Particulate matter · Smoke · IC engines · Exhaust emissions

1 Introduction

Exhaust emissions from automobiles are one of the primary sources of pollution disrupting the environment and damaging human health. Studies reveal that almost 60–70% of damage that is being done to the atmosphere is caused due to the release of harmful emissions from automobiles. These pollutants get deposited on the leaves and damage the crops. And the damage is not confined to atmosphere, certain pollutants such as Particulate Matter (PM) are the reason for respiratory and cancerous diseases [1–3].

Of all the diesel emissions, PM is one of the most problematic emission that directly effects the health of human. Numerous research and studies are underway to determine the ways to substantially decrease the release of particles of size less than 2.5 microns. Although automobiles and industries prevent the particulate matter from entering into the atmosphere by installing filters, some particles which are less than 2.5 microns, which are difficult to be filtered through conventional filers, gets released. These particles enter into human body damaging the respiratory system and lungs. When compared to

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 95–103, 2023.
https://doi.org/10.1007/978-3-031-25863-3_9

other emissions, the intensity of harm caused by PM to the environment and direct and immediate impact on human health is relatively high [4–6].

Briefly, the primary reason for the formation of Particulate matter in a CI (Compression Ignition) engine can be categorized into inhomogeneity of air-fuel mixture and the deficiency of oxygen for the last injected fuel. Particulate matter consists of unburnt hydrocarbons, soot (elementary carbon), sulfur and unburnt lubricating oil particles. It is emitted from engine exhaust as black smoke and hence the intensity of smoke is considered to be directly proportional to the PM levels [1, 7, 8].

Black smoke which is released by the diesel consists of carbon particles which are released by thermal cracking of large hydrocarbon fuel molecules. Smoke production can be decreased by decreasing the time taken for diffusion combustion. This can be done by having rapid mixing of air and fuel mixtures or by adjusting the injection timing. By advancing the injection, we are allowing more time for the expansion stroke for oxidation thereby reducing smoke. Smoke production is also directly influenced by load in linear manner.

Smoke levels or opacity in the exhaust emissions are believed to maintain a stable relationship with the levels of particulate matter in the fuel. Often times, smoke levels are measured for the determination of particulate emissions, in the belief that with reduction in smoke levels there is less particulate matter in the exhaust gas. There has been a pre-existing correlation between these two emission parameters [9, 10]. Many studies have been conducted over the last 3 decades validating the correlation between PM emissions and smoke levels [9–13]. The measurement of PM often involves highly efficient staff and precise equipment, which often consumes high amount of time and huge sums of money. Although those equipment's are used in places that requires topmost precession, often times in universities and research institutes, it is replaced by simpler and uncomplicated smoke measuring instruments which provide an estimation of exhaust PM [8, 11].

We plan to begin the article with the study of similarities between measuring principles associated with Smoke levels and Particulate emissions followed by the analysis of the test results that proves a linear relation between the two. This gives a better understanding of reasons for the correlation.

The primary aim of this article is to study the correlation between Smoke level and Particulate Matter emissions. This research article has 2 main objectives, 1. To understand all of the principles that are associated in the measurement of Smoke and PM. 2. To analyze the research results of experiments that were previously conducted and study their result to find any significant correlation.

2 Literature Review

The measurement of Particulate Matter and Smoke levels are researched in this literature review for a better understanding of the principles associated with measuring each of the pollutants. With the apprehension of similarities in the measuring principles, it would be easy to understand the research results, which are discussed in detail in the following chapter.

2.1 Measurement of Particulates

Instruments that are used to measure particulate matter work either by measuring the particle size distribution or by measuring the concentration of the PM.

Gravimetric method is used to get more accurate readings. In this method air is drawn into a filter where the particles are collected. The weight of this filter is taken before and after the air is drawn and the sample is collected. It is then compared and analyzed. By doing so, the particles can be collected in their raw form and enables us to analyze the composition of the particles chemically.

This test is done with high accuracy and precision, it is generally used in governing bodies like European Union where high standards are required. The primary drawback of this test method is that it only measures the PM emissions at that point of time, no real time data is produced. Other downsides of this method are the cost and professionals that are required for conducting the tests.

The volumetric way of measuring Particulates is by weighing a filter paper before and after passing a certain volume of exhaust gas. It is a slow process and cannot be used in rapid testing purpose.

A rapid way of testing is by using an e-Tapered Element Oscillating Micro-balance (TEOM) detector. Here, a very small filter paper is fitted to the narrow end of a tapered tube in 50 °C constant-temperature oven. The tube is left free at the filter corner and held from the wider side. The flow of particulates is calculated by monitoring the change in mass of the assembly. As a cantilever, tube is excited to vibrate in its natural frequency and the mass is measured. According to the below relation, the filter mass rises as the natural frequency declines:

$$f = \sqrt{\frac{k}{m}}, \tag{1}$$

where f – frequency (rad/sec); k – spring rate (N/m); m – mass (kg).

Using this process, Particulate mass flow is updated at <2 Hz.

Optical instruments can also be used for measuring the PM concentration. By examining and understanding how it reacts with different lights. Optical particle counter (OPC) is one such method where a laser diode (source of light) is passed to illuminate the particles. The scattered light due to the presence of particles is then measured using a photodetector. Flame Ionization Detector method can also be used to determine the real time results.

To show its concentration in the air, PM is expressed in micrograms per cubic meter ($\mu g/m^3$). This concentration level is then compared to the standard Air Quality Index (AQI) which is divided into 6 categories depending on the level of health concern associated with the pollution [14–16].

2.2 Smoke Measurement

Smoke measurement is a clear indication of efficiency of the combustion process. It can be measured using 2 principles, reflectivity or opacity.

During the measurement of smoke using the principle of reflectivity, a filter paper is fitted and a known volume of exhaust is sent through the paper. The reflectivity of that

filter paper is analyzed after this process and compared with the scale. Bosch meter is one such instrument that measures the smoke in terms of reflectivity. A perfectly clean paper is given with a 0 value and 10 in Bosh scale indicates that it does not reflect any light at all.

A continuous monitoring is not possible with this meter as the filter paper is needed to be replaced and it takes certain time for the known amount of exhaust to pass through the filter paper [17].

Smoke is predominantly measured using the principle of opacity. Opacity measurement is the assessment of optical properties exhibited by the diesel exhaust. They quantify the black smoke emission with the help of a light beam. It, to some degree, works in the same phenomenon explained in case of quantification of Particulate matter measurement. Although the function is similar, opacity meters are much simpler and cheaper compared to the instruments used in the particulate measurement [18].

3 Study of Research Results and Discussion

In a test, carried by Sung et al., to validate the existence correlation between the smoke level and particulate mass in a directly fuel-injected single cylinder engine equipped with a Protech, V-smoke meter and PM collector, they confirmed the preexisting relationship between PM emissions and smoke levels to be true and proportional (see Fig. 1) [9].

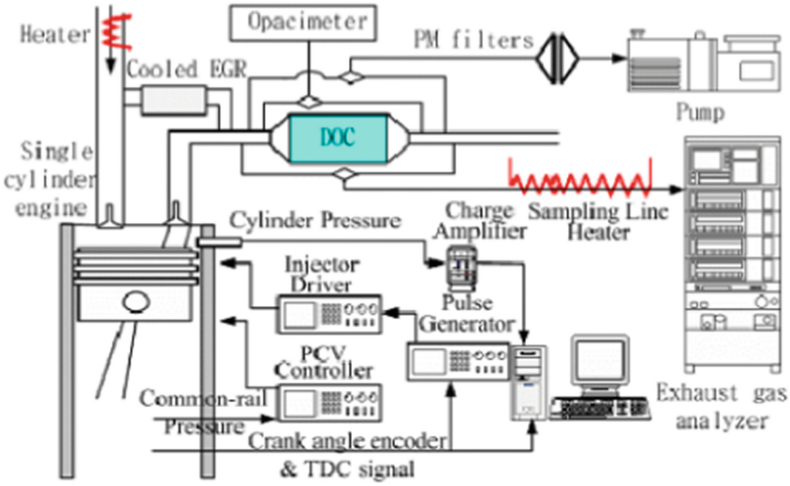


Fig. 1. Sung et al.'s experimental schematic diagram.

As shown (see Fig. 2), particulate matter is observed to change with load but maintained a steady and proportional relation with smoke level. This linear relation helps research centers and universities in replacing the cost burden and complex PM measuring equipment with that of convenient Smoke Opacity meters.

In another research, with an attempt to provide a low-cost, indirect PM measuring method at an assumed accuracy, Merkisz and Pielecha presented an article comparing

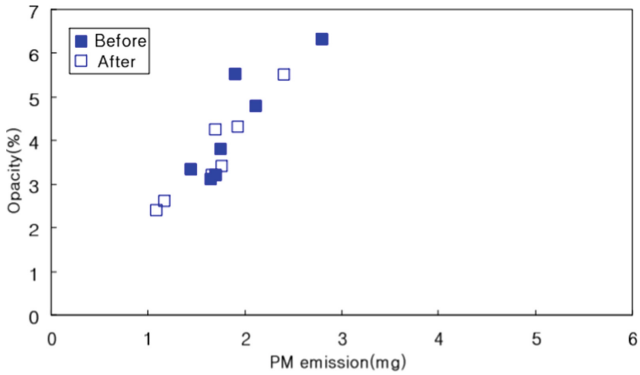


Fig. 2. Sung et al.'s correlation between smoke and PM emissions in diesel combustion.

Horiba 1220 PM analyzer (PM emission) results with those of indirectly tested PM results of AVL 438 Opacimeter which measures the exhaust gas smoke value. The tests are carried out on a 4-cylinder common rail diesel engine (see Fig. 3) [14].

After analyzing their results (see Fig. 4), it is concluded that it is possible to estimate PM levels through the smokiness in the exhaust gas. They also found a significant correlation where the R^2 coefficient (coefficient of determination) is above 0.5 between the hourly particle emission and exhaust smoke. It suggests the possibility of substitution of Horiba analyzer (0.7 R^2) with opacity meter (0.9 R^2).

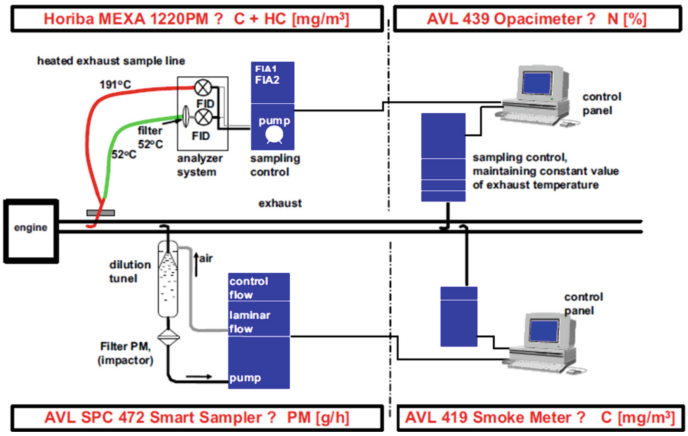


Fig. 3. Merkisz's test apparatus.

In an attempt to address the correlation between opacity and particulate emissions, Hassami and Child performed a statistical analysis to develop empirical equations to calculate Particulate Emissions in terms of Opacity (one of the factors). One of their specific areas covered in their research is to provide a reasonable approximation in the

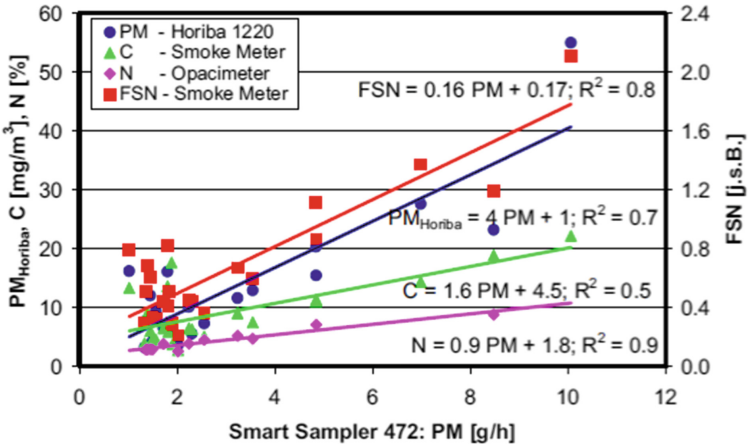


Fig. 4. Merkisz's test results of Correlation of particle emissions and exhaust smoke.

estimation of their interdependency. Data was collected from 72 vehicles (see Table 1) across different types [11].

Table 1. Tested vehicle categories.

Vehicle description	Number of vehicles tested
Passenger/off road passenger $\leq$ 9 seats	12
Heavy bus	6
Light Goods vehicle	18
Medium goods vehicle	14
Goods vehicle	13
Heavy goods vehicle	9

After analyzing the results of their research, they found that a linear relationship is found between particulate matter and average opacity with an R^2 coefficient value of 0.87 (see Fig. 5). They concluded that they found the best model for predicting particulate matter. While their research included many other factors like vehicle mass, fuel consumption, O_2, CO, CO_2 and NO_X, the graph showing the relationship between average opacity and Particulate Matter is what lies in our interest.

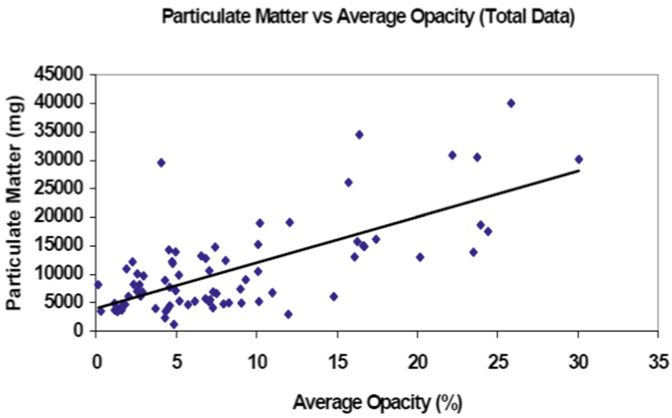


Fig. 5. Particulate – opacity relationship.

4 Conclusions

1. Of all the emissions from an Internal Combustion engine, the harmful effects of PM to agriculture, environment and direct and immediate impact on human health is relatively high and widely studied.
2. Particulate matter, which is a mixture of unburnt hydrocarbons, soot (elementary carbon), sulfur and unburnt lubricating oil particles is emitted from engine exhaust as black smoke and hence the intensity of smoke is considered to be directly proportional to the PM levels.
3. For more than 3 decades, some researchers measure smoke levels for the determination of particulate emissions, in the belief of a preexisting correlation that with reduction in smoke levels there is less particulate matter in the exhaust gas.
4. Instruments needed for PM measurement often involves highly efficient staff and precise equipment. They are costlier and takes a lot of time to be precise. These instruments are often used in places that requires topmost precession.
5. Gravimetric method is often used for PM measurement. In this method air is drawn into a filter where the particles are collected. The weight of this filter is taken before and after the air is drawn and the sample is collected. It is then compared and analyzed. It also analyzes the chemical composition of the particles.
6. Although this method is precise it provides no real time data. Other downsides of this method are the cost and professionals that are required for conducting the tests.
7. Smoke Opacity is the assessment of optical properties exhibited by the diesel exhaust. They quantify the black smoke emission with the help of a light beam. Although the function is similar, opacity meters are much simpler and cheaper.
8. Almost all the research results that are studied shows a linear relationship between Particulate matter emissions and exhaust smoke levels. While there is a long existing correlation between Particulate matter and Smoke levels, this article presents all the results and analysis that proves it to be true.

References

1. Ashok, B., Kumar, A.N., Jacob, A., Vignesh, R.: Chapter 1 - emission formation in IC engines. In: Ashok, B. (ed.) NOx Emission Control Technologies in Stationary and Automotive Internal Combustion Engines. Elsevier, pp. 1–38 (2022). ISBN 978-0-12-823955-1
2. Rodriguez-Alvarez, A.: Air Pollution and life expectancy in Europe: does investment in renewable energy matter? Sci. Total Environ. **792**, 148480 (2021). https://doi.org/10.1016/j.scitotenv.2021.148480
3. Leach, F., Kalghatgi, G., Stone, R., Miles, P.: The scope for improving the efficiency and environmental impact of internal combustion engines. Transp. Eng. **1**, 100005 (2020). https://doi.org/10.1016/j.treng.2020.100005.
4. Rayapureddy, S.M., Matijošius, J.: Reviewing the concept of acoustic agglomeration in reducing the particulate matter emissions. In: Prentkovskis, O., Yatskiv (Jackiva), I., Skačkauskas, P., Junevičius, R., Maruschak, P. (eds.) TRANSBALTICA XII: Transportation Science and Technology. TRANSBALTICA 2019. Lecture Notes in Intelligent Transportation and Infrastructure, pp. 303–311. Springer, Cham (2022).. https://doi.org/10.1007/978-3-030-94774-3_30
5. Kinney, P.L.: Interactions of climate change, air pollution, and human health. Curr. Environ. Health Rep. **5**, 179–186 (2018). https://doi.org/10.1007/s40572-018-0188-x
6. Huang, Y., Ng, E.C.Y., Surawski, N.C., Zhou, J.L., Wang, X., Gao, J., Lin, W., Brown, R.J.: Effect of diesel particulate filter regeneration on fuel consumption and emissions performance under real-driving conditions. Fuel **320**, 123937 (2022). https://doi.org/10.1016/j.fuel.2022.123937
7. Serrano, J.R., Piqueras, P., Angiolini, E., García-Afonso, Ó.: Fuel economy benefits in internal combustion engines due to soot restructuring in the particulate filter by water injection. Int. J. Eng. Res. 14680874221099898 (2022). https://doi.org/10.1177/14680874221099898
8. Lapuerta, M., Armas, O., Hernández, J.J., Ballesteros, R.: Estimation of diesel particulate emissions from hydrocarbon emissions and smoke opacity. In: Whitelaw, J.H., Payri, F., Arcoumanis, C., Desantes, J.M. (eds.) Thermo- and Fluid Dynamic Processes in Diesel Engines 2, , pp. 487–501. Springer, Heidelberg (2004). https://doi.org/10.1007/978-3-662-10502-3_25
9. Sung, Y., Jung, G., Park, J., Choi, B., Lim, M.T.: Relation between particulate emissions and exhaust smoke level in premixed charge compression ignition engine. J. Mech. Sci. Technol. **28**, 783–787 (2014). https://doi.org/10.1007/s12206-013-1144-1
10. Gautam, M., Byrd, R.L., Carder, D.K., Banks, P.D., Lyons, D.W.: Particulate matter emissions and smoke opacity from in-use heavy-duty vehicles. J. Environ. Sci. Health, Part A **35**, 557–573 (2000). https://doi.org/10.1080/10934520009376986
11. Hessami, M.-A., Child, C.: Statistical analysis of diesel vehicle exhaust emission: development of empirical equations to calculate particulate emission, October 25, pp. 2004–01–3066 (2004)
12. Black, J., Eastwood, P.G., Tufail, K., Winstanley, T., Hardalupas, Y., Taylor, A.M.K.P.: Intercorrelations between smoke opacity, legal particulate sampling (LPS) and TEOM, during Transient Operation of a Diesel Engine, July 23; pp. 2007–01–2060 (2007)
13. Muntean, G.G.: A theoretical model for the correlation of smoke number to dry particulate concentration in diesel exhaust. SAE Trans. **108**, 316–322 (1999)
14. Merkisz, J., Pielecha, J.: Analysis of particle concentrations and smoke in common-rail diesel engine, June 23, pp. 2008–01–1743 (2008)
15. Air Quality Measurements Series: Particulate Matter Available online: https://www.clarity.io/blog/air-quality-measurements-series-particulate-matter. Accessed 12 June 2022

16. Beutner, H.P.: Measurement of opacity and particulate emissions with an on-stack transmissometer. J. Air Pollut. Control Assoc. **24**, 865–871 (1974). https://doi.org/10.1080/00022470.1974.10469984
17. Gary Hawley, J., Brace, C.J., Wallace, F.J., Horrocks, R.W.: Chapter 10 - Combustion-related emissions in CI engines. In: Sher, E. (ed.) Handbook of Air Pollution From Internal Combustion Engines. Academic Press, San Diego, pp. 280–357 (1998). ISBN 978-0-12-639855-7
18. Zahoransky, R.A., Laile, E., Terwey, B., Konstandopoulos, A.: On-line/in-line measurements of particle emissions of diesel engines by optical multi-wavelengths technique (2000)

Comparative Assessment of Organic Rankine Cogeneration Cycle Efficiency with Secondary Heat Sources from Marine Diesel

Tomas Čepaitis(✉) and Sergejus Lebedevas

Faculty of Marine Technology and Natural Sciences, Marine Engineering Department, Klaipeda University, Klaipėda, Lithuania
tomas.cepaitis@wsy.lt, sergejus.lebedevas@ku.lt

Abstract. Research focuses on secondary heat sources utilization of medium speed Wartsila power plants in 25–100% load range due to the new restrictions of the marine transport CO2 emissions by IMO Energy Efficiency Design Index requirement. The uncertainty of cogeneration cycle implementation to marine transport arises in the configuration of the Organic Rankine Cycle (ORC) rational operation due to the energy potential change accordingly to high and low temperature heat sources in the power plant load modes. The research involves numerical programming energy performance studies of the ORC system by Klaipeda University, identifying and comparing rational ORC configuration options, alternatively connecting exhaust gas, engine cooling system and scavenge air heat sources in cycle, to achieve maximum efficiency and performance with respect to the outboard water conditions, load modes of power plant and selected working fluid. First phase of the study the implementation strategy of the cogeneration cycle by regulating working fluid flow in the wide load range of the power plant. Second phase is main emphasis of the study, where alternative heat source variations such as scavenge air and cooling jacket and their by-pass options were evaluated to the cycle at the nominal load of the power plant for the rational implementation for marine transport. The plant efficiency increases by 4% when only scavenge air heat source is used in cogeneration cycle. Significant increase of generated power and efficiency up to 11% is noticed when all heat sources are included in the cycle. Generated power with all heat sources reaches 1,676 kW, while using only exhaust gas heat it reaches 830 kW which is significant. Though lower temperature heat sources can decrease efficiency of the cycle depending of the ambient conditions of outboard water temperatures and working fluid selection, to evaluate impact rational and alternative heat source options for the specific load modes further researches are required. The main diesel engine coefficient of performance with cogeneration systems improved from 4% using only scavenge air and by 11% using all three heat sources. Considering the received results, further studies of cogeneration with secondary heat sources are needed for more rational results in specific load modes and various ambient conditions.

Keywords: Organic Rankine cycle · Heat recovery · Energy efficiency · Main engine load cycle · Heat sources · Load modes · Energy performance

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 104–115, 2023.
https://doi.org/10.1007/978-3-031-25863-3_10

1 Introduction

There is a need to decarbonize maritime transport in order to reduce greenhouse gas emissions. The entire transport sector is impacted by this problem but only maritime transport is being addressed in terms of IMO CO_2 emission norms on a normative basis. In July 2011, the Marine Environment Conservation Commission introduced the Energy Efficiency Design Index (EEDI) requirements, which took effect on January 1st, 2013, and will be tightened in three stages every five years from 2015 [1, 2]. New restrictions on CO_2 emissions from marine transport and the instability of fossil fuel reserves led to the development of high efficiency combustion engines and alternative fuel sources solutions, such as bio-ethanol, to reduce the amount of CO_2 in the atmosphere [3, 4]. Dual fuel is another promising technology for marine diesel engines which can decrease CO_2 emissions up to 25% and NOx emission up to 85% due to the natural gas lower carbon to hydrogen ratio and flexible control of premixed fuel fraction, regardless of the operation conditions [5, 6].

Recent studies [7–10] indicates that waste heat cogeneration systems have greater potential than operational and design measures, due to the fact that approximately 50% of fuel energy is wasted through exhaust gases, cooling jacket, scavenge air and other sources [10–12], with different temperatures ranging from 70–400 °C which makes it possible to use it in cogeneration systems to receive such amount of the amount of steam in boilers that can be used to increase energy efficiency and to provide the consumer's household needs of heating and electricity as a pair. The temperature of the exhaust gases drops to a level of 250–300 °C in slow-running ship diesel engines and is also significantly lower under partial load conditions, which makes energy recovery in waste heat boilers with water as the working medium more difficult [9–11]. In addition, heat is available in the engine cylinder cooling jacket, along with the reduction in scavenge air temperature occurs in the intercooler where a significant amount of fuel energy is wasted that can be utilized [12, 13].

In onshore plants the solution of organic fluid selection is used to significantly lower boiling point in comparison with water to the increase of energy efficiency indicators. However, maritime transport is lacking researches in order to properly assess energy aspects for practical application of specific load modes [12]. The specific viewpoints are related to the cycle energy efficiency indicators in association with necessity to choose a rational strategy for managing the operational indicators of the cycle with the load modes of the main power plant, as well as ambient conditions heat sources with different temperatures available [14, 15].

It makes sense to expand the study of the cogeneration cycle's energy indicators to take alternative uses of different working fluids (Wet, Dry, Isentropic), dependencies on load mode, and heat sources utilized in the cycle into account [16–18]. Given aspects were implemented in the comparative model studies that were done of the organic Rankine cycle as a component of a medium-speed, medium-speed, four-stroke power engine.

The results achieved in the first phase of the research became the basis for expanding the study to assess the aspects of rational cogeneration cycle in ships application. One of these aspects is several heat sources from marine diesel implementation to the cycle [19–22]. The paper presents of the Klaipeda University first stage concise results, but

the main emphasis is aimed at the research evaluating the secondary heat sources of the complex use: exhaust gas, cooling jacket, scavenge air.

2 Methodological Aspects of the Research

For the research single stage organic Rankine cycle was modelled using the Thermoflow software with three different temperatures heat sources from exhaust gas, scavenge air, cooling jacket accordingly. Scheme includes the recuperator exchanger between the condenser inlet and outlet lines to improve the energy efficiency indicators of cycle.

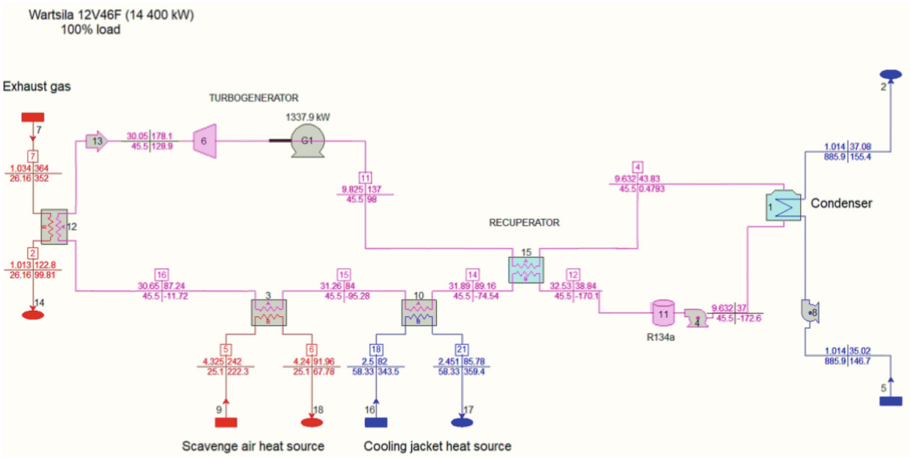


Fig. 1. Single stage pressure organic Rankine cycle with exhaust gas, cooling jacket and scavenge air heat sources utilization: 1 – condenser; 2 – outboard; 3 – heat exchanger (from sc. Air); 4 – working fluid pump; 5 – seachest inlet; 6 – turbine; 7 – exhaust gas heat source; 8 – sea water pump; 9 – scavenge air heat source; 10 – heat exchanger (from cooling jacket); 11 – working fluid tank; 14 – atmosphere; 15 – recuperator; 16 – cooling jacket heat source.

The cycle's principles are as follows: In a regenerative heat exchanger (pos. 15), the working fluid is heated and evaporated to the state of saturated vapor; saturated vapor of the working material is supplied to the heat exchangers of heat sources (pos. 10, 3, 12) where it is superheated gradually. Superheated working fluid vapor energy is converted into mechanical work in the turbogenerator turbine (pos. 6), and the working fluid passes the recuperator (where energy is transferred), afterwards enters the condenser (pos. 1) and exits in the state of saturated liquid (by applying saturation condensation pressure according outboard water temperature). The heat sources can be cut out or included to the cycle by regulating butterfly vales in the pipelines accordingly. In this setup, various options of connecting and disconnecting the heat sources can be achieve in cycle to find rational application depending of the load mode, ambient conditions.

The power plant of the ship is equipped with Wartsila 12V46F medium speed four-stroke engine with main specific parameters listed in Table 1:

Table 1. Table captions should be placed above the tables.

Cylinder bore	460 mm
Piston stroke	580 mm
Cylinder output	1,200 kW/cyl
Number of cylinder quantity	12
Speed	600 rpm
Piston speed	11.6 m/s

Several working fluid types (dry; wet; isentropic) application to the cycle for evaluation of energy indicators by differentially setting flow of the working material in the system $G_{w.fl.}$ in the load modes of the power plant were evaluated, in order to achieve maximum energy utilization of the exhaust gas (decreasing the exhaust gas temperature to the dew point 120 °C); simulating a turbogenerator design with a fixed geometry turbine characterized by hydrodynamic relationship between working fluid flow $G_{w.fl.}$ and the degree of pressure drop in the turbine turbogenerator π_T; evaluation of energy indicators of the cogeneration cycle improving possibilities by changing fixed geometry turbine design of the turbogenerator to a turbine with variable geometry (ensuring $\pi_T = const$ at different working material flow ($G_{w.fl.}$).

The evaluation of different organic working materials (R134a; R141b; R142b; R123; R245fa) in the cogeneration Rankine cycle was performed according to the change of the energy efficiency index of the running engine, the effective COP, including the components, by evaluating the additional form $\delta\eta_{eR}$ of mechanical energy generation power of the turbogenerator powerplant balance.

More detailed simulations to be performed using only exhaust gas heat energy at 25–100% load range of the power plant with several different working fluids to get overall cycle impact of cogeneration system. In order to evaluate several heat sources with different temperatures infusion in the cycle.

Below presented used methodology with common equations. Coefficient of performance of main engine with Rankine cycle when exhaust gas heat source is used:

$$\eta_{eR} = \frac{P_e \cdot 3600}{G_f \cdot H_u}, \text{ main engine with cogeneration cycle COP;}$$

$$\eta_{eR} = \frac{H_u \cdot G_f \cdot \eta_e + H_u \cdot G_f \cdot q_{ex.g} \cdot \eta_{cog.c.}}{G_f \cdot H_u} = \eta_e \cdot q_{ex.g} \cdot \eta_{cog.c.} \tag{1}$$

Then, the change of coefficient of performance in relation with main engine COP:

$$\delta\eta_{eR} = \frac{\eta_{eR} - \eta_e}{\eta_e} = \frac{(P_e + P_{gen}) \cdot 3600}{G_f \cdot H_u} - \frac{P_e \cdot 3600}{G_f \cdot H_u} = \frac{P_{gen}}{P_e}. \tag{2}$$

To evaluate COP of cogeneration cycle with exhaust gas and the increase of the plant below equation used accordingly:

$$\eta_{eR} = \eta_e + q_{ex.g} + \eta_{cycle}.$$

As in the research also three different heat sources in the cycle are valued then the total amount of heat can be described:

$$Q = Q_{ex.g} \cdot Q_{coolj.} \cdot Q_{sc.air} = Q_f \cdot q_{ex.g} \cdot \eta_{h.ex} \cdot \eta_{tg.r} + Q_f \cdot q_{coolj.} \cdot \eta_{h.ex} \cdot \Psi_{coolj.} + Q_f \cdot q_{sc.air} \cdot \eta_{h.ex} \cdot \Psi_{sc.air} \quad (3)$$

then, $q_{ex.g} = \frac{Q_{coolj}}{G_f \cdot H_u}$ and $q_{sc.air} = \frac{Q_{sc.air}}{G_f \cdot H_u}$.

Coefficient of performance of main engine with Rankine cycle when three heat sources used:

$$\eta_{eR} = \frac{P_e \cdot 3600 + Q(\eta_{T.ad} \cdot \eta_m \cdot \Psi_{turb})}{G_f \cdot H_u} = \eta_e + \left(q_{ex.g} \cdot \eta_{h.ex} \cdot \eta_{tg.r} + q_{coolj.} \cdot \eta_{h.ex} \cdot \Psi_{coolj.} + q_{sc.air} \cdot \eta_{h.ex} \cdot \Psi_{sc.air}\right). \quad (4)$$

Total cogeneration cycle COP with three heat input sources would be:

$$\eta_{eR_\in} = \frac{H_u \cdot G_f \left(q_{ex.g} \cdot \eta_{h.ex} \cdot \eta_{tg.r} + q_{coolj.} \cdot \eta_{h.ex} \cdot \Psi_{coolj.} + q_{sc.air} \cdot \eta_{h.ex} \cdot \Psi_{sc.air}\right)}{H_u \cdot G_f \left(q_{ex.g} + q_{coolj.} + q_{sc.air}\right)}. \quad (5)$$

where $q_{ex.g}$ – relative part used of the exhaust gas energy of power plant the heat balance kJ/h; $\eta_{h.ex}$– thermal COP of the exhaust gas heat exchanger; $\eta_{tg.r}$ – the relative COP of the turbogenerator; η_{Tad}; η_m – turbogenerator internal (adiabatic) and mechanical COP; Ψ – exhaust heat recovery factor; H_u – lower calorific value of fuel used by the traction engine, kJ/kg; G_f – hourly fuel consumption of the main engine, kg/h; η_e – main power plant coefficient of performance. Exhaust heat recovery factor is determined according the ratio of the enthalpy of exhaust gas before h_{tg1} and after h_{tg2} the heat exchanger and the enthalpy of exhaust gas at dew point h'_{tg2}: $\Psi = \frac{h_{tg1} - h_{tg2}}{h_{tg1} - h'_{tg2}}$.

The thermal efficiency of the turbogenerator is determined by the ratio of the enthalpies of the working fluid before h_{tg1} and after h_{tg2} the turbine and the enthalpy of the working fluid h'_{tg2} corresponding to the boiling temperature: $\eta_{tg.r} = \frac{h_{R1} - h_{R2}}{h_{R1} - h'_{R2}}$.

Heat utilization factors $\Psi_{coolj.}$; $\Psi_{sc.air}$ determined also as the exhaust gas by the temperature decrease in the heat exchangers to the temperature point described in engine specification: for scavenge air 50 ºC and the cooling jacket 75 °C.

$$\Psi_{coolj.} = \frac{h_{w1} - h_{w2}}{h_{w1} - h'_w}; \Psi_{sc.air} = \frac{h_{air1} - h_{air2}}{h_{air1} - h'_{air}},$$

where h_{w1} and h_{air1} – input heat enthalpy (before the heat exchanger); h_{w2} and h_{air2} – real heat reduction (temperature after heat exchanger); h'_w and h'_{air} – reduction needed according engine specification value.

These fixed values are accepted in the calculations (fixed values according specific to existing models): $\eta_{Tad} = 0,7$; $\eta_m = 0,95$; $\eta_{h.ex(exhaust\ gas\ heat\ exchanger)} = 0,97$; $\eta_{h.ex(cooling\ jacket)} = 0,97$; $\eta_{h.ex(scavenge\ air)} = 0,97$ $\eta_{h.ex(condenser)} = 0,97$; $\eta_{h.ex(rekuperator\ heat\ exchanger)} = 0,95$; pressure drop in exhaust gas heat exchanger 2%; pressure drop in recuperator heat exchanger 2%.

Several analytical dependencies were used to determine the power generated by the turbogenerator P_{gen} in a cogeneration cycle component analysis. P_{gen} should be described in multiple ways, first to evaluate their potential improvement in order to identify the elements controlling the efficiency of the cogeneration cycle, and secondly to define the relationship between the turbogenerator operating parameters for their reasonable choice:

$$P_{gen} = \frac{G_{w.fl.}\left(h_{tg1} - h_{tg2}\right)}{3600}, \tag{6}$$

where $G_{w.fl.}$ – working material flow, kg/h; h_{tg1}; h_{tg2} – working material enthalpy before and behind the turbogenerator turbine, kJ/kg.

The total mechanical energy generated by ME (main engine) is then determined using the COP of turbogenerator mechanical energy:

$$\eta_{\sum e} = \frac{\left(P_e + P_{tg}\right)3600}{H_u \cdot G_f}, \text{ and its change :}$$

$$\delta\eta_{\sum e} = \frac{\eta_{\sum e} - \eta_e}{\eta_e} = \frac{\left(P_e + P_{tg}\right)}{H_u \cdot G_f} - \frac{(P_e)}{H_u \cdot G_f} \cdot \frac{1}{3600} = \frac{P_{tg}}{P_e}. \tag{7}$$

The equation describes the efficiency of the cogeneration cycle in terms of power according to energy efficiency appliance - COP of the turbogenerator:

$$P_{gen} = \frac{q_{ex.g} \cdot \eta_{h.ex(exhaustgas)} \cdot q_{sc.air} \cdot \eta_{h.ex(sc.air)} \cdot q_{coolj} \cdot \eta_{h.ex(cool.j.)} \cdot \eta_{tg.r} \cdot \eta_{T.ad} \cdot \eta_m \cdot \Psi}{3600}. \tag{8}$$

The $\delta\eta_{eR}$ is obtained from the compared solution $Q_{ex.g}$; $Q_{coolj.}$; $Q_{sc.air}$ and $P_e = \frac{G_f \cdot H_u \cdot \eta_e}{3600}$, as a result we get a function from relative values: $\delta\eta_{\sum e} = \frac{q_{ex.g} \cdot q_{sc.air} \cdot q_{coolj} \cdot \eta_{h.ex} \cdot \eta_{tg.r} \cdot \eta_{T.ad} \cdot \eta_m \Psi}{\eta_e}$. When undertaking comparative studies of cycle efficiency prediction, the value of $G_{w.fl.}$ can be used as a constant with the main engine running at rated nominal power, as long as the exhaust gas temperature outside the regenerative heat exchanger does not drop below the dew point. If there is a need to reduce $G_{w.fl.}$ in part-load engine load modes due to the same condition, it is performed at the interface with π_T changes.

The relationship between $G_{w.fl.}$ and π_T is determined using the second turbocharger equation when performing cogeneration cycle comparisons at the level where the turbogenerator type and its actual characteristics are unknown [23].

3 Results

Two operational strategies of cycle for 25% to 100% load modes of the power plant were evaluated:

- When working fluid material flow rate and the turbogenerator's pressure expansion in its turbine remain constant $(G_{w.fl.} - \pi_T) = const.$

- When working fluid material flow rate is variable and turbogenerator's pressure expansion in its turbine is constant ($G_{w.fl.} = var.$ ($\pi_T = const$).

The dew point $T_{ex.g.}$, which corresponds to the level of the power plant's exhaust gases leaving the heat exchanger, limits the working material flow's maximum value (pos. 12, Fig. 1). Conditions are created for the condensation of sulfuric acid from Sulphur oxides in exhaust gas when the temperature falls below 120 ºC [24, 25].

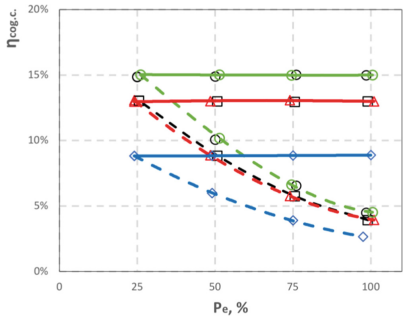


Fig. 2. ORC energy indicator $\eta_{cog.c.}$ comparison of strategies $G_{w.fl.} = const$ (- - -); $G_{w.fl.} = var.$ (——); blue line – dry fluid; red line – isentropic/dry fluids; green line – wet/isentropic fluids

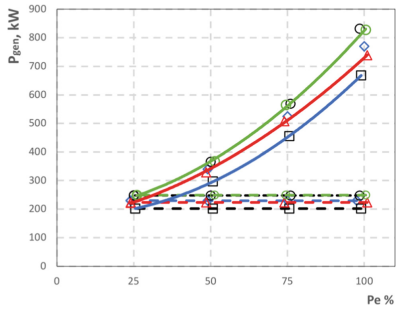


Fig. 3. ORC energy indicator P_{gen} comparison of strategies $G_{w.fl.} = const$ (- - -); $G_{w.fl.} = var.$ (——); blue line – dry fluid; red line – isentropic/dry fluids; green line – wet/isentropic fluids

With variable working fluid material flow (($G_{w.fl.} = var.$ ($\pi_T = const$)) cycle COP remains constant and the generated power increasing 248 to 830 kW from 25% to 100% load respectively. The amount of transferred heat increases accordingly with the flow rate of the working fluid in connection with the increase of the internal energy potential $Q_{ex.g.}$ of the exhaust gas when the heat utilization factor is closer to maximum (Fig. 2–3). This strategy is more effective than constant working fluid flow due to temperature drop to the dew point. The maximum increase of P_{gen} is independent of working fluid type and characteristic are equal of R134a (Wet), R142b (Isentropic), Isopetane (Dry) fluids. Surprisingly, regardless of the effect of P_{gen} increase, the relative change for all evaluated working fluids is the same.

The largest P_{gen} increase effect in the mode - P_{enom} up to 3–4% was achieved by increase of the $\delta\eta_{\sum e}$ the power plant COP in the logical sequence.

Although, there are no noticeable generated power and cycle efficiency differences between studied working fluids, graphical form was made to have a better view for comparative evaluation for different types of fluids (Fig. 4):

Furthermore, a cycle with heat input from three different temperature sources is considered (exhaust gas, scavenge air and cooling jacket). For rational results and operation of the cycle, alternative options of heat sources by-pass were researched for the nominal load to see the impact of the efficiency for the plant. By the Mollier diagram of the working fluid thermodynamic properties can be represented. Mollier diagram

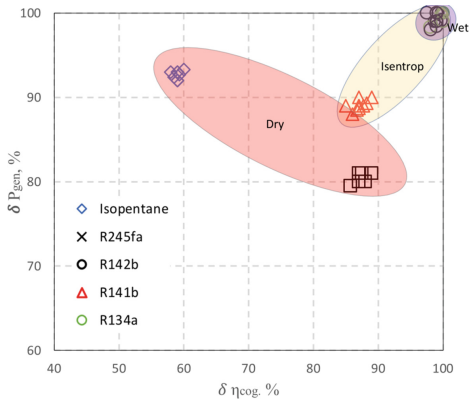


Fig. 4. Comparative evaluation of working fluid type to energy indicators according ORC.

shows aggregate state changes of working material in the cycle and by heat input working material changes state from saturated liquid to saturated steam and to superheated steam, where change of the internal energy of the working material is evaluated as increasing enthalpy form (see Fig. 5).

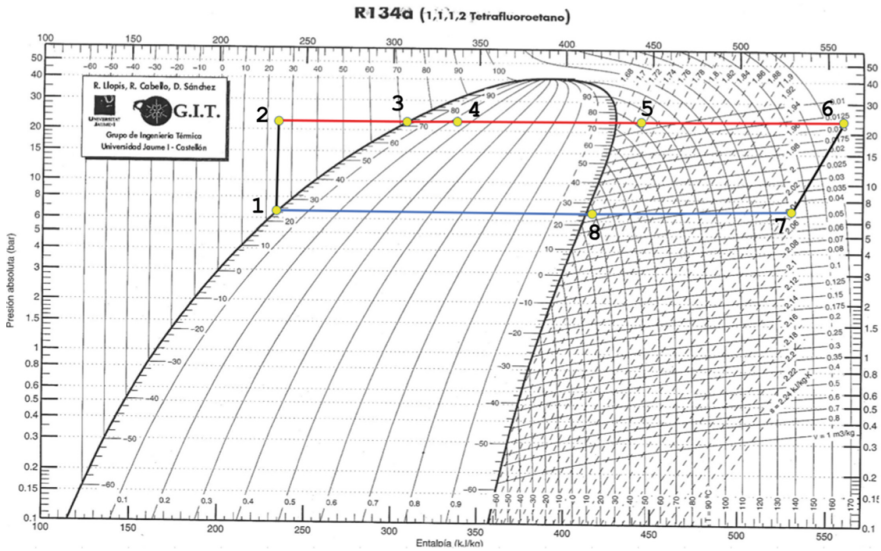


Fig. 5. Dependence of the cogeneration cycle parameters on specified boundary conditions (red – heat input, blue – heat transfer).

In Fig. 5 represents changes in energy and aggregate state of the working fluid R134a with three heat sources. In Section 1–2 working fluid pressure is increased by the pump to the point of required pressure turbine decrease ratio which has direct connection to cycle efficiency. When the pressure is increased first heat inlet from recuperator in the

cycle is performed, where working fluid state changes from saturated liquid to saturated team. After that heat input is carried out in three stages from lower temperature sources to higher (4 cooling jacket → 5 scavenge air → 6 exhaust gas), where working fluid reaches state of superheated vapor in result increased net output and efficiency of the cycle. Next follows the working material expansion in the turbine where net power output is received (Section 6–7). After the expansion in the turbine, heat transfer is performed in recuperator, where state of working material changes from superheated steam to saturated steam and increases average temperature during heat input which respectively increases efficiency of the cycle (Section 7–8). Condensation process is established in the condenser where working fluid material changes the state from saturated steam to saturated liquid (Section 8–1) and the cycle repeats. Dependencies are observed when studying Moller diagram of the working fluid: outboard water determines the pressure in the cycle for condensation according to available temperature and turbine pressure decrease ratio, which has direct connection to cycle efficiency. The results showed that generated power and the efficiency is increasing with additional heat sources at the nominal load mode of the power plant.

The result of alternative heat source variation in cogeneration cycle presented in Table 2:

Table 2. Results efficiency and received power of alternative heat sources options in the cycle.

		Outboard water temp.	Load	η_{ϵ}	$\eta_{\epsilon(\text{with cogen})}$	$\delta\eta_{\epsilon}$	$\eta_{\text{cogen. cycle}}$	$\eta_{\text{tg. r}}$	Generated power, kW
Exhaust gas	R134a	20 C	100%	0,469	0,496	5,70%	0,110819	0,2301	891,7
Exhaust gas + cooling jacket	R134a	20 C	100%	0,469	0,505	7,61%	0,124093	0,2205	1168,6
Exhaust gas + cooling jacket + scavenge air	R134a	20 C	100%	0,469	0,521	11,12%	0,105789	0,2191	1676,2
Cooling jacket + scavenge air	R134a	20 C	100%	0,469	0,497	5,98%	0,10053	0,2229	770,5
Scavenge air	R134a	20 C	100%	0,469	0,489	4,26%	0,156864	0,2881	524,7
Exhaust gas + scavenge air	R134a	20 C	100%	0,469	0,520	10,93%	0,114844	0,2195	1479,3

When the one or several heat sources are by-passed, generated power decreases at the nominal load. Least impact has the cooling jacket heat source as the temperature is the lowest and it should be considered whether it be efficient to use it in cogeneration cycles instead of other vessel need (for e.g., heating, desalination).

Comparing the achieved result, observed that using only scavenge air heat source at the cycle has the lowest energy performance, however the cycle COP has highest results. Highest net output 1,676 kW at nominal load received with all three heat sources, but the cogeneration cycle COP is highest with scavenge air. This is related to the low efficiency

(about 0.21) of the relatively low COP of cooling jacket heat utilization. In this context, the by-pass of the heat exchanger of cooling jacket heat source forms the basis for increasing the heat utilization of the scavenge air, reducing the air temperature close to the required 50 ºC, which can simultaneously achieve optimized COP and energy cycle performance.

4 Conclusion

The strategy of differentiated regulation of working fluid flow control to maximize energy potential of exhaust gas utilization in different load modes has the best efficiency of the cycle. Implementation of the pressure drop rate $\pi_T = const$ in a variable geometry turbine model characterized by the best indicators of cycle efficiency $\eta_{cog.c.}$ and generated mechanical energy P_{gen}: the cogeneration cycle $\eta_{cog.c.}$ acquires the maximum value in the whole load range for all working fluids – 15% (R134a), 8.8% (Isopentane), and the respective power plant COP and $\eta_{eplant.}$ increase by 6.2% and 5.3%.

Wet (R134a) and Isentropic (R141b) working fluids have better parameters; however, Dry (R145fa, Isopentane) type working fluids typically have energy efficiency cycle efficiency indicators that are about 10% lower; one of Isentropic representatives, R142b, also has a similar decrease in $\eta_{cog.c.}$ parameter.

From alternative heat source variations results can be noticeably seen that cycle has significant improvements of generated power and COP at the nominal power load of the plant. Indicator $\delta\eta_{eplant.}$ increases up to from 4% when only scavenge air heat are input in the cycle to 11% when all three heat sources are included in the cycle. Generated power with all three heat sources reaches 1,676 kW, while using only exhaust gas heat it reaches 830 kW which is significant. Scavenge air has the best heat utilization efficiency in studied variations and can be optimized depending of other heat sources.

There are several options to improve the cycle according Mollier diagram, one of them is superheating the working material which can be achieved with several heat sources. Recuperator also improve the cycle efficiency due to increase average temperature at heat inlet section. Turbine pressure decrease ratio also has an impact to the cycle efficiency, the higher ratio determines higher efficiency and net output. Outboard water is another factor that has influence on the cycle, it determines the condensation pressure needed the working material to reach the saturated liquid state. However, it should be considered if all heat would be transferred to the cogeneration cycle, other systems like heating, water desalination etc., will be left without thermal energy. For further implementation, in order to apply a system of simplified and reliable construction by combining sequential heat sources and a regenerative heat exchanger, it is necessary to expand the research to specific load modes of the plant, working fluids and outboard temperatures in order to optimize the single-circuit ORC cycle structure for marine transport implementation.

References

1. Smith, T.W.P., et al.: International Maritime Organization. Third IMO GHG study 2014, London, UK (2014)

2. IMO: Annex 5, Resolution MEPC.245(66), Guidelines on the Method of Calculation of the Attained Energy Efficiency Design Index (EEDI) for New Ships; IMO, EU: London, UK (2015)
3. Al Baroudi, H., Awoyomi, A., Patchigolla, K., Jonnalagadda, K., Anthony, E.J.: A review of large-scale CO2 shipping and marine emissions management for carbon capture, utilisation and storage, Appl. Energy **287**, 116510 (2021)
4. Chang, C., Wang, C.: Evaluating the effects of speed reduce for shipping costs and CO2 emission. Transp. Res. Part D **31**, 110–115 (2014)
5. Xing, H., Spence, S., Chen, H.: A comprehensive review on countermeasures for CO2 emissions from ships. Renew. Sustain. Energy Rev. **134**, 110222 (2020)
6. Tang, X., Chen, X., Dong, Y., Wei, X., Yang, Q.: The prospective analysis of marine dual fuel engine application based on emission and energy efficiency. In: Applied Mechanics and Materials, vol. 291–294 (2022)
7. Det Norske Veritas: Energy management study, Technical report, Det Norske Veritas (2015)
8. Bombarda, P., Invernizzi, C.M., Pietra, C.: Heat recovery from diesel engines: a thermodynamic comparison between Kalina and ORC cycles. Appl. Therm. Eng. **30**, 212–219 (2010). https://doi.org/10.1016/j.applthermaleng.2009.08.006
9. Mohammadkhani, F., Khalilarya, S., Mirzaee, I.: Exergetic analysis of internal combustion engine cogeneration system. J. Energy Eng. Manag. **2**(4), Winter 1391, 24–31 (2012)
10. Schmid, H.: Less emissions through waste heat recovery. In: Proceedings of the Green Ship Technology Conference, London, UK, 28–29 April (2014)
11. Ancic, I., Sestan, A., Vladimir, N., Klisaric, V.: Influence of new power sources on the Attained EEDI. In: Proceedings of the International Conference on Influence on Ship Design, London, UK, 24–25 September (2014)
12. Ancic, I., Sestan, A.: Influence of the required EEDI reduction factor on the CO2 emission from bulk carriers. Energy Policy **84**, 107–116 (2015)
13. Waste Heat Recovery System (WHRS) for Reduction of Fuel Consumption, Emissions and EEDI, MAN Energy Solutions
14. Sencic, T., Racic, N., Frankovic, B.: Influence of low-speed marine diesel engine settings on waste heat availability. Brodo Gradnja **63**, 329–335 (2014)
15. Doseva, N., Chakyrova, D.: Energy ANS exergy analysis of cogeneration system with biogas engines. J. Therm. Eng. **1**(3), 391–401 (2015)
16. Wang, Z., Jiang, Y., Han, F., Yu, S., Li, W.: A thermodynamic configuration method of combined supercritical CO2 power system for marine engine waste heat recovery based on recuperative effects. Appl. Therm. Eng. **200**, 117645 (2022)
17. Liona, S., Vlaskosb, I., Taccanic, R.: A review of emissions reduction technologies for low and medium speed marine diesel engines and their potential for waste heat recovery. Energy Convers. Manage. **207**, 112553 (2020)
18. Nagelhout, E.: Combined Heat and Power (CHP) Smart Power Generation - District Heating Solutions, Wärtsilä Power Plants, May 2012
19. Singh, D.V., Pedersen, E.: A review of waste heat recovery technologies for maritime applications. Energy Convers. Manage. **111**, 315–328 (2016)
20. Mahmoudi, M., Fazli, M.R., Morad: A recent review of waste heat recovery by Organic Rankine Cycle. Appl. Therm. Eng. **143**, 660–675 (2018)
21. Andreasen, J., Larsen, U., Haglind, F.: Design of organic Rankine cycles using a nonconventional optimization approach. In: Proceedings of the 28th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, Pau, France, pp. 1–12 (2015)
22. Soffiato, M., Frangopoulos, C.A., Manente, G., Rech, S., Lazzaretto, A.: Design optimization of ORC systems for waste heat recovery on board a LNG carrier. Energy Convers. Manag. **92**, 523–534 (2015)

23. Rama, S.R., Gorla, A., Khan, A.: Turbomachinery design and Theory, Marcel Dekker Incl. (2003)
24. Ozdemir, N.: Thermodynamic analysis of gas turbine cogeneration powerplants. Int. J. Eng. Sci. Res. Technol. (2016). ISSN: 2277-9655
25. Ushakov, S., Valland, H., Nielsen, J.B., Hennie, E.: Effects of high sulphur content in marine fuels on particulate matter emission characteristics. J. Mar. Eng. Technol. **12**(3), 30–39 (2013). https://doi.org/10.1080/20464177.2013.11020283

Methodological Aspects of Numerical Studies of Ammonia Use in Diesel Cycle

Martynas Drazdauskas and Sergejus Lebedevas(✉)

Klaipeda University, Bijunu 17, Klaipeda, Lithuania
Sergejus.Lebedevas@ku.lt

Abstract. More than 10% of emissions from the European transport sector are accounted by maritime transport sector. Due to climate change problem, to reduce the emissions of GHG in maritime transport sector one of the promising solutions is to use ammonia. However, the properties of ammonia are very different from those of petroleum-based fuel (higher auto-ignition temperature, lower calorific value, lower flame propagation speed), therefore this complicates ammonia usage in diesel cycle. This publication presents initial stage results of innovative research in Lithuania. The essential goal is to analyze the main features of ammonia combustion cycle of CI engine by evaluating its properties based on research data available in literature to simulate the combustion cycle of a dual ammonia – diesel fuel mixture, and to optimize it using the multi-zone "AVL FIRE" software mathematical model which is based on chemical kinetics principle. The change in ecological and energetic parameters compared to a diesel cycle is also determined. When using ammonia in a diesel engine, the ignition duration increases which leads to a lower cylinder pressure, temperature, and a series of environmental and efficiency parameters deterioration. Also, depending on the boundary conditions of ICE combustion cycle, one of the most harmful exhaust components nitrogen oxides NO_x increase intensively in individual cases. However, one of the essential prospects of ammonia is a significant reduction of CO_2. Therefore, the ongoing scientific project of Klaipeda University studies physical processes of ammonia combustion cycle in ICE to identify its rational execution conditions and to implement technological combustion cycle optimization principles for rational use in ship power plants.

Keywords: Ammonia combustion cycle · Numerical studies · ICE · AVL FIRE · Simulation

1 Introduction

The decarbonization topic of maritime transport sector is widely discussed. Maritime transport alone accounts for 2.7% of CO_2 emissions annually [1], which is one of the main contributors to GHG. To reduce these emissions International Maritime Organization (IMO) issued a strategy aiming to reduce GHG by 50% by 2050. According to the strategy guidelines, the goal can be achieved by short, medium and long-term measures by increasing energy efficiency of new building ships, applying energy efficiency

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 116–124, 2023.
https://doi.org/10.1007/978-3-031-25863-3_11

project index (EEDI) [2], or converting ships to work on alternative fuels. Currently amendments adopted by IMO MEPC which will come into a force as of November 1, 2022, are a short-term measure which by introducing the energy efficiency index (EEXI) for ships in operation which are subject to MARPOL Annex VI directly oblige to reduce CO_2 emissions for ships in operation above 400 GT [3]. However, in the long term it is planned to adopt more advanced technologies and alternative fuels. One of such could be ammonia NH_3 as it is a renewable fuel and does not release CO_2 when burned [4]. Due to its widespread use in the global industry [5], there is a sufficiently developed infrastructure that could easily be adapted to serve maritime transport. Also, the number of hydrogen atoms in liquid ammonia is 1.7 times higher than in liquid hydrogen at the same volume [5], resulting in attractive application conditions for practical use especially in marine transport, where the volume for fuel tanks is limited. Limited ammonia application studies in ICE are related to its physical and chemical properties peculiarities. Firstly, combustion properties of ammonia differ from those of petroleum-based fuel (higher auto-ignition temperature, lower calorific value, lower flame propagation speed) and this complicates ammonia usage in diesel engines (see Table 1). Due to low cetane number (5–7) and high auto-ignition temperature (651 °C), ammonia ignition is possible at engine compression ratios of 35:1 and more, which is unrealistic to achieve given to geometrical parameters of marine engine [6]. Therefore, it is only possible to ensure ammonia combustion by using a pilot fuel with good autoignition characteristics such as diesel.

This paper aims to analyze the main features of ammonia combustion cycle of CI engine by evaluating its properties based on research data available in literature to provide methodological aspects for simulation and optimization of dual ammonia – diesel fuel combustion cycle using the multi-zone "AVL FIRE" software mathematical model. The change in ecological and energetic parameters compared to a diesel cycle is also determined. As well as simulation software "AVL FIRE" capabilities for numerical studies of ICE combustion cycle based on diesel cycle simulation results.

Table 1. Comparison of fuel physical properties [6, 8, 9].

Fuel Type	Ammonia	Hydrogen	Methanol	DME	LNG	Diesel
Formula	NH_3	H_2	CH_3OH	CH_3OCH_3	CH_4	$C_{12}H_{23}$
Density (liquid), kg/m^3	602.8	70.8	786.3	668	187.2	832
Lower calorific value, MJ/kg	18.8	120	19.7	28.4	38.1	42.7
Octane number	110	130	113	60	107	30
Cetane number	5–7	–	5–8	55–60	–	40–55
Auto-ignition temperature, °C	651	585	385	350	540	254–285
Flame propagation speed, m/s	0.07–0.14	2.70	0.50	0.47	0.38	0.87
Heat of vaporization, kJ/kg	1,370	461	1,103	467	510	232

1.1 Features of Ammonia Use in Diesel Engine Cycle

In the literature, the beginning of individual ammonia research dates to WWII [7], however only in recent years intensive research has been started with NH_3 in ICE. Based on theoretical and experimental research publications related to use of ammonia in diesel engine, it can be stated that ammonia usage in diesel engines is rational solution to decarbonize maritime transport. In all investigated cases, CO_2 emissions decreased almost proportionally when increasing ammonia ratio in dual fuel mixture [6, 8, 11–13]. Depending on ammonia injection strategy, studies show that engine's efficiency is close to that of a diesel engine, and in some cases (at D20/A80 fuel ration) an increase in efficiency of up to 3.5% is observed [14]. However, several other negative aspects related to ammonia usage in diesel engines emerge. When a low-pressure ammonia injection strategy is used, fuel is supplied together with compressed air at a pressure of 3–5 bar through the intake manifold, and when ammonia ratio in dual fuel balance is more than 60%, 2–5 times increase in harmful NO_x emissions is observed [8]. However, recent studies show that a high-pressure ammonia injection strategy where fuel is directly injected in the cylinder above 500 bar pressure, results in lower NO_x formation and in some cases, such as A97/D03 – A90/D10 fuel ratios, can reach lower limits than a diesel engine (see Fig. 1) [14].

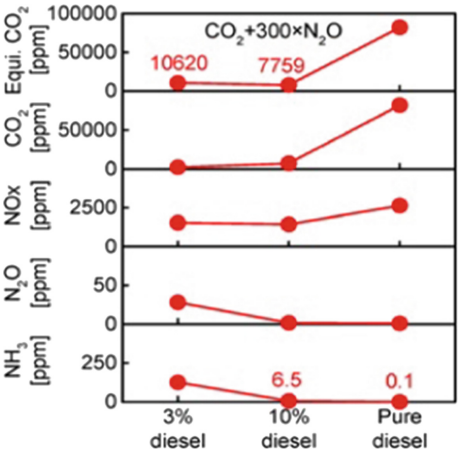


Fig. 1. Effects of the diesel ratio by energy on the emission characteristics of the diesel ammonia engine using high pressure fuel injection strategy [14].

Emissions of unburned ammonia, their slip into the exhaust system, which are toxic and dangerous to human health, are the main problem of the ammonia fueled engine. Analysis shows that NH_3 emissions from ammonia fueled engine are more than 100 times higher than a safe rate [8], therefore operation of such engine without emissions treatment technologies or proper combustion cycle optimization is not possible considering environmental regulations. Also, emissions of carbon monoxide CO and incomplete combustion products HC increase from 1.5 to 3 times at low engine loads, especially at higher diesel ratios in the dual fuel balance [15].

Based on publications results [14, 16], it is stated that the minimum required proportion of diesel as a pilot portion in a dual fuel balance is ~3% in terms of energy value. This ratio is sufficient to ensure a stable ammonia combustion process using high pressure injection strategy. The influence of ammonia and diesel injectors nozzle hole position and fuel injection sequence on induction period, combustion efficiency and emissions were also investigated. It was found that the shortest induction period and the most efficient combustion and less formation of harmful substances are achieved at the nozzle distribution angle of 0–7.5°, i.e., fuel injection takes place horizontally in the same line. In this way, ammonia masses penetrate more effectively into the areas of the diesel and air mixture. It is important to mention that induction period is shorter when diesel is injected fist and a period of 500–1,000 μs is maintained until ammonia is injected [16]. If the period is extended, diesel flame quenching is observed due to ammonia's high heat of vaporization. If ammonia is injected first, diesel struggles to ignite due to low fuel-air ratio in the active radical zones. These recent years discoveries make it easier to define ammonia combustion cycle performance characteristics to carry out numerical studies of diesel engine running on a dual ammonia diesel fuel.

2 Research and Results

2.1 Methodological Aspects of Numerical Studies of Ammonia Combustion Cycle

Simulation of dual ammonia diesel fuel with "AVL FIRE" software is based on published engine test bench experimental research data running on dual ammonia diesel fuel [8]. In the last year of doctoral studies [17], during evaluation of these data using the single-zone mathematical model software "WIBE" and the method of logarithmic anamorphosis, it was determined that with an ammonia ratio above 40% in dual fuel balance, the combustion cycle is characterized by a two-phase combustion character (see Fig. 2). Diesel burns kinetically in the first phase (blue curve) and ammonia burns diffusively in the second phase (red curve). For this reason, traditional Vibe combustion model is not suitable for numerical simulation of ammonia combustion as it is based on a single-phase combustion.

Ammonia combustion simulation requires a specific gas combustion model that would accurately reveal the peculiarities of physical processes occurring in the cylinder. Currently, such model is being developed in AVL and will be released this fall. To qualitatively model combustion cycle of ammonia and diesel dual fuel mixture, it is appropriate to define the main features of ammonia combustion based on literature analysis. The model could be built dividing it into two groups according to fuel injection strategy. For the first group, simulation would be performed by injecting ammonia gas into the cylinder through intake manifold just before intake valve at different fuel ratios in range of 20–80% ammonia by energy value at −39° to 34° TDC injection angles respectively, to validate the model by experimental data. In this case, the aim is to achieve the most accurate match between cylinder pressure curves, combustion cycle parameters and emissions. Only after accurate model fit with experimental data it could be applied to the second group with high-pressure direct injection strategy.

Literature analysis shows that by applying this strategy it can achieve a low ratio of pilot diesel fuel ~3% in terms of energy value. Since use of ammonia is aimed at

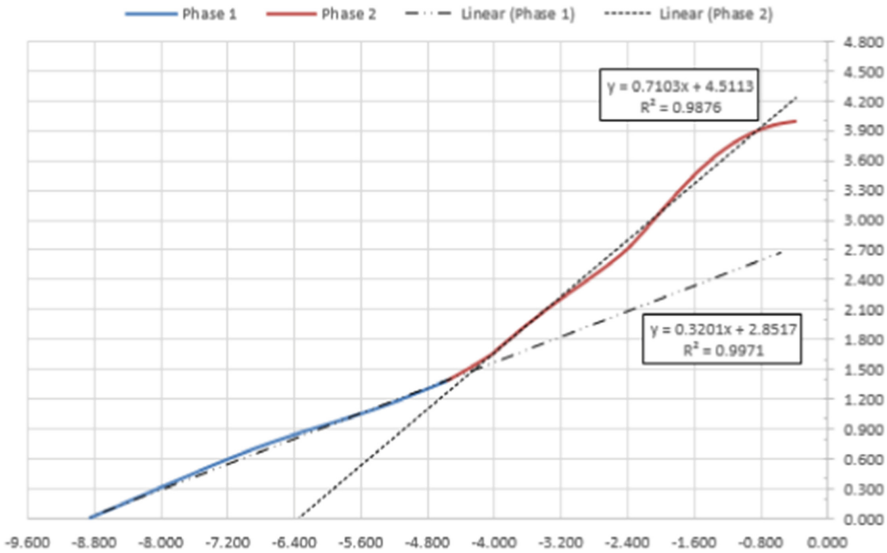


Fig. 2. Logarithmic anamorphosis analize results showing two phase ammonia combustion character at D60/A40 dual fuel ratio [17].

decarbonizing maritime transport, and since the main part of CO_2 emissions depends on diesel fuel mass in the cylinder, the main goal is to use the lowest possible pilot fuel ratio to ensure stable ammonia combustion. Then simulation should be performed with an ammonia ratio in range of 90–97% to determine the most optimal ratio for its practical use. By varying inlet air pressure and temperature, injection angle, injection duration and injected fuel mass can be determined the effects on maximum cycle pressure, efficiency, exhaust gas temperature and pressure considering engine performance, piston group stresses and harmful emissions of HC, NO_x, CO, CO_2, NH_3. On this principle, the optimization of combustion cycle is carried out to achieve the highest energy and environmental efficiency.

2.2 AVL FIRE Software Features, Diesel Combustion Cycle Compatibility

AVL FIRE multi-zone mathematical modelling software is a professional tool for simulating ICE combustion cycle and extending its results to 3D analysis. In the initial stage, combustion cycle simulation of John Deere 4045T, 4-cylinder diesel engine is carried out based on experimental data [8] at 100% load of engine running on diesel to check reliability of calculation results and prepare model transferring for operation with a dual diesel ammonia fuel using the expected gas reaction model developed by AVL. During calculations, geometric engine parameters, inlet air pressure and temperature, injected fuel mass, injection angle and duration were maintained. It can be seen from pressure curves (see Fig. 3) that compatibility of calculation results is acceptable for solving practical problems. The maximum cycle pressure difference between experimental data is 0.85%. It can be stated that AVL FIRE calculation results correspond to engine test bench measured data. Also, using “AVL FIRE” physical processes taking place in the

cylinder in relation to kinetics of NOx formation are investigated. For this purpose, visual results of temperature and NO mass distribution in the cylinder are presented in a 2D cylinder cross-section in range of 712–740° TDC, when 720° corresponds to TDC (see Fig. 4, 5). The results make it possible to determine distribution of temperature fields and combustion intensity in parallel with harmful substances formation regions in the cylinder which allows to evaluate optimization measures to reduce formation of toxic emissions during combustion cycle. The error of NO exhaust gases compared to measured engine test bench values is 4.9% which is an acceptable limit.

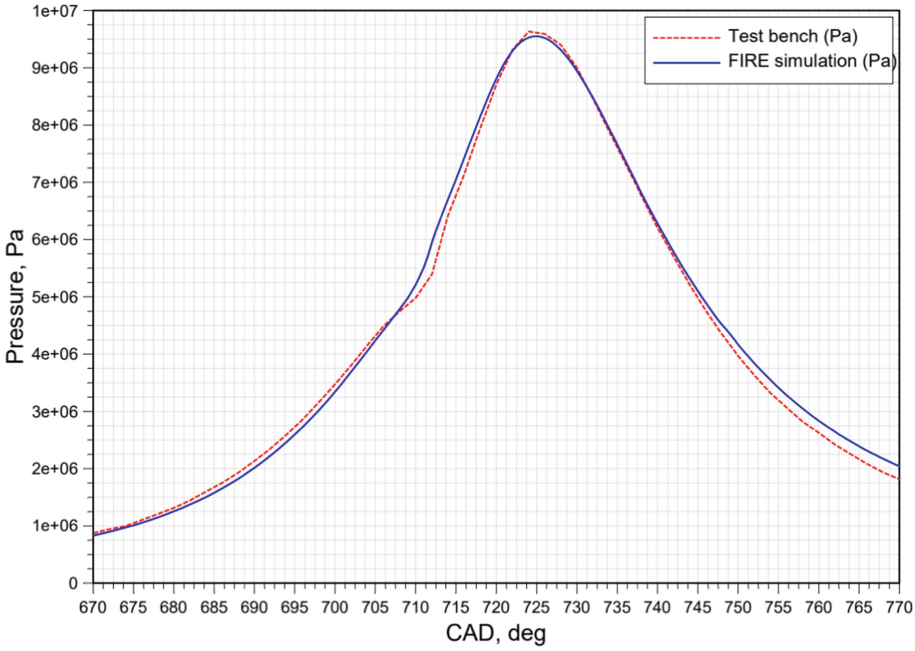


Fig. 3. Compatibility of experimental and numerical pressure cycle results at 100% engine load running on diesel fuel.

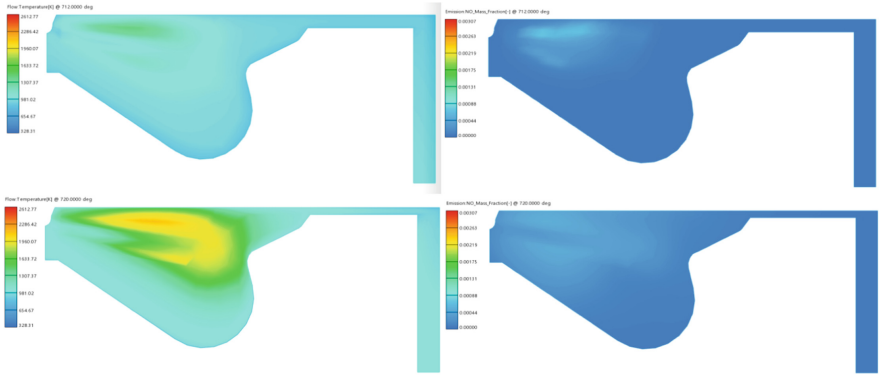


Fig. 4. Cylinder temperature distribution in 1/6 cylinder section from the left and NO mass distribution from the right at 712°, 720°, TDC when 720° corresponds to TDC, at 100% engine load running on diesel.

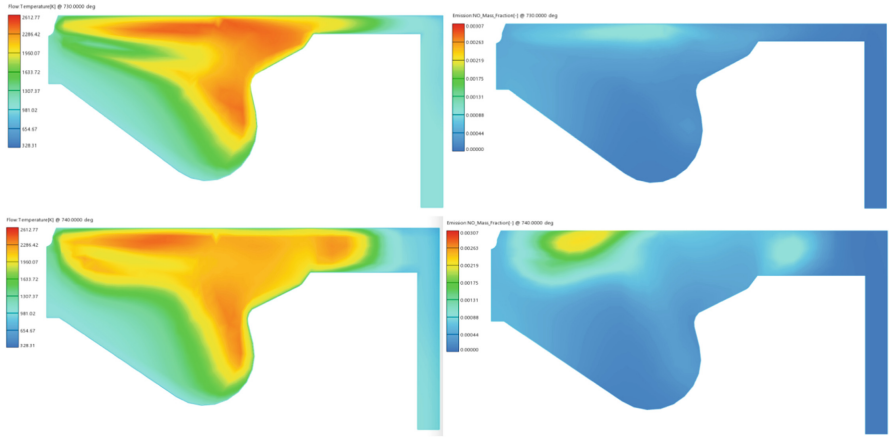


Fig. 5. Cylinder temperature distribution in 1/6 cylinder section from the left and NO mass distribution from the right at 730°, 740° TDC when 720° corresponds to TDC, at 100% engine load running on diesel.

3 Conclusions

There is a limited studies of combustion cycle when NH_3 is used in ICE. Therefore, Klaipeda University conducts research on physical processes of NH_3 combustion cycle to identify the conditions for their execution and based on that provide technological and optimization principles for rational use in ship power plants. At this stage of research, it is established:

- When using NH_3 in ICE, the engine efficiency is close to that of diesel cycle, but environmental performance is deteriorated. NO_x emissions can increase up to 5 times, HC and CO emissions from 1.5 to 3 times, and unburned NH_3 more than 100 times

above safe levels for humans. Only CO_2 emissions decrease proportionally when replacing diesel with NH_3 in dual fuel balance.

- Technologically NH_3 is injected into the cylinder using a low-pressure strategy together with air through intake manifold in gaseous form at a pressure of 3–5 bar or in liquid form using a high-pressure strategy through a separate fuel injector above a pressure of 500 bar. With a low-pressure strategy, the maximum ammonia ratio in dual fuel balance can reach up to 80% still providing stable combustion, but with a high-pressure strategy, the maximum ammonia ratio can reach up to 97%. Also, a high-pressure strategy achieves minimal emission values compared to a low-pressure strategy and almost zero CO_2, so technologically it is rational to use this ammonia injection strategy for diesel engines.
- Methodology is based on complex numerical studies of single-zone and multi-zone mathematical model research using software "AVL FIRE, AVL BOOST, IMPULS" and applying a low-pressure fuel injection strategy at 20–80% NH_3 ratio for model validation according to experimental data and a high-pressure direct injection strategy at an NH_3 ratio of 90–97% to determine the minimum diesel pilot injection portion for rational practical use to achieve the lowest CO_2 emissions. It is also rational to carry out extensive adjustment of combustion cycle parameters using 2D and 3D results analysis capabilities of "AVL FIRE" software to achieve the highest energy and environmental efficiency.
- The multi-zone mathematical model simulation software "AVL FIRE" is suitable for numerical studies of ICE combustion cycle and optimization, since the initial compatibility of diesel combustion cycle results with experimental data show sufficiently accurate results, the calculated maximum cycle pressure error is 0.85% and NO emission error is 4.9%.

References

1. International Energy Agency – Transport homepage. https://www.iea.org/topics/transport
2. MARPOL Annex VI resolution MEPC 203(62). https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Technical%20and%20Operational%20Measures/Resolution%20MEPC.203(62).pdf
3. MARPOL Annex VI resolution MEPC 328(76). https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/MEPC.328%2876%29.pdf
4. Chiong, M.-C., et al.: Advancements of combustion technologies in the ammonia-fuelled engines. Energy Convers. Manag. **244**, 114460 (2021)
5. Dincer, I., Bicer, Y.: Ammonia production. In: Comprehensive Energy Systems, vol. 3, pp. 41–94 (2018)
6. Ryu, K., Zacharakis-Jutz, G.E., Kong, S.-C.: Performance characteristics of compression-ignition engine using high concentration of ammonia mixed with dimethyl ether. Appl. Energy **113**, 488–499 (2014)
7. Kroch, E.: Ammonia a fuel for motor buses. Claverton Energy (1945)
8. Reiter, A.J., Kong, S.-C.: Combustion and emissions characteristics of compression-ignition engine using dual ammonia-diesel fuel. Fuel **90**, 87–97 (2011)
9. Dimitriou, P., Javaid, R.: A review of ammonia as a compression ignition engine fuel. Int. J. Hydrogen Energy **45**, 7098–7118 (2020)

10. Mounaim-Rousselle, C., Brequigny, P., Valera Medina, A., Boulet, E., Emberson, D., Lovas, T.: Ammonia as fuel for transportation to mitigate zero carbon impact. In: Kalghatgi, G., Agarwal, A.K., Leach, F., Senecal, K. (eds.) Engines and Fuels for Future Transport, pp. 257–279. Springer, Singapore (2021). https://doi.org/10.1007/978-981-16-8717-4_11
11. Sahin, Z., Akcanca, I.Z., Durgun, O.: Experimental investigation of the effects of ammonia solution (NH_3OH) on engine performance and exhaust emissions of a small diesel engine. Fuel **214**, 330–341 (2018)
12. Lasocki, J., Bednarski, M., Sikora, M.: Simulation of ammonia combustion in dual-fuel compression-ignition engine. IOP Conf. Ser. Earth Environ. Sci. **214**, 012081 (2019)
13. Liu, L., Yue, W., Wang, Y.: Numerical investigation on the combustion and emission characteristics of ammonia in a low-speed two-stroke marine engine. Fuel **314**, 122727 (2022)
14. Li, T., et al.: A comparison between low and high-pressure injection dual-fuel modes of diesel-pilot-ignition ammonia combustion engines. J. Energy Inst. **102**, 362–373 (2022)
15. Yousefi, A., Guo, H., Dev, S., Liko, B., Lafrance, S.: Effects of ammonia energy fraction and diesel injection timing on combustion and emissions of an ammonia/diesel dual-fuel engine. Fuel **314**, 122723 (2022)
16. Scharl, V., Sattelmayer, T.: Ignition and combustion characteristics of diesel piloted ammonia injections. Fuel Commun. **11**, 100068 (2022)
17. Drazdauskas, M., Lebedevas, S., Klyus, O.: Comparative studies of ammonia combustion cycle parameters in marine compression ignition engines. In: Proceedings of 25th International Scientific Conference Transport Means, pp. 890–893 (2021)

Possibilities of Legislative and Economic Support for Electromobility in Slovakia

Kristián Čulík[1](✉), Karol Hrudkay[1], and Vladimíra Štefancová[2]

[1] University Science Park, University of Žilina, Univerzitná 1, 010 26 Žilina, Slovakia
kristian.culik@fpedas.uniza.sk, hrudkay@uniza.sk
[2] Department of Railway Transport, University of Žilina, Univerzitná 1, 010 26 Žilina, Slovakia
vladimira.stefancova@fpedas.uniza.sk

Abstract. The transport sector generates almost 25% of European greenhouse gas emissions and is the city's leading cause of air pollution. Almost 90% of urban dwellers in the European Union are exposed to harmful levels of air pollutants. Around 95% of vehicles on European roads still use fossil fuels. The transport policy of the European Union aims to reduce greenhouse gas emissions by 20% by 2030 and by 60% by 2050 compared to 1990 values. One of the means of achieving these goals is the use of electric cars. This article aims to process the current state of passenger and small freight electric vehicles registered in the Slovak Republic and to compare them with other countries. This article proposes measures that would support electromobility in Slovakia. These proposals are based on an analysis of weaknesses in legislation, taxes, and fees. Currently, several forms of electromobility support are used. They aim to overcome obstacles preventing the successful implementation of electromobility in practice. These are direct subsidies for electric vehicles or relief from taxes and fees. Individual governments or self-governments also provide non-financial benefits to motivate residents to use electric cars largely.

Keywords: Electromobility · BEV · PHEV · Legislation · Taxes

1 Introduction

Transport was the second largest polluter with a quarter share of total emissions in 2019 [1, 2]. For this reason, it is necessary to look for ways to reduce emissions in this sector [3], for example, by adjusting the modal split so that more ecological modes of transport should be used [4, 5]. In field of electromobility, there is possible to introduce technical and regulatory restrictions or change taxes, fees, and subsidies.

Several studies compare the energy and environmental impacts of vehicles with different fuels. For example, extensive comparative studies [6, 7] found that few research papers report a full Life Cycle Assessment. Such an assessment considers not only the fuel but also the vehicle itself. In economics, researchers evaluate the vehicle costs with Total Costs of Ownership (TCO). For example, studies [8–10] compare the TCO of a conventional Internal Combustion Engine Vehicle (ICEV) and a Battery Electric Vehicle (BEV) in different parts of the world.

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 125–134, 2023.
https://doi.org/10.1007/978-3-031-25863-3_12

This article does not focus on the contentious environmental or economic questions of operation BEV compared to ICEV. The authors in [11] discuss whether BEVs should be subsidised or, on the contrary, taxed. For example, authors in [12] found that in China BEVs are not economically competitive compared with ICEVs. The most important motivators for buying a BEV or HEV are financial savings [13, 14] and the safety of new vehicles [15, 16].

2 An Overview of Legislation Related to the Electromobility

This section describes the most important documents related to electromobility at the level of the European Union, as well as national laws in Slovakia. These help the development of electromobility and can be an example for foreign countries. In some cases, the measures concern BEV and HEV (Hybrid Electric Vehicle), BEV and PHEV (Plug-in Hybrid Electric Vehicle), or only BEV.

This article describes only the basic and most important documents about reducing emissions in transport. More information about electromobility, automation, connectivity and safety of mobility can be obtained from the research roadmaps published by The European Road Transport Research Advisory Council (ERTRAC) [17].

2.1 White Paper on Transport

The European Union has developed a White Paper [18], which contains a Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system. The main goal is to achieve a 60% reduction in emissions in the context of growing traffic and mobility support by 2050. The goal is to eliminate oil dependence without sacrificing transport system efficiency.

Urban transport is responsible for approximately one-quarter of CO_2 emissions from transport. In addition, 69% of traffic accidents occur in cities. The gradual ICEV elimination from the urban environment contributes the most to a significant reduction in dependence on oil, greenhouse gas emissions, and local air and noise pollution.

The EU wants to support smaller, lighter, and more specialised road passenger vehicles. Extensive fleets of city buses, taxis, and vans are particularly suitable for alternative powertrain systems and fuels. It could significantly reduce the intensity of carbon oxides in urban transport and prepare the conditions for testing new technologies and the opportunity for their timely introduction to the market. Charging for the use of communications and removing irregularities in taxation can also enhance public transport and the gradual introduction of alternative fuels.

2.2 The European Green Deal

The agreement [19] goal is for Europe to become the first climate-neutral continent by 2050. The European Commission has adopted a set of proposals to adapt climate, energy, transport, and taxation policies to reduce greenhouse gas emissions by at least 55% by 2030 compared to 1990. It will create new opportunities for innovation, and investment,

reduce emissions, create new jobs, solve energy poverty, reduce energy dependence, and improve the health of EU citizens.

The European Commission supports the growth of the market for vehicles with zero and low emissions. It is also trying to ensure that citizens have the infrastructure for charging these vehicles over short and long distances. From 2026, road transport will be subject to emissions trading, which will set a price for pollution and encourage the use of cleaner fuels.

2.3 The Paris Agreement

The Paris Agreement [20] is the United Nations Framework Convention on Climate Change. The purpose of the Paris Agreement is to keep global warming at an acceptable level. According to the agreement, one of the tools for achieving this goal is the reduction of greenhouse gas emissions. The framework of the Paris Agreement defines the tools for achieving the goals as follows:

- keep the global temperature increase below 2 °C compared to pre-industrial levels and make efforts to limit the temperature increase to 1.5 °C compared to pre-industrial levels, which would significantly reduce the risks and consequences of climate change,
- increase the ability to adapt to the adverse effects of climate change and support climate change resistance and low-emission development,
- harmonise financial flows with the path to low greenhouse gas emissions and climate-resilient development.

2.4 National Acts and Related Measures

The emissions are also related to Act No. 137/2010 Coll. on Air Protection [21]. Based on it, it is possible to establish a low-emission zone. The municipality determines in this way:

- the territory of the municipality or specific the streets or their parts falling into the low-emission zone (marked with traffic signs, an example in Fig. 1),
- the lowest emission class of vehicles and powertrain,
- details of the temporary entry and permanent entry permit and the vehicle operator's application form.

Fig. 1. Traffic signs indicating the beginning and end of the low-emission zone [22].

Slovakia also adopted the new Act No. 214/2021 Coll. on the Support of Ecological Road Transport Vehicles [23]. This law regulates the minimum percentage share of ecological vehicles when entering an above-limit order in public procurement and ensuring the provision of services in the public interest in passenger transport.

There was necessary to improve Decree No. 9/2009 Coll. [24], which implements the law on Toad Traffic. The decree introduced special registration numbers for BEVs and PHEVs (Fig. 2).

Fig. 2. Special vehicle registration plate for BEV and PHEV [25].

BEVs and HEVs are also benefits in Motor Vehicle Tax Act No. 361/2014 Coll. [26]. The law regulates the taxation of motor vehicles and trailers with motor vehicle tax. The tax subject is a vehicle registered in Slovakia and used for business during the tax period.

All road vehicles (cars, trucks, buses and motorcycles) whose only energy source is electricity (BEV) are charged at a zero rate, regardless of engine power. In addition, the annual tax rate is reduced by 50% for HEVs, motor vehicles powered by CNG (Compressed Natural Gas) or LNG (Liquefied Natural Gas), and motor vehicles powered by hydrogen.

An adequate charging network is required to operate BEVs and PHEVs. Act on Energy Efficiency of Buildings No. 555/2005 Coll. [27] deals with this requirement. New and significantly renovated existing non-residential buildings with more than 10 parking spaces must have at least one charging point (CP) for electric vehicles (with traffic signs Fig. 3). At least one of the five parking spaces must have wiring infrastructure (electric cables) into ensuring the later installation of CP for electric vehicles. If the building has more than 10 parking spaces, it must have the wiring infrastructure for each parking space.

Fig. 3. Traffic sign indicating a CP [22].

Amendment to the Income Tax Act No. 595/2003 Coll. [28] introduced a new depreciation group "0" with a depreciation period of 2 years in Slovakia from 2019. Depreciation group 0 includes BEVs and PHEVs in any combination with another type of fuel or energy source. It is possible to use only the straight-line depreciation method.

In November 2016, the Slovak government also adopted the National Policy Framework for the Development of the Alternative Fuels Market [29]. This document sets out

various measures to support alternative fuels in the transport sector and to improve the relevant infrastructure. Although these documents are not legally binding, they formed the basis of legally binding measures in the coming years. Ultimately, the government aims to have at least 35,000 EVs and plug-in hybrids by 2030.

The electromobility promotion in Slovakia also includes an exemption from the registration fee for the first BEV registration (33 EUR). The operation of a publicly accessible CP is also exempt from the licensing obligation.

3 State of Electromobility in Slovakia

The following graphs show the number of BEVs registered in Slovakia. However, only the number of vehicles up to 3.5 tons of total weight will be analysed, which means the following two categories [30]:

- M1 – vehicles designed and constructed for the transport of passengers, with a maximum of 8 seats in addition to the driver's seat,
- N1 – vehicles designed and constructed for the transport of goods with the largest permissible total weight not exceeding 3,500 kg,

The analysis focuses only on vehicles up to 3.5 tons due to their large share. Other categories are rare because current technological progress limits the use of electric motors in heavy trucks. Full electric buses are expanding in urban public transport. There are short routes and a possibility of charging in a city environment. A thorough analysis of the vehicle fleets of Slovak transport companies shows only 47 electric buses registered in Slovakia in 2022. According to sources [31, 32], not all electric buses are in daily operation.

The following figure (Fig. 4) shows the number of passengers and small freight BEVs registered in Slovakia since 2016. Although there is a considerable increase, it is still only an increase in hundreds of vehicles. In the case of small freight vehicles of category N1, there is only an increase in dozens of registered cars per year.

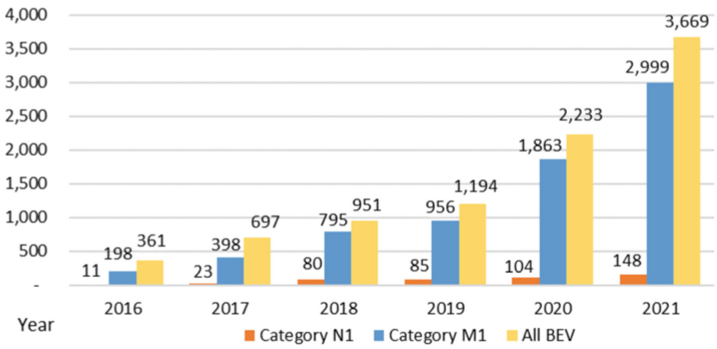


Fig. 4. Total number of M1 and N1 BEV registered in Slovakia [31].

Charging points (CP) are built relatively quickly. Figure 5 shows their absolute numbers. In 2021, 1,367 public CPs were available. The most extensive percentage increase of 238% occurred between 2015 and 2016 when the charging infrastructure in Slovakia began to develop significantly.

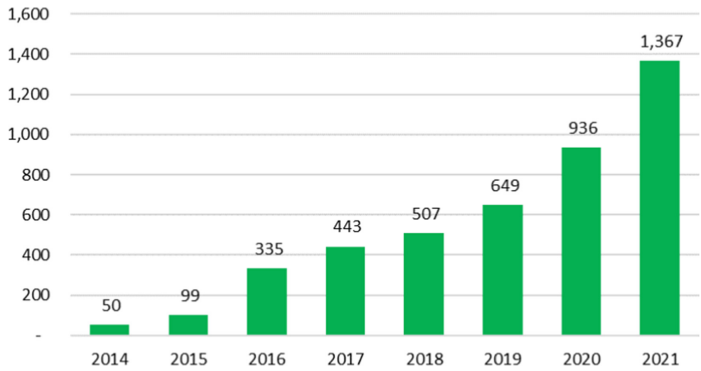


Fig. 5. Total number of public charging points in Slovakia [33].

Some studies show the recalculation of BEVs per one CP. It is questionable whether to include all BEVs in the calculation or only vehicles up to 3.5 tons. Most CPs are not suitable for trucks and buses. One CP in Slovakia is for about 2.70 BEVs or 2.30 BEVs up to 3.5 tons. Calculations for selected countries are in Table 1.

Table 1. Calculation of BEVs per one CP.

Country	BEVs	CPs	BEVs per 1 CP
Norway	463,579	18,656	24.8
Germany	740,632	59,410	12.5
Austria	87,881	13,110	6.7
Sweden	132,850	25,197	5.3
Czech Republic	11,457	2,189	5.2
Poland	14,242	2,811	5.1
Hungary	11,204	2,541	4.4
Netherlands	261,732	90,284	2.9
Slovakia	3,669	1,367	2.7

The numbers of registered BEVs in Slovakia and other EU Countries are very different. Slovakia has less than 4 thousand registered BEVs. On the other hand, there are 1,367 CPs. It means 2.7 BEV per one CP. It is the best number from all compared countries.

4 Proposal for Electromobility Support

This chapter will summarise the measures to date, the aim of which was to support the development of electromobility in road transport. Slovakia has already made many legislative changes. On the other hand, some modified regulations can still help electromobility. This article presents only part of the economic calculations of individual measures.

4.1 Subsidies for BEVs and PHEVs

Many authors [34, 35] currently ask whether the BEV market can function without subsidies. In the Slovak Republic, as part of the subsidy program that ended at the end of June 2018, every citizen, entrepreneur, company, city, or municipality could apply for a subsidy. Its amount was 5,000 € for a BEV and 3,000 € for a PHEV purchase. The vehicle had to be new, purchased in the country and registered for at least two years in Slovakia. The total amount of the distributed subsidy was approximately 5 million €.

The second subsidy call was in 2019. The individual contribution was 8,000 € per one BEV and 5,000 € per one PHEV. Applicants booked all these subsidies in a few minutes.

The Slovak Republic will not have subsidies even in 2022. Citizens can expect the next round in 2023. At the end of 2022, the governments should develop a new action plan for the field of electromobility. It will include the creation of a financial mechanism for subsidies.

One of the recommendations is the support of electromobility through an appropriate amount of subsidy. An extremely high subsidy amount will cause extreme interest. On the contrary, a low amount could cause a considerable lack of interest.

During the first two calls, there was no available BEV with a price lower than 20,000 € in the Slovak Republic. Currently, the cheapest BEV Dacia Spring is also on the domestic market with a base price of 19,000 €. This particular vehicle could improve the availability of BEVs to the public.

4.2 Legislation Measures

Motor vehicle tax applies only to vehicles used for business. BEVs currently have a zero rate. It is no longer possible to reduce the fee in this area.

Another option for supporting electromobility in Slovakia is to reduce the tax burden on the employee (taxpayer) when using a company BEV car for private purposes. This support would affect the amount of tax collected by the financial administration. We have made several calculations in this area. We made two model cases. When 1 BEV is used for private purposes out of 50 registered, such a measure would cost approximately 40 thousand Euros. The price of the BEV with value added tax influenced this tax. Therefore, we calculated the average price of BEV €30,620. If 1 BEV out of 10 were used continuously for private purposes, this measure would cost 179 thousand Euros.

Another proposal for the possibility of supporting electromobility is the reduction of VAT when buying a new electric car. Natural persons could also use this form of price reduction. The lower percentage of VAT can reduce the purchase price of BEV.

This proposal is significant, as the purchase price of BEVs is currently a major problem. Such a vehicle needs several tens of thousands of kilometers to compensate for the high investment with low operating costs.

One of the advantages of electric vehicles could be free vignettes for BEVs. It is another possibility to support electromobility in Slovakia. The one-year vignette for Slovak motorways and expressways costs 50 €. Free vignettes for all BEVs for category M1 would cost the 149,950 €, for M1 and N1 157,350 €. The following table (Table 2) shows details.

For comparison, in 2021 the National Motorway Company's one-year vignette revenue was 33,439,000 € which means they sold 668,780 one-year vignettes. With this number of vignettes sold, 3,147 free one-year vignettes would represent a negligible number. Also, the sum of 157,350 € for this measure represents 0.47% of the sales [36].

Table 2. Calculation of BEVs per one CP.

Vehicle category	Registered BEVs in 2021	Vignette for all BEVs (€)
N1	2,999	149,950
N1	148	7,400
M1 + N1	3,147	157,350

Price manipulation is also possible in the area of parking fees. In Slovakia, there is free parking while charging at public CP. Some operators charge a fee of 3 € for each hour after the end of active charging. It is also appropriate to consider discounted rates for BEV and PHEV in individual cities.

5 Conclusion

As can be concluded from the previous text, support for electromobility is primarily related to the economy. It is inverse proportionality. The more BEVs the state wants, the more it will cost. Some of the measures described in this paper are not economically demanding with hundreds of registered BEVs. However, as the experience of Western Europe shows, reduced or waived fees related to electric cars can be considered temporary. If we were to imagine such an abstraction that all vehicles will eventually be electric, there could not be zero tax rates and fees. In Slovakia, relatively quickly measures positively affect the development of electromobility. However, the question is what still discourages people from buying a BEV? There is a wide range of answers. These are psychological (distrust of new technology), technological (short distance, lack of infrastructure), and economic aspects (procurement price, charging price, electricity price, expensive service), which are still obstacles, especially for residents with lower incomes. In this case, it is possible to observe that legislation, economy, and technology are interconnected in transport and cannot be separated.

Acknowledgement. This publication was realised with support of Operational Program Integrated Infrastructure 2014–2020 of the project: Innovative Solutions for Propulsion, Power and

Safety Components of Transport Vehicles, code ITMS 313011V334, co-financed by the European Regional Development Fund.

EUROPEAN UNION
European Regional Development Fund
OP Integrated Infrastructure 2014 – 2020

MINISTRY
OF TRANSPORT
AND CONSTRUCTION
OF THE SLOVAK REPUBLIC

References

1. CO2 emissions from fuel combustion: overview, global CO2 emissions by sector. International Energy Agency (IEA) (2020)
2. Suttakul, P., Fongsamootr, T., Wongsapai, W., Mona, Y., Poolsawat, K.: Energy consumptions and CO2 emissions of different powertrains under real-world driving with various route characteristics. Energy Rep. **8**, 554–561 (2022)
3. Bristow, A., Pridmore, A., Tight, M., May, T., Berkhout, F., Harris, M.: How can we reduce carbon emissions from transport? Tyndall Centre Technical Report 15 (2004)
4. Gogola, M.: Are the e-bikes more dangerous than traditional bicycles? In: 2018 XI International Science-Technical Conference Automotive Safety, Častá-Papiernička, Slovakia, pp. 1–4. IEEE (2018)
5. Macurová, L., Kohút, P., Čopiak, M., Imrich, L., Rédl, M.: Determining the energy equivalent speed by using software based on the finite element method. Transp. Res. Procedia **44**, 219–225 (2020)
6. Hawkins, T.R., Gausen, O.M., Strømman, A.H.: Environmental impacts of hybrid and electric vehicles – a review. Int. J. Cycle Assess. **17**(8), 997–1014 (2012)
7. Hawkins, T.R., Singh, B., Majeau-Bettez, G., Strømman, A.H.: Comparative environmental life cycle assessment of conventional and electric vehicles. J. Ind. Ecol. **17**(1), 53–64 (2013)
8. Figenbaum, E.: Retrospective Total cost of ownership analysis of battery electric vehicles in Norway. Transp. Res. Part D Transp. Environ. **105**, 103246 (2022)
9. Suttakul, P., Wongsapai, W., Fongsamootr, T., Mona, Y., Poolsawat, K.: Total cost of ownership of internal combustion engine and electric vehicles: a real-world comparison for the case of Thailand. Energy Rep. **8**, 545–553 (2022)
10. Bhosale, A.P., Sharma, S., Mastud, S.A.: Characterising the economic competitiveness of battery electric vehicles in India. Asian Transp. Stud. **8**, 100069 (2022)
11. Cavallaro, F., Danielis, R., Nocera, S., Rotaris, L.: Should BEVs be subsidized or taxed? A European perspective based on the economic value of CO2 emissions. Transp. Res. Part D Transp. Environ. **64**, 70–89 (2018)
12. Zhao, X., Doering, O.C., Tyner, W.E.: The economic competitiveness and emissions of battery electric vehicles in China. Appl. Energy **156**, 666–675 (2015)
13. Gallagher, K.S., Muehlegger, E.: Giving green to get green? Incentives and consumer adoption of hybrid vehicle technology. J. Environ. Econ. Manag. **61**(1), 1–15 (2011)
14. Jenn, A., Azevedo, I.L., Ferreira, P.: The impact of federal incentives on the adoption of hybrid electric vehicles in the United States. Energy Econ. **40**, 936–942 (2013)
15. Kalašová, A., Krchová, Z.: Telematics applications and their influence on the human factor. Transp. Probl. **8**(2), 89–94 (2013)
16. Kalašová, A., Kučuljaková, J.: The future in the telematics applications as support for increased safety. Transp. Probl. **7**(1), 103–109 (2012)

17. ERTRAC Roadmaps. https://www.ertrac.org/index.php?page=ertrac-roadmap. Accessed 23 Aug 2022
18. White Paper Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system. https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2011:0144:FIN:en:PDF. Accessed 10 Aug 2022
19. European Commission: A European Green Deal. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en. Accessed 10 Aug 2022
20. The Paris Agreement. https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement. Accessed 10 Aug 2022
21. Act No. 137/2010 Coll. on Air Protection. https://www.slov-lex.sk/pravne-predpisy/SK/ZZ/2010/137/20200409. Accessed 10 Aug 2022
22. Decree No. 30/2020 Coll. on Traffic Signs. https://www.slov-lex.sk/pravne-predpisy/SK/ZZ/2020/30/. Accessed 10 Aug 2022
23. Act No. 214/2021 Coll. on the Support of Ecological Road Transport Vehicles. https://www.slov-lex.sk/pravne-predpisy/SK/ZZ/2021/214/20210802. Accessed 10 Aug 2022
24. Decree No. 9/2009 Coll. https://www.slov-lex.sk/pravne-predpisy/SK/ZZ/2009/9/20220. Accessed 10 Aug 2022
25. Vehicle registration plates for BEV and PHEV. https://www.minv.sk/?elektro-tec-na-elektromobily-a-plug-in-hybridy. Accessed 10 Aug 2022
26. Act No. 361/2014 Coll. Motor Vehicle Tax Act. https://www.slov-lex.sk/pravne-predpisy/SK/ZZ/2014/361/20201201. Accessed 10 Aug 2022
27. Act No. 555/2005 Coll. on energy performance of buildings as amended. https://www.slov-lex.sk/pravne-predpisy/SK/ZZ/2005/555/20200425. Accessed 10 Aug 2022
28. Act No. 595/2003 Coll. Income Tax Act. https://www.slov-lex.sk/pravne-predpisy/SK/ZZ/2003/595/20220701. Accessed 10 Aug 2022
29. Draft of the National Policy Framework for the Development of the Alternative Fuels Market. https://rokovania.gov.sk/RVL/Material/21564/1. Accessed 10 Aug 2022
30. Ondruš, J., Hockicko, P.: Braking deceleration measurement using the video analysis of motions by SW tracker. Transp. Telecommun. **16**(2), 127–137 (2015)
31. Electromobility in Numbers. https://e-mobility.sk/wp-content/uploads/2022/01/Elektromobilita-v-%C4%8D%C3%ADslach-Q42021-2.pdf. Accessed 10 Aug 2022
32. Vehicle Registry of Slovak carriers. https://evidencia-dopravcov.eu/. Accessed 10 Aug 2022
33. European Alternative Fuels Observatory. https://alternative-fuelsobservatory.ec.europa.eu/. Accessed 10 Aug 2022
34. Li, L., Guo, S., Cai, H., Wang, J., Zhang, J., Ni, Y.: Can China's BEV market sustain without government subsidies?: an explanation using cues utilization theory. J. Clean. Prod. **272**, 122589 (2020)
35. Breetz, H.L., Salon, D.: Do electric vehicles need subsidies? Ownership costs for conventional, hybrid, and electric vehicles in 14 US cities. Energy Policy **120**, 238–249 (2018)
36. SME.sk: Vignette. https://index.sme.sk/c/22812108/tento-rok-sme-najviac-kupovali-desatdnovu-dialnicnu-znamku.html. Accessed 10 Aug 2022

Numerical Analysis of Combustion Parameters of a Spark Ignition Engine Fuelled with CNG and Variable Valve Timing

Gediminas Mikalkėnas(✉), Alfredas Rimkus, and Saugirdas Pukalskas

Vilnius Gediminas Technical University, J. Basanavičiaus Str. 28, 03224 Vilnius, Lithuania
{gediminas.mikalkenas,alfredas.rimkus,
saugirdas.pukalskas}@vilniustech.lt

Abstract. Spark ignition engines are still widely used in transport and natural gas could be a great alternative to conventional fuels. This article presents the combustion characteristics of natural gas at various engine speeds (2,000, 2,500 and 3,000 rpm) obtained by experiment and numerical simulations using AVL BOOST. The rate of heat release can be obtained from measured cylinder pressure curves. The influence of variable valve timing was determined by changing the angle of intake valve closing while the engine was running at the stoichiometric air-fuel mixture at fixed spark timing and the throttle angle.

Keywords: Spark ignition engines · Natural gas · Combustion parameters · Variable valve timing · Vibe function

1 Introduction

Natural gas (NG) is known fuel for internal combustion engines [1]. The vehicle powered by natural gas has higher brake thermal efficiency (BTE) and lower emissions [2, 3]. Methane has the lowest carbon and hydrogen ratio compared to other fossil fuels, thus reducing emissions such as carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxide (NO_x), and for sure particulate matter (PM) level. Also, natural gas has a higher octane number (>110) than petrol (85–91) and due to the possibility of increasing the engine compression ratio to improve thermal efficiency and lower CO_2 emissions (Table 1) [4, 5].

One of the most dangerous spark ignition (SI) engine pollutants is (NO_x), because these gases react with ozone, which is the main part of photochemical smog. In addition, NO_x emissions result in acid rain. NO_x in the combustion chamber is formed mainly from nitrogen in the atmospheric air. [6–9]. However, it is possible to reduce NO_x emissions through other technologies such as exhaust gas recirculation (EGR), selective catalyst (SCR) and water injection technologies. Water can be supplied in several ways: direct injection into the cylinder using a high pressure injector; injection into the intake manifold; water-fuel emulsions, or steam injection [10].

With variable valve timing (VVT) possible to improve engine volumetric efficiency and reduce emissions [12]. The objective of this article is to investigate the influence of VVT on engine characteristics when an engine is fuelled with CNG.

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 135–143, 2023.
https://doi.org/10.1007/978-3-031-25863-3_13

Table 1. Properties of CNG compared to gasoline [11].

Fuel	CNG	Gasoline
Chemical formula	CH_4	$C_nH_{1.87n}$
Molecular weight	16.4	114.24
Equivalence ratio ignition lower limit in air[a]	0.53	0.70
Flammability limits in air (%vol.)[a]	5–15	1.4–7.6
Flammability limits (λ)	2–0.6	1.51–0.26
Minimum ignition energy in air (mJ)	0.29	0.28
Auto ignition temperature[b] (°C)	540	247–280
Mass lower heating value[b] (kJ/kg)	50.020	44.50
Density of gas[b] (kg/m^3)	0.65119	750
Diffusivity in air (cm^2/s)	0.2	~ 0.07
Octane number	120	87
Volumetric lower heating value[a] (kJ/m^3)	32.573	195.80
Stoichiometric air-fuel ratio (kg/kg)	17.19	14.7
Volumetric fraction of fuel in air, $\lambda = 1$	0.095	0.0165
Laminar burning velocity (m/s)	0.38	0.45
Laminar burning speed in air[a] (cm/s)	37–45	37–43
Quenching distance in air[a] (cm)	0.21	0.2
Flame temperature in air (K)	2,148	2,470

[a] at 293.15 K and 1 atm.
[b] at 0 °C and 1 bar.

2 Research Methodology

The experiments were carried out on a bench with the HR16DE spark ignition engine of the Nissan Qashqai vehicle (Table 2) and afterward carried out numerical modeling. Test carried out at 3 different engine speeds: n = 2,000 rpm, n = 2,500 rpm, and n = 3,000 rpm, throttle position fixed at 15% and ignition timing Θ = 22 Crank Angle Degree (CAD) before the top dead center (bTDC). CNG is used for all tests and with an excess air ratio of $\lambda = 1.0$. In AVL BOOST utility for combustion analysis BURN the rate of heat release (ROHR) has been obtained from measured cylinder pressure curves, fuel and air consumption, fuel properties. Regarding the bench experiment, an analysis of the combustion process was performed and the trends of changes in Vibe function (combustion duration (CD), start of combustion (SOC), shape parameter m, brake thermal efficiency (BTE) were determined. The influence of VVT was determined by changing the angle of intake valve closing (IVC) while the engine was running at the stoichiometric air-fuel mixture at fixed spark timing and the throttle angle (15%).

According to the simulation of the combustion process with the BURN trends, an additional angle of VVT (5 CAD was added (5 CAD for each corner). This means that IVC timings of 19 and 59 CAD aBDC are interpolated from tendencies calculated with BURN.

Table 2. Engine HR16DE technical characteristics.

Parameter	Value
Number of cylinders	4
Cylinder bore, mm	78
Piston stroke, mm	83.6
Number of valves per cylinder	4
Displacement, cm^3	1,598
Compression ratio	10.7
Nominal power, kW (rpm)	84 (6000)
Maximum engine torque, Nm (rpm)	156 (4400)
Number of valves	16
Intake valve open (IVO), CAD bTDC	24…11
Intake valve close (IVC), CAD aBDC	24…54
Intake valve duration (IVD), CAD	228
Exhaust valve open (EVO), CAD bBDC	24
Exhaust valve close (EVC), CAD aTDC	4
Exhaust valve duration (EVD), CAD	208

At the initial stage, engine experimental tests were carried out in the laboratory of internal combustion engines of the VILNIUS TECH Faculty of Transport Engineering. The tested engine is controlled by the MoTeC M800 programmable ECU and AMX 200/100 load stand. An AVL ZI31 pressure sensor installed in the spark plug determined the pressure in the engine cylinder, and the signals were recorded by the AVL DiTEST DPM 800 device. During the experimental tests, the gas consumption (debit) was measured using a mass flow meter RHEONIK RHM 015, and the mass of air sucked into the engine was measured using the device HFM 5 m.

3 Results and Their Analysis

The engine's energy performance is measured when it operates with CNG. During the tests, a stoichiometric combustible mixture of $\lambda = 1$ was maintained and the engine throttle was opened at 15%. The research team recorded the engine performance at various RPMs and varying the intake valve closing (IVC) timing.

The maximum brake mean effective pressure (*BMEP*) was reached when the engine was run at 2,000 rpm with an IVC timing of 34 CAD aBDC and $BMEP = 0.513$ MPa

(Fig. 1). After the IVC timing was advanced from 34 to 24 CAD aBDC, the *BMEP* was only reduced by 0.22% due to the fairly low inertia of the intake gas mixture. Advancing IVC even more, the calculated point at 19 CAD aBDC decreases to $BMEP = 0.505$ MPa, which is 1.5% lower than the maximum point at 34 CAD aBDC. Retarding the IVC timing from 34 to 54 CAD aBDC reduced *BMEP* by 5.4% because part of the gas mixture returns to the intake manifold. This behaviour is expected because at low engine speed, gas flow speed also low. By the tendency, the interpolated point at IVC 59 shows an obvious lower volumetric efficiency at $BMEP = 0.461$ MPa, which is 11.2% lower than the maximum point. This effect is even stronger than when the engine is running on gasoline, because a low density of CNG dilutes the gas mixture in the intake manifold. Increased engine speed to 2,500 rpm and 3,000 rpm reduces *BMEP* by 28.9% and 62.9% accordingly compared to 2,000 rpm. This effect is caused by hydraulic losses in the throttle valve, which open is fixed at 15%.

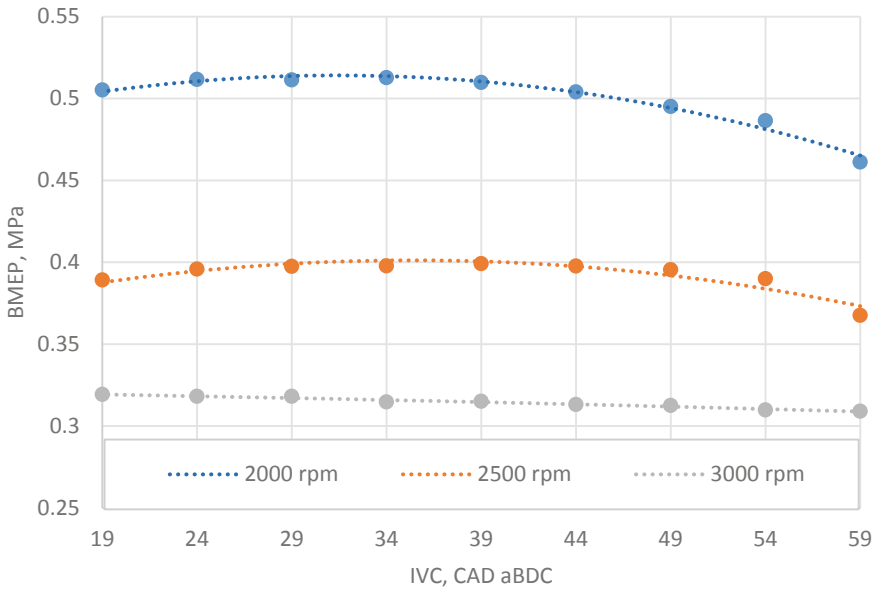


Fig. 1. Dependence of Brake mean effective pressure on the intake valve closing when the engine is operating at 2,000, 2,500 and 3,000 rpm.

Engine cylinder pressure, fuel mass, air mass and fuel composition results obtained during the tests were entered into the AVL BURN programme. Since the heat release calculation algorithm is based on the first law of thermodynamics, with the help of AVL BURN, the start of combustion, the duration of combustion in the cylinder and the intensity of combustion, characterized by the shape parameter m, were determined. These indicators are the most important in Vibe's heat release formula [13].

The start of combustion determines the point where the pressure starts to rise. The ignition timing is always the same 22 CAD bTDC. The *SOC* curve at 2,000 rpm is quite linear and equals 18.5 CAD bTDC at IVC 24 CAD aBDC and 19.45 CAD bTDC. This

means that the combustion delay is quite stable during IVC adjustments. With higher engine speed the *SOC* angle changes significantly, especially at 3,000 rpm the *SOC* angle varies from $SOC = 17.1$ CAD bTDC at IVC 24 CAD aBDC to $SOC = 14.1$ CAD bTDC at IVC 19 aBDC. A likely reason for the SOC delay is worse cylinder filling (Fig. 2).

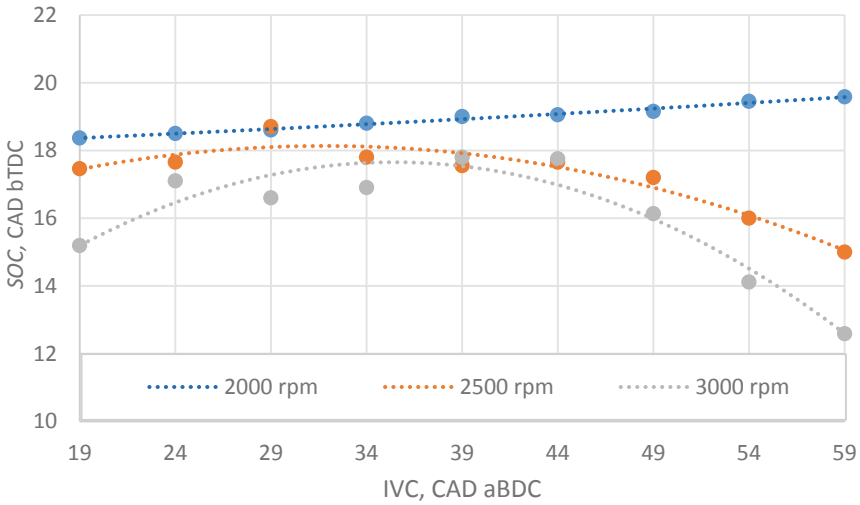


Fig. 2. Dependence of Start of combustion on the intake valve closing when the engine is operating at different speeds.

The shape parameter m determines the combustion intensity. At low m values, the combustion intensity is concentrated at the beginning of the combustion process and with higher m values, the combustion is more intense in the middle or end of the process. This means that at 2,000 rpm the ROHR its highest point reaches later, especially at IVC 34 CAD aBDC, when $m = 2.315$ (Fig. 3). If the IVC is retarded to 54 CAD bTDC, the $m = 2.12$ shows more intense combustion. By trend, the interpolated point at IVC 59 gives the shape parameter $m = 1.95$. With higher engine speed, the m parameter decreases significantly to very similar values in the range of IVC 39–54 CAD aBDC, due to more intensive turbulation inside combustion chamber.

The duration of combustion varies significantly from $CD = 56.35$ CAD at IVC 24 CAD aBDC to $CD = 65.7$ at IVC 24 CAD aBDC when the 2,000 rpm speed is selected (Fig. 4). The duration of combustion increased because the actual compression ratio decreased due to the retarded closing of the intake valve, the volumetric efficiency worsened due to the small flow speed of the gases. Longer combustion duration has a negative influence on the BTE of the engine. With higher speeds the tendency is very similar, with lower variations due to IVC angle changes.

When the engine ran at 2,000 rpm, the maximum $BTE = 35.13\%$ was reached at IVC timing 34 CAD aBDC (Fig. 5). When the IVC timing advanced to 24 CAD aBDC, the BTE decreased by a negligible amount of 0.08%. Advancing IVC even more, the calculated point at 19 CAD aBDC decreases to $BTE = 35\%$, which is 0.37% lower than the maximum point at 34 CAD aBDC. Retarding the IVC timing from 34 to 54 CAD

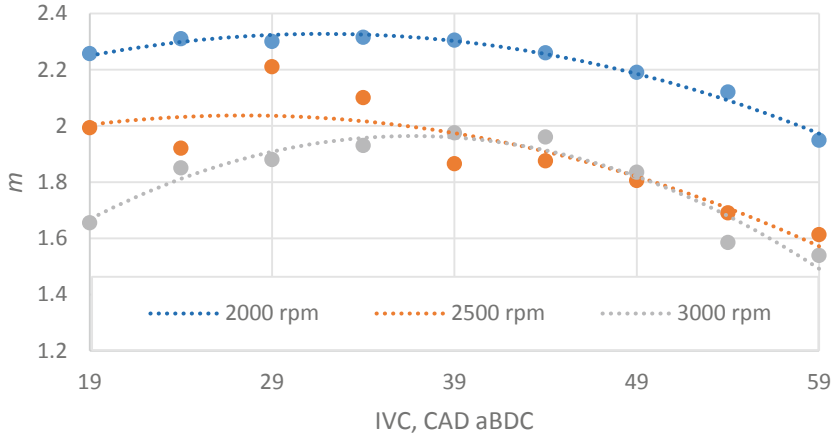


Fig. 3. Dependence of Shape parameter *m* on the intake valve closing when the engine is operating at different speeds.

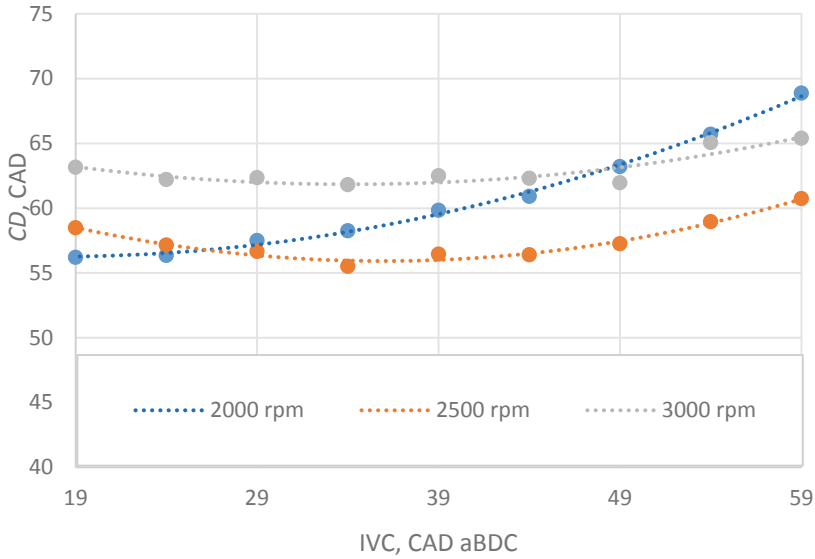


Fig. 4. Dependence of Combustion duration CD on the IVC when the engine is operating at different speeds.

aBDC reduced the *BTE* by 1.5%. By the tendency, the interpolated point at IVC 59 shows a lower volumetric efficiency at $BTE = 34.599\%$, which is 1.9% lower than the maximum point.

At engine speed of 2,500 rpm, BTE decreases due to increasing mechanical losses, but as IVC retards, BTE increases slightly. Hence, with an increase in engine speed, the hydraulic resistance of the intake gas mixture increased slightly, but the inertia of the

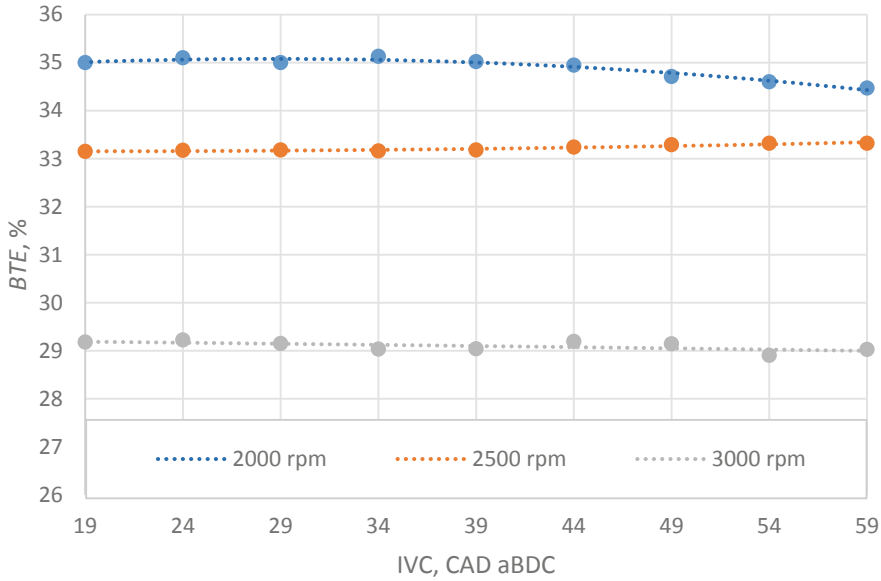


Fig. 5. Dependence of brake thermal efficiency on the IVC when the engine is operating at 2,000, 2,500 and 3,000 rpm.

gas improves the volumetric efficiency. After increasing the engine speed to 3,000 rpm, the BTE is significantly reduced, because the 15% open throttle prevents from filling the cylinders, and mechanical losses use more engine energy. The later IVC already has a negative effect, as the mass and inertia of the intake gas is reduced due to the increased hydraulic resistance. This negative effect of later IVC closure is more pronounced with NG fuel compared to gasoline because the gas has a lower density and inertia compared to gasoline[14].

4 Conclusions

Differences in combustion parameters were determined when the engine ran on CNG fuel with a stoichiometric mixture and IVC angles between 24 and 54 CAD aBDC. Additional angles of 19 and 59 CAD aBDC were calculated according to tendencies and points:

1. The maximum BMEP was reached when the engine was run at 2,000 rpm with an IVC timing of 34 CAD aBDC and BMEP = 0.513 MPa. At same point the maximum *BTE* was reached 35.13%.
2. The *SOC* curve at 2,000 rpm is quite linear and this means that the combustion delay is quite stable during IVC adjustments. With higher engine speed the *SOC* angle changes significantly, especially at 3,000 rpm. A likely reason for the *SOC* delay is worse cylinder filling.

3. With higher engine speed, the *m* parameter decreases significantly to very similar values in the range of IVC 39–54 CAD aBDC, due to more intensive turbulation inside combustion chamber.
4. The duration of combustion varies significantly when the 2,000 rpm speed is selected. The duration of combustion increased because the actual compression ratio decreased due to the retarded closing of the intake valve, the volumetric efficiency worsened due to the small flow speed of the gases. Longer combustion duration has a negative influence on the *BTE* of the engine. With higher engine speeds of 2,500 rpm and 3,000 rpm, the tendency is very similar, with lower variations due to IVC angle changes.

Acknowledgement. To obtain the results, an AVL BOOST virtual internal combustion engine simulation tool was used. It was acquired by signing an agreement between AVL Advanced Simulation Technologies and the Faculty of Transport Engineering of VILNIUS TECH.

References

1. Karim, G.A., Wierzba, I., Al-Alousi, Y.: Methane-hydrogen mixtures as fuels. Int. J. Hydrogen Energy **21**(7), 625–631 (1996). https://doi.org/10.1016/0360-3199(95)00134-4
2. Chen, H., He, J., Zhong, X.: Engine combustion and emission fuelled with natural gas: a review. J. Energy Inst. **92**(4), 1123–1136 (2019). https://doi.org/10.1016/j.joei.2018.06.005
3. Kosmadakis, G.M., Rakopoulos, D.C., Rakopoulos, C.D.: Performance and emissions of a methane-fueled spark-ignition engine under consideration of its cyclic variability by using a computational fluid dynamics code. Fuel **258**, 116154 (2019). https://doi.org/10.1016/j.fuel.2019.116154
4. Chen, Z., Wang, L., Zeng, K.: A comparative study on the combustion and emissions of dual-fuel engine fueled with natural gas/methanol, natural gas/ethanol, and natural gas/n-butanol. Energy Convers. Manag. **192**, 11–19 (2019). https://doi.org/10.1016/j.enconman.2019.04.011
5. Chen, Z., Zhang, F., Xu, B., Zhang, Q., Liu, J.: Influence of methane content on a LNG heavy-duty engine with high compression ratio. Energy **128**, 329–336 (2017). https://doi.org/10.1016/j.energy.2017.04.039
6. Hutter, R., De Libero, L., Elbert, P., Onder, C.H.: Catalytic methane oxidation in the exhaust gas aftertreatment of a lean-burn natural gas engine. Chem. Eng. J. **349**, 156–167 (2018). https://doi.org/10.1016/j.cej.2018.05.054
7. Yu, X., et al.: Experimental study on lean-burn characteristics of an SI engine with hydrogen/gasoline combined injection and EGR. Int. J. Hydrogen Energy **44**(26), 13988–13998 (2019). https://doi.org/10.1016/j.ijhydene.2019.03.236
8. Duan, X., et al.: Experimental study the effects of various compression ratios and spark timing on performance and emission of a lean-burn heavy-duty spark ignition engine fueled with methane gas and hydrogen blends. Energy **169**, 558–571 (2019). https://doi.org/10.1016/j.energy.2018.12.029
9. Fu, J., Shu, J., Zhou, F., Zhong, L., Liu, J., Deng, B.: Quantitative analysis on the effects of compression ratio and operating parameters on the thermodynamic performance of spark ignition liquefied methane gas engine at lean burn mode. Fuel **263**, 116692 (2020). https://doi.org/10.1016/j.fuel.2019.116692

10. Gonca, G.: Effects of engine design and operating parameters on the performance of a spark ignition (SI) engine with steam injection method (SIM). Appl. Math. Model. **44**, 655–675 (2017). https://doi.org/10.1016/j.apm.2017.02.010
11. Mehra, R.K., Duan, H., Juknelevičius, R., Ma, F., Li, J.: Progress in hydrogen enriched compressed natural gas (HCNG) internal combustion engines - a comprehensive review. Renew. Sustain. Energy Rev. **80**, 1458–1498 (2017). https://doi.org/10.1016/j.rser.2017.05.061
12. Bari, S., Sawant, P.: Improvement of performance by 2-Step variations of intake runner length and intake valve timing in the induction system of a SI engine. Energy Procedia **160**, 108–115 (2019). https://doi.org/10.1016/j.egypro.2019.02.125
13. Vibe, I.I.: Brennverlauf und Kreisprozeß von Verbrennungsmotoren. Verlag Technik, Berlin (1970)
14. Rimkus, A., Vipartas, T., Kriaučiūnas, D., Matijošius, J., Ragauskas, T.: the effect of intake valve timing on spark-ignition engine performances fueled by natural gas at low power. Energies **15**(2), 398 (2022). https://doi.org/10.3390/en15020398

Improving the Energy Efficiency of a Vehicle by Implementing an Integrated System for Utilizing the Thermal Energy of the Exhaust Gases of an Internal Combustion Engine

Yurii Gutarevych[1], Jonas Matijošius[2(✉)], Dmitrij Trifonov[1], Oleksandr Syrota[1], Alfredas Rimkus[2], Yevhenii Shuba[1], and Urtė Radvilaitė[3]

[1] Faculty of Automotive and Mechanical Engineering, Department of Engines and Thermal Engineering, National Transport University, Mykhaila Omelianovycha-Pavlenka Str. 1, Kyiv 01010, Ukraine
{d.trifonov,shuba}@ntu.edu.ua

[2] Department of Automobile Engineering, Faculty of Transport Engineering, Vilnius Gediminas Technical University, Basanavičiaus Str. 28, 03224 Vilnius, Lithuania
{jonas.matijosius,alfredas.rimkus}@vilniustech.lt

[3] Department of Information Systems, Faculty of Fundamental Sciences, Vilnius Gediminas Technical University, Saulėtekio Al. 11, 10223 Vilnius, Lithuania
urte.radvilaite@vilniustech.lt

Abstract. The rapid increase in the number of fossil fuel vehicles in recent decades has led to stricter standards for their environmental safety, carbon dioxide emissions and fuel efficiency. Advances in the production technologies of the internal combustion engine (ICE) and systems that ensure its operation have led to a significant reduction in emissions of harmful substances with exhaust gases. Meanwhile, increasing the thermal efficiency of the internal combustion engine without significantly increasing production and operating costs is an urgent task and one of the priority areas of scientific research in this field. The article considers the most rational schemes for the recovery of thermal energy of exhaust gases, which ensure the minimization of operating costs of the vehicle. The implementation of the proposed system of complex energy-efficient disposal is evaluated taking into account the expectations of compliance with the requirements for emissions of harmful substances with exhaust gases during the operation of the vehicle.

Keywords: Secondary energy resources · Utilization of thermal energy of waste gases · Thermal battery of phase transition · Thermoelectric generator · Accumulator battery

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 144–151, 2023.
https://doi.org/10.1007/978-3-031-25863-3_14

1 Introduction

The car has become an integral part of modern life. At the same time, its use causes a number of problems, primarily related to environmental pollution and rather low energy efficiency of the internal combustion engine [1–3].

The internal combustion engine is one of the most efficient and universal sources of mechanical energy used in cars [4], construction and agricultural machinery [5], stationary power plants [6], etc. Non-renewable resources (fossil fuels) are mainly used as primary energy resources (PER) for vehicles [7]. The main problems with the burning of fossil fuels, where the chemical energy of the fuel is transformed with the help of thermal energy into mechanical work, are harmful emissions and non-productive losses of a large share of the received energy (equivalent to the chemical energy of fuel combustion) [8]. Nevertheless, it is expected that 85…90% of transport energy will come from internal combustion engines running on conventional fossil fuels, even by 2040 [9].

All losses of received energy during the operation of internal combustion engines can be divided into two large groups: mechanical and thermal (see Fig. 1).

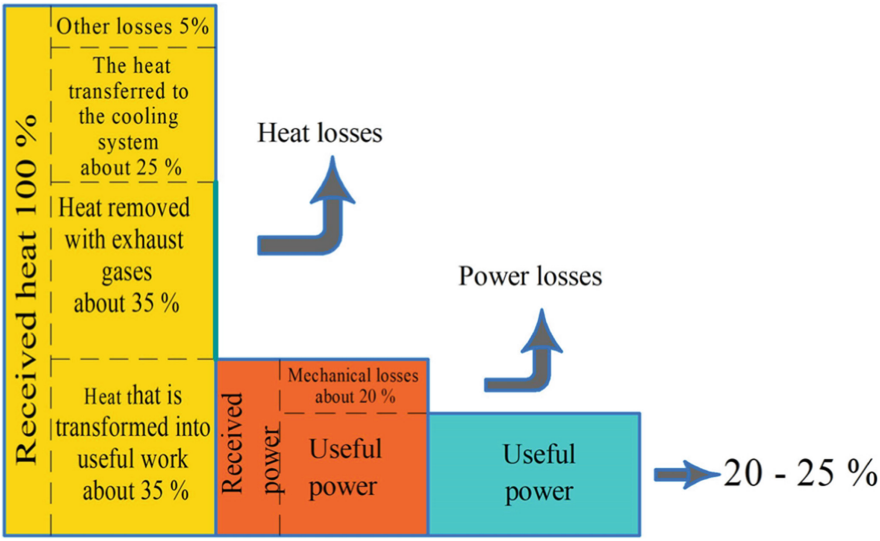


Fig. 1. The structure of distribution of losses in ICE.

Mechanical losses in internal combustion engines include power losses - due to friction in mating pairs of parts, pumping strokes of the piston, and driving auxiliary mechanisms. Heat losses include the heat transferred to the cooling and lubrication systems of the internal combustion engine, the heat that goes with the exhaust gases, etc.

An increase in the energy efficiency of an internal combustion engine can be realized by utilizing part of the secondary energy resources (SER), which are generated in large volumes during the operation of an internal combustion engine [10]. The energy saving potential through the use of SER is very large and can be up to 40% of the cost of PER.

It is known that up to 35% of the thermal energy obtained from fuel combustion is lost in an internal combustion engine with exhaust gases (EG), and their temperature can be +350…700 °C [11, 12].

Many researchers recognize that the utilization of a part of the thermal energy of the HV engine is one of the most effective, which allows to reduce the total specific fuel consumption, while ensuring an increase in the total power of the power plant and a reduction in the negative impact of the vehicle on the environment, in particular, a reduction in the volume of dioxide emissions carbon Conducted studies have shown that the conversion of 6% of thermal energy into electrical energy allows to reduce fuel consumption to 10%, which accordingly reduces the emissions of harmful substances with exhaust gases of internal combustion engines [13, 14].

Recent technological advances have made SER recovery systems cost-effective, and the strengthening of environmental and fuel-economy requirements for vehicles is also necessary, as they allow to increase the efficiency of the use of PER by a vehicle based on its purpose and operating conditions.

Issues related to the use of excess thermal energy, in particular EG thermal energy, are intensively researched by domestic and foreign scientists in various fields of technology. Thus, in the automobile industry, this problem was reflected in works [14–19] and others.

In this regard, increasing the energy efficiency of the internal combustion engine of the vehicle, first of all due to the reduction of SER losses, is an urgent task and one of the priority areas of scientific research in this area.

This article presents the results of functional studies of the system, which allows converting the thermal energy of waste gases into electrical energy. The obtained electrical energy can be used to power various on-board systems of the car, which will reduce the load on the generator and reduce fuel consumption. This article does not include studies of fuel efficiency, and they will be conducted in our next works.

2 Problem Statement

The goal of the study is to increase the energy efficiency of the internal combustion engine by utilizing part of the thermal energy of the exhaust gases.

The authors propose a system of complex energy-efficient utilization of a part of the thermal energy of the exhaust gases of the internal combustion engine, which consists of a thermal accumulator (TA), a thermoelectric generator (TEG), a buffer battery (AB) and devices that ensure an increase in the technical readiness of the vehicle. Functional experimental and calculation studies of the components of the proposed system were carried out in order to determine the optimal ways of using the thermal energy accumulated in the TA and the electrical energy produced by the TEG.

In the proposed system, a two-way heat accumulator of the shell-and-tube type with a box casing is used, which is due to the simplicity of the design and its reliability, which ensures the accumulation and preservation of a part of the thermal energy of EG for a fairly long time in the heat-accumulating material (HAM) with a phase transition of the “melting-crystallization” type [20]. The use of a phase transition heat accumulator (PTHA) ensures a high density of accumulated energy and a fairly stable air temperature

at the outlet of the TA, which allows maintaining the optimal air temperature in the intake manifold in conditions of low ambient air temperatures [17, 18].

The thermoelectric generator provides direct conversion of thermal energy stored in TA into electrical energy. The use of TA makes it possible to generate electrical energy, both during the operation of the internal combustion engine and for a long time after the engine stops, which is determined by the thermophysical characteristics of the heat-accumulating material, its quantity and conditions of heat exchange with the surrounding air.

TEG is based on the thermoelectric phenomenon described in the early 20s of the 19th century by the German physicist Thomas Johann Seebeck. The advantages of TEG are the absence of moving parts, silent operation, environmental cleanliness, versatility in the methods of supplying and removing thermal energy and their installation, potentially high reliability [21, 22]. Thermoelectric converters are increasingly popular. The number of articles published in recent years on the topic of "automotive thermoelectric generator" has increased many times [19].

The basis of the thermoelectric generator is a fairly common thermoelectric module TES1-12706 in the number of four pieces connected in series. Fastening of thermoelectric modules to the surface of the TA and the radiator of the heat removal system is made using a thermally conductive electrically insulating elastic silicone substrate. The gaps between the thermoelectric modules are filled with thermal insulation mastic. The use of silicone components makes it possible to reduce the influence of vibration and shock loads on TES modules (see Fig. 2).

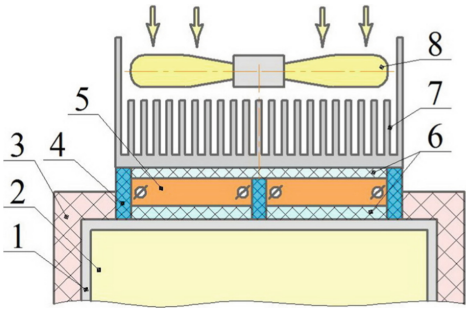


Fig. 2. Structural diagram of installation of thermoelectric modules on a heat accumulator: 1 – Corps of TA; 2 – Heat-accumulating material; 3 – Covering layer of thermal insulation; 4 – Thermal insulation mastic; 5 – Thermoelectric modules; 6 – Thermally conductive electrically insulating elastic silicone pads; 7 – Heat removal system; 8 – Fan.

The buffer battery performs two main functions, saving the electrical energy received from the TEG and ensuring a stable output voltage for powering low-power devices, primarily related to increasing the technical readiness of the vehicle [16, 23]. The use of a new generation lead-acid battery of the AGM type (12 V, 2.3 Ah) to power the proposed device provides a number of advantages. AGM batteries do not require additional maintenance, batteries are more resistant to the effects of vibration and shock loads, due to the recombination of gas in a sealed housing, they are safe for use in limited and closed

spaces, they can withstand a deep discharge of up to 30% without a significant reduction in service life, and they have a much lower internal electrical resistance compared to traditional ABs.

According to the selected scheme for utilization of part of the thermal energy of the exhaust gases, the scheme of energy flows in the proposed system has the form shown in Fig. 3.

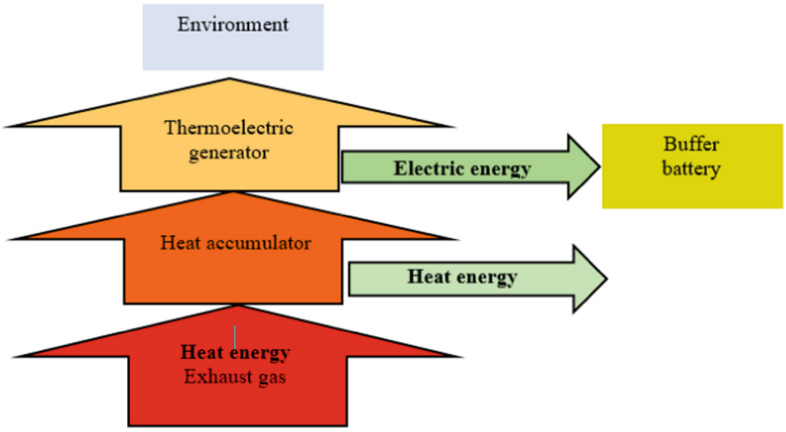


Fig. 3. Scheme of energy flows in the system of complex energy-efficient utilization of part of the thermal energy of the spent gases of the internal combustion engine.

The principle of operation of the proposed system is as follows: during the operation of the internal combustion engine, the coolant flow (exhaust gases) passes through the PTHA, giving it part of the thermal energy and further into the environment. The HAM, which is located in the middle of the PTHA, ensures the accumulation of thermal energy due to the passage of the flow of exhaust gases through it along bundles of tubes. The thermoelectric generator converts the temperature difference between the PTHA surface and the environment into electrical energy, which is stored in a buffer battery.

3 Research Results

During functional experimental studies of PTHA at an ambient air temperature of about 18 °C, the temperature of the surface of PTHA under the layer of thermal insulation and in the place of contact with "hot" TEG joints was +100 °C.

During natural cooling, the discharge time of PTHA in the temperature range from 100 °C to 60 °C was 396 min, during this time the average rate of temperature decrease of PTHA was about 0.1 °C per minute (see Fig. 4).

Deceleration of the temperature decrease of the surface of PTHA under the layer of thermal insulation from 72 to 322 min. Figure 4 can be explained by the time of TAM crystallization. The duration of the TAM crystallization period is about 250 min. The temperature of the TAP surface at the point of contact with the "hot" TEG joints

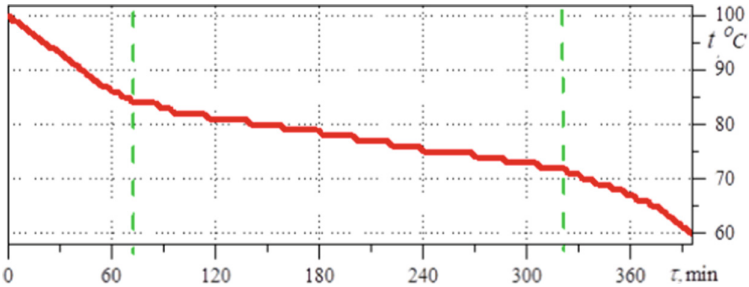


Fig. 4. Change in temperature of the surface of TAFP under the thermal insulation layer and in the place of contact with "hot" joints of TEG during natural cooling (a – beginning, b – end of TAM crystallization).

relatively stabilized in the temperature range of +84…72 °C, the average temperature is +78 °C, while the rate of temperature decrease was about 0.048 °C per minute. In this way, TA provides a temperature difference between "hot" and "cold" TEG junctions of about 60 °C practically constant for more than four hours.

According to the results of experimental studies, it was found that when using TEG at an average temperature between "hot" and "cold" junctions of about 60 °C, the average voltage of four TEC1-12706 modules was about 5.18 V, while the current was about 0.118 mA.

In order to determine the required number of thermoelectric modules in the thermoelectric generator of the system of complex energy-efficient utilization of the thermal energy of the exhaust gases of the vehicle to maintain the buffer AB in a charged state, calculation studies were carried out.

Based on the results of the calculation, it was established that when using a lead-acid battery of the AGM type (12 V, 2.3 Ah) to power low-power devices, for example [16, 23], it is necessary to use twelve TEC1-12706 modules connected in series. This scheme will provide a charging current of the buffer battery up to 0.12 mA with a corresponding voltage of up to 15.0 V, which meets the requirements for the operation of the selected battery manufacturer's battery, namely, the charging voltage should be about 14.4 V, with a charging current of up to 0.05 of the battery capacity, namely about 0.115 mA.

4 Conclusions

1. A technical solution is proposed for autonomous provision of vehicle devices with thermal and electrical energy without consuming primary energy resources.
2. The thermal battery of the phase transition, at an ambient air temperature of about 18 °C, provides a temperature difference between the "hot" and "cold" TEG junctions of about 60 °C almost constant for more than four hours, which allows generating electrical energy after the end of the internal combustion engine.
3. According to the results of the functional tests of the working model of the complex energy-efficient utilization of part of the thermal energy of the exhaust gases of the internal combustion engine, the possibility of using the proposed system for the

autonomous supply of the vehicle devices with thermal and electrical energy without consuming primary energy resources has been confirmed.

References

1. Bereczky, Á.: The past, present and future of the training of internal combustion engines at the department of energy engineering of BME. In: Jármai, K., Bolló, B. (eds.) Vehicle and Automotive Engineering. LNME, pp. 225–234. Springer, Cham (2017). https://doi.org/10.1007/978-3-319-51189-4_22
2. Tucki, K., Orynycz, O., Wasiak, A., Świć, A., Mieszkalski, L., Wichłacz, J.: Low emissions resulting from combustion of forest biomass in a small scale heating device. Energies **13**, 5495 (2020). https://doi.org/10.3390/en13205495
3. Caban, J., Gniecka, A., Holeša, L.: Alternative fuels for diesel engines, vol. 7, p. 5 (2013)
4. Zoldy, M., Hollo, A., Thernesz, A.: Butanol as a diesel extender option for internal combustion engines. Presented at the (A Comprehensive Review on the Application of Bioethanol/Biodiesel in Direct Injection Engines and Consequential Environmental Impact). https://doi.org/10.4271/2010-01-0481
5. Duda, K., Wierzbicki, S., Mikulski, M., Konieczny, Ł, Łazarz, B., Letuń-Łątka, M.: Emissions from a medium-duty CRDI engine fuelled with diesel-biodiesel blends. Transp. Probl. **16**, 39–49 (2021). https://doi.org/10.21307/tp-2021-004
6. Warguła, Ł, Kukla, M., Krawiec, P., Wieczorek, B.: Reduction in operating costs and environmental impact consisting in the modernization of the low-power cylindrical wood chipper power unit by using alternative fuel. Energies **13**, 2995 (2020). https://doi.org/10.3390/en13112995
7. Rimkus, A., Matijošius, J., Manoj Rayapureddy, S.: Research of energy and ecological indicators of a compression ignition engine fuelled with diesel, biodiesel (RME-Based) and isopropanol fuel blends. Energies **13**, 2398 (2020). https://doi.org/10.3390/en13092398
8. Valeika, G., Matijošius, J., Górski, K., Rimkus, A., Smigins, R.: A study of energy and environmental parameters of a diesel engine running on hydrogenated vegetable oil (HVO) with addition of biobutanol and castor oil. Energies **14**, 3939 (2021). https://doi.org/10.3390/en14133939
9. Wang, Z., Shuai, S., Li, Z., Yu, W.: A review of energy loss reduction technologies for internal combustion engines to improve brake thermal efficiency. Energies **14**, 6656 (2021). https://doi.org/10.3390/en14206656
10. Gutarevych, Y., et al.: Improving fuel economy of spark ignition engines applying the combined method of power regulation. Energies **13**, 1076 (2020). https://doi.org/10.3390/en13051076
11. Hunicz, J., Matijošius, J., Rimkus, A., Kilikevičius, A., Kordos, P., Mikulski, M.: Efficient hydrotreated vegetable oil combustion under partially premixed conditions with heavy exhaust gas recirculation. Fuel **268**, 117350 (2020). https://doi.org/10.1016/j.fuel.2020.117350
12. Hunicz, J., Mikulski, M., Koszałka, G., Ignaciuk, P.: Detailed analysis of combustion stability in a spark-assisted compression ignition engine under nearly stoichiometric and heavy EGR conditions. Appl. Energy **280**, 115955 (2020). https://doi.org/10.1016/j.apenergy.2020.115955
13. Sztekler, K., Wojciechowski, K., Komorowski, M.: The thermoelectric generators use for waste heat utilization from conventional power plant. E3S Web Conf. **14**, 01032 (2017). https://doi.org/10.1051/e3sconf/20171401032

14. Romagnoli, A., Martinez-Botas, R., Pesiridis, A., Rajoo, S., Copeland, C., Mamat A.M.I.: Automotive Exhaust Waste Heat Recovery Technologies. NOVA Science Publishers (2014). https://doi.org/10.13140/2.1.4809.0565
15. Dmytrychenko, M., Gutarevych, Y., Trifonov, D., Syrota, O., Shuba, Y.: On the prospects of using thermoelectric generators with the cold start system of an internal combustion engine with a thermal battery. J. Thermoelectr. **4**, 49–54 (2018)
16. Dmytrychenko, M., Gutarevych, Y., Trifonov, D., Syrota, O.: The use of thermoelectric energy converters to reduce the influence of natural and climatic factors on the technical readiness of a vehicle. J. Thermoelectr. **2020**, 56–68 (2020)
17. Dmytrychenko, M., Gutarevych, Y., Shuba, Y., Syrota, O., Trifonov, D., Matijošius, J.: Improvement of fuel economy and starting properties of the diesel engine by heating the air at the inlet. In: Gopalakrishnan, K., Prentkovskis, O., Jackiva, I., Junevičius, R. (eds.) TRANSBALTICA 2021. LNITI, pp. 494–503. Springer, Cham (2020). https://doi.org/10.1007/978-3-030-38666-5_52
18. Gutarevych, Y., Shuba, Y., Syrota, O., Trifonov, D., Ovchinnikov, D.: Effect of air heating at the intake on the energy and environmental performance of a transport engine when running on alcohol containing gasoline at low temperatures. Natl. Transp. Univ. Bull. A Sci. Tech. J. **50**, 46–56 (2021)
19. Sivaprahasam, D., Harish, S., Gopalan, R., Sundararajan, G.: Automotive waste heat recovery by thermoelectric generator technology. In: Aranguren, P. (ed.) Bringing Thermoelectricity into Reality. InTech (2018). https://doi.org/10.5772/intechopen.75443
20. Gutarevych, Y., Trifonov, D., Syrota, O., Shuba, Y., Kukhtyk, N.: Systema pidihrivu povitria na vpusku dvyhuna vnutrishnoho zghorannia z teplovym akumuliatorom fazovoho perekhodu (2018)
21. Anatychuk, L., Pribyla, A.: Camparative analysis of thermoelectric and compression heat pumps for individual air-conditioners. J. Thermoelectr. **2**, 31–39 (2016)
22. Anatychuk, L., Lysko, V.: On the possibility of using thermoelectric generators for high-power transport starting pre-heaters. J. Thermoelectr. **3**, 80–92 (2019)
23. Dmytrychenko, M., Gutarevych, Y., Syrota, O., Shuba, Y., Trifonov, D.: On the prospects of using thermoelectric coolers to maintain optimal air temperature in the intake manifold of internal combustion engine for improving its performance characteristics. J. Thermoelectr. **2**, 89–97 (2021)

The Comparison and Potential of CO2 Capture Technologies Implementation on the Marine Transport

Audrius Malūkas(✉) and Sergejus Lebedevas

Klaipeda University, Herkaus Manto 84, 92294 Klaipeda, Lithuania
malukasaudrius@gmail.com, sergejus.lebedevas@ku.lt

Abstract. The research assesses and compares the technological possibilities to capture the greenhouse gas emissions on marine transport power plans generated exhaust gas emissions in order to minimize carbon emissions release into the atmosphere. The research determinates that a few different principal technologies are available for CO2 capture on energy plants: pre-combustion capture, post-combustion capture and the oxyfuel solution. According to the outlook the emission from Maritime industry by 2050 will increase in-between 50 and 250 percent and the International Maritime Organization (IMO) goal is to minimize the greenhouse has emission generation at least 50% by 2050 towards Paris climate agreement policy. The LNG fuel allows vessels to comply with Tier II/Tier III regulations where from the view of long perspective range the LNG serves as a transition fuel. The resolution of carbon intensity indicator (CII) MEPC.328(76) was introduced as a new vessels' efficiency measure standard. According to established standard from 01st of January 2023 all ships will require to present their annual operational carbon intensity indicator (CII) and CII rating. The low-class vessels accordingly will be encouraged by authorities to introduce action measures to improve cargo handling efficiency level therefore the introduced grading will likewise force shipowners to revise technological availabilities to retrofit vessels into more efficient. The situation in maritime sector towards carbon emission minimization has led Klaipeda University to establish research to analyses and compare technological solutions which would benefit to maritime transport sector to comply with introduced regulations. The publication represents the first stage research results of available carbon capture technologies.

Keywords: LNG · Carbon capture · Emissions · Post-combustion · Pre-combustion · Oxyfuel

1 Introduction

To curb global warming and climate change, a global goal of carbon offsets has emerged to reduce CO2 emissions primarily from industrial and energy systems of transport sectors. In 2015, 175 members of the world community, including Lithuania, have signed the Paris Agreement of the United Nations Framework Convention on Climate Change.

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 152–161, 2023.
https://doi.org/10.1007/978-3-031-25863-3_15

With this commitment, the parties have set themselves the ultimate goal of keeping global warming well below 2 °C above pre-industrial levels and not rising by more than 1.5 °C. The members of the Community, under the Paris Agreement, have committed themselves jointly with the EU and its Member States for the period 2021–2030 to reduce greenhouse gas (GHG) emissions by at least 40% from 1990 levels [1].

In order to achieve climate goals and to reduce carbon emission footprint the measures are being implemented which are focused to limit emission access to the atmosphere. Two measures can be distinguished: the tax liability and the strengthening of environmental requirements for industry and transport sectors. There is currently a system in which industry, electricity producers and airlines have to pay for their emissions financially, and this economic-tax tool encourages companies to look for ways to reduce emissions and thus benefit from lower taxes on emissions: EU Emissions Trading System (EU ETS) which is a cornerstone of the EU's policy to combat climate change and its key tool for reducing greenhouse gas emissions cost-effectively [4]. The stationary installations covered by EU ETS is limited by a 'cap' on the number of emission allowances (EUA) and within the cap, companies receive or buy emission allowances, which they can trade as needed. The cap sets a limit on the total amount of GHGs that can be emitted to the atmosphere per annum by the stationary installation however when the limit is being exceeded the operator of installation must cover the exceeding volume with emission allowances purchased in the marked where 1tCO2 is equal to 1 EUA. The price of EUA traded on the EU's Emissions Trading System (ETS) has jumped from less than €10 per metric ton of carbon to above €90 since the beginning of 2018 [5]. Following EU ETS example, China and Singapore in 2021 have launched national carbon emissions training scheme to meet a 2060 decarbonization target by implementing tool for the GHGs control. In the near future the tax on GHGs emissions may be introduced on maritime transport, as several maritime industry organizations: Baltic and International Maritime Council (BIMCO) and Cruise Lines International Association (ICS) have addressed concerns to IMO to introduce CO2 tax liability on the vessels activity.

Another measure is to strengthen the environmental requirements for installations that generate CO2 and other emissions. This tightening is most noticeable in the transportation sector, where international shipping accounts for about 2–3% of the world's greenhouse gas emissions. In 2008, the International Maritime Organization (IMO) reviewed and implemented new regulation to minimize the sulphur content of marine fuels on the vessels. As an outcome – four emission control areas (ECAs) where developed on the following regions: the Baltic Sea, North Sea, North America Sea, and Caribbean Sea, the established areas enforced the regulation that no heavy fuel oil containing more than 0.1 percent sulphur content by weight after 2015 can be used as a fuel vessel at the established regions. Meanwhile, the global limit was set to 3.5% in a first step (2012) but in the context of the 2008 revision of MARPOL Annex VI, the new 0.5% limit for fuels was introduced, which came into force as from 1st of January 2020 (excepting those ships using exhaust gas cleaning equipment or alternative fuels) [6]. The available and nowadays expending LNG infrastructure which is now being utilized for energy trading purposes together is creating an opportunity for LNG segment to become the transition fuel towards global decarbonization goal. It is being remarked that the

rapid growth of LNG handling infrastructure plays a key role in energy transition however the LNG infrastructure in the future could be reused as compatible infrastructure to handle an alternative liquefied fuel such as liquefied biomethane or green liquefied synthetic methane until the supply infrastructures of more competitive fuel alternatives: ammonia or hydrogen will take a lead in energy and bunkering sector. In order to comply with introduced regulations, LNG fuel vessel fleet have been growing rapidly. In parallel with compliance with the adopted emission limits for ships and with the aim of increasingly stringent regulation and compliance with environmental legislation, shipping is experiencing a significant increase in the number of LNG-powered fleets, where the number of ships has increased since 2010 and the number of ships has been growing steadily between 20% and 40% per year. In the general context, at the beginning of 2020, the fleet of LNG-powered vessels consisted of 175 vessels, not counting the number of 600 LNG carriers and the additional 200 vessels still under construction. Then in the beginning of 2022, the LNG fleet was even wider and consisted of 700 LNG tankers [4]. The LNG fuel allows vessels to comply with Tier II/Tier III regulations where from the view of long perspective range the LNG serves as a transition fuel solution as LNG fuel characteristics allows to reduce NOx, SOx emissions by 90% and SO2 emission even by 100% comparing to regular diesel fuel features, however the LNG is a fossil fuel thus the CO2 emission at combustion process remains and when comparing with diesel fuel, the LNG generates only 25% less of carbon emissions. While various low carbon fuels are being developed such as hydrogen, methanol, or ammonia, they are still commercially immature and expensive a bigger role for LNG as transition fuel is foreseen [5]. During the transition period LNG fuels allows to reduce CO2 emissions slightly, but additional solutions are needed to meet the IMO's objectives which would even allow to capture emission before they are released into the atmosphere. Nevertheless, there are no CO2 capture technologies established in maritime industry on the vessels, but various researchers are targeting industry sector to follow on developed alternative solutions which could potentially be adapt on transport sector.

2 CO2 Capture Technologies

As presented in the previous section, one of the measures to reduce the release of greenhouse gases into the environment is the technological development of alternative fuels and their applicability in shipping as a standard for bunkering services. However, the realization of these technologies is presented in long term prospective. Therefore, the market, especially in the industrial sector, identifies alternative preventive measures to reduce carbon emissions, one of which is carbon capture technology. The industry already has integrated technologies that minimize CO2 emissions. Technological applicability is divided into 3 technical categories: post-combustion, oxy-fuel combustion and pre-combustion. The pre-combustion and oxy-fuel technologies refers to removing CO2 from the fossil fuel before combustion process is finished. Meanwhile, the post-combustion technology is linked to the treatment of exhaust gases on the output side of natural gas combustion cycle.

2.1 Oxy-Fuel Combustion Capture

Oxy-fuel combustion capture uses high purity oxygen for combusting with high CO2 effluent concentration. According to the Stanger the main purpose of using this technology is to generate a flue gas with high concentration of CO2 and water vapor; and then separate the CO2. Oxy-fuel combustion technology is a unit which consists of following equipment:

- Air Separation Unit (ASU) – pure oxygen production plant.
- Boiler/Gas turbine – combustion of fuel and generation of heat.
- Flue Gas Processing Unit – flue gas cleaning or gas quality control system (GQCS).
- CO2 Processing Unit (CPU) – final purification of the CO2 for the transport and storage.

During the process nearly a pure oxygen (95–97%) is being streamed to boiler/gas turbine, only a very limited amount of nitrogen remains as the majority of it is separated in air separation unit. In oxy-fuel combustion processes, fuel and oxygen are mixed at the boiler with recycled flue gas. After combustion, the CO2 composition in the exhaust gases is about 75% on wet gas. On the further process is to condense the water and purify the CO2 to achieve close to 100% pure, then pure CO2 can be loaded into storage [8]. Air for combustion is replaced by pure O2, then CO2 and H2O are separated.

The integration of technology allows to capture CO2 and in addition to capture the rest of standard combustion process emissions such as NOx, CO, PM. The ratio percent of NOx capture seeks 60–70% of NOx emissions. However, to achieve capture a large volumes of flue gas must be recycled to reduce high temperatures at the combustion. When the fuel is burned in air environment the flame temperature at combustion is lower comparing to high oxygen environment so in order to retrofit the existing ship propulsion complex the technology would require evaluating engines and the rest of propulsion complex unit compatibility with oxyfuel technology. Moreover, the technology requires to produce pure oxygen for the combustion process which means the high costs of air separation unit and additional power consumption on the air separation unit, and this could be a limiting factor of available space onboard to implement oxyfuel technology (Fig. 1).

2.2 Pre-combustion Capture

Pre-combustion capture technology is based on process when CO2 is being removed from fossil fuels before combustion is completed when fossil fuel is catalytically reformed by the chemical reaction to decompose fuel and convert into synthesis gas. In gasification stage fuel is partially oxidized in steam and oxygen/air under high temperature and pressure to form synthesis gas/syngas where the composition majority are mixture of hydrogen, carbon monoxide, CO2. The syngas can then pass the water-gas shift reaction to convert CO and water (H2O) to H2 and CO2, creating separate elements: H2 and CO2-rich gas mixture where the concentration of CO2 deviates between 15–50% and this stage the CO2 can be separated for capture, and the H2-rich gas combusted as a fuel.

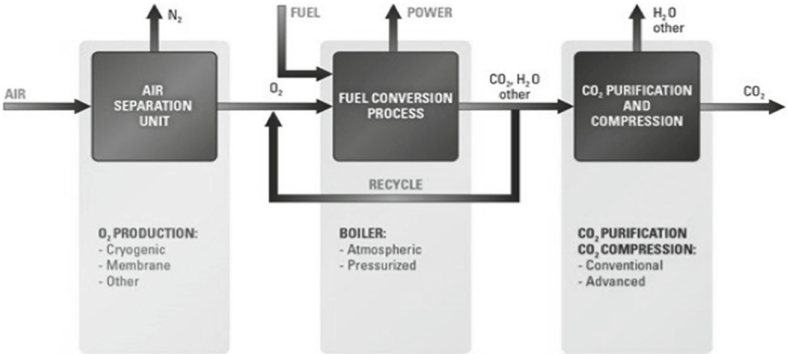


Fig. 1. Scheme of oxy-fuel combustion capture technology [6].

After gasification stage the generated synthesis gas (composed of hydrogen (H2), carbon monoxide (CO) and minor amounts of other gaseous particles) is then processed in water-gas-shift plant (WGS) which transforms CO to CO2 and increases the CO2 and H2 mole concentrations to about 40 percent and 55 percent. At this stage the generated CO2 is pressurized, and this allows to apply on it the separation and capture technologies. Following processes can be implemented to separate CO2 from pressurized syngas: 1) the Selexol process, which uses a mixture of dimethyl ethers of polyethylene glycol; 2) the Rectisol process, which uses cold methanol as a solvent; 3) the Purisol process, which is based on the N-methyl-2-pyrrolidone solvent. Regardless type of process the solvents are being used as agent to capture CO2 from the shifted syngas during the absorption stage and release it during regeneration by reducing the pressure. Low energy requirement for solvent regeneration is one of the advantages of these processes. One of the main issues is the need for syngas cooling before capture of CO2 and then repeated reheating of the gas before combustion, these thermal activities decrease the plant efficiency and together increases the overall costs [8]. Figure 2 shows a scheme of a plant integrated with pre-combustion capture technology [10].

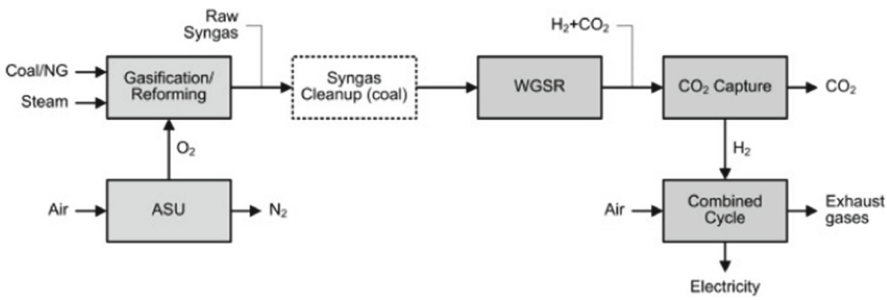


Fig. 2. Scheme of pre-combustion carbon capture technology [11].

In general, the technology realizes the possibility to carry out the hydrogen production process on board for further use as a fuel in ship propulsion complex or plans related

to ship. However, the disadvantage of technology reflects on limited space onboard to accommodate necessary equipment in addition, technology include high retrofit costs. The technology is based on fuel quality exchange before the combustion process and the vessel retrofit option within installation of pre-combustion technology would require to upgrade vessels' engines to be compatible within technology.

2.3 Post-combustion Capture

Post-combustion capture technology consists of threating exhaust gases after combustion process at the output stage when fuel is burned with air in engines or another type of plant. The exhaust gas consists mostly of nitrogen (N2), and CO2 but due to low pressure at the exhaust for natural gas-fired plants the CO2 concentration variates at 9% hence a large volume of gas has to be treated at capture stage. With this technology, CO2 is separated from the flue gas by scrubbing with a chemical solvent such as amin. In general, the post-combustion capture technology due to an aqueous solution of mines is one of the most feasible technologies for low pressure CO2 sources.

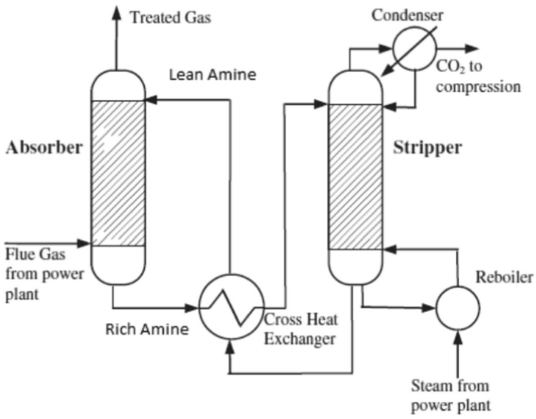


Fig. 3. Scheme of post-combustion carbon capture technology [12].

At post-combustion capture process first of all the flue gas is cooled when the impurities are removed. The NOx and SOx materials are linked to form into heat stable salts therefore they are removed to low concentration before the CO2 capture process. Then CO2 is being streamed to bottom of absorption column where CO2 reacts chemically with the absorbent. On the next step the absorbent is transfer to desorber, where CO2 is released separated from absorbent at temperature of 120 °C. The regenerated absorbent is recycled to the absorber, and CO2 is dried and compressed for transport conditions (between 100–150 bar). The most common chemical soblents used for CO2 capture from low-pressure flue gas are amines. When the CO2 reacts with solvent in the absorption vessel, the CO2 rock solvent passes through the stripping column, where it is heated with steam to reverse the CO2 absorption reaction. The CO2 collected in the stripper is compressed for transport and storage and then the CO2 lean solvent is recycled to

the absorption stage. The Fig. 3 presents a principal scheme of post-combustion CO2 capture technology [12].

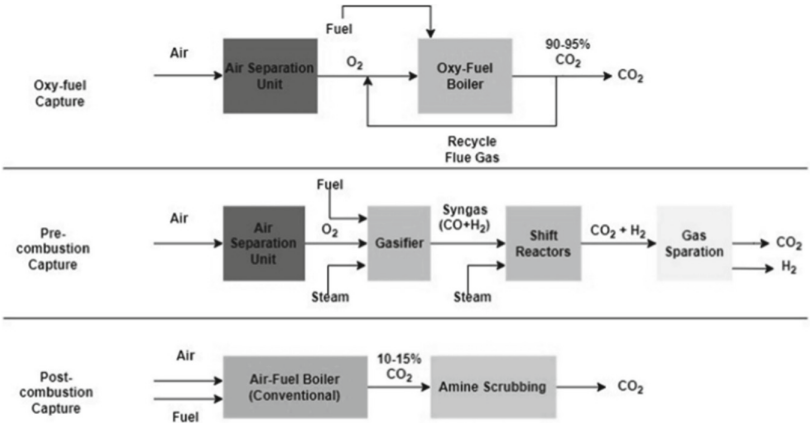


Fig. 4. Scheme of CO_2 capture technologies [12].

The scheme in Fig. 4 present the main differences between three different CO2 capture technologies. In general, it can be stated that pre-combustion capture technology allows to separate carbon from H2 and then H2 is used for combustion cycles. With the Oxy-fuel combustion technology for combustion the air is replaced by pure oxygen and then CO2 and H2O are separated. Finally, the post-combustion capture technology removes CO2 from flue gases produced during the combustion of fuels. At all cases the captured CO2 emission is compressed in gas phase and storage for the further utilisation. However, if the cryogenic cold potential would be introduced into captured CO2 emission process it would simplify and solve the challenges of captured CO2 storage and utilisation. Such process in the industry is called the Cryogenic Carbon Capture (CCC). With cold potential the removal of CO2 from the exhaust gases converts the captured emission into a liquid (−50 C) or solid (−78 C) phase – dry ice. 1 tonne of liquid phase CO2 equals a volume of 1 m^3, meanwhile 1 m^3 of volume can accommodate 1.6 tonnes of dry ice which allows to reduce the storage space for captured emission (Fig. 5).

The CCC technology basically separates carbon emission from light gases. The CCC cools the gases to −100 to −135 °C, at this stage the solids are being separated and pressurized and then warms streams to generate a CO2 depleted stream at ambient pressure and a pure (99+%) pressurized liquid CO2 stream typically to about 150 bar. The CCC technology almost eliminates refrigeration energy for sensible temperature changes through heat integration. Also, technology require energy to change the CO2 phase from vapor to a pressurized fluid which stands for the minimum amount of energy needed for any procedure to achieve this separation. The CCC technology could be attractive to industrial sources which are equipped with LNG fuel to perform combustion on energy plans. The LNG cold potential could be introduced into CCC process as an advantage to achieve higher efficiency. Considering that LNG temperature remains at −160 °C and for combustion must be vaporized the cogeneration cycle would benefit

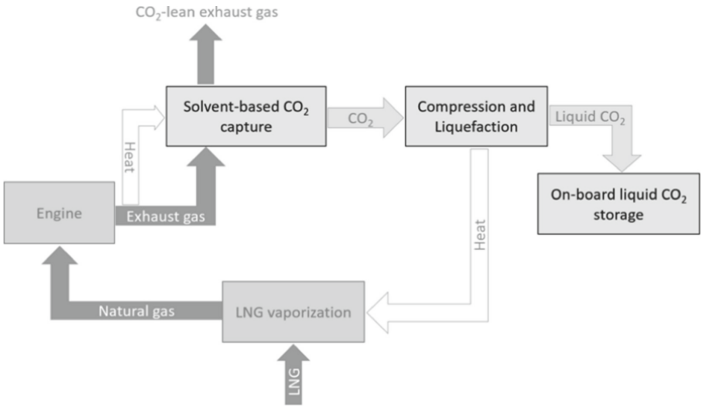


Fig. 5. Scheme of cryogenic carbon capture technology [18].

in order to warm cold LNG and likewise to cool down the exhaust gas. Especially the technology would be beneficial to maritime industry with potential to achieve IMO goals and comply with emissions standards the CCC technology might be introduced on the LNG fueled vessels [18]. To date, no technology has been introduced to capture CO2 emissions from the transport sector. Mitsubishi Shipyard in Japan is currently developing the fleet's application of industrial CO2 capture technology and plans to install it in a coal-fired dry cargo ship owned by Tohoku Electric Power over a 2-year period. It can be assumed that the application of CO2 elimination technology in the transport sector is underdeveloped, and this allows to state the novelty of the implementation of such technology, therefore it is important to perform an analysis of how the technology could be applied in the fleet.

3 Conclusion

During the past decade various regulations were introduced to control emissions and reduce industry and transport sector expansion negatively impact on the environment pollution. Therefore, to achieve climate goals and to reduce carbon emission footprint the measures are being implemented which are focused to limit emission access to the atmosphere. Maritime transport sector has established IMO regulations on the fuel quality to be used at different vessels' navigation regions. The introduced emission limitations boosted the attention to an alternative fuel which is environmentally friendly and allows compliance with the regulations, the LNG is being treated as transition fuel towards the IMO goals in the transport sector. However, despite LNG fuel advantages versus LS-MDO quality fuel in order to achieve regulations additional technologies must be implemented on the vessels to limit carbon emission access to the atmosphere. In the industry three main technologies exist: pre-combustion capture, post-combustion capture and the oxyfuel solution. Due to high cost of pre-combustion and oxyfuel technology implementation on the ships the most advantageous technology is the post-combustion as the vessel retrofit mainly would require modifications on the vessels exhaust system at post-combustion stage meaning the propulsion complex would not require modifications.

The carbon capture would be more efficient on the vessels which are powered by LNG fuel, the cold energy potential from LNG creates availability to capture CO2 emissions based on cryogenic principle. With cold potential the removal of CO2 from the exhaust gases converts the captured emission into a liquid (−50 °C) or solid (−78 °C) phase – dry ice. 1 tonne of liquid phase CO2 equals a volume of 1 m^3, meanwhile 1 m^3 of volume can accommodate 1.6 tonnes of dry ice which allows to reduce the storage space for captured emission. In order to evaluate further economic and technological possibilities to implement CCC technology on the vessel the authors will continue to develop and evaluate feasibility of CCC compatibility with dual-fuelled LNG fuelled vessels.

References

1. United Nations Climate Change: World Nations Agree to At Least Halve Shipping Emissions by 2050 (2018)
2. Feenstra, M., Monteiro, J., van den Akker, J.T., Abu-Zahra, M.R., Gilling, E., Goetheer, E.: Ship-based carbon capture onboard of diesel or LNG-fuelled ships. Int. J. Greenhouse Gas Control **85**, 1–10 (2019)
3. European Commission: 2030 climate & energy framework (2022)
4. European Commission: EU Emissions Trading System (EU ETS). https://ec.europa.eu/clima/eu-action/eu-emissions-trading-system-eu-ets. Accessed 14 June 2022
5. European Central Bank. https://www.ecb.europa.eu/pub/economic-bulletin/focus/2022/html/ecb.ebbox202203_06~ca1e9ea13e.en.html. Accessed 03 June 2022
6. National Energy Technology Laboratory. https://netl.doe.gov/node/7477. Accessed 14 May 2022
7. W. G. &. D. Ltd.: IMO global 0.50 percent fuel sulphur regulation, 2020. https://www.wingd.com/en/documents/technical-information-notes/wingd_tin011_imo-2020-operation-guideline/. Accessed 03 June 2022
8. GIIGNL: Importers, the LNG industry GIIGNL Annual Report (2022)
9. Stanger, R., et al.: Oxyfuel combustion for CO_2 capture in power plants. Int. J. Greenhouse Gas Control **40**, 55–125 (2015)
10. N. E. T. Laboratory (2022). https://netl.doe.gov/node/7477. Accessed 06 June 2022
11. Cebrucean, I.I.D.: Pre-combustion capture. In: Comprehensive Renewable Energy, 2nd edn. (2022)
12. Nuamah, A., Malmgren, A., Riley, G., Lester, E.: Biomass co-firing with carbon capture. In: Comprehensive Renewable Energy, vol. 5, 2nd edn., pp. 330–347 (2022)
13. Chen, Y.S.C.: The energy demand and environmental impacts of oxy-fuel combustion vs. post-combustion capture in China. Energy. Strateg. Rev. **38**, 100701 (2021)
14. Fei, L., Zhang, J., Shang, C.: Modelling of a post-combustion CO_2 capture process using deep belief network. Appl. Therm. Eng. **130**, 997–1003 (2018)
15. Akeeb, O., Wang, L., Xie, W., Davis, R., Alkasrawi, M., Toan, S.: Post-combustion CO_2 capture via a variety of temperature ranges and material adsorption process: a review. J. Environ. Manag. **313**, 115026 (2022)
16. N. E. T. Laboratory: Carbon dioxide capture approaches. https://netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/capture-approaches. Accessed 15 June 2022

17. Alterainfra: Stella Maris CCS to Explore Full Value Chain. https://alterainfra.com/articles/stella-maris-ccs-to-explore-full-value-chain. Accessed 05 June 2022
18. Luo, X.W.M.: Study of solvent-based carbon capture for cargo ships through. Appl. Energy **195**, 402–413 (2017)
19. Feenstra, M., Monteiro, J.: Ship-based carbon capture onboard of diesel or LNG-fuelled. Gas Control **85**, 1–10 (2019)
20. Ros, J., Skylogianni, E., Doedee, V.: Advancements in ship-based carbon capture technology on board of LNG-fuelled ships. Int. J. Greenhouse Gas Control **114**, 103575 (2022)

Scenarios of Accident Events of Electric Vehicles

Jozef Kubás(✉), Michal Ballay, and Katarína Zábovská

University of Zilina, University Science Park UNIZA, Zilina, Slovak Republic
{jozef.kubas,michal.ballay,katarina.zabovska}@uniza.sk

Abstract. The article focuses on the issue of electric cars, with an emphasis on possible accidents and related dangers and threats. Vehicles with an alternative energy source have been on the rise in recent years. The article briefly provides an overview of the current state and forecasts of the development of these vehicles. Subsequently, the technological elements of vehicles with electric drive are evaluated. The supporting part of the article is the identification of scenarios of electric car accident events, which also defines their possible consequences and causes. The article deals with scenarios of accident events - vehicle fire, complete sinking of the vehicle, rescue of persons and battery damage caused by fire. It also includes a numerical part where, based on an expert estimate for the probability of occurrence, significance and prevention of an accident, the risk level of the accident scenario was determined. The part is dedicated to the special solution of possible accident events from the point of view of rescue units. In the article are procedures for dealing with accidents with an emphasis on the danger and threat resulting from these events are established.

Keywords: Electric vehicle · Accident event · Fire brigade · Danger · Threat · Integrated rescue system

1 Introduction

The green economy aims at reducing environmental risks and ecological deficiencies, the goal of which is sustainable development without harming the environment. Currently, it represents one of the most discussed topics in the world, and it is transferred to the production of cars. From the point of view of transport, you can describe this state as an industrial crossroads, which indicates prospective and non-prospective directions in the choice of vehicle propulsion. Electricity, hydrogen and Compressed natural gas (CNG) can be described as the most promising energy sources for driving vehicles.

2 Evaluation of Technological Elements of Vehicles for the Selected Alternative Energy Source

In transport, specific types of drives were characteristic for individual periods. The 19th century was dominated by steam, the 20th century is referred to as the century of oil, and the current 21st century will be marked by new alternative fuels, and one of them is

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 162–171, 2023.
https://doi.org/10.1007/978-3-031-25863-3_16

the use of electricity. Technology that was just an idea in the past has quickly become a reality. The key insight that, according to the International Energy Agency (hereafter IEA), in 2050 only a very small part of cars will be powered by the way we know it today: by a petrol or diesel engine. The IEA estimates that the number of such cars will begin to decline after 2025, and this decline will occur in favor of fully or partially electric vehicles [1, 2].

In order to predict the development of electric vehicles in the coming years, it is also necessary to address the complexity of the systems. It represents defining various other subsystems and technologies. With any engineering systems with high social interaction, the assessment cannot be limited to the technology itself, but must incorporate and assess current trends in mobility, infrastructure (accessibility), energy, economic and environmental concerns [3, 4].

Currently, there are already technologies relevant to electric vehicles. For the needs of other parts of the article based on a simple configuration, individual parts of the electric car will be defined. An electric vehicle is a vehicle driven exclusively by electric energy - an electric motor. It receives this energy, which is necessary for the drive, from the batteries. The energy supply is ensured by a regulator that responds to the driver's instructions and supplies him with the necessary information. Existing concepts of electric vehicle can be divided according to certain aspects, while the choice of version is mainly subject to the expected operating conditions [3, 4].

The basic part of electric vehicles consists of batteries (accumulator), which represent the primary factor of the vehicle's range. Accumulators with the support of Li-Ion (Lithium - Ion cells) are currently most often used, which are very similar to "pencil" batteries, but larger and have a higher energy density. An example is the 85 kWh Tesla Model S battery, which consists of 7,104 battery cells and each of them has a dimension of 65x18 mm. The location of the red or of the battery block is in the floor of the vehicle. The advantage is a lower center of gravity and better maneuverability of the vehicle. Next, the control unit (inverter) is placed near the electric motor. This is due to smaller spaces and shorter cable lengths. The drive unit is an electric motor. Its advantage is its simple design and efficiency, which is on average 3 times higher (90%) than that of combustion engines (25–34%). However, the overall efficiency is also affected by the efficiency of the batteries and charging. The use of electric motors has significant design advantages. Thanks to its size, it can be mounted directly on the axle of an electric car. Electric cars with rear drive (e.g., Tesla), lack the engine in the front part of the engine. This creates a deformation zone in the event of a frontal impact, which has a significant impact on safety. The electric motor is usually placed in such a way that the electric motor-differential-transmission system has a common center of gravity closest to the center. Furthermore, electric motors with the presence of high voltage. The wiring of the high voltage red system was clearly separated by color directly from the car manufacturers (orange - high voltage, yellow and blue - transient voltage, and black - low voltage). High voltage cabling is placed in vehicle structures and protected in a protective wiring layer. In some models of current vehicles, blue and yellow wiring has appeared, which is a risk of electric shock, but they are not high voltage colors [3–5].

3 Identification of Accident Scenarios of Electric Vehicles

The area of safety is closely connected with the introduction of energy sources into vehicles. The most likely emergency event in road transport is vehicle accident, which is logical. Figure 1 shows the accident events that can occur.

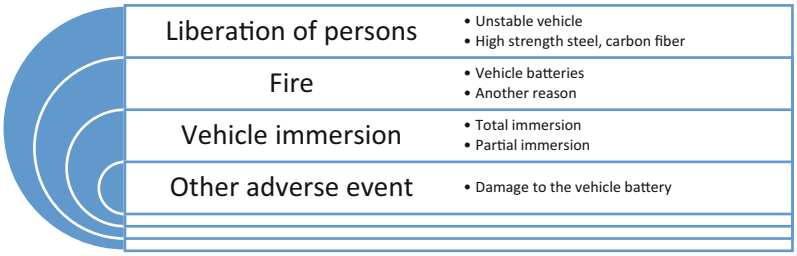


Fig. 1. Possible scenarios in the event of an electric vehicle accident [5].

In this case, there are four main groups of scenarios, under which many subgroups can fall. As part of the identification of scenarios, it was based on a survey that was focused on the most frequently occurring accidents of electric cars. For this reason, the article further describes and discusses the vehicle fire, the complete sinking of the vehicle, the rescue of people and the damage to the battery caused by the fire. Obviously, several scenarios are usually playing out at the same time in an accident.

3.1 Accident Scenario: Electric Vehicle Battery Fire and Rescue/Extrication of Persons

An electric vehicle fire can be caused by several factors. One of them is, for example, an impact in a traffic accident. It mostly occurs on/in the battery; from which it then spreads further. This event is very risky and dangerous, because it can take a long time to put out a fire in an electric vehicle, which puts the crew of the vehicle and the responding units at risk. During extinguishing, a large amount of water is consumed, which is subsequently contaminated. Some real-life traffic accidents in which there was a fire were also accompanied by battery explosions. Persons trapped in a car are also exposed to the risk of electric shock if the high-voltage cables are damaged in an accident. Other people's property can also be devalued as a result of an impact or fire. Usually, such an event can limit traffic for several hours. Example vehicle fire and rescue works are in the Fig. 2 [5, 6, 9].

Table 1 was created for a better understanding of the issue. The table shows the most common possible causes of accidents with fire and their most frequent negative impacts.

3.2 Accident Scenario: Total Submersion of the Vehicle/ Damage to the Battery

Vehicles stuck under water pose a risk to the crew because their lives are at risk. Rescuers face various unexpected situations that can endanger their health, as the vehicle is

Fig. 2. Electric vehicle fire (left) and rescue work of fire brigades (right) [7].

Table 1. Possible consequences and causes of an electric vehicle accident - fire and rescue of people.

Electric vehicle fire	Freeing people from the electric vehicle
Possible consequences of the accident	
Environmental pollution	Danger to health, life
Danger to health, life	Financial loss
Traffic restriction	Traffic restriction
Financial losses	Environmental pollution
Possible causes of the accident	
Vehicle technology failure	Human factor failure
Human factor failure	Technical condition of the road
Technical condition of the road	Vehicle technology failure
Charging device failure	

unstable in the water. Water can also cause a short circuit in electrical wiring, or degrade the battery or other parts of the vehicle. If a hybrid vehicle were to find itself in the water, the water could be contaminated with fuel. Other consequences are financial and material losses. If the vehicle hits an obstacle in a traffic accident, the battery may be damaged. As a result of burning, it releases electrolytes into the air, which are dangerous and cause health problems. An explosion can also occur in the event of a fire. Spontaneous ignition and battery explosion have been reported in some vehicles, which brings with it other consequences and threats. The submersions vehicle and damage vehicle battery are shown in Fig. 3 [5, 6, 11].

Table 2 shows the most common possible consequences and causes of an accident associated with a submerged vehicle or damage to the vehicle's battery.

3.3 Risk Assessment of Accident Scenarios

The numerical part of the analysis will be carried out using the Failure modes and effects analysis (FMEA), which is based on the data presented in Table 3, when the parameter values are displayed using a scale with a scale of 1 to 5 (probability of the occurrence of an accident - 1: unlikely, 5 high), (significance of an accident - 1: the accident cannot be

Fig. 3. Total submersion of the vehicle (left) and damage to the vehicle battery followed by fire (right) [8].

Table 2. Possible consequences of an electric vehicle accident - complete immersion and damage to the vehicle's battery.

Immersion of an electric vehicle	Damage to the battery of the electric vehicle
Possible consequences of the accident	
Property damage	Vehicle fire
Danger to health, life	Financial loss
Damage to the electric vehicle	Leakage of dangerous substances
Environmental pollution	Danger to health, life
Possible causes of the accident	
Deteriorated weather conditions	Human factor failure
Human factor failure	Spontaneous ignition
Technical condition of the road	Vehicle technology failure

foreseen, 5: extremely serious accident), (accident avoidance – 1: high, 5: negligible). The result of the numerical phase is the calculation of the risk rate expressed using the RPN risk number according to the formula:

$$\mathrm{RPN} = \mathrm{PV} \times \mathrm{VV} \times \mathrm{PO}, \tag{1}$$

where PV – probability of occurrence of an accident, VV – significance of the accident, PO – probability of preventing the occurrence of an accident.

The values shown in Table 3 are determined on the basis of expert estimation.

Figure 4 shows the results of the FMEA analysis, where it is clear that the riskiest accident event is an electric car fire with the consequences of a traffic accident [12, 13].

Based on the legally established risk level, a diagram is created using Pareto analysis that shows the acceptability of specific scenarios. The purpose of this analysis is to reveal a small number of causes that significantly affect the overall result, specifically the consequences of traffic accidents (Fig. 5).

From the results, it is clear that the riskiest scenarios of electric car accident events can be identified as an accident with a subsequent fire and the rescue of people from the vehicle.

Table 3. Evaluation of accident scenarios with the resulting RPN.

The identification stage		The numerical phase			
		Current status			
The scenario	The manifestation of an accident	Meaning	Occurrence	Prevention	RPN
Electric car fire	Without the consequences of a traffic accident (1A)	4	3	4	48
	As a result of a traffic accident (1B)	5	3	5	75
Immersion of an electric car in water	Without the consequences of a traffic accident (2A)	4	3	3	36
	As a result of a traffic accident (2B)	5	2	3	30
Freeing people from the vehicle	Without the consequences of a traffic accident (3A)	4	3	4	48
	As a result of a traffic accident (3B)	5	3	4	60
Damage to the vehicle battery	Without the consequences of a traffic accident (4A)	4	3	3	36
	As a result of a traffic accident (4B)	5	2	4	40

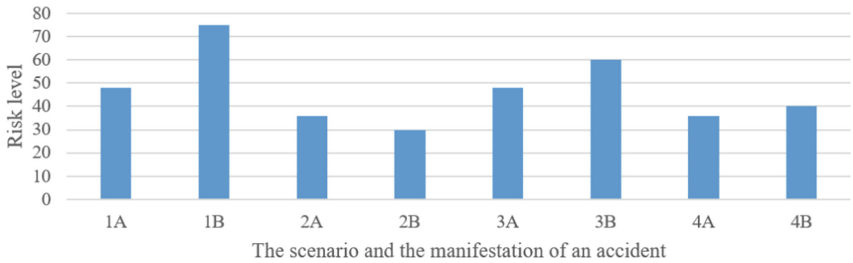


Fig. 4. Risk level.

Accident event - Traffic accident, electric car fire. Designation 1A - without the consequences of a traffic accident and 1B - with the consequences of a traffic accident. The probability of such an accident occurring is small. This is due to the relatively low number of electric powered vehicles. A vehicle fire can cause a serious threat to

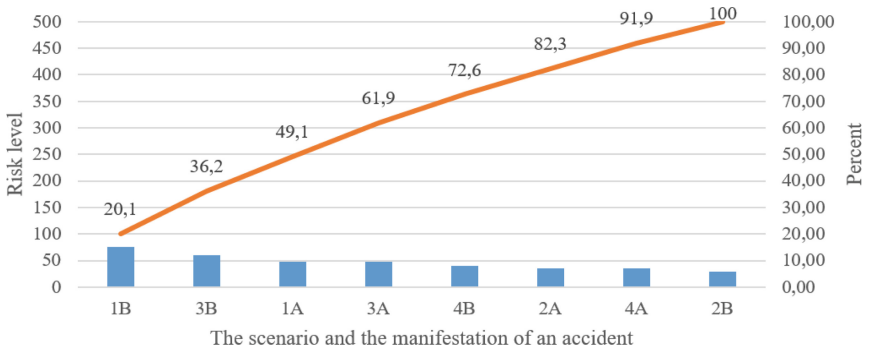


Fig. 5. Pareto analysis.

health or even life. There is also damage to the car, financial losses and environmental contamination.

Accident event, rescue of persons from the vehicle. Designation 3A - without the consequences of a traffic accident and 3B - with the consequences of a traffic accident. The main risk in an accident is a threat to the health and life of the crew or rescuers. If the injury had not occurred, there are still major consequences in the form of financial and material losses. Damaged vehicles cause traffic restrictions and can also pollute the environment. However, the incidence of accidents is low.

4 Solving Accident Scenarios from the Point of View of Fire Brigades

The rupture of damaged cells of the high-voltage traction battery accompanied by an exothermic reaction cannot be ruled out. In the event of a fire, gases from the high-voltage battery are likely to be released. The battery and its cells are equipped with mechanical safety devices that open, for example, in response to an increase in temperature and pressure due to a fire, releasing gases and pressure as a precautionary measure. When working in exposed terrain, it is necessary to use breathing apparatus. Water mist should be used to disperse vapours and gases. As with ordinary vehicles, in the event of an electric car fire, smoke harmful to health is produced due to burning materials (e.g., plastics). In the case of traffic accidents, the residual risk of later fire cannot be ruled out, this applies especially to damaged batteries. Water is preferred as an extinguishing agent for extinguishing an electric vehicle, because it also cools the battery. It is necessary to extinguish or cool with a large amount of water (200 l/min.) from a safe distance. As part of the danger of electric shock, this threat does not exist in principle, but everything depends on the type of accident. Damaged wires and high voltage components are the main risk. Vehicles are equipped with various protection.

mechanisms:

- the high voltage system is designed to be protected against contact,
- the high voltage system is completely electrically isolated from the vehicle body,

- in severe accidents with airbag activation, the high voltage system in most vehicles will be disconnected [14].

The state of charge of the high-voltage traction battery or the individual cells inside the battery is not changed by deactivating the high-voltage system, although deactivation electrically isolates the battery from the rest of the system. Electric vehicles can also be active while stationary (for example air conditioning). In severe accidents, the vehicle's high voltage system must be deactivated. This also applies to a vehicle connected to an electric charging station and also to parked cars that are not connected to an electric charging station. In the event of an electric car accident, the battery also poses a certain risk for fire brigades. Handling a damaged battery is prohibited at the scene of a traffic accident. If the battery temperature is much higher than the outside temperature and constantly rises, it must be cooled with water. Intervention requires monitoring the battery for smoke, sound, sparks, and heat. In electric car accidents, there is also a chemical threat. In the event of an accident, electrolytes can escape from the battery, which are generally irritating, flammable and potentially corrosive substances. Common absorbents are used to remove them. When handling electrolytes, it is necessary to avoid contact with the skin and inhalation of released gases resulting from chemical reactions with the leaked electrolyte. These gases may have a pungent odor. If they escape, the rescue process must be interrupted and the next procedure must be agreed with the intervention commander [6, 14].

The National Fire Protection Association has compiled "universal" measures for fire brigades in the event of rescue operations in the event of accidents involving electric cars or vehicles with a hybrid drive. These points relate to the knowledge fire brigades need to know about the safety of electric vehicles:

- it is necessary in the case of rescue work to make sure that the vehicle is turned off,
- high-strength steel is largely found in the structures of vehicles with an electronic drive. In the event of an emergency, it is important to correctly identify these places and determine the places that will be subject to cutting,
- approach vehicles only from the side, not from behind or from the front - danger of vehicle movement,
- if it is found that the vehicle has a remote start key, it must be moved away from the vehicle (approx. 15 m),
- in the event of a vehicle fire, it is necessary to maintain a safety distance of approx. 15–20 m,
- never touch cut orange cables or components marked with orange labels,
- in the event of a fire that occurs as a result of damage to the battery or part of the system, let the vehicle burn, because with some types of vehicles, the vehicle does not need to be extinguished.

Within electric vehicles, specifically in the event of an accident, there will always be unexpected moments threatening the responding members of the fire and rescue service. It is crucial to know these moments, which is why additional training of firefighting

units and educational measures are necessary. Determining the exact procedure for effective intervention in the event of an electric car accident is currently very difficult, but necessary with the increasing number of vehicles [6, 14].

5 Conclusion

It can be concluded that there is currently a great interest in the use of vehicles with an alternative source of energy, and forecasts speak of their expansion. The article was focused on electric cars. Obviously, the scenarios of these vehicles are different. The identification of these scenarios was based on a survey that focused on the most honest events that arise and that rescuers may encounter during their work. Four main groups emerged, which subsequently point to the possible consequences and causes of the accident. It is clear from the results that the riskiest scenarios of electric car accidents can be described as an accident with a subsequent fire and the rescue of people from the vehicle.

The main part of the article points to the solution of accidents from the point of view of fire brigades. It is important to know that the successful performance of rescue work in traffic accidents involves the cooperation of medical and physical rescuers. The "Golden Hour" philosophy presented by Dr. R. Adams Cowley in 1961, states that in traffic accidents, the crew of the vehicle will have a much better chance of survival if they receive help from emergency services within one hour of the accident. The golden hour includes the time required for emergency services to leave, arrive at the scene, perform rescue work and transport to the hospital. In most traffic accidents, the time of rescue work should not exceed 15 min. This step can be taken if emergency personnel are trained and work as a team at the scene of an emergency. For this reason as well, the area of safety is closely linked to the introduction of new fuels and energy sources in cars. In the event of an emergency, it is important to understand clearly and quickly all the risks that rescue services face when carrying out rescue work. Compared to conventional vehicles, which are well known to the emergency services, vehicles with alternative propulsion are characterized by different types of risks and require a higher level of access in the case of rescue operations, that is, beyond the scope of normal training and experience.

Acknowledgements. This publication was realized with support of Operational Program Integrated Infrastructure 2014–2020 of the project: Innovative Solutions for Propulsion, Power and Safety Components of Transport Vehicles, code ITMS 313011V334, co-financed by the European Regional Development Fund.

EUROPEAN UNION
European Regional Development Fund
OP Integrated Infrastructure 2014 – 2020

MINISTRY
OF TRANSPORT
AND CONSTRUCTION
OF THE SLOVAK REPUBLIC

References

1. International Energy Agency: Energy Technology Perspectives. Scenarios and Strategies to 2050 (2010). ISBN: 978-92-64-08597-8

2. Strategy for the development of electromobility in the Slovak Republic and its impact on the national economy of the Slovak Republic. Proposal approved by the Government of the Slovak Republic on September 9, 2015. MH SR, Bratislava. http://www.rokovanie.sk/File.aspx/ViewDocumentHtml/Mater-Dokum163255?prefixFile=m_. Accessed 18 July 2022
3. Hromádko, J.: Special Combustion Engines and Alternative Drives. Grada Publishing, Prague (2012). ISBN: 978-80-247-4455
4. Ballay, M., Monoši, M.: Technology of electric cars in relation to firefighting units during rescue operations. University of Žilina in Žilina, Žilina (2016). https://www.fbi.uniza.sk/uploads/Dokumenty/casopis_km/archiv/2016_02/06O1%20Ballay%20Monosi.pdf. Accessed 27 July 2022
5. Accident and Extrication Manual for Motor Vehicles with High-Voltage Traction Batteries, 1st edn. Volkswagen Slovakia, a.s. (2018)
6. Lebkowski, A.: Electric vehicle fire extinguishing system. Przeglad Elektrotechniczny **93** (2017). https://doi.org/10.15199/48.2017.01.77
7. Paulraj, P.: EV BASICS 1O6: How to extinguish electric vehicle fire? | Step-by-Step Video Guide (2020). https://www.emobilitysimplified.com/2020/02/how-to-extinguish-electric-vehicle-fire-video-guide.html
8. Mitro, M.: Putting out a burning electric car or hybrid is difficult. This method is the most effective for firefighters. https://fontech.startitup.sk/uhasit-horiaci-elektromobil-ci-hybrid-je-zlozite-tentosposob-je-pre-hasicov-najucinnejsi/. Accessed 20 July 2022
9. Ballay, M., Monoši, M.: Knowledge of the key elements of electric car technology in relation to fire brigades during rescue operations. University of Žilina in Žilina, Žilina (2016)
10. Tánczos, P., Sláviková, V.: Electromobility in relation to the response activity of firefighters in fires or traffic accidents of electric cars. Professional article. Accessed 24 Jan 2019
11. Prievozník, P., Strelcová, S., Sventeková, E.: Economic security of public transport provider in a three-dimensional model. Transp. Res. Procedia **55**, 1570–1577 (2021). ISSN 2352-1465
12. Ristvej, J., Lacinák, M., Ondrejka, R.: On smart city and safe city concepts. Mob. Netw. Appl. **25**(3), 836–845 (2020). https://doi.org/10.1007/s11036-020-01524-4
13. Puna, M.: Alternative energy sources for driving cars - hazards for fire fighters and their minimization. In: Proceedings of the International Conference FIRECO 2019 Safety and Innovations in the Automotive Industry held on May 2, 2019 in Trenčín. Fire Engineering and Expertise Institute of the Ministry of the Slovak Republic, Bratislava (2019). ISBN 978-80-89051-23-6
14. Manual for emergency situations. TESLA Motors (2020)

Vehicle Engineering and Dynamics

The Use of Mineral Powders of Various Nature to form the Structure of Asphalt Concrete

Kateryna Krayushkina[1](✉), Oleksandra Akmaldinova[2], Kyrylo Fedorenko[3], and Oleksandra Skrypchenko[2]

[1] National Aviation University, Kyiv 02156, Ukraine
ekrayushkina15@ukr.net
[2] National Aviation University, Lubomyra Huzara Ave., 1, Kyiv 03058, Ukraine
{oleksandra.akmaldinova,oleksandra.skrypchenko}@npp.nau.edu.ua
[3] National Transport University, Kyiv 02115, Ukraine

Abstract. It is known that a significant role in regulating the process of interaction of the binder with mineral surfaces belongs to mineral powder. Due to the highly developed specific surface area, the mineral powder helps to increase the number of contacts between the structure-forming components of asphalt concrete. The main purpose of mineral powder is to transfer the binder from a bulk state to a film state. In this state, the binder acquires increased characteristics, which, thanks to the stabilizing action of the mineral powder, change less under the influence of temperature. Together with the binder, the mineral powder forms a structured dispersed system that acts as an asphalt binder. The greater the specific surface of the mineral powder, the greater its structuring effect on the binder and asphalt concrete. The purpose of this work was to determine the degree of mineral powders impact, depending on their chemical-geological composition, on the asphalt-polymer concrete properties and to reveal the differences between the features of asphalt concrete and asphalt-polymer concrete.

Keywords: Asphalt concrete · Mineral powders · Bitumen

1 Introduction

The asphalt concrete quality is determined by the properties of all its components, i.e., the properties of both organic binders (bitumen, modified bitumen) and the properties of mineral components (sand, gravel and mineral powder). The nature of the interaction between all these components affects not only the asphalt concrete structure but its physical and mechanical properties as well. The processes occurring in the surface layers determine the strength of bitumen adhesion to the surface of mineral components, form adsorption-solvate layers, and determine their nature, structure and thickness, which ultimately affects the structure formation processes in asphalt concrete and its properties.

The tasks associated with obtaining asphalt concrete, equally well resisting the formation of shear deformations at high temperatures and crack formation at low ones, are quite complex. The complexity is primarily due to the fact that asphalt concrete tends

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 175–188, 2023.
https://doi.org/10.1007/978-3-031-25863-3_17

to change its properties with changing temperatures significantly. Therefore, one of the most important ways to improve the asphalt concrete quality is to increase its thermal stability.

The asphalt concrete resistance to forming plastic deformations depends primarily on the composition of the mixture mineral part, the shape of the stone materials used and the binder properties.

Asphalt concrete mix preparation technology is based on using natural stone materials with inherent physical and chemical properties [1]. Primary processing of mineral materials (except for activated mineral powders) is associated only with a change in their geometry and is based on forced crushing and sorting into fractions of the required size. As a result of such processing, the particles sizes change, and with them, a specific surface of mineral materials changes, but the surface character of the particles changes little or doesn't change at all.

Directional structuring in asphalt concrete can be produced due to the artificial replacement of the mineral surface properties interacting with bitumen. One of these materials is a mineral powder.

Therefore, the main role of the mineral powder is to structure the binder and the formation of an asphalt binder, which contributes to increasing the strength of asphalt concrete and asphalt concrete polymer concrete, their heat and water resistance, and reducing their water saturation [15, 16].

1.1 Modification of Mineral Surfaces

Modification of mineral surfaces consists of improving conditions of mineral surfaces' interaction with bitumen (it does not allow for the improvement of the most important structural and mechanical properties of asphalt concrete). Improving the bitumen properties in the adsorption layers (and preventing the selective filtration of bitumen components into the mineral material); expanding the range and improving the properties of the mineral materials used.

High activity of a new surface is not used in time, can practically have a negative result because the freshly formed surface, one way or another, adsorbs various substances, then impairing the interaction with binders.

The mineral powder plays a significant role in regulating the bitumen interaction with mineral surfaces. Thanks to the highly developed mineral powder specific surface (up to 95% of the total surface of grains being a part of asphalt concrete gets to a particle of mineral powder), it promotes an increase in the number of contacts between asphalt concrete structure-forming components. Another purpose of mineral powder is to fill small pores between larger particles. An insufficient amount of mineral powder leads to the need to increase the amount of bitumen to fill the pores [2].

In order to determine the optimal use of mineral powders in asphalt concrete mixtures without deterioration of their properties, it is necessary to determine the interactions between the mineral powder and the binder. Basically, they occur on the surface of the interface of phases; therefore, the study of the properties of the surface layers is necessary for understanding the structure and mechanism of formation of a mixture of mineral powder with a binder.

It is known that the orientation of the hydrocarbon chains of the organic binder can be different: the part of the chain that contains active functional groups can be oriented towards the surface of the mineral powder and away from its surface [12, 14].

Powders of the first type, which have a positive surface charge, are proposed to be called active in relation to the organic binder, and the second type – with a negative surface charge – inactive. At the same time, the active functional groups of the organic binder, when interacting with active powders, spend chemical energy on the formation of compounds that firmly hold organic molecules on the surface of the powder and lose their initial reactivity, that is, the mineral powder blocks the active groups of the binder. Components of the binding type of oils can either be filtered inside the mineral particles (porous powders) or adsorbed completely on their surface (dense powders) [17].

However, the main function of the mineral powder is to convert bitumen from the bulk state to film. In this state, the bitumen gets high viscosity and strength, and due to the mineral powder stabilizing effect, it changes less under the action of temperature. Together with bitumen, the mineral powder forms a structured dispersed system acting as an asphalt binder.

Significant strengthening of the mineral powder structure-forming role in asphalt concrete and, accordingly, improvement of structural and mechanical properties of this material can be achieved by physicomechanical or physicochemical activation of the powder.

One of the purposes of mineral powders' physicochemical activation is the formation of adsorption-solvate layers on the surface of mineral grains, which are close to bitumen by their molecular nature.

Using activated powders allows for the regulation of important properties of asphalt concrete in a wide range.

In order to preserve the positive properties of freshly formed surfaces of mineral powders, various surfactants activate them during crushing.

2 Use of Activated Mineral Powders

Asphalt concretes with activated mineral powders have good heat resistance. Even with low-viscosity bitumens, such asphalt concretes are characterized by high durability indicators at a temperature of 50 °C.

The use of activated powders not only increases the strength and viscosity of highly structured bituminous layers formed on the grains of powders but also significantly facilitates the conditions of mineral particles wetting with bitumen and creates conditions for their uniform distribution in the mixture. Thus, a larger number of mineral particles and, accordingly, a larger of the potentially possible total surface area is involved in active work in asphalt concrete.

The strength of asphalt concrete with activated powders, especially at the temperature of 50 °C, is higher than that of the same type of asphalt concrete with inactivated powder. But very high strength values with activated mineral powders are not considered a necessary asphalt concrete property. In this case, the amount of mineral powder can be reduced, as well as the use of less viscous bitumens, in which the decrease in strength

to the optimum value will be compensated by increasing the deformation capacity of asphalt concrete at low temperatures.

The degree of change in the asphalt concrete strength and the degree of decrease in bitumen consumption can be regulated by the properties of the activated mineral powder and its amount in the asphalt mixture. Necessary physical and mechanical properties of asphalt concrete and bitumen content in it should be assigned according to climatic and operational conditions [3]. The ability to control the amount of bulk bitumen in asphalt concrete is important. Thus, for areas of excessive moisturizing, to increase the asphalt concrete water resistance and coatings corrosion resistance, the bulk bitumen should be greater than for areas with hot climates. In all cases, it is advisable to avoid excessive amounts of bulk bitumen, which impairs the performance of the coating. This is less relevant for bitumen-polymer binders, as their rheological characteristics differ significantly from the characteristics of conventional bitumens.

Slowing down the asphalt concrete ageing occurs as a result of prevention or a sharp decrease in the filtration of bitumen low molecular weight components into the mineral particles pores due to activation on mineral powder grains of bitumen adsorption layers with surfactants strongly attached to the mineral surface. This kind of filtration, observed when using ordinary (not activated) limestone powder, is one of the forms of bitumen ageing in asphalt concrete. In addition, the ageing process is influenced by the fact that the vast majority of closed pores characterize asphalt concrete containing activated powder. This reduces the circulation of air and water and, respectively, the oxidizing effect of oxygen.

The positive properties of activated mineral powders lead to the widespread use of industrial waste, which makes it possible to expand the range of raw materials used to obtain mineral powders and reduce the total cost of asphalt pavements construction [4].

Limestone crushing waste, including crushing screenings, accounts for 50–70% of the volume of rock mass processed. As a rule, limestone waste is represented by low-strength materials, which vary in the range of 100–300 and less. This indicates their high porosity causes low water and frost resistance, which limits their use in road construction. Studies have shown that one rational way to dispose of limestone waste is its activation and further use in asphalt mixtures. Asphalt concrete mixtures with such powders, compared with inactivated powder mixtures, are characterized by significantly higher corrosion resistance; the frost and water resistance coefficients increase almost twice, the number of swelling decreases sharply, and the indicators of long-term water and frost resistance improve.

Under the activation condition, we can use mineral powders with a less active surface of interaction with bitumen. This makes it possible to use the acid rocks crushing waste and slag to obtain mineral powders.

Mineral powders from acid rocks slightly reduce the structure of bituminous films. This negatively affects all the properties of asphalt concrete, especially its heat resistance and long-term water and frost resistance. An increase in the number of acid rock particles less than 0.071 mm negatively affects not only the long-term water and frost resistance of asphalt concrete, but almost all the properties of this material. First, asphalt concrete density decreases, which negatively affects the overall structure, especially the pore

space structure of asphalt concrete – the volume of closed pores decreases sharply. It is almost zero for a mixture where the entire dispersed part consists of acidic particles.

As the number of acid particles increases, the water saturation increases. This leads to intense water diffusion through bituminous films to the interface "bitumen-mineral material" and, consequently, the violation of structural bonds. Insufficient structure of bituminous films due to weak interaction of acid particles with bitumen and lack of chemisorption process (emergence of water-soluble neoplasms) leads to a rapid destruction of samples of such mixtures due to the action of water and alternating temperatures.

It is known that organic binder films are more intensively attracted to the surface of mineral particles with a large number of positive electrical centres. At the same time, the stronger the positive charges on the surface of the mineral, the higher the adhesion of organic binders to them. In addition, adhesive forces increase compared to cohesive forces with increasing wetting of the surface of mineral parts with an organic liquid. When the mineral powder is combined with an organic binder, physical adsorption and chemisorption processes occur at the interface. The latter determines the high viscosity and strength of the mixture. The most characteristic powder with a large number of positive adsorption centres and a high structuring role is limestone [17, 18].

When the mixture of this powder with organic binder water is saturated, some part of the films of the binder is displaced from areas where there was only selective wetting, and the processes of physical adsorption took place. However, there are not many such areas in this system, and they mainly appear on sufficiently large particles. This is especially noticeable with a low-active binder that has a small number of compounds that include the COOH-group [17, 19].

The critical ratio, followed by a significant deterioration of the properties, is 50:50% of acidic and basic powders. Mixtures with a 35:65% show the best results. Such mixtures are characterized by rather high long-term water and frost resistance indicators and optimal values of other properties.

These conclusions are valid for asphalt mixtures without surfactants and activated mineral powders, as the latter's action can compensate for the negative effects of acid particles and expand their percentage range in the mixture.

A specific feature of acidic mineral powders is the increased acid resistance of asphalt concretes due to their use. For example, an aggressive medium with a pH value of <7 destroys the bitumen-limestone contact zone more intensively than bitumen-quartzite.

When crushing rock in screenings, the average grain content smaller than 0.071 mm is about 10%. The classification of igneous rocks shows that most of them are acidic.

Acid rocks crushing screenings are mainly a product of crushing granites, syenites, and diorites and constitute a significant reserve of mineral materials that can be used in road asphalt concrete as mineral powders. These screenings are 70% silica.

The use of polymeric additives gives a chance to use acid rocks crushing waste as a part of asphalt concrete. At the same time, small fractions of waste (less than 0.071 mm) replace limestone mineral powder. It is recommended to use such asphalt concrete in areas with increased humidity, with frequent changes in temperatures, in places of intensive braking, and on roads with high loading.

3 Use of Spent Moulding Sands and Other Waste

An alternative method of improving physical-mechanical, physical-chemical, and operational characteristics is the use of artificial materials in the composition of polydisperse, polymineral composite structures, which by virtue of their formation, are cheap raw materials that will make it possible to reduce the cost of construction work. Both domestic and foreign scientists were engaged in research in this area. Developed technologies for using the resource potential of waste are primarily aimed at replacing inert mineral materials (natural, traditionally used) in composite construction materials. In particular, such waste can include metallurgical slag and sludge, fly ash, moulding sands, and waste from various chemical industries. As a rule, they do not enter into chemical reactions with other components of composite materials, while the specified strength and performance indicators of the final product are achieved [18–20].

The properties of spent moulding sands (SMS) indicate the possibility of their use for the production of mineral powders. Fineness and the presence of organic binders on the surface of SMS grains contribute to the production of activated mineral powders on their basis. However, due to the large specific surface area, SMS require high binder consumption. The SMS properties are formed under the action of high temperatures (up to 1,400 °C). The quartz of moulding sand grains gradually passes from one modification to another, causing the cracking of the grains, transformation of their dust and a corresponding change in their composition.

The chemical analysis of SMS shows that the bulk (85–97%) is silica (SiO_2). But the presence of oxides in alkaline earth metals (CaO + MgO), the content of which is 6.2%, as well as Al_2O_3 and Fe_2O_3 oxides, improve the SMS properties, as they tend to interact strongly with bitumen. The sulfur content (up to 0.25%) on the surface of the grains can contribute to the better structuring of organic binders [5].

It is possible to use sludge from the foundry of the Makiivka Pipe Plant as mineral powders to produce asphalt mixtures. The annual sludge output is 4 thousand tons. The chemical composition of the sludge is characterized by the content of oxides (%): SiO_2 - 28; Al_2O_3 - 2.68; CaO - 7.27; Fe_2O_3 - 5.18; MnO - 1.17; S - 0.92. Losses during calcination are 38.0. Particles smaller than (%): 1.25 mm - 100; 0.315 mm - 97.8; 0.071 mm - 93. The total specific surface area of the sludge is 25,200 cm^2/g. The external specific surface area is 4,210 cm^2/g. The sludge has a significant internal specific surface area (20,990 cm^2/g), indicating its higher porosity compared to limestone powder. The sludge contains some technical oils from hydraulic cupolas.

The corresponding chemical and mineralogical composition of powdered industrial waste indicate the possibility of its use as mineral powders in asphalt concrete. These are, for example, the tailings of sulfur ore flotation, the decomposition products of metallurgical slag, cement dust, filter dust, phosphogypsum, coal fly ash. Limestone flotation waste from sulfur production is formed in the process of sulfur concentrate production by flotation from crushed rocks containing sulfur.

The chemical composition of flotation tails has more than 80% of calcium carbonate, up to 10% of sulfur, a small number of other compounds and traces of flotation reagents. Granulometric composition: particles smaller than 0.315 mm - 94%, particles smaller than 0.071 mm - 68%. The presence of sulfur in flotation waste is not an obstacle to its

use as a mineral powder because when interacting with bitumen, it helps to improve its binding properties and, accordingly, the quality of asphalt concrete.

Inserting 10% of flotation waste into bitumen significantly increases its viscosity, especially at positive temperatures. It positively affects the heat resistance of the asphalt binder composition and slightly increases its viscosity at negative temperatures.

Among the other industry by-products, ferromanganese slag is the most suitable for preparing asphalt concrete mixtures as mineral powders. Filter press dust, fly ash and cement dust can be used if they are physicomechanical or physicochemically activated.

In the process of preparing asphalt concrete mixture, mechanical mixing increases the equalization rate of active bitumen group concentration and increases the rate of heterogeneous processes, but the dependence of these processes on diffusion is not completely released. The more intense the mechanical mixing, the thinner the diffusion layer, the lesser the role of diffusion in the physicochemical processes of microstructure formation, the more intensely less active polar molecules displaced from the surface, and the higher the adsorption saturation. When using mineral materials, especially powders made of porous and rough rocks, longer mixing is required to provide complete enveloping of particles with bitumen and complete selective adsorption [6, 7].

With an increase in temperature, the rates of volumetric and surface diffusion increase, but the processes of interaction at the interfaces are delayed significantly compared to those occurring in direct contact with the reacting components. The impact of the direct contact can be increased by intensifying mixing due to the vibration effect, spraying the most active components (bitumen and powder), using the principle of mixing in a "boiling ball", by means of ultrasonic mixing methods.

Regulating the kinetics of the processes occurring during the mixing of the components is complicated due to the high sensitivity of reactions to the conditions in which they occur, as well as the influence of catalytic factors that often cannot be taken into account. It should be borne in mind that [6, 7]:

- the reaction rates during the mineral materials' interaction with organic substances are relatively low;
- the interaction between strongly polar molecules occurs at a higher rate than that between non-polar molecules; therefore, an increase in the polarity of the contacting components by introducing optimal amounts of surfactants or using catalytic additives always fosters the development of adsorption phenomena kinetics;
- the relative decrease in the asphalt concrete strength and elastic properties under the influence of watering is the more intensive, the higher the degree of mineral mixture dispersion, especially in the total surface of the mineral powder;
- the nature of minerals and their crystalline features significantly affect the magnitude of the change in the indicators of asphalt concrete structural and mechanical properties after water saturation associated with both diffusion and short-term saturation. The greatest effect is exerted by water when using mineral powders with high negative potential and a neutral surface, as well as those having a large amount of Mg^{2+} cations. As a result of water impact, asphalt concrete with these powders loses a significant part of its mechanical strength, which, in some cases, cannot be compensated for even by the high dispersion of the powder (granite, quartz, flint, feldspar);

– the aquatic environment's negative impact increases with asphalt concrete cyclic saturation and drying, freezing and thawing, especially during the first cycles;
– the asphalt concrete quality deteriorates with moisturizing. The more intensively, the higher the moisture content of the freshly prepared asphalt concrete mixture. Asphalt concrete mix can get wet, especially as a result of incomplete drying of cold and wet mineral powder in a mixer. At a moisture content of 1.5%, the asphalt concrete quality deteriorates almost twice in all the physical and mechanical properties;

The use of activated mineral powders improves the performance of the technological process. It lies in reducing the asphalt concrete mixtures temperature by 15–25 °C at all stages of its preparation and laying. The use of surfactants for activating mineral powders plasticizes bitumen, which increases the asphalt concrete mixtures' mobility and reduces their temperature.

4 Results of the Research

Earlier studies [13] found that there is a significant difference between traditional limestone mineral powder and slag and shale powders. The surface of the slag grains has a much more complex microrelief, with more depressions and depressions, which provides the grain with a larger specific surface compared to the same grain of traditional mineral powder. This feature can lead to a higher structuring ability of such a mineral powder in relation to an organic binder and the phenomenon of selective adsorption of bitumen components on its surface.

Previous studies of raw materials have shown that, based on the set of properties, slag material and shale powder can be used as a part of natural raw material for the production of mineral powder for asphalt concrete. The granulometric composition and surface properties are corrected by additional grinding. Modern grinding technologies make it possible to achieve the required parameters of coarseness and homogeneity and perform mechanical or mechanical activation to achieve the required surface properties.

According to the regulatory documents in Ukraine [8–11], in the laboratory of the Faculty of Architecture, Construction and Design, asphalt concrete mixtures were made using mineral powders of different nature and different binders. The tests were conducted according to the standard methods outlined in [9] for testing.

The obtained test results were compared with the requirements [8].

The purpose of this work was to determine the degree of mineral powders' impact, depending on their chemical-geological composition, on the asphalt-polymer concrete properties and to reveal the differences between the features of asphalt concrete and asphalt-polymer concrete.

The values of the physical and mechanical characteristics of asphalt concrete mixtures prepared using mineral powders of different nature and different binders are given in Tables 1, 2, 3 and 4.

The physical and mechanical properties and composition of asphalt-concrete mixtures prepared using mineral powders of different nature and BND 60/90 (P_{25}-75°) bitumen of the Lysychansk refinery are shown in Table 1.

Analyzing the data in Table 1, we can conclude that the insertion of mineral powders of various natures into asphalt concrete mixtures in the amount of 12% contributes to

Table 1. Physical and mechanical properties of asphalt concrete mixtures made using mineral powders of different nature and bitumen of BND 60/90 grade of the Lysychansk Refinery.

Indicator	Granite screening - 100% bitumen – 6.5%	Granite screening - 95% Skala-Podolsk mineral powder – 5%; bitumen – 6.5%	Granite screening - 95% crushed blast furnace slag – 5%; bitumen – 6.5%	Granite screening - 95% Crushed shale – 5%; bitumen – 6.5%	Granite screening - 95% Crushed Ovruch quartzite – 5%; bitumen – 6.5%	DSTU B V.2.7-119-2011 Requirements
Average density, g/cm^3	2.29	2.33	2.35	2.36	2.35	–
Water saturation, % by volume	3.1	1.5	1.6	1.6	2.4	1.0–2.5
Swelling, % by volume	0.2	0.1	0.1	0.1	0.2	Not higher 0.5
Compressive strength, MPa, at temperature: 0 °C 20 °C 50 °C	8.6 3.8 1.9	10.7 5.0 2.7	10.4 4.8 2.6	10.5 5.0 2.6	9.9 4.1 2.1	<11 >2.5 >1.6
Water resistance coefficient	0.93	0.97	0.96	0.98	0.92	>0.9

a slight (6–7%) increase in the asphalt concrete strength, an increase in its water and heat resistance, as well as a slight decrease in water saturation compared with asphalt concrete, containing mineral powders of various natures in the amount of 5%.

The use of mineral powder from crushed quartzites of the Ovrutsk quarry in an amount of 12% practically does not change the properties of asphalt concrete, containing 5% of the same powder.

Studies of asphalt-polymer concrete mixtures were carried out using mineral powders of different nature and a polymer-bitumen binder of the BMTE 60/90 (P_{25}-75°) grade.

The physical and mechanical properties and composition of such mixtures are shown in Table 2 and Table 3.

The data in Tables 2 and 3 indicate that asphalt-polymer concrete based on the polymer-bitumen binder of the BMTE 60/90 grade has better properties than asphalt concrete of the same composition with pure bitumen of the same viscosity. Thus, the

Table 2. Physical and mechanical properties of asphalt-polymer concrete mixtures made using mineral powders of different nature and BMP 60/90 polymer-bitumen binder.

Indicator	Granite screening - 100% BMP – 6.5%	Granite screening - 95% Skala-Podolsk mineral powder – 5%; BMP – 6.5%	Granite screening - 95% Crushed blast furnace slag – 5%; BMP – 6.5%	Granite screening - 95% Crushed shale – 5%; BMP – 6.5%	Granite screening - 95% Crushed Ovruch quartzite – 5%; BMP – 6.5%	DSTU B V.2.7-119-2011 Requirements
Average density, g/cm^3	2.31	2.33	2.35	2.34	2.34	–
Water saturation, % by volume	2.5	1.6	1.9	2.0	2.4	1.0–2.5
Swelling, % by volume	0.2	0.1	0.1	0.1	0.2	Not higher 0.5
Compressive strength, MPa, at temperature: 0 °C 20 °C 50 °C	9.6 4.6 2.4	11.0 5.6 2.7	10.4 5.4 2.5	10.8 5.6 2.8	9.9 4.3 2.2	<11 >2.5 >1.6
Water resistance coefficient	0.94	0.98	0.96	0.97	0.93	>0.9

strength of ordinary asphalt concrete at 20 °C is 3.8 MPa versus 4.6 MPa of asphalt polymer concrete. This increases the heat resistance by 25%.

The data in Table 2 indicate that the insertion of mineral powders of various natures into the asphalt-polymer concrete mixture in an amount of 5% increases the asphalt-polymer concrete strength from 4.6 MPa to 5.6 MPa, increases its heat and water resistance and leads to a decrease in water saturation.

The use of mineral powder from crushed quartzites of the Ovruch quarry in an amount of 5% does not in any way affect the properties of asphalt-polymer concrete mixtures.

The data in Tables 2 and 3 indicate that the insertion of mineral powders of various natures into asphalt-polymer concrete mixtures in an amount of 12%, having previously screened out dusty particles (<0.071 mm) in an amount of 7%, does not change the physical and mechanical properties of asphalt-polymer concrete.

Table 3. Physical and mechanical properties of asphalt-polymer concrete mixtures made using mineral powders of different nature and polymer-bitumen binder of BMP 60/90 grade.

Indicator	Granite screening - 100% BMP – 6.5%	Granite screening - 95% Skala-Podolsk mineral powder – 5%; BMP – 6.5%	Granite screening - 95% Crushed blast furnace slag – 5%; BMP – 6.5%	Granite screening - 95% Crushed shale – 5%; BMP – 6.5%	Granite screening - 95% Crushed Ovruch quartzite – 5%; BMP – 6.5%	DSTU B V.2.7-119-2011 Requirements
Average density, g/cm^3	2.31	2.34	2.36	2.36	2.36	–
Water saturation, % by volume	2.5	1.2	1.4	1.3	2.1	1.0–2.5
Swelling, % by volume	0.2	0.1	0.1	0.1	0.1	Not higher 0.5
Compressive strength, MPa, at temperature: 0 °C 20 °C 50 °C	9.6 4.6 2.4	11.4 5.6 2.8	11.1 5.4 2.8	11.0 5.7 2.8	10.0 4.5 2.2	<11 >2.5 >1.6
Water resistance coefficient	0.94	0.97	0.97	0.98	0.92	>0.9

Studies were carried out on the effect of the UDOM-3 adhesive additive on the asphalt polymer concrete properties. For this purpose, we have used mineral powder based on crushed Ovruch quartzite, one of the most acidic rocks. The physical and mechanical properties and composition of asphalt concrete mixtures prepared using the UDOM-3 adhesive additive are shown in Table 4.

The data in Table 4 indicate that the use of the UDOM-3 adhesive additive in an amount of 0.6% of the bitumen mass contributes to an increase in the asphalt concrete water resistance.

If the rheology of modified bitumen is, as a rule, more complex than that of pure bitumen, then established the pure bitumen ratio between the complex module of the binder and the asphalt concrete module based on it is true both for the modified bitumen and for asphalt concrete based on it.

Table 4. Physical and mechanical properties of asphalt concrete mixtures prepared using UDOM surfactant additive.

Indicator	Granite screening - 95% Crushed Ovruch quartzite – 5%; bitumen – 6.5%	Granite screening - 95% Crushed Ovruch quartzite – 5%; bitumen with addition UDOM (0.6%) – 6.5%	DSTU B V.2.7-119-2011 Requirements
Average density, g/cm^3	2.33	2.33	–
Water saturation, % by volume	2.8	2.7	1.0–2.5
Swelling, % by volume	0.2	0.2	<0.5
Compressive strength, MPa, at temperature: 0 °C 20 °C 50 °C	9.7 4.0 2.0	9.8 4.0 2.1	<11 >2.5 >1.6
Water resistance coefficient	0.92	0.94	>0.9

The change in the rheological characteristics of the binder occurs, with some approximation, to the rheological characteristics of asphalt concrete. In this case, the asphalt concrete elasticity modulus increases with an increase in the bitumen hardness; the thermal sensitivity of asphalt concrete is changed using bitumen with a wide plasticity range; the values of the asphalt concrete elasticity modulus at high temperatures increases with the use of bitumen-polymer binders.

Therefore, the results of all studies on the effect of the asphalt concrete mixtures components on the asphalt concrete based on conventional bitumen can be predicted, with the corresponding correction factor, for asphalt polymer concrete.

5 Conclusion

In the course of the work, research was carried out on non-traditional mixtures for the preparation of mineral powder, namely from the addition of slag materials and shale. In terms of their granulometric composition and properties, these materials are close to the traditional mineral powder used in Ukraine. However, the surface of the grain of the slag material has a more complex surface, with a large number of recesses and depressions, which provides the grain with a sufficiently large specific surface. This feature can lead to a high structuring ability of such a mineral powder in relation to an organic binder and the phenomenon of selective adsorption of binder components on its surface.

The use in asphalt concrete mixtures of limestone mineral powder produced by OAO Skala-Podolsky Zavod Mineralnyh Poroshkov, crushed blast furnace slag or crushed crystalline shale of Kryvorozhsky TsGKZ in the amount of 5% helps to increase the strength of asphalt concrete and asphalt concrete polymer concrete, their heat and water

resistance, by reducing their water saturation, increasing their service life, reducing repair intervals, which leads to savings of budget funds, especially in the conditions of limited funding.

The use of mineral powder from crushed quartzites insignificantly affects the physical and mechanical properties of both asphalt concrete and asphalt polymer concrete, and therefore the use of crushed quartzite as a mineral powder is impractical.

The use of polymer additives makes it possible to use the waste from the crushing of acidic rocks in the composition of asphalt concrete. At the same time, small fractions of waste (less than 0.071 mm) are replaced with limestone mineral powder. Such asphalt concrete is recommended for use in areas with high humidity, with frequent temperature drops, in places of intensive braking and on roads with high traffic.

The critical ratio of acidic and basic rocks, accompanied by a significant deterioration of properties, is 50:50%. Mixtures show the best results with a percentage ratio of 35:65. Such mixtures are characterized by sufficiently high indicators of long-term water and frost resistance and optimal values of other properties. These conclusions are valid for asphalt concrete mixtures without surfactants and activated mineral powders, since the latter's action allows you to compensate for the negative impact of acid particles and expand their percentage range in the mixture.

Taking into account the fact that in the mineral powder from the crushed crystalline shales of the Kryvyi Rih TsGKZ the total content of Al_2O_3 and Fe_2O_3 is sesquioxides 20–25% (according to the DSTU B V.2.7-121-2003 requirements - no more than 1.7%), it is necessary to carry out additional studies to determine the possibility of using such shale in asphalt mixes.

References

1. Gureyev, A.A., Chernysheva, E.A., Konovalov, A.A., Kozhevnikova, Yu.V.: Production of oil bitumens, p. 103 (2007)
2. Rudenskaya, I.M., Rudensky, A.V.: Rheological properties of bitumens. Higher School, p. 118 (1967)
3. Zolotarev, V.O.: Depth of needle penetration as a characteristic of shear bitumen resistance. Motorway Ukraine **1**, 25–29 (2012)
4. Modified bituminous binders and bitumens with additives in road construction. Under the general editorship of V.A. Zolotarev, V.I. Bratchun. Special bitumens, p. 229. KhNADU Publishing House, Kharkiv (2003)
5. Turenko, F.P., Filatov, S.F., Shipicin, V.V.: Improving the efficiency and environmental friendliness of road asphalt concrete pavement repair by cold regeneration using slow hardening mineral and organic additives. Omsk Sci. Herald **3**(36), 89–91 (2004)
6. Barackh, G.S.: The influence of the structure of asphalt granulobeton on its properties, p. 60 (automobile roads: Inform. Sb./Informautodor: rel. 3) (2001)
7. Prokopets, V.S., Filatov, S.F., Ivanova, T.L., Tarasova, M.V., Pomorova, L.V.: Restoration of asphalt concrete pavements by cold recycling and chemical additives. Bashkir Chem. J. **13**(5), 61–65 (2006)
8. DSTU B V. 2.7-119-2013 Building materials. Asphalt concrete mix for roads and airfields. Specifications (2013)
9. DSTU B V.2.7–319:2016 Building materials. Asphalt concrete mix for roads and airfields. Testings (2016)

10. DSTU 8772;2018 Building materials. Mineral powder for asphalt concrete mix. Testings (2018)
11. DSTU B V.2.7-121;2014 Building materials. Mineral powder for asphalt concrete mix. Specifications (2014)
12. Trautvain, A.I., Yadykina, V.V., Gridchin, A.M., Peshkova, C.: Evaluating the effectiveness of preparing activated mineral powders from technogenic raw materials for asphalt mixtures. Proc. Eng. **117**, 355–361 (2015)
13. Krayushkina, K., Khimerik, T., Pershakov, V., Bieliatynskyi, A.: Use of slag materials in road materials in road construction. Visnik NAU **77**(4), 88–93 (2018)
14. Kumar, A., Kumar, C.A.: Experimental investigation of bituminous mixes using fly ash as filler material. J. Civ. Eng. Environ. Technol. **1**, 4–6 (2016)
15. Bratchun, V.I.: Poetapnaya optymyzatsyya sostavov asfaltoshlakobetonov, pryhotovlennyh na anyonnoy bytumnoy emulsyy/Gradual optimization formulations asfaltoshlakobetonov prepared anionic emulsion. In: Proceedings of the 40th International Workshop on Modeling and Optimization of Composites "Simulation and Optimization in Materials Science", pp. 45–47. Astroprint, Odessa (2001)
16. Bratchun, V.I.: Optymyzatsyya sostavov asfaltoshlakobetonov na anyonnoy bytumnoy emulsyy. Optimization of structure asphaltoshlakobetonov anionic emulsion. Modern Problems of Construction/Annual Scientific and Technical Collection. - Donetsk: Donetsk PromstroyNIIproject, LLC "Lebed", vol. 2, pp. 5–9 (2000)
17. Tao, G., Xiao, Y., Yang, L., Cui, P., Kong, D., Xue, Y.: Characteristics of steel slag filler and its influence on rheological properties of asphalt mortar. Constr. Build. Mater. **201**, 439–446 (2019). https://doi.org/10.1016/j.conbuildmat.2018.12.174
18. Maghool, F., Arulrajah, A., Horpibulsuk, S., Mohajerani, A.: Engineering and leachate characteristics of granulated blast-furnace slag as a construction material. J. Mater. Civ. Eng. **32**, 04020153 (2020). https://doi.org/10.1061/(ASCE)MT.1943-5533.0003212
19. Arabani, M., Tahami, S.A., Taghipoor, M.: Laboratory investigation of hot mix asphalt containing waste materials. Road Mater. Pavement Des. (2017). https://doi.org/10.1080/14680629.2016.1189349
20. Sangiorgi, C., Tataranni, P., Mazzotta, F., Simone, A., Vignali, V., Lantieri, C.: Alternative fillers for the production of bituminous mixtures: a screening investigation on waste powders. Coatings **7**, 76 (2017). https://doi.org/10.3390/coatings7060076

Experimental Approach to Water Hammer Phenomenon

Michał Stosiak[1](✉), Kamil Urbanowicz[2], Krzysztof Towarnicki[1], Marijonas Bogdevičius[3], and Mykola Karpenko[3]

[1] Faculty of Mechanical Engineering, Wrocław University of Science and Technology, Łukasiewicza 5, 50-371 Wrocław, Poland
{michal.stosiak,krzysztof.towarnicki}@pwr.edu.pl
[2] Faculty of Mechanical Engineering and Mechatronics, West Pomeranian University of Technology in Szczecin, Al. Piastów 19, 70-310 Szczecin, Poland
kamil.urbanowicz@zut.edu.pl
[3] Faculty of Transport Engineering, Vilnius Gediminas Technical University, Saulėtekio av. 11, 10223 Vilnius, Lithuania
{marijonas.bogdevicius,mykola.karpenko}@vilniustech.lt

Abstract. The paper indicates the frequent occurrence of transient states in hydraulic systems. Particular attention was paid to the phenomenon of water hammer - the causes and effects of this phenomenon. The necessity to modify the theoretical description of this phenomenon was indicated. The work focuses on the presentation of the development of the structure of experimental stands to study the phenomenon of water hammer. The research results obtained on the presented experimental stands were used to verify the theoretical considerations presented in other papers by the authors. The presented successive concepts of the test stand enable the research to be carried out to a greater extent and at the same time eliminate the disadvantages of the previous versions of the test stand. The stand presented as the final one also allows the testing of transients in hydraulic lines for various types of working fluid (oil, emulsion, distilled water).

Keywords: Hydraulics · Unsteady flow · Water hammer · Test stand · Experiment

1 Introduction

Unsteady states occur in hydraulic, water, heating, transmission and other systems more often than one might think. They are always accompanied by pressure pulsations, the peak values of which definitely exceed the set values, while the minimum ones may reach the level of the vapor pressure, thus the dangerous cavitation areas may occur. Therefore, both the maximum and minimum pressures may be responsible for the emerging system damage, among them the most dangerous are leaks related to damage to the walls of pipes or resulting from the unsealing of hydraulic connections, which result in significant financial losses, and in the case of oil spills, also a significant threat to the environment

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 189–199, 2023.
https://doi.org/10.1007/978-3-031-25863-3_18

[1]. Among the unsteady flows, there are accelerated, decelerated, reverse, pulsating flows and those which will be discussed in this paper, namely water hammer. Water hammer effect may be caused by the intentional closing of the valve, for example as a result of a power failure, or by deliberate control of the elements of hydraulic systems, including valves. During the impacts, there are intense changes in the basic parameters of the flow, i.e. pressure and velocity averaged in the cross-section. The intensity of the effect depends on the intensity of changes in these parameters. Quick-closing valves are often used in modern systems. It is their closure that often leads to the appearance of simple water hammers, characterized by the fact that closing the valve takes less time than the reflection (from reservoir) and return to the valve section of the original water hammer wave (increased pressure wave). In this case, the pressure increase may reach maximum values, which, when areas of vapour cavitation appear, could be almost twice as high as the pressures determined from formulas used in practice, e.g. the popular Joukowski formula.

Apart from the aforementioned water hammer, the hydraulic system often experience a periodic excitation. Such excitation comes, for example, from the flow pulsation of the displacement pump and is the result of the kinematics of the pump displacement elements [2, 3]. In a hydraulic system, due to the occurring impedance, pulsation of flow results in pressure pulsation [4]. The resulting pressure pulsation has frequencies corresponding to the flow pulsation [5, 6]. The real excitation signal in the hydrostatic system (in the form of pressure pulsation) is caused not only by the flow pulsation and can be approximated as a sinus series with different frequencies and amplitudes. Periodic pressure changes in the hydraulic system cause a number of negative effects on the components and the environment, including humans. The most important include:

- uneven operation of the hydraulic or pneumatic actuators,
- vibrations of the hydraulic system components, including hoses, which may lead to further critical damage (abrasion of hoses, fatigue load on the walls of the bodies of hydraulic components) [7],
- excitation of vibrations of hydraulic valve elements [8],
- increased noise of hydrostatic systems in a wide frequency range [5].

Transient states causing vibrations and noise in hydrostatic systems in relation to humans can cause, among others:

- disturbances in coordination of movements,
- increasing the time of visual or motor reaction [9],
- fatigue [10],
- changes in the nervous system [11],
- changes in peripheral vessels [12],
- changes in the osteoarticular system.

The harmful effect of vibroacoustic signals generated by transient states in the hydraulic system leads to a reduction in the quality of work performed and the formation of vibration disease in the human body. The resulting changes can be further

divided into acute and chronic [9]. Furthermore, one of the main requirements for modern hydraulically or pneumatically driven machines and equipment is precision [13]. Due to the occurrence of pressure pulsations of the working medium, the precision of hydraulic or pneumatic actuators can be significantly reduced.

For the above-mentioned reasons, the ability to model transients, especially the phenomenon of water hammer, is extremely important, in particular during the modernization of existing pressure systems as well as during the design of new ones. Due to the occurrence of reflected waves, the mathematical description of the water hammer phenomenon is based on the system of partial differential equations of the hyperbolic type [14]. For its solution and flow modeling, first of all, numerical programs are used, among which the dominant solution is based on the method of characteristics [15]. Analytical models are a minority and they have been derived for the simplest systems, e.g. for reservoir-pipe-valve system [16–18].

In order to better understand the water hammer phenomenon, experimental research is necessary in a wide spectrum of the dimensionless parameter defining it, namely the water hammer number $Wh = \frac{vL}{cR^2}$ [19]. These studies have been conducted at the Wrocław University of Science and Technology since 2007 [20] (by Zygmunt Kudźma and Michał Stosiak) with the participation of theoreticians from the then Szczecin University of Technology (Zbigniew Zarzycki and Sylwester Kudźma) and, in recent years, of the West Pomeranian University of Technology in Szczecin (Kamil Urbanowicz) [21, 22].

This paper will describe in detail the modification process of the hydraulic water hammer test stand built at the Wrocław University of Science and Technology. Examples of the obtained results will be presented and a discussion will be held on the further necessity of this type of research as well modification of test stand.

2 Water Hammer Effect Test Stand

In order to conduct experimental research and verify the modified mathematical models of the water hammer effect, a number of test stands were built in the laboratory of the Department of Technical Systems Operation and Maintenance, Wrocław University of Science and Technology. The first stand is presented in Fig. 1 [20]. This stand made it possible to achieve a full water hammer effect for lines with a minimum length of 13.1 m (assuming the pressure wave speed of 1,309 m/s and the switching time of the 4/2 directional control valve of 20 ms).

In the test stand, a steel pipe (L = 18 m, d = 9 mm), (section between points 7 and 9, Fig. 1) is supplied by a variable displacement pump (6) PTOZ2-K1-100R1 with manual adjustment. The pressure (constant and variable components) at the beginning and end of the tested pipe was measured with strain gauge pressure transducers 7 and 9 in Fig. 1. Due to the significant distance between the main pump (PTOZ2) and the oil tank, an auxiliary pump (1) was installed in the suction line of the pump (6) ensuring appropriate suction conditions. Pressure in the PTOZ2 pump suction line was monitored with a vacuum gauge (5). The adjustable throttle valve (11) was used to set the value of the loading pressure after a sudden switching of the 4/2 directional valve (10). The check valves (12) were used to eliminate the possible influence of the reflected pressure wave

between the directional control valve (10) and the oil tank. The cooler (14) stabilized the oil temperature with an accuracy of ±1 °C. The test stand used L-HL68 hydraulic oil with a viscosity of 68 cSt at 40 °C. Safety valves 2 and 8 protected the relevant parts of the hydraulic system against overload. The flow meter (13) measured the value of the volumetric flow rate. Instantaneous pressure values at measurement points were recorded on a Tektronix TDS-224 digital oscilloscope and a computer with a dedicated WaveStar software.

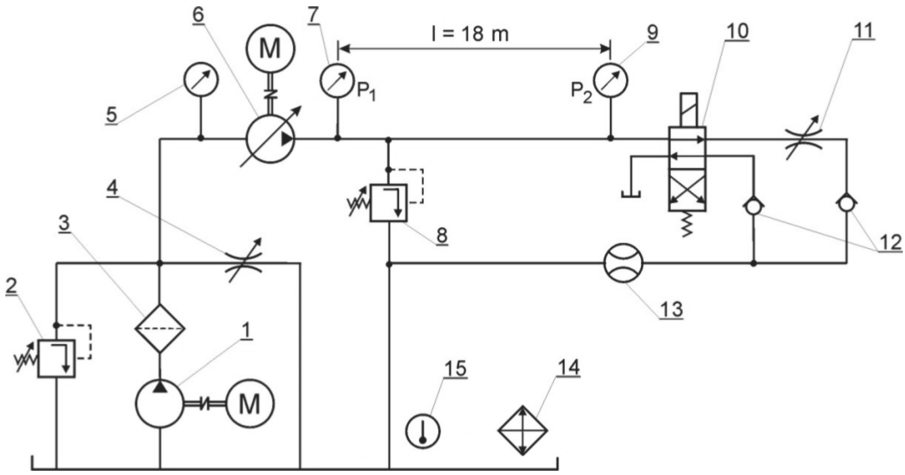


Fig. 1. Diagram of the stand for testing the water hammer effect in closed pressure lines: 1 – fixed displacement pump, 2 – safety valve, 3 – oil filter, 4 – adjustable throttle valve, 5 – pressure gauge, 6 – variable displacement pump, 7 – pressure sensor, 8 – safety valve, 9 – pressure sensor, 10 – directional control valve 4/2, 11 – adjustable throttle valve, 12 – check valve, 13 – flowmeter, 14 – fluid cooler, 15 thermometer, [20].

In the quasi-steady state (prior to transient), the pressure was recorded as a function of time, and then, using specialized software, the amplitude-frequency spectra were determined, as shown in Fig. 2.

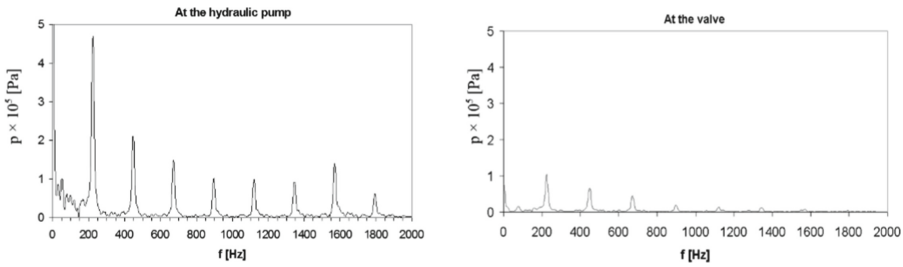


Fig. 2. Amplitude-frequency spectrum of pressure pulsation caused by pump flow pulsation (ν = 100 cSt, mean pressure at the valve 1.2 MPa, mean pump flow rate 50 dm^3/min) [20].

As can be seen in Fig. 2, in both spectra the dominant component is the fundamental component resulting from the pulsation of the flow of the pump, $f_1 = 225$ Hz. Successive components of the spectrum are its multiple.

These components will also be visible in time domain graph of pressure during the water hammer (lines 3 and 4). This is shown in Fig. 3 in comparison to the simulation runs (lines 1 and 2). The method of determining the simulation runs has been given in [8] and will not be discussed in detail in this paper. The simulation runs do not take into account the pressure pulsation resulting from the pulsation of the displacement pump flow.

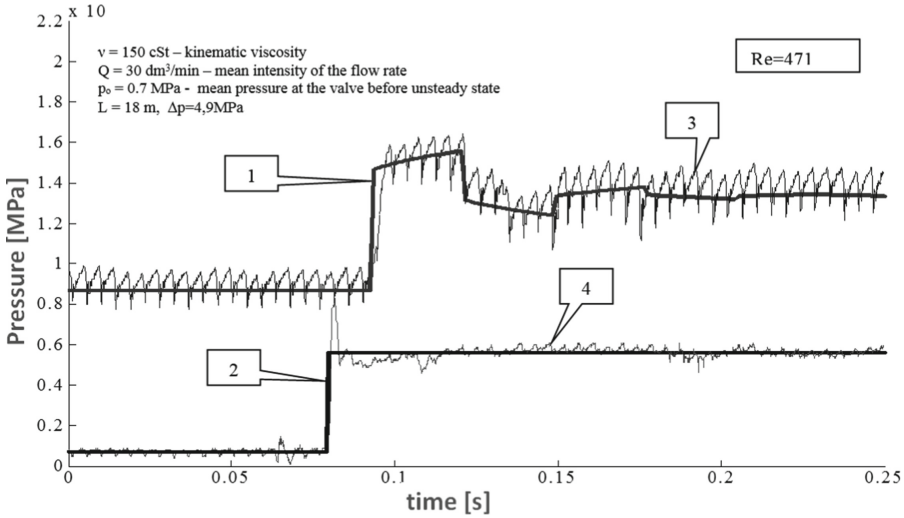


Fig. 3. Pressure run in water hammer effect and theoretical simulations [20].

The development of analytical considerations on the occurrence of water hammer in hydraulic lines of small diameters [22] forced the design of a new test stand. The constructed test stand made it possible to test relatively long and short hydraulic lines, and its limitation was the actuation time of shut-off valves. Ultimately, experimental tests were carried out for steel pipes with a length of 7 and 2.3 m and an internal diameter of 4 mm. At the ends of the tested pipes, strain gauge pressure sensors (13) and (14) AT-5230 were installed, both with a measuring range of 25 MPa and a measuring accuracy of ±0.025 MPa. A quick shut-off valve (17) of poppet type was installed at the end section of the tested pipe, whose task was to suddenly stop the flow. The leakage rate on this valve is indicated by the manufacturer in drops per minute. The valve was controlled by a conventional electromagnetic coil. The actuation times of both valves (at the beginning and the end of the tested pipe) were selected to be identical and equal 10 ms. An accumulator (9) with a volume of 13 dm^3 was installed in the system, the role of which was to allow the reflection of the wave running in the direction from the valve (17) to the accumulator (9) after closing the valve (17) at the end of the line. A check valve (11) was installed on the accumulator supply line to ensure unidirectional flow.

The test system contained ISO32 mineral oil with a reduced viscosity ($1 * 10^{-4}$ m^2/s at 20 °C). The tested pipe was supplied by an external gear micropump, driven by an electric motor with an inverter. This solution allowed for a smooth change of the flow rate in the tested micropipe. The scheme of the test stand is shown in Fig. 4.

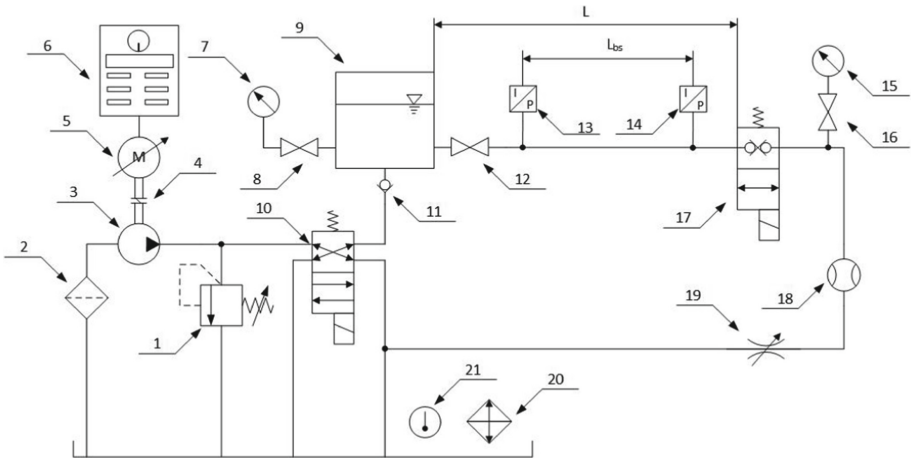


Fig. 4. Diagram of the hydraulic system of the test stand: 1 – pressure relief valve, 2 – suction filter, 3 – gear micropump, 4 – clutch, 5 – electric motor with adjustable speed, 6 – control cabinet, 7 – pressure gauge, 8 – shut-off valve, 9 – liquid tank (accumulator), 10 – electrically controlled directional control valve 4/2, 11 – check valve, 12 – shut-off valve, 13, 14 – strain gauge pressure transducers, 15 – manometer, 16 – shut-off valve, 17 – poppet shut-off valve, 18 – flow meter, 19 – adjustable throttle valve, 20 – oil cooler, 21 – thermometer.

Using the stand shown in Fig. 4, the experimental results of the pressure as a function of time at the end of the pipe (just before the shut-off valve 17) were obtained and used to validate the results of the numerical solutions. Figure 5 shows an example of the results obtained for the following conditions: oil temperature 21 °C, average initial velocity of the liquid flow in the pipe 1.83 m/s, pressure wave speed 1,273 m/s. The simulation results were obtained for the conditions of sudden shut-off valve closure and unsteady friction losses.

The presented pressure results obtained from the experimental measurements (dashed line) has a pressure pulsation component originating from the pulsation of the displacement pump flow. However, the simulation solution does not take this into account. The elimination of pressure pulsation caused by pulsation of the displacement pump flow can be achieved by using a hydropneumatic accumulator - provided that the natural frequency of the accumulator corresponds to the pulsation frequency, i.e. it is usually in the range 175–350 Hz.

In further development of the water hammer effect test stand, an attempt was made to minimize the pressure pulsation from the pulsation of the displacement pump flow through changes in the supply system of the tested pipe. Unlike in the systems presented so far, the tested pipe was supplied by a hydraulic actuator acting as a single-piston displacement pump. This actuator was driven by a second actuator, which was powered

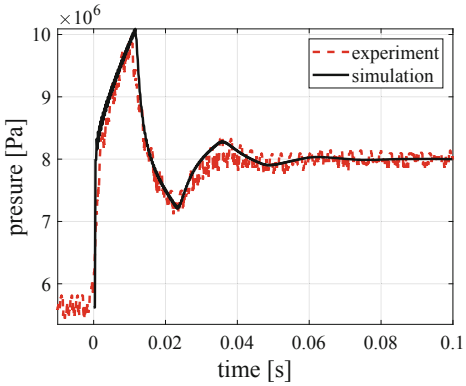


Fig. 5. Pressure as a function of time at the shut-off valve: $\nu = 100$ cSt, Q = 1.38 dm^3/min.

by a hydraulic power unit with a constant displacement pump with an electric motor with adjustable rotational speed. Due to this solution, the impact of pulsation of the displacement pump flow on the tested pipe was limited under the condition of smooth operation of the supply actuator. Moreover, this solution increased the capacitance of the system on the supply side. The diagram of the hydraulic system of the modified test stand is shown in Fig. 6.

The tested copper pipe (length 30 m, internal diameter 4 mm) was wound on a drum with a diameter of 1.2 m and supplied by an actuator (11). The adjustable throttle valve (23) is responsible for generating the mean pressure for the set flow rate. After their actuation, the quick shut-off valves (15) and (22) are used to cause a water hammer effect in the pipe. Simultaneously with the actuation of the shut-off valves (15) and (22), the pump (3) is connected with the oil tank by switching the directional control valve (7) into the neutral position.

During the operation of the pump (3) to supply the actuator (10), its performance is stabilized by a two-way flow control valve (9). This valve also causes that the pump works under a constant load resulting from the setting of the pressure relief valve (1), which eliminates changes in its performance caused by the actual characteristics of the pump. Dynamic changes in pressure at the beginning and at the end of the tested pipe were recorded using pressure transducers (19) and (20) with a measuring range up to 40 MPa and accuracy of ±0.15% (BSFL), and the flow rate with a flow meter (24). The pressure transducers used were integrated with the fluid temperature meters. Thus, the liquid temperature was recorded at the beginning and end of a 30 m long cable. The modular structure of the test stand enables the use of different working fluids in two parts of the test stand. The pump with power supply has its own tank. On the other hand, the part of the test stand where the tested pipe is located has its own tank, separate from the power supply. Therefore, in the presented stand, various fluids can be used in the test part, even those that are not recommended by the manufacturer of the pump (3) supplying the driving cylinder (10).

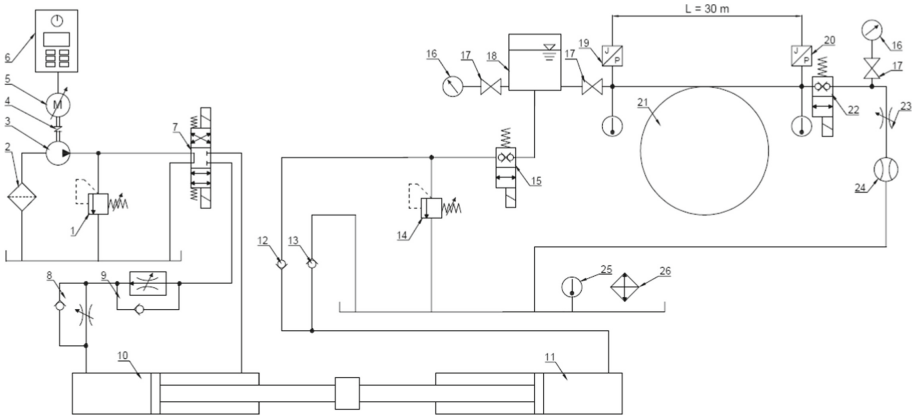


Fig. 6. Diagram of the system for water hammer effect testing for a 30 m long pipe: 1 – pressure relief valve, 2 – suction filter, 3 – pump, 4 – clutch, 5 – electric motor, 6 – control cabinet, 7 – 4/3 electrically controlled directional control valve, 8 – throttle-check valve, 9 – two-way flow control valve, 10 – driving actuator, 11 – driven actuator (source of flow in the tested line), 12, 13 – check valves, 14 – pressure relief valve, 15 – electrically operated cut-off valve, 16 – pressure gauge, 17 – shut-off valve, 18 – accumulator, 19, 20 – strain gauge pressure transducer, 21 – tested pipe, 22 – electrically controlled shut-off valve, 23 – adjustable throttle valve, 24 – flow meter, 25 – thermometer, 26 – oil cooler.

As can be seen from Fig. 7, the use of a modified supply of the tested pipe eliminated the pressure pulsation caused by the pulsation of the pump flow. As a result, all the obtained dynamic pressure changes are smoothed, and thus they are ideal for comparisons with the results of numerical tests.

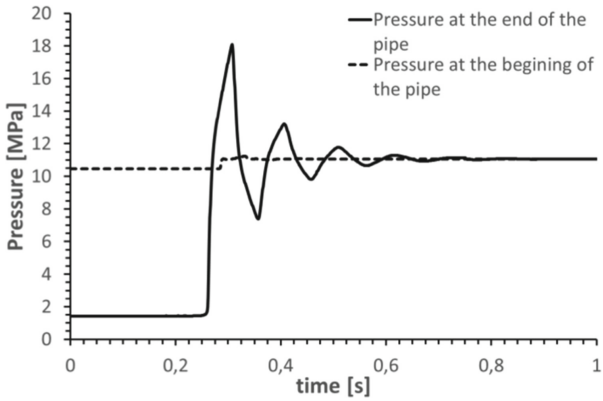


Fig. 7. Pressure as a function of time during water hammer in a 30 m long pipe: $\nu = 10$ cSt, Q = 7 dm^3/min.

3 Summary

The paper presents the development of the concept of test stands for researching the phenomenon of water hammer effect. All this stands have been built and the exemplary results of experimental studies of dynamic pressure change have been recorded. As demonstrated by experimental and numerical simulations presented in other studies, it is very important to assure an accurate stable initial flow velocity and dynamical stabilization of the working fluid temperature. In the latest version of our test stand shown in Fig. 6, the value of the initial flow rate was stabilized by a two-way flow control valve. In the same system, the two-way flow control valve cooperated with the pressure relief valve at the pump, thanks to which the pump worked at a set operating point, which ensured the stability of internal leaks (at a constant temperature of the working fluid). In Figs. 3, 5 and 7 we can observe the pressure time course recorded at the test stands. The pressure time course (at the valve, at the end of the tested pipe) shown in Fig. 7 is less damped than the pressure time course shown in Fig. 5: it has a larger maximum amplitude and the unsteady state lasts longer. This is due to the significant differences in viscosity of the working fluid. In the system in Fig. 6 the kinematic viscosity of the oil is 10 cSt, while in the system in Fig. 4 the kinematic viscosity of the oil is 100 cSt. The higher oil viscosity results in greater energy dispersion and greater internal friction damping.

As the further development of tests the medium of reduced viscosity (e.g. water) will be used as a working fluid and the flow rate will be increased so as to move into the strongly developed turbulent flow range with the possibility of cavitation during dynamic pressure changes. Moreover, the test stand will be extended with two hydropneumatic accumulators in which the gas pressure value will be controlled. A test pipe will be installed between the accumulators. This will make it possible to realise non-pulsatile flows and flows with cavitation. Also, the use of pneumatically or mechanically operated shut-off valves will shorten the valve actuation time, which will allow for the testing of pipes of shorter lengths.

In the future, it is also planned to test the flow in the plastic micropipes (with lower operating pressures). In this case, retarded strain occurs, which significantly affect the pressure changes.

The registered dynamic pressure changes will be used to verify the developed mathematical models of the water hammer effect. Correct models will be used to analyze newly designed and modernized pressure systems and will be used for follow-up (online - using algorithms based on artificial intelligence) protection of these systems against excessive, destructive pressure increases and leak detection. Accurate determination of maximum pressures during water hammer will allow determination of maximum loads to which the pipeline will be subjected during operation. In addition, reliable modelling of unsteady states in hydraulic systems will enable changes to be made to the hydraulic system at the design stage in order to reduce negative effects, such as vibroacoustic signals and critical damage to pipelines. As of today, the base of completed water hammer experiments is still limited. Most of the tests were performed for a medium with low viscosity, i.e. water. Hence, the implementation of new tests in a wide range of water hammer number *Wh* is so important.

References

1. Leishear, R.A.: Water hammer causes water main breaks. J. Press. Vessel Technol. **142**, 18 (2020)
2. Stryczek, S.: Napęd hydrostatyczny [Hydrostatic drive]. WNT, Warsaw (2014). (in Polish)
3. Karpenko, M., Bogdevičius, M.: Investigation into the hydrodynamic processes of fitting connections for determining pressure losses of transport hydraulic drive. Transport **35**(1), 108–120 (2020)
4. Bogdevičius, M., Lingaitis, L.P.: Simulation of dynamics processes of hydraulic system with axial-reciprocating piston pump and electrical engine. In: Proceedings of the 6th JFPS International Symposium on Fluid Power: JFPS, Tsukuba (2005)
5. Kudźma, Z.: Tłumienie pulsacji ciśnienia i hałasu w układach hydraulicznych w stanach przejściowych I ustalonych [Damping of pressure pulsations and noise in hydraulic systems in transient and steady states]. Publishing House of Wrocław University of Science and Technology, Wrocław (2012). (in Polish)
6. Karpenko, M., Bogdevičius, M.: Investigation of hydrodynamic processes in the system—"axial piston pumps – pipeline – fittings". In: Transport Problems 2018, X International Scientific Conference, VII International Symposium of Young Researchers: Proceedings, pp. 832–843. Silesian University of Technology, Gliwice (2018)
7. Karpenko, M.: Investigation of Energy efficiency of mobile machinery hydraulic drives. Doctoral dissertation. Technical sciences, Transport Engineering (T003), Vilnius (2021)
8. Stosiak, M.: Identyfikacja oddziaływania drgań i metody ich redukcji w wybranych zaworach hydraulicznych [Identification of vibration effects and methods for their reduction in selected hydraulic valves]. Publishing House of Wrocław University of Science and Technology, Wrocław (2015). (in Polish)
9. Engel, Z., Zawieska M.: Hałas i drgania w procesach pracy: źródła, ocean, zagrożenia [Noise and vibration in work processes: sources, evaluationocean, threats]. Central Institute for Labour Protection—National Research Institute, Warsaw (2010). (in Polish)
10. Tonin, R., Brett, J., Colagiuri, B.: The effect of infrasound and negative expectations to adverse pathological symptoms from wind farms. J. Low Freq. Noise Vib. Active Control **35**(1), 77–90 (2016)
11. Gužas, D., Viršilas, R.: Infrasound hazards for the environment and the ways of protection. Ultragarsas (Ultrasound) **64**(3), 34–37 (2009)
12. Chaban, R., Ghazy, A., Georgiade, E., Stumpf, N., Vahl, C.F.: Negative effect of high-level infrasound on human myocardial contractility: in-vitro controlled experiment. Noise Health **23**(109), 57–66 (2021)
13. Savkiv, V., Mykhailyshyn, R., Maruschak, P., Kyrylovych, V., Duchon, F., Chovanec, Ľ: Gripping devices of industrial robots for manipulating offset dish antenna billets and controlling their shape. Transport **36**(1), 63–74 (2021)
14. Wylie, E.B., Streeter, V.L.: Fluid Transients in Systems. Prentice Hall, New York (1993)
15. Urbanowicz, K.: Modern modeling of water hammer. Pol. Marit. Res. **24**(3), 68–77 (2017)
16. Urbanowicz, K., Jing, H., Bergant, A., Stosiak, M., Lubecki, M.: Progress in analytical modeling of water hammer. In: Proceedings of the Fluids Engineering Division Summer Meeting, FEDSM 2021 (2021)
17. Urbanowicz, K., Bergant, A., Stosiak, M., Lubecki, M.: Analytical solutions of water hammer in metal pipes. Part I - brief theoretical study, Chap. 7. In: Lesiuk, G., et al. (eds.) Structural Integrity 24: Fatigue and Fracture of Materials and Structures, pp. 57–68 (2022)
18. Urbanowicz, K., Bergant, A., Stosiak, M., Towarnicki, K.: Analytical solutions of water hammer in metal pipes. Part II - comparative study, Chap. 8. In: Lesiuk, G., et al. (eds.) Structural Integrity 24: Fatigue and Fracture of Materials and Structures, pp. 69–83 (2022)

19. Urbanowicz, K., Bergant, A., Karadzić, U., Jing, H., Kodura, A.: Numerical investigation of the cavitational flow for constant water hammer number. J. Phys. Conf. Ser. **1736**, 012040 (2021)
20. Zarzycki, Z., Kudźma, S., Kudźma, Z., Stosiak, M.: Simulation of transient flows in a hydraulic system with a long liquid line. J. Theoret. Appl. Mech. **45**(4), 853–871 (2007)
21. Urbanowicz, K., Stosiak, M., Towarnicki, K., Duan, H.-F., Bergant, A.: Simulation of transient flow in micro-hydraulic pipe system. In: Stryczek, J., Warzyńska, U. (eds.) NSHP 2020. LNME, pp. 205–215. Springer, Cham (2021). https://doi.org/10.1007/978-3-030-59509-8_18
22. Urbanowicz, K., Stosiak, M., Towarnicki, K., Bergant, A.: Theoretical and experimental investigations of transient flow in oil-hydraulic small-diameter pipe system. Eng. Fail. Anal. **128**(12), 1–16 (2021)

Assessment of Hydrogen Assisted Degradation of Stacker Conveyor Boom Steel

Olha Zvirko[1](✉), Oleksandr Tsyrulnyk[1], and Leonid Polishchuk[2]

[1] Karpenko Physico-Mechanical Institute of the National Academy of Sciences of Ukraine, 5 Naukova St., Lviv 79060, Ukraine
olha.zvirko@gmail.com

[2] Vinnytsia National Technical University, 95 Khmelnytsky Highway, Vinnytsia 21021, Ukraine

Abstract. An experimental investigation of operational degradation of the low carbon steel long-term operated under combined cyclic loading and environmental actions was carried out. The steel in different states, after 30-year operation under tensile and compressive cyclic loading and unloading one, the reference steel, was studied. The degradation degree of the post-operated steel was evaluated by mechanical, electrochemical and corrosion fatigue testing. A significant decrease in impact toughness, plasticity and corrosion resistance of the operated steel, compared to these characteristics of the reference steel, was revealed. The residual hydrogen concentration in the operated steel was significantly higher than in the reference steel. The environmental acceleration effect on crack growth rate was not revealed for the reference steel. However, fatigue crack growth rate in the operated metal was accelerated in the environment simulating acid rainwater in industrial region.

Keywords: Steel · Hydrogen assisted degradation · Corrosion resistance · Mechanical behaviour · Corrosion fatigue · Crack propagation · Long-term service

1 Introduction

Stacker conveyors are used to stockpile material for later use, being an essential part of large-scale production in many industries. Mechanical parts of stacker conveyors are frequently subjected to cyclically varying loads under environmental conditions. Their service lifetime depends on resistance of the steel to corrosion fatigue as well as on physical and mechanical properties degradation under long-term operation [1]. Degradation of steel structures is usually manifested in decreasing corrosion resistance, plasticity, resistance to brittle fracture and corrosion fatigue [2–13], which defined their serviceability. For structures operated under the influence of corrosive environments and cyclic loading, the most important characteristic is corrosion fatigue crack growth rate in a metal [2, 9, 10, 14–16].

Boom frame of stacker conveyor is usually made from carbon steels and it is subjected to cyclic loading and atmospheric corrosion under operation. It is known [17, 18] that

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 200–207, 2023.
https://doi.org/10.1007/978-3-031-25863-3_19

atmospheric corrosion is accompanied by hydrogen evolution. Therefore, environmental degradation by hydrogen, delayed fracture and hydrogen affected fatigue crack growth could the main problems for such structural components made of carbon steels. Both mechanical and electrochemical characteristics of steels due to long-term operation can be significantly deteriorated [19].

The present study is devoted to assessment of operational degradation of the low carbon steel of stacker conveyor, developing previous researches [14, 20] and considering possibility of hydrogen charging under long-term operation.

2 Objects, Materials and Methods

2.1 Materials

The study object was stacker conveyor boom after 30 years of operation. The boom frame was made from angle bars of the cold-formed low carbon steel (~0.2 C). The steel had a typical ferritic–pearlitic structure. An angle bar was 45 × 45 × 5 mm in size. Based on structural and stress analysis of boom frame, some structural elements of the frame were distinguished and cut off for further studies: section with minimal loading under operation was considered as unloading one (reference steel); section operating under tensile cyclic loading and section operating under compressive cyclic loading.

The degradation degree of the operated steel was evaluated by mechanical, electrochemical and fatigue testing. Properties of the operated steel were compared with that of the reference steel. Residual hydrogen concentration was also determined.

Degree of in-service degradation was estimated as relative change in each determined mechanical property (strength and plasticity) by using an index λ given by:

$$\lambda = \frac{M_{op} - M_{in}}{M_{in}} \cdot 100\%, \tag{1}$$

where M_{op} and M_{in} – values of a certain mechanical property of the steel in the post-operated state and reference one, respectively.

2.2 Determination of Residual Hydrogen Concentration

Determination of residual hydrogen content in steels was performed by the heat extraction method at temperature of 950 °C using Eltra Hydrogen Analyzer H-500. The steel samples of 2 × 6 × 40 mm in size were used.

2.3 Tensile Testing

Tensile tests were carried out at the strain rate $\varepsilon = 3 \cdot 10^{-3}\ s^{-1}$ to obtain the basic mechanical properties of the steel: ultimate strength σ_{UTS}, yield strength σ_Y, reduction in area RA and elongation δ. The flat tensile specimens of 2 × 10 × 40 mm in size were used.

2.4 Impact Testing

Impact toughness KCV was evaluated by impact tests using Charpy V-notch specimens of the cross section of 4 × 10 mm with 0.25 mm radius of V-notch. The tests were carried out within the temperature range from –40 °C to 20 °C.

2.5 Electrochemical Investigations

Potentiodynamic polarisation curves were recorded in a 0.3% NaCl aqueous solution by sweeping potential at a sweep rate of 1.0 mV · s^{-1} under room temperature, using a standard three-electrode electrochemical cell consisting of working electrode, Ag/AgCl (saturated KCl) reference electrode and auxiliary Pt electrode. The basic electrochemical characteristics of steels, corrosion potential E_{corr} and corrosion current density i_{corr}, were determined by the graph-analytic method.

2.6 Fatigue Testing

Fatigue crack growth experiments were carried out on beam specimens made of the low carbon steel of two boom frame sections, namely, unloading reference section and section, operating under tensile cyclic loading. The tests were performed in air and in corrosive environment, 0.01 N NaCl solution with pH4 (acidified by adding HCl) simulating acid rainwater in industrial region. The environment was applied to stress concentrator zone of the specimen by dropping. Beam specimens 4 × 18 × 140 mm in size with notch were deformed by cantilever bending. The test frequency was 5 Hz in air and 0.3 Hz in the corrosive environment, respectively. Stress ratio was 0.1 and 0.75. High value of stress ratio (0.75) was applied to simulate working cyclic loading of the boom frame of stacker conveyor. Finally, fatigue crack growth curves (fatigue crack growth rate da/dN vs. stress intensity factor range ΔK) were plotted.

3 Results of Experimental Studies and Discussion

3.1 Residual Hydrogen Concentration in the Low Carbon Steel of Stacker Conveyor Boom

Table 1 reports the values of hydrogen content measured in steels with different states by heat extraction at temperature of 950 °C. The residual hydrogen concentration in both studied post-operated steels is approximately 2 times higher than in the reference one.

Such an increase in hydrogen content in the operated steels can be associated with their hydrogen charging under operation, taking into account that stacker conveyor was operated under environmental conditions for many years and possibility of hydrogen evolution and absorption under atmospheric corrosion as demonstrated in researches [17, 18]. It should be also noted that hydrogen solubility in steels increases under cyclic loading conditions, as it was demonstrated for low alloy steel in [21].

Table 1. Hydrogen concentration in the low carbon steel in different states.

Steel state	Hydrogen concentration C_H (ppm)
Reference	0.14
After operation under tensile cyclic loading	0.29
After operation under compressive cyclic loading	0.32

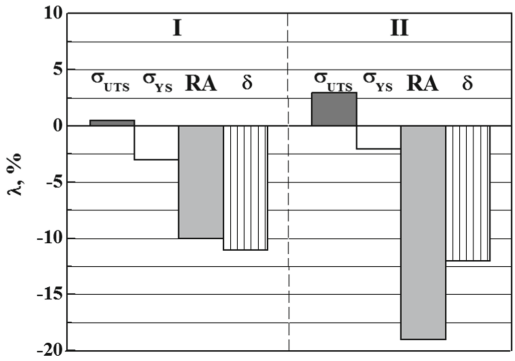


Fig. 1. Changes in the mechanical properties of strength and plasticity for the low carbon steel in different states: I – after operation under tensile cyclic loading; I – after operation under compressive cyclic loading.

3.2 Basic Mechanical Characteristics of the Low Carbon Steel of Stacker Conveyor Boom

Changes in basic mechanical properties of the studied steels caused by operation were analysed using index λ (Fig. 1).

A minor change in strength characteristics of the operated steels compared with the reference one was observed. Nevertheless, reduction in area and elongation were significantly decreased as a result of long-term operation. Both tensile and compressive cyclic loading under operation leads to plasticity characteristics degradation of the low carbon steel.

3.3 Brittle Fracture Resistance of the Low Carbon Steel of Stacker Conveyor Boom

The reference steel was characterized by the highest resistance to brittle fracture among all studied steel states (Table 2). Thus, at ambient temperature (20 °C), the values of fracture energy of the operated steels were in 1.25–1.3 times lower than that of the reference one. The post-operated steel had lower impact toughness value compared with that of the reference steel at all test temperatures. The extremely low values of impact toughness were obtained at testing at temperature of –40 °C for all investigated states of the steel. Decreasing impact toughness of the steel due to long-term operation was almost

the same for both studied post-operated steels, irrespective of the sign of operating cyclic loading, at testing at temperature of 0 °C and 20 °C.

Table 2. Impact toughness KCV (J/cm^2) of the studied low carbon steel at different test temperatures.

Steel state	−40 °C	0 °C	20 °C
Reference	21	158	159
After operation under tensile cyclic loading	12	125	127
After operation under compressive cyclic loading	18	120	123

The impact toughness was revealed to be more sensitive parameter to in-service degradation of the steel in comparison with strength and plasticity properties.

3.4 Corrosion Resistance of the Low Carbon Steel of Stacker Conveyor Boom

The steel operated under the action of tensile or compressive cyclic loading was characterised by higher corrosion intensity and more negative values of the corrosion potential in comparison with the reference one (Table 3).

Both steels after operation were characterized by the same corrosion resistance, and the highest corrosion resistance was typical for the reference steel. Thus, corrosion current density i_{corr} of the post-operated steel is approximately 25% higher compared with the reference one (Table 3), irrespectively of the sign of operating cyclic loading.

Table 3. Electrochemical characteristics of the studied low carbon steel in different states in 0.3% NaCl solution.

Steel state	E_{corr} (V)	i_{corr} (μA/cm^2)
Reference	−0.52	7.86
After operation under tensile cyclic loading	−0.53	9.82
After operation under compressive cyclic loading	−0.55	9.89

Corrosion degradation of the steel is obviously associated with increasing thermodynamic instability, which leads to acceleration of anodic dissolution reaction. The steel can be hydrogenated under atmospheric corrosion as shown in [17, 18] and mechanical stresses intensify hydrogen diffusion. The higher residual hydrogen content in the post-operated steel (Table 1) compared with that in the reference one confirms this assumption. Therefore, it can be suggested that deterioration of corrosion and electrochemical characteristics of the low carbon steel of stacker boom frame after operation is caused by its hydrogen assisted degradation.

3.5 Resistance to Fatigue and Corrosion Fatigue Crack Growth in the Low Carbon Steel of Stacker Conveyor Boom

The variation in fatigue crack propagation rate (*da*/*dN*) with stress-intensity range (ΔK) for the low carbon steel in different states is shown in Fig. 2 at a stress ratio of 0.1 and 0.75, in environments of 0.01 N NaCl solution (pH4), simulating acid rainwater in industrial region, and air.

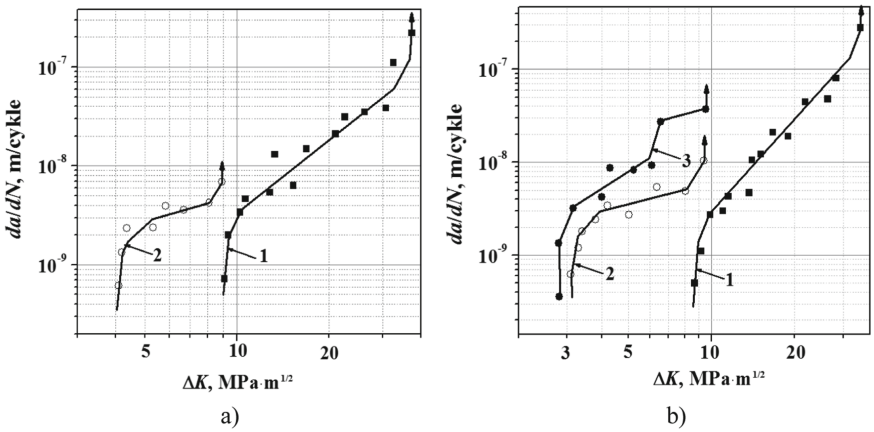


Fig. 2. Fatigue crack propagation in the steel in air (1, 2) and in 0.01 N NaCl solution (pH4) (3) at a stress ratio of 0.1 (1) and 0.75 (2, 3): a) the reference and b) the post-operated steels.

Stress intensity factor range ΔK for which it was possible to investigate fatigue crack growth in the low carbon steel was limited due to thin thickness of the specimens. The values of ΔK, which satisfies the requirement of minimum thickness of specimen to insure plane strain state, for the reference and post-operated steels were 10.98 and 10.62 MPa · $m^{1/2}$ at a stress ratio of 0.1, and 3.05 and 2.95 MPa · $m^{1/2}$ at a stress ratio of 0.75, respectively. Therefore, only the threshold stress intensity factor range ΔK_{th} can be considered as characteristic of the steel.

For a stress ratio of 0.1, in-service degradation of the steel had no noticeable effect on fatigue crack growth rate in air (Fig. 2). Nevertheless, the difference in rate values *da*/*dN* for the steel in different states, mainly in the near-threshold region of ΔK, was detected at testing at a stress ratio of 0.75. For higher values of ΔK the difference was not observed, which agreed with assumption concerning low sensitivity of fatigue crack growth rate to microstructural changes in steels caused by operation within the mid-region of stress intensities, where power-law behaviour nominally described by the Paris equation (the Paris regime where the logarithm of da/dN is linearly dependent on ΔK).

The environmental acceleration effect on crack growth rate was not revealed for the reference steel. However, fatigue crack growth rate in the post-operated steel was accelerated in 0.01 N NaCl solution with pH4 (Fig. 2b) in the whole range ΔK, being typical for high-strength steels. The corrosion fatigue threshold for the post-operated steel was significantly lower (2.82 MPa · $m^{1/2}$) compared to that determined for the

reference steel (4 MPa · $m^{1/2}$). The rapid increase in corrosion fatigue crack growth rate in the post-operated steel observed for $\Delta K = 6$ MPa · $m^{1/2}$ is associated with its susceptibility to stress corrosion fatigue. Possible hydrogenation of metal at a crack tip under operating conditions as a result of atmospheric corrosion should be also considered [17, 18].

4 Concluding Remarks

Long-term operation of the low carbon steel of the stacker conveyor boom under combined action of cyclic loading and atmospheric corrosion caused deterioration of the mechanical and corrosion behaviour, which is obviously caused by its hydrogen assisted degradation. A remarkable decrease in plasticity, impact toughness and corrosion resistance of the operated steel, irrespectively of the sign of operating cyclic loading, in comparison with these characteristics of the reference steel was revealed. Thus, reduction in area was decreased in ~10–19%, elongation – 12%, impact toughness – 20% (at 20 °C) and corrosion current density was increased in ~25% as a result of long-term operation of the investigated steel. The residual hydrogen concentration in the operated steel was significantly higher (in 2.1–2.3 times) than in the reference one, which can be associated with hydrogen charging under atmospheric corrosion during operation. The environmental acceleration effect on crack growth rate was not revealed for the reference steel. At the same time, the corrosion fatigue threshold was decreased in ~40% and fatigue crack growth rate in the post-operated metal was accelerated in corrosive environment, especially within the mid-region of stress intensities, indicating its susceptibility to stress corrosion fatigue.

References

1. Polishchuk, L., Bilyy, O., Kharchenko, Y.: Prediction of the propagation of crack-like defects in profile elements of the boom of stack discharge conveyor. East.-Eur. J. Enterp. Technol. **6**(1), 44–52 (2016)
2. Lesiuk, G., Szata, M.: Kinetics of fatigue crack growth and crack paths in the old puddled steel after 100-years operating time. Frattura ed Integrità Strutturale **9**(34), 290–299 (2015)
3. Pustovoi, V.M., Reshchenko, I.O., Zvirko, O.I.: Influence of long-term cyclic deformation on the electrochemical behavior of steels of marine gantry cranes. Mater. Sci. **51**(1), 125–130 (2015)
4. Ohaeri, E., Eduok, U., Szpunar, J.: Hydrogen related degradation in pipeline steel: a review. Int. J. Hydrogen Energy **43**(31), 14584–14617 (2018)
5. Zvirko, O., Gabetta, G., Tsyrulnyk, O., Kret, N.: Assessment of in-service degradation of gas pipeline steel taking into account susceptibility to stress corrosion cracking. Proc. Struct. Integr. **16**, 121–125 (2019)
6. Lesiuk, G., Rymsza, B., Rabiega, J., Correia, J.A.F.O., De Jesus, A.M.P., Calcada, R.: Influence of loading direction on the static and fatigue fracture properties of the long term operated metallic materials. Eng. Fail. Anal. **96**, 409–425 (2019)
7. Marushchak, P.O., Kret, N.V., Bishchak, R.T., Kurnat, I.M.: Influence of texture and hydrogenation on the mechanical properties and character of fracture of pipe steel. Mater. Sci. **55**(3), 381–385 (2019)

8. Nemchuk, O.O.: Influence of the working loads on the corrosion resistance of steel of a marine harbor crane. Mater. Sci. **54**(5), 743–747 (2019)
9. Voloshyn, V.A.: Cyclic corrosion crack resistance of an exploited welded joint of 17G1S pipe steel. Mater. Sci. **56**(1), 119–124 (2020)
10. Kret, N.V., Svirska, L.M., Venhrynyuk, T.P.: Corrosion-fatigue crack propagation in exploited pump rods made of 20N2M steel. Mater. Sci. **56**(2), 279–283 (2020)
11. Wang, Y., Wang, W., Zhang, B., Zhao, Y., Li, C.-Q.: Fracture resistance of naturally corroded steel after service for 128 years. Eng. Fract. Mech. **265**, 108367 (2022)
12. Boiko, A.V., Makarenko, V.D., Maksymov, S.Yu.: Some mechanical characteristics of structural steels of cooling systems of continuous operation. Strength Mater. **53**(2), 272–276 (2021)
13. Cai, J., Sun, L., Ma, H., Li, X.: Corrosion characteristics of Q690qE high-strength bridge steel in simulated coastal–industrial environment and its influence on mechanical and corrosion fatigue behaviors. Constr. Build. Mater. **341**, 127830 (2022)
14. Polishchuk, L.K., Kharchenko, H.V., Zvirko, O.I.: Corrosion-fatigue crack-growth resistance of steel of the boom of a clamp-forming machine. Mater. Sci. **51**(2), 229–234 (2015)
15. Syrotyuk, A.M., Babii, A.V., Barna, R.A., Leshchak, R.L., Marushchak, P.O.: Corrosion-fatigue crack-growth resistance of steel of the frame of a sprayer boom. Mater. Sci. **56**(4), 466–471 (2021)
16. Zhang, Y., Liu, X., Lai, J., Wei, Y., Luo, J.: Corrosion fatigue life prediction of crude oil storage tank via improved equivalent initial flaw size. Theoret. Appl. Fract. Mech. **114**, 103023 (2021)
17. Tsuru, T., Huang, Y., Ali, M.R., Nishikata, A.: Hydrogen entry into steel during atmospheric corrosion process. Corros. Sci. **47**(10), 2431–2440 (2005)
18. Li, S., Akiyama, E., Shinohara, T., Matsuoka, K., Oshikawa, W.: Hydrogen entry behavior into iron and steel under atmospheric corrosion. ISIJ Int. **53**(6), 1062–1069 (2013)
19. Zvirko, O., Nykyforchyn, H., Tsyrulnyk, O.: Evaluation of impact toughness of gas pipeline steels under operation using electrochemical method. Proc. Struct. Integr. **22**, 299–304 (2019)
20. Kharchenko, E.V., Polishchuk, L.K., Zvirko, O.I.: Estimation of the in-service degradation of steel shapes for the boom of a clamp-forming machine. Mater. Sci. **49**(4), 501–507 (2014)
21. Cabrini, M., Lorenzi, S., Pastore, T., Pesenti, B.D.: Hydrogen diffusion in low alloy steels under cyclic loading. Corros. Rev. **37**(5), 459–467 (2019)

Numerical Analysis of Passenger Car Wheel Suspension Models in a Vertical Test of an Axle

Miroslav Blatnický, Ján Dižo(✉), and Denis Molnár

University of Žilina, Univerzitná 8215/1, 010 26 Žilina, Slovak Republic
{miroslav.blatnicky,jan.dizo,denis.molnar}@fstroj.uniza.sk

Abstract. The paper is a continuation of ongoing research focused on evaluation of the magnitude of passenger car body roll (around longitudinal axis) and pitch (around transverse axis) for slalom and braking manoeuvres. Data from experimental runs will be compared with numerical simulation of a passage of the modelled vehicle. In the previous output, the authors performed an analysis of the current state along with presenting the most relevant kinematic parameters that affect the dynamic behaviour of the vehicle and described the simulation tool used. Furthermore, they carried out measurements and put forward the results of the measured kinematic parameters of the vehicle (Alfa Romeo 156) that is intended for the simulations. In the current work, they set out to describe other important wheel geometry parameters in the theoretical part and in the practical part to monitor the characteristics of a wheel camber alteration in the course of the vertical test of axle. The findings resulting from this work are particularly essential for the development companies when observing comparable kinematic parameters. A predictive nature of the program will allow the authors in future work to simulate vehicle braking with different deceleration input values, which would be problematic in the case of real braking.

Keywords: Driving manoeuvres · Multi-body dynamic simulation · Automobile axles · Kinematic parameters

1 Introduction

The history of the vehicle dates to the end of the 18th century, when the first successful experiments with steam-powered vehicles were carried out. These vehicles had simple fixed axles. With the advent of industrial development and the requirements for driving dynamics and comfort [1–3], new types of axles and their suspensions were developed. Improving the axle characteristics of road vehicles is still a hot topic today. With the advent of computers in the 20th century, new programs began to be used by various design companies in an attempt to make engineers' work easier. Therefore, modern MBS (multibody system) and FEA (finite element analysis) computational programmes are employed in design, calculations, and simulations [4–6]. These programs can simulate the behaviour of bodies in a real environment with relatively high accuracy [7–9]. Some of these software programs are particularly suitable for simulating and analysing the driving characteristics of vehicles with different types of axles [10, 11].

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 208–223, 2023.
https://doi.org/10.1007/978-3-031-25863-3_20

Suspension system of road vehicles are quite difficult systems, which have to guide wheels in proper positions not only in the straight road, but also during driving in curves and on the uneven roads. Currently, the double wishbone and the MacPherson suspension systems are commonly used independent suspensions in passenger cars [12]. The kinematics of these systems is complicated and the existing literature sources do not include its sufficient analysis. The work by Reddy et al. [13] provides a comprehensive kinematic analysis of these two suspension systems. They have developed the mathematical models and numerical computation methods to perform analysis of the design, kinematics and dynamic behaviour as well as optimisation of the suspension systems. The results can help for setting-up a computational model and to compare findings with commercial software such Simpack, Adams and other.

The Adams software is widely used computational programme and its Car module is intended to be used for design, analysis and optimization of driving properties of road vehicles including suspension system. Researchers Ţoţu and Alexandru [14] have used this software for their research focused on the design, optimization and tests of an innovative suspension system of a race car. They have referred to advantages and disadvantages of double wishbone and MacPherson suspension systems and they have developed their own version of suspension system of wheels for a race car.

Other scientists exceed the use of multibody software and they interconnect Adams software with Simulink programme. Such a work is the research performed by Hui [15], who has analysed and evaluated the dynamics of a car equipped by an air spring system controlled by an electronic way. On one hand, a car equipped by an air spring suspension system is more difficult for proper controlling, on the other hand, it reaches more favourable driving properties regarding to ride comfort, driving stability and similar [16].

The main objective of the authors' work is to determine the influence of the kinematic parameters of the axle on the dynamic response of the vehicle using the above-mentioned predictive dynamic simulations. In the work [17], the authors performed an analysis of the current state of the issue of automotive axles and their kinematic parameters. They described in detail the axle kinematic parameters that affect the vehicle behaviour [18–21]. In addition to the above-mentioned parameters (wheel camber angle, a wheel toe, a caster angle, a caster trail, steering axis inclination, and scrub radius), the analysis also needs to be supplemented by the pitch centre – anti-dive and anti-lift effect. Moreover, the Ackermann steering geometry or the centre of gravity of the vehicle needs to be included in the analysis [22].

The pitch centre is the point on the car body around which the wheel rotates during wheel compression in the longitudinal plane. It is determined by the inclination of the straight lines passing through the pivots of the arms which meet at one intersection. The centre of body pitch (Fig. 1) is given by the intersection of the lines passing through the centres of the pitch of the front wheel and rear wheel, in other words, front and rear axles with the contact point of a wheel on the ground [23, 24].

The anti-dive effect is a phenomenon in which we observe the body pitch downwards when the vehicle brakes. A similar phenomenon, the Anti-lift effect, is observed when

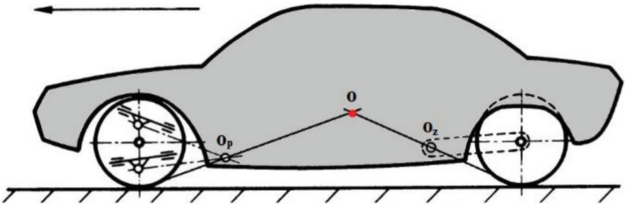


Fig. 1. Determining of a car body pitch axis.

the vehicle accelerates. In terms of the Anti-lift effect, the rear-axle squat and the front-axle raise occur. Both quantities are expressed in percentages (%). Both the Anti-dive and Anti-lift effects depend on the following factors:

- the position of the vehicle's centre of gravity,
- the distribution of braking/driving force between the front and rear axles,
- axle design and wheelbase.

Provided that the pitch centre is located at the vehicle's centre of gravity, no pitching moment is generated with regard to the centre of rotation of the body in the course of braking or acceleration, and therefore no vehicle pitch is generated (100% Anti-dive). The arm pivot axes of the front and rear axles must be inclined towards each other or parallel to each other and join at a common point. However, this condition (100% Anti-dive) is not desirable on a real vehicle. For the sake of the limitation of body pitch, the vertical force acting on the front axle during braking is reduced and part of this force acts in the longitudinal direction on the axle arms. This results in a stiffer suspension and reduced ride comfort for the driver. In terms of extreme cases, the axle may also bounce on uneven surfaces. Additionally, the disadvantage of this setting is the reduction of the braking effect on the front axle. In practice, thus, Anti-dive arms of up to 30% are chosen, especially for vehicles with a front-wheel drive along with a heavy engine positioned ahead of the front axle [25].

The position of the centre of gravity of the vehicle in the longitudinal direction can be determined from the moment equilibrium to point 1 or 2 (Fig. 2). From this equilibrium the load on the front (Z_1) or rear (Z_2) axle and the distance of the centre of gravity from the selected axle are then expressed. For instance, the equation of moment equilibrium (1) to point 2 (rear axle) is constructed according to Fig. 2. The equation of the front axle load Z_1 is obtained from Fig. 2 as:

$$\sum M_2 = 0 : -Z_1 \cdot L_v + G_v \cdot L_z = 0 \Rightarrow Z_1 = \frac{G_v \cdot L_z}{L_v}. \tag{1}$$

As a further step, the distance of the centre of gravity from the rear axle (2) is expressed from the axle load Eq. (1):

$$L_z = \frac{Z_1 \cdot L_v}{G_v}. \tag{2}$$

By determining the distance of the centre of gravity from the rear axle and the wheelbase, it is not difficult to calculate the distance of the centre of gravity from the

front axle using the following Eq. (3):

$$L_p = L_v - L_z. \tag{3}$$

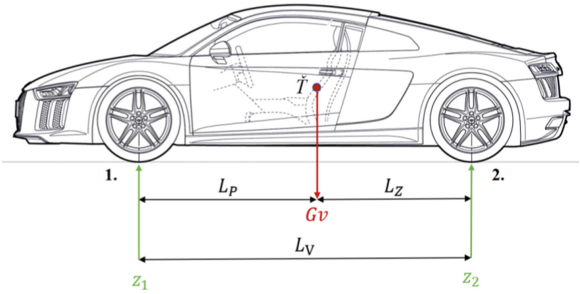


Fig. 2. Determining the position of the vehicle's centre of gravity in the longitudinal direction.

The force Z_1 and Z_2 is the load on the front and rear axle respectively, G_v is the weight of the vehicle, L_p is the distance of the centre of gravity from the front axle axis, L_z is the distance of the centre of gravity from the rear axle axis, and L_v is the wheelbase. All the above-mentioned quantities are plotted in Fig. 2. The position of the centre of gravity in lateral view can be calculated in a similar way to formulae (1), (2), and (3), except that the right and left sides of the vehicle are weighed, and the centre of gravity position is subsequently calculated.

In course of cornering, the inner wheel is turned at a greater angle than the outer wheel due to the geometry of the steering mechanism, which must satisfy the Ackerman condition. On the basis of this condition, the vehicle is assumed to roll the wheels correctly and there is no wheel slippage. The principle of Ackerman condition is that the extended axes of rotation of all wheels intersect at a single point which lies on the axis of the rear axle. The Ackerman steering geometry, shown in Fig. 3, is valid under the following conditions:

- the vehicle is cornering at an extremely low speed,
- wheels are perfectly rigid with no directional deviations,
- passage at a large turning radius [22, 26, 27].

Mathematically, this condition can be expressed by means of (4) and (5):

$$\text{cotg}\ \beta_1 = \frac{R + \frac{B}{2}}{L_v}. \tag{4}$$

$$\text{cotg}\ \beta_2 = \frac{R - \frac{B}{2}}{L_v}. \tag{5}$$

or after adjustment (6):

$$\text{cotg}\ \beta_1 - \text{cotg}\ \beta_2 = \frac{B}{L_v}, \tag{6}$$

where L_v denotes the wheelbase, B is the wheel track, R is the theoretical turning radius, β_1 represents the steering angle of the outer wheel, and β_2 is the steering angle of the inner wheel. In a real passage, the directional deviations of the wheels occur due to the elastic deformation of the tires and the effect of centrifugal forces [22, 26, 27].

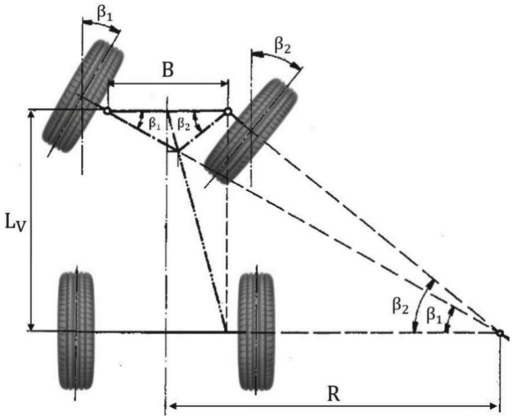


Fig. 3. Ackermann steering geometry.

Wheel geometry analysis is an essential aspect in understanding the kinematic parameters of axles.

2 Materials and Methods

In the paper [17], the Altair MotionView simulation tool, which will be employed specifically for dynamic simulations of the research in question, was presented in detail. The program can simulate the entire vehicle including engine, steering, transmission, front and rear axles, brakes. This chapter deals with the sensitivity analysis of the wheel camber variation during the vertical motion of the front axle of the simulated car (Alfa Romeo 156). The car was also presented in the paper [17], together with the measurement of its required steering geometry. The sensitivity analysis was based on the characteristics of BMW, Mercedes-Benz and Honda vehicles described by Prof. Reimpell et al. in their book, namely The Automotive Chassis: Engineering Principles [28]. The graphical dependencies show the front axle behaviour of the different car brands when the wheels travelling in bump and rebound. Moreover, the characteristic of the simulated Alfa Romeo was included in the graph (Fig. 4).

In the experimental part, the effect of the dimensions of the upper and lower arms on the change of wheel camber was observed. Four front axle models were built in MotionView. All models of the wheel suspension system come out from the known double wishbone suspension system consisting of two wishbone arms and spring-damping components [29]. Figure 5 shows a scheme of a double wishbone suspension system with geometric parameters [30].

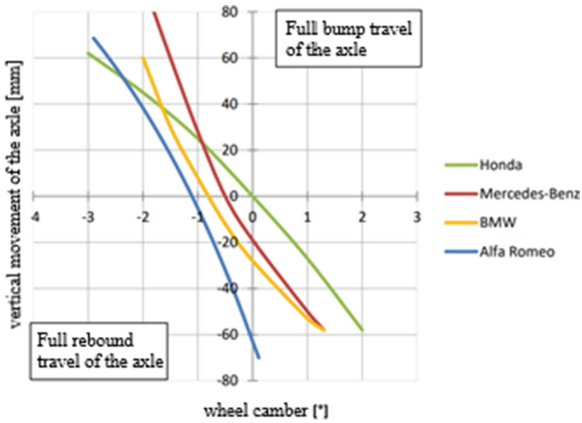


Fig. 4. Characteristics of the wheel camber alteration as a function of vertical movement of the vehicle of different car brands.

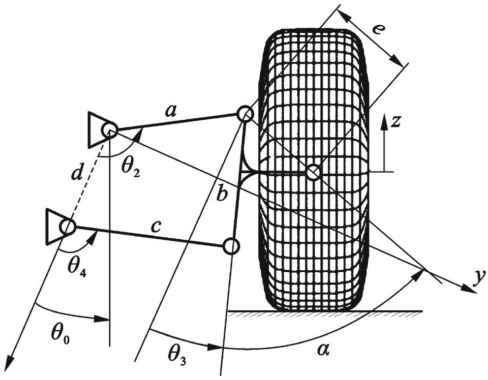


Fig. 5. A scheme of a double wishbone suspension system and its geometric parameters [30].

Geometric parameters (Fig. 5) are as following: y and z are axes in the coordinate system, a, b, c and d mark lengths of individual links, e is the shortest distance between the upper pivot and a point of wheel rotation and α, θ_1, θ_2, θ_3 and θ_4 are angles depicted orientation of the links.

The first model is the initial one and was created by measuring the parameters of the Alfa Romeo, the other models are modified:

- axle with non-parallel arms of different length (Alfa Romeo initial model),
- axle with parallel arms of different length,
- axle with parallel long arms,
- axle with parallel short arms.

In addition to the four models mentioned above, two more were created. These models were structurally based on the initial Alfa Romeo model (non-parallel arms of different length) by modifying the nominal camber value (−1.1°):

- initial Alfa Romeo model with zero camber 0°,
- initial Alfa Romeo model with a positive camber of +1°.

All built models are depicted in Fig. 6.

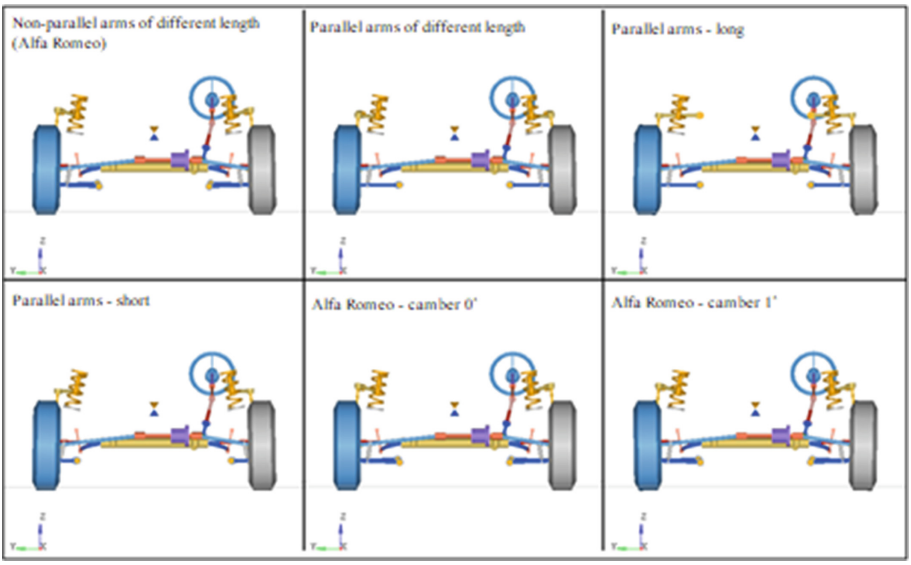


Fig. 6. Overall depiction of axle models built in MotionView program.

In order to obtain the wheel camber characteristic, it was necessary to create a kinematic study (simulation) of the front axle in MotionView. In the course of simulation, the axle was performing a vertical straight downward motion along a path of 70 mm from its nominal position. After reaching the lower extreme position, the axle moved vertically upwards along a 140 mm path to reach the upper extreme position (70 mm above nominal position). Wheel camber measurements could be made using fixed joints that were positioned aligned with the axis passing through the centre of the wheel. The joints reproduced the wheel camber and compared the angular rotation of the coordinate system with the coordinate system of the environment in which the vehicle was located. By means of creating these joints, it was possible to measure the camber on both the left and right wheels [30]. The kinematic behaviour of individual axles with diverse designs, in this case different arm lengths and orientations, will be described in the following chapter.

3 Results

3.1 Axle with Non-parallel Arms of Different Length (Alfa Romeo)

This front axle design is likewise the design of the simulated Alfa Romeo 156 vehicle being measured. The front axle design itself can be seen in Fig. 7 below.

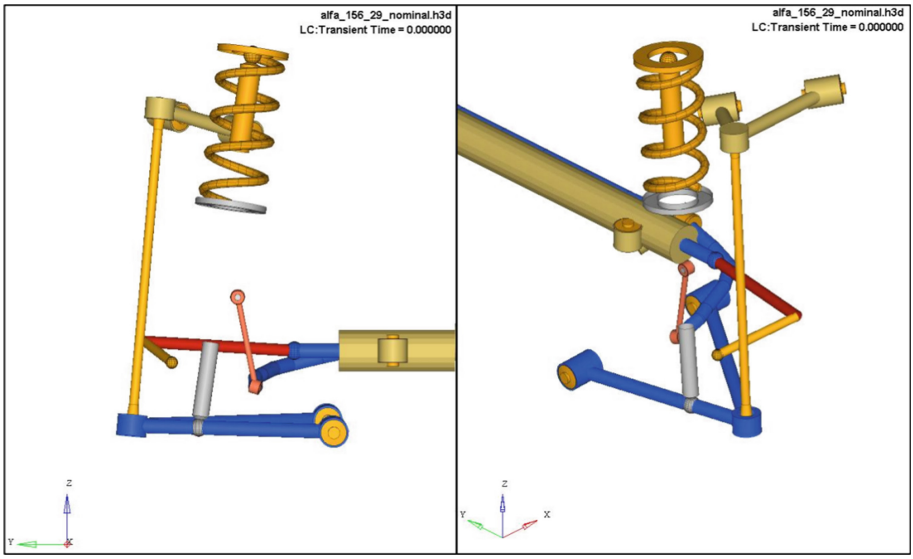


Fig. 7. An axle design of Alfa Romeo vehicle.

The design is made up of longer lower arms and substantially shorter upper arms. The upper arms are turned at an angle to the lower arms and point towards the centre of gravity of the vehicle. The kinematics of the Alfa Romeo axle (Fig. 8) shows the greatest possible value of camber obtained at full bump. The behaviour of the axle is due to the favourable position of the point at which the axles of the upper and lower arms intersect (Instantaneous centre point), being relatively close to the point around which the body rolls (Roll Centre). By means of extending the distance of this imaginary IC point(s) from the centre line of the wheel, from which the axes of the arms were guided (Swing arm length), we attain a steeper characteristic, and thus a lower camber value. The behaviour of these imaginary points is explained by Caroll Smith in his book Tune to win [6].

A minor disadvantage of this setting is in achieving a negative camber during the vehicle braking when there is no perpendicular contact between the wheel and the road. In spite of this disadvantage, this setting is preferred as it is perfectly suitable for roads where there are relatively frequent changes of direction.

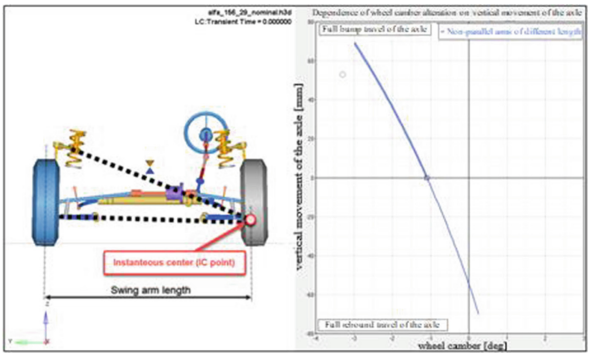


Fig. 8. Alfa Romeo axle characteristics.

3.2 Axle with Parallel Arms of Different Length

The design of this axle was created by modifying the initial model - by modifying the arms in order to form a zero angle together. The mutual parallelism of the arms can be seen in Fig. 9 on the left.

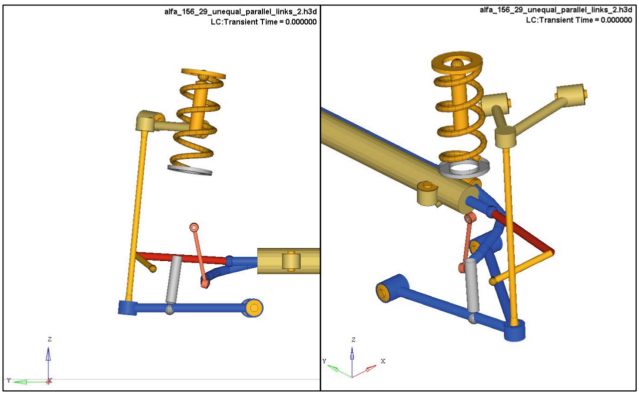


Fig. 9. Design of an axle with parallel arms of different lengths.

The characteristic depicted in Fig. 10 reaches smaller values of camber in the extreme positions in contrast to the previous variant as a result of the parallelism of the arms. For the sake of the parallelism, the point of the axis of individual arms arises further away from the axis intersecting the centre of the wheel. Inasmuch as the upper arm has a smaller radius around which it rotates in comparison with the lower arm, this axle achieves acceptable camber values in contrast to the axle with parallel arms of the same length. In fact, the point at which the axes of the arms intersect is (because of design) displaced closer to the wheel of the vehicle during the bump/rebound travel.

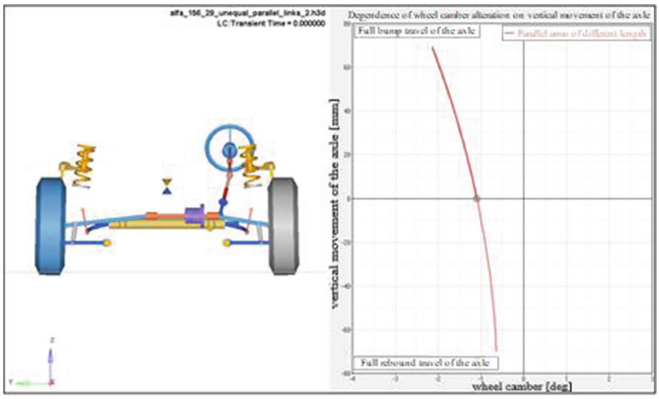


Fig. 10. Characteristics of an axle with parallel arms of different length.

3.3 Axle with Parallel Long Arms

The axle model was created by extending the upper arms of the original model by 150 mm, which resulted in the length of the modified arms being approximately equal to the length of the lower arms. The arms along with their design are shown in Fig. 11.

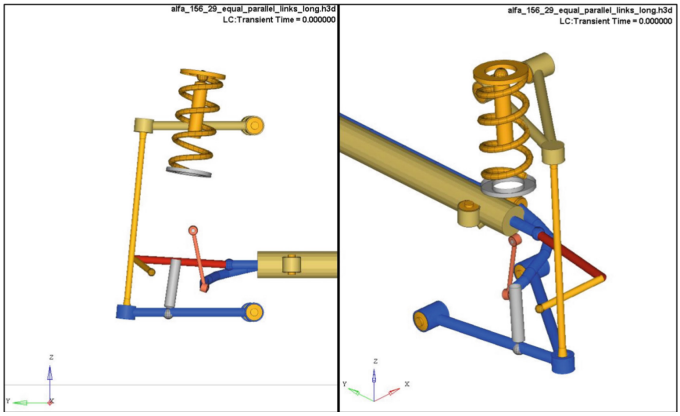


Fig. 11. Design of an axle with parallel long arms.

It can be seen from the characteristic in Fig. 12 that the wheel camber is almost invariable depending on the bump and rebound travel movements of the axles. This is due to the fact that the intersection point of the axes of axle arms is at infinity and the long arms, which change the angle of rotation minimally when moving in vertical direction. This setup is used in off-road racing vehicles that travel on unpaved roads at high speeds and the chassis is subjected to frequent bounces (intentionally unchanged camber characteristics of the wheels during bump and rebound). This setup has no significant utilisation from the point of view of road vehicles.

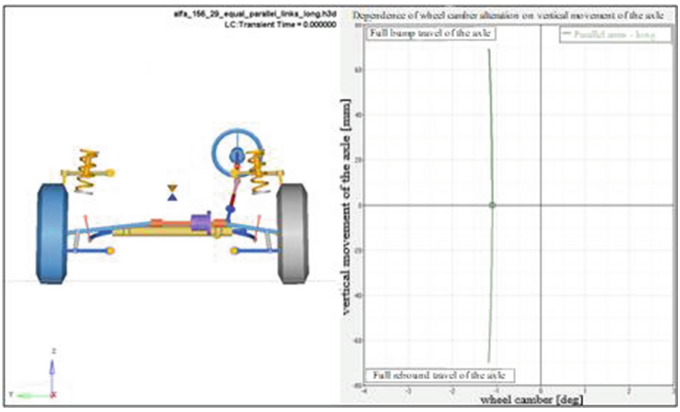


Fig. 12. Characteristics of an axle with parallel long arms.

3.4 Axle with Parallel Short Arms

The axle design was created by shortening the lower arms of the initial model by 150 mm, see Fig. 13.

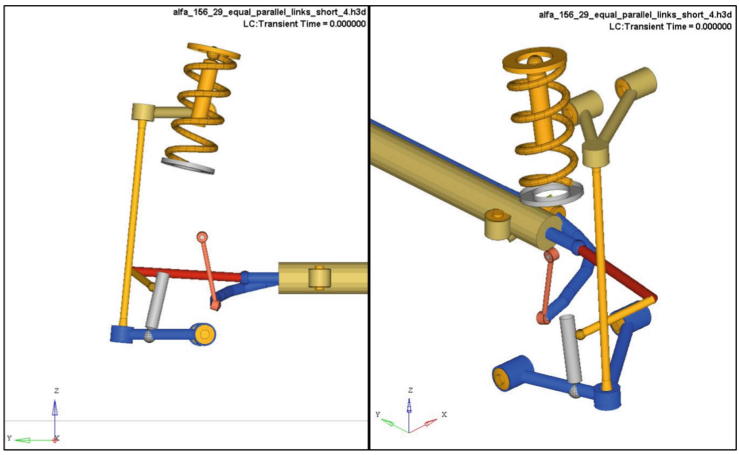


Fig. 13. Design of an axle with parallel short arms.

The point at which the axes of the arms intersect is at infinity. This setup hardly alters the camber when the axle moves vertically, it only changes in the extreme positions (Fig. 14). When cornering, this axle design represents the worst option in comparison with the other three models for the reason that wheel camber is strongly influenced by body roll in the course of cornering. Another disadvantage of the design is the relatively large change in wheel track at the time of bump travel due to the small radius of the arms [31].

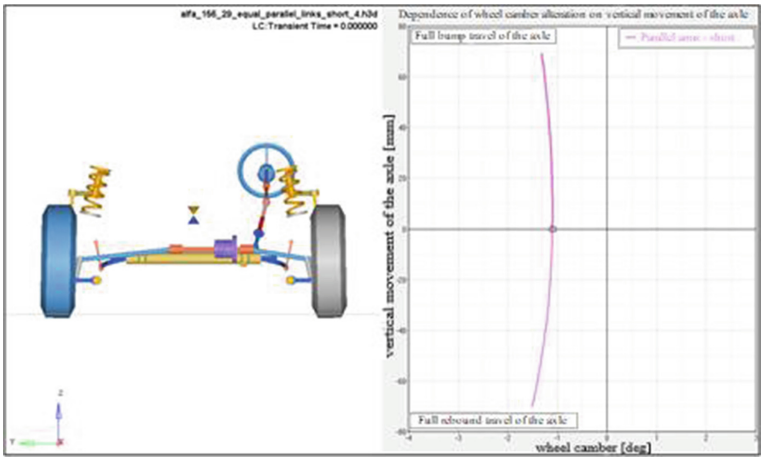


Fig. 14. Characteristics of an axle with parallel short arms.

4 Discussion

The described dependencies of the alteration in wheel camber from the bump and rebound travel of axle have been included in one common graph because of better comparison. In addition, the characteristics of the modified initial model with camber values of 0° and +1° (parallel characteristics of the Alfa Romeo 156) were included in mentioned graph. The graph showing all the characteristics of the wheel camber alteration in relation to the bump and rebound travel of axle is depicted in Fig. 15. It is evident from the graph that altering the nominal value of the camber does not change the course of the characteristic.

The conducted research sets out in detail the design of the considered and built axle models, including the initial model of Alfa Romeo 156, by means of which the authors will verify the results of numerical analyses in further research because of correlation of values. On the basis of this verification, it will be possible to conclude whether such numerical simulations are predictive and whether the authors have a well-tuned model representing the real state. The presented simulations were carried out for the vertical test of axles. In future research, the authors will focus on the analysis of the behaviour of the prepared models in the course of cornering.

Table 1 includes values of the load of right and left front wheels of the four evaluated design of an axle.

As it can be seen from Table 1, the biggest difference of vertical wheel forces is for an axle with non-parallel arm of different lengths and the smallest difference is for an axle with parallel short arms.

The aim of the analysis will be to observe the directional deviation of the centre of gravity of the vehicle, the forces acting in the contact surfaces of the wheels and, last but not least, the obtained values of the wheel camber when the vehicle is cornering. By means of such an analysis, the influence of kinematic parameters on the dynamic behaviour of the vehicle will be evaluated. Subsequently, experimental runs will be performed on the Alfa Romeo vehicle and the experimental results will be compared

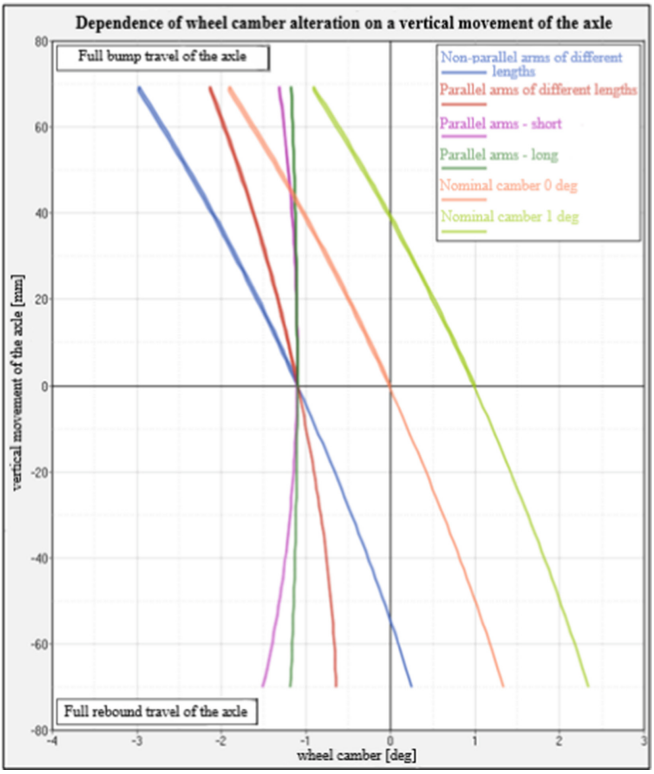


Fig. 15. Graphical dependence of individual characteristics.

Table 1. Load of individual wheel (a front axle) for different design of an axle.

Type of an axle	A wheel	Vertical load of a wheel	Vertical load of a wheel
An axle with non-parallel arms of different length	Left	2,924.50 N	32.1%
	Right	6,185.84 N	67.9%
An axle with parallel arms of different length	Left	3,106.45 N	34.1%
	Right	5,995.71 N	65.9%
An axle with parallel long arms	Left	3,164.39 N	34.8%
	Right	5,932.20 N	65.2%
An axle with parallel short arms	Left	3,200.53 N	35.2%
	Right	5,897.45 N	64.8%

with the results of numerical simulations of the tuned models, in particular the body roll and pitch during slalom and braking manoeuvres.

5 Conclusion

The use of multi-body simulation programs in the field of automotive axle development helps manufacturers to predict the dynamic behaviour of a vehicle, and thus to reduce the time required to develop and debug a prototype vehicle. In practice, this type of program has significant economic benefits for the company in terms of reducing production costs and bringing a serial product to market in a brief period of time.

The presented research has revealed the results, which will be further investigated and assessed by means of simulation computations and experimental tests with a real Alfa Romeo vehicle. The research to date can be summarized as follows:

- an axle with non-parallel arms of different length – a minor disadvantage is a negative camber during braking of a car, because a perpendicular contact of a wheel and road is not reached. Despite of this disadvantage, this system is preferred for roads with many curves,
- an axle with parallel arms of different length – this system reaches lower values of the camber win comparison with a previous one. It is due to the parallel arms,
- an axle with parallel long arms – the camber is almost immutable depending on the vertical motion of a wheel. This system is often applied for off-road cars,
- an axle with parallel short arms – during driving in a curve, this design represents the most unfavourable variant in comparison with the previous three models. The camber is namely influenced by the car body roll motion during driving in a curve.

Acknowledgement. "This research was supported by the Cultural and Educational Grant Agency of the Ministry of Education of the Slovak Republic in the project No. KEGA 023ŽU-4/2020: Development of advanced virtual models for studying and investigation of transport means operation characteristics."

"This research was supported by the Cultural and Educational Grant Agency of the Ministry of Education of the Slovak Republic in the project No. KEGA 036ŽU-4/2021: Implementation of modern methods of computer and experimental analysis of the properties of vehicle components in the education of future vehicle designers."

References

1. Žuraulis, V., Sivilevičius, H., Šabanovič, E., Ivanov, V., Skrickij, V.: Variability of gravel pavement roughness: an analysis of the impact on vehicle dynamic response and driving comfort. Appl. Sci. **11**(16), 1–18 (2021)
2. Žuraulis, V., Surblys, V.: Assessment of risky cornering on a horizontal road curve by improving vehicle suspension performance. Baltic J. Road Bridge Eng. **16**(4), 1–27 (2021)
3. Leitner, B., Figuli, L.: Fatigue life prediction of mechanical structures under stochastic loading. In: 22nd Slovak-Polish Scientific Conference on Machine Modelling and Simulation 2017 (MMS 2017), pp. 1–11. Sklene Teplice, Slovakia (2017)
4. Alexandru, C., Pozna, C., Alexandru P.: Virtual mechatronic simulator for the dynamic analysis of the automotive guiding & suspension system. In: 20th International Danube-Adria-Association-for-Automation-and-Manufacturing Symposium, Vienna, Austria, pp. 263–264 (2009)

5. Rulka, W., Pankiewicz, E.: MBS approach to generate equations of motions for HiL-simulations in vehicle dynamics. Multibody Syst. Dyn. **14**(3–4), 367–386 (2005)
6. Konieczny, L., Burdzik, R., Figlus, T.: Use of MBS (ADAMS/Car) software in simulations of vehicle suspension systems. Transp. Probl. **9**(1), 111–118 (2014)
7. Gerlici, J., Sakhno, V., Yefymenko, A., Verbitskii, V., Kravchenko, A., Kravchenko, K.: The stability analysis of two-wheeled vehicle model. In: 22nd Slovak Polish Scientific Conference on Machine Modelling and Simulations 2017 (MMS 2017), pp. 1–10. Sklene Teplice, Slovakia (2017)
8. Hauser, V., Nozhenko, O., Kravchenko, K., Loulova, M., Gerlici, J., Lack, T.: Impact of three axle boxes bogie to the tram behavior when passing curved track. In: 12th International Scientific Conference of Young Scientists on Sustainable, Modern and Safe Transport, pp. 295–300. High Tatras, Slovakia (2017)
9. Bazhinov, O., et al.: Development of a Method for Evaluating the technical condition of a cars hybrid powertrain. Symmetry **13**(2), 1–13 (2022)
10. Caban, J., Drozdziel, P., Krzywonos, L., Rybicka, I., Sarkan, B., Vrabel, J.: Statistical analyses of selected maintenance parameters of vehicles of road transport companies. Adv. Sci. Technol. – Res. J. **13**(1), 1–13 (2019)
11. Drozdziel, P., Komsta, H., Krzywonos, L.: An analysis of the relationship among selected operating and maintenance parameters of vehicles used in a transportation company. Transp. Probl. **6**(4), 93–99 (2011)
12. Vignesh, B.S., Sufiyan, A., Chandan, V., Shrivastava, P.K.: Double wishbone suspension system; a research. Int. J. Recent Technol. Eng. **8**(2), 5033–5037 (2019)
13. Reddy, K.V., Kodati, M., Chatra, K., Bandyopadhyay, S.A.: A comprehensive kinematic analysis of the double wishbone and MacPherson strut suspension system. Mech. Mach. Theory **105**, 441–470 (2016)
14. Ţoţu, V., Alexandru, C.: Multi-criteria optimization of an innovative suspension system for race cars. Appl. Sci. **11**, 4167 (2021)
15. Hui, W.: Research on dynamics of vehicle height adjustment for automobile with double-wishbone ECAS. In: 7th International Conference on Manufacturing Technology and Applied Materials, ICAMMT 2021, vol. 1885, pp. 1–8. Sanya, China (2021)
16. Ryu, W., Zhou, G.: Optimal locations of springs and dampers of planar car suspension model considering roll stability. In: 6th IFAC Conference on Engine Powertrain Control, Simulation and Modeling E-COSM 2021, Tokyo, Japan, vol. 54, pp. 418–432 (2021)
17. Blatnický, M., Dižo, J., Molnár, D.: Development of a numerical model of a reference vehicle for monitoring the characteristics of changes in wheel camber under spring compression. In: Machine Modelling and Simulations 2022 (MMS 2022), Rydzyna, Poland (2022, to be published)
18. Saga, M., Jakubovicova, L.: Simulation of vertical vehicle non-stationary random vibrations considering various speeds. Sci. J. Silesian Univ. Technol. – Ser. Transp. **84**, 113–118 (2014)
19. Saga, M., Vasko, M., Handrik, M., Kopas, P.: Contribution to random vibration numerical simulation and optimisation of nonlinear mechanical systems. Sci. J. Silesian Univ. Technol. – Ser. Transp. **103**, 143–154 (2019)
20. Leitner, B., Uricek, J.: A method for adaptive identification of stochastically loaded parts of mechanical systems. In: Proceedings of the 3rd International Multi-Conference on Engineering and Technological Innovation, Orlando, FL, USA, vol. II, pp. 174–179 (2010)
21. Labuda, R., Barta, D., Kovalcik, A.: Effective use of the braking effect of vehicle drivetrain at deceleration. In: 41st International Scientific Conference of Czech and Slovak University Departments and Institutions Dealing with the Research of Internal Combustion Engines, pp. 206–211. Liberec, Czech Republic (2010)
22. Veneri, M., Massaro, M.: The effect of Ackermann steering on the performance of race cars. Veh. Syst. Dyn. **59**(6), 907–927 (2021)

23. Vlk, F.: Chassis of Engine Vehicles, 3rd edn. František Vlk Publishing, Brno, Czech Republic (2006). (in Czech)
24. Vlk, F.: Dynamics of Engine Vehicles, 2nd edn. František Vlk Publishing, Brno, Czech Republic (2003). (in Czech)
25. Milliken, W.: Race Car Vehicle Dynamics. Society of Automotive Engineers, Inc., USA (1995)
26. Paszkowiak, W., Bartkowiak, T., Pelic, M.: Kinematic model of a logistic train with a double Ackermann steering system. Int. J. Simul. Model. **20**(2), 243–254 (2021)
27. Miah, S., Farkas, P.A., Gueaieb, W., Chaoui, H., Hossain, M.A.: Linear time-varying feedback law for vehicles with Ackermann steering. Int. J. Robot. Autom. **32**(1), 33–40 (2017)
28. Reimpell, J., Stoll, H., Betzler, J.W.: The Automotive Chassis: Engineering Principles, 2nd edn. Society of Automotive Engineers, Inc., USA (2001)
29. Mahmoodi-Kaleibar, M., Javanshir, I., Asadi, K., Afkar, A., Paykani, A.: Optimization of suspension system of off-road vehicle for vehicle performance improvement. J. Central South Univ. **20**(4), 902–910 (2013)
30. Kamal, M., Rahman, M.M.: Study on dynamic Behaviour of Wishbone Suspension System. In: 1st International Conference on Mechanical Engineering Research (ICMER), pp. 1–8. Kuantan, Malaysia (2011)
31. Smith, C.: Tune to Win. Aero Publishing Inc., Fallbrook, CA, USA (1978)

Research of Efficiency of Anti-lock Braking System During Emergency Cornering Manoeuver

Airidas Staputis and Vidas Žuraulis(✉)

Vilnius Gediminas Technical University, J. Basanavičiaus 28, LT 03224 Vilnius, Lithuania
airidas.staputis@stud.vilniustech.lt,
vidas.zuraulis@vilniustech.lt

Abstract. In this paper, the efficiency of the anti-lock braking system (ABS) during an emergency braking in a turn was examined. Analysis of the paper reviews various modules and algorithms which are used in modern ABS systems, also relevant vehicle's dynamic properties and mathematical models. Experiments of vehicle braking in a turn were performed under different road conditions and two generations of ABS systems. Additional analysis was made on behalf of the influence of driver behaviour in situations of emergency braking with cornering. It was found that the force applied to the braking pedal and its moment (according to moment of steering) affects the manoeuvring of the vehicle when ABS is engaged or disengaged. Vehicle's lateral acceleration is up to 40% higher with ABS active because driver do not have to precisely dose the braking force (part of ABS), therefore he is more involved in course change; however, from vehicle dynamics point of view the sequence of braking and steering actions is still important for safe obstacle avoidance during emergency braking.

Keywords: Anti-lock braking system (ABS) · Emergency braking · Turning manoeuvre · Vehicle cornering · Braking in a turn

1 Introduction

Since the beginning of the automotive industry, safety on roads remains the number one priority to this day. According to the World Health Organization, 1.35 million people die in road accidents every year, and up to 20 to 30 million people are injured [1]. Active safety measures help prevent accidents, while passive ones protect drivers and passengers from injury in the event of an accident. One of the most important active safety measures in vehicles is the anti-lock braking system (ABS).

The ABS ensures that vehicle's brakes, during emergency braking, are the most efficient – the wheels will not lock or slip. Also, this system allows the driver to brake and steer the vehicle, thus potentially avoiding an obstacle. Most studies that involve vehicle braking systems are based on ensuring the shortest stopping distance, but there is a limited amount of research done that takes into account the stability and handling of

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 224–235, 2023.
https://doi.org/10.1007/978-3-031-25863-3_21

the vehicle when there is a turning manoeuvre during braking. It is considered that this area could be improved.

The objective of this research is to evaluate the efficiency of the ABS system and areas for improvement when vehicle is braked and a turn (to avoid an obstacle). The aim of this study is to determine the operating limits of the ABS system (acting accelerations, rotations and oscillations, slip angles, achieved trajectories, etc.).

2 Electronically Controlled Car Braking

2.1 Operation, Main Functions

The current ABS system is a significant improvement over its predecessors, and today's technologies are significantly more reliable and advanced than those used for the first ABS systems. However, although the system has been improved, its goal has remained the same – to increase driving safety.

A traditional ABS system usually consists of several input and output devices that form a closed-loop system with each other. Operation of ABS system consists of mechanics, hydraulic, electro-magnetic and data transmission processes, that ensure best vehicle safety performance during extreme braking [2]. The system includes wheel angular speed sensors that provide the system control unit with real-time information on the status of the wheel movement: whether the wheel speed matches the speed of the vehicle, whether it tends to lock (negative angular acceleration), or whether it is completely locked. The wheel angular speed sensor continuously calculates the wheel angular acceleration – it informs the ABS control unit about the changed wheel – road pavement interaction (level of slip). Angular acceleration and slip values are compared with the thresholds and the electronic control unit (ECU) decides on the ABS control actions: pressure build, dump or hold [3].

2.2 ECU Types and Algorithms

Like any safety system, ABS must meet specific requirements. It is crucial to ensure reliable system operation when it is necessary, instantly, whether the driver is experienced or not, regardless of how the vehicle is braked. Also, in the event of a failure in this system, the driver must not lose control of the vehicle, the system must report that it is currently inoperative [4]. One of the main part that ensures stable operating conditions of ABS system it is ECU.

Main objective of the ECU is to ensure that the wheels of braked vehicle do not lock and maximum traction between the tire and the road surface is achieved. The braking process is a very complex phenomenon as it is unsolvable using traditional linear solution methods; therefore, making reliable ECU in ABS it needs to meet some specific criteria's [5]: a) For optimal performance, the controller must operate at an unstable equilibrium point; b) Depending on road conditions, the maximum braking torque may vary over a wide range; c) Tire slippage measurement signal, crucial for controller performance, is both highly uncertain and noisy; d) On a rough roads tire slip ratio varies widely and rapidly due to tire bouncing; e) Friction coefficient of brake pad changes; and f) Braking system contains transportation delays which limit the control system bandwidth.

ABS uses PID (proportional integral derivative), Sliding-Mode Control (SMC), fuzzy-control and other types of ECU algorithms. Classical ABS control methods are based on PID operation, which is a feedback logic controller used in industrial control systems. The controller consists of 3 circuits: proportional (P), integrating (I) and differentiating (D). The controller must perform the action set, so it constantly compares the input devices (usually various sensors) with a set process value and seeks to determine an error value between them [8]. In the event of an error, the PID controller makes corrections using the laws P, I and D. The purpose of adjustments is to achieve the desired set process value and maintain it throughout the process.

PID controller is simple to use and cheap to produce, but it is not the only one used in ABS algorithms. Another commonly used ABS ECU controller is SMC, which is based on algorithms for "slip surface" or goal optimization. Comparing PID with SMC, the algorithms used in SMC ECU are more stable, faster, and more reliable. As a controller, SMC is more robust choice for ABS application. This is especially noticeable when the ECU has to process rapidly changing signals and when there are possible interferences in the existing signals [9]. SMC design consists of two steps. First, a sliding surface is designed to define the desired closed loop system performance. Secondly, a control law is derived to drive the system states towards the designed sliding surface and subsequently ensure that the states stay on the surface [10]. The principle of operation of the SMC is based on the pursuit of a defined average, the aim of which is to achieve a certain value set by the ECU. SMC aims to manage the ongoing process, it seeks to optimize the available value and direct it to the 'slip surface' (function optimization curve), the purpose of which is to optimize the ongoing process and achieve the optimal system solution. In this way, rapid control of the ongoing process is achieved, and a rapid system response is ensured. The SMC in the ABS system aims to ensure that maximum traction between the tire and road surface is achieved, thus ensuring that braking is effective, and the vehicle does not lose control [5].

2.3 Vehicle Braking Dynamics

In the lateral dynamics of a vehicle, stability, control, external forces, the influence of the road surface and other problems are considered [6]. Theoretical analysis of vehicle motion and dynamic processes often results in mathematical models. These models are analysed in terms of the required nature and usefulness because the designed models allow simplifying the kinematic scheme of the modelled vehicle without considering the known forces when examining one or another dynamic property of the vehicle [7]. It is important to mention that the simplifications adopted in the resulting model cannot have a significant impact for the dynamic process of the vehicle under study, and the designed mathematical model must reproduce the dynamic properties of the vehicle as accurately as possible [8]. A mathematical model of 4 degrees of freedom is often used in studies of lateral dynamics. In it, the vehicle can move in the longitudinal and lateral directions also rotate around its vertical axis and oscillate about the longitudinal axis. Figure 1 shows vehicle mathematical model and acting forces distribution dependent on a longitudinal slip when vehicle is braking in a turn.

Such a mathematical model allows for analysing the lateral redistribution of the vertical forces of the wheels of a manoeuvring vehicle, and this type of model also

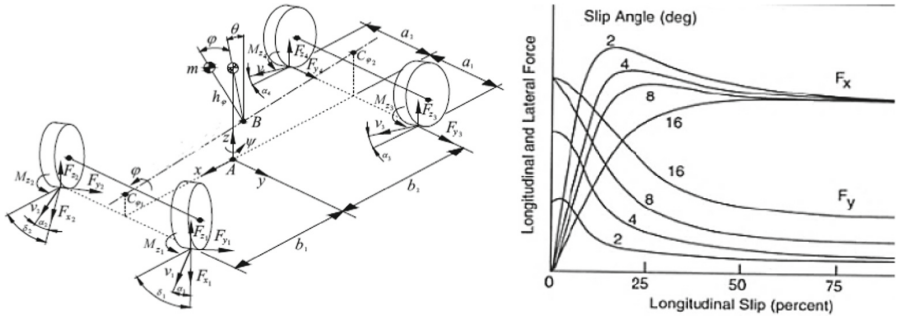


Fig. 1. Mathematical model of a vehicle braking in a turning (left) [9] and acting forces distribution dependent on a longitudinal slip (right) [10].

includes a separate movement of the vehicle body as a damped mass. The characteristics of the suspension elements are summarised by oscillation stiffness [11].

Vehicle's front axle is subjected to an additional load, and the rear axle load is reduced because of longitudinal weight transfer, while the wheels on the outside are also subjected to additional loads, and the wheels on the inside are unloaded because of lateral weight transfer. For these reasons, the longitudinal and lateral friction forces changes, which means that the angular torque in a turn is affected resulting in loss of traction of the rear axle to the road surface and during the manoeuvre, it would rotate around the inner turning trajectory [7].

During the braking in a turn manoeuvre, various dynamic processes take place in the vehicle. One of the main parameters determining the course of these processes is vehicle yaw rate, longitudinal and lateral acceleration, wheel longitudinal slip-ratio and side-slip angle, wheel normal and tangential forces, vehicle speed and body oscillations.

3 Experimental Studies

In this paper, the experimental research aims to determine the accelerations acting on the vehicle when it is braked and cornering at the same time (obstacle avoidance). Firstly, the longitudinal and lateral accelerations, that occur during extreme braking in a turn, are measured. For this study two generations of ABS are compared. In second part of this experimental research, what kind of influence does driver's behaviour on vehicle manoeuvring while described event occurs. After the measurements, the data are processed and presented in graphical form, and data analysis is performed.

Two vehicles (BMW 3 Series) were selected for this experimental study: 2003 (E46 body) and 2013 (F30 body) production. Specifications are provided in Table 1. The aim of such analysis is to compare the different generations of ABS systems that the manufacturer has developed and adapted to vehicles in term of course change capability during extreme braking.

The tests are performed several times under different weather and road conditions:

1. In the first part of experiment, the road surface was extremely slip, covered with a thin layer of ice and wetland; constant precipitation, air temperature −3 °C.

Table 1. Specifications of the vehicles used in experimental research [12].

Vehicle	E46	F30
Year of production	2003	2013
Weight, kg	1,390	1,530
Body dimensions, m	4.47 × 1.74 × 1.42	4.62 × 1.81 × 1.53
Wheelbase, m	2.72	2.81
Rims and tyres dimensions that were on a car during the experiments	Front – R17 225/45 Rear – R17 225/45	Front – R19 225/40 Rear – R19 255/40
Tyre manufacturer, type	*Kelly*, M + S❄	*Pirelli*, M + S❄
Tyre tread depth, mm	Front – 8.5; Back – 8.5	Front – 5; Back – 6

2. In the second part of experiment, the road surface was dry, clear on the day; no precipitation, air temperature 3 °C.

In order to maintain the uniformity of the performed tests and ensure that the results are obtained under the same conditions, a manoeuvre control zone and sequence of manoeuvre operations have been established during the test. The study simulates a manoeuvre to avoid vehicle colliding with an obstacle on the road – vehicle is extremely braked and steering wheel turned at the same time, thus an attempt is made to avoid an obstacle on the road. The obstacle avoidance plan is shown in Fig. 2.

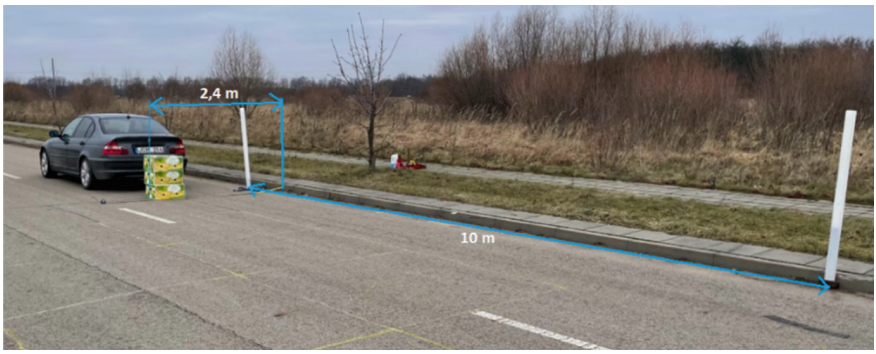


Fig. 2. Test conditions with obstacle avoidance scheme.

The sequence of manoeuvre operations were arranged:

1. Vehicle is accelerated up to 60 km/h and cruise control system is activated to maintain the speed.
2. At a constant speed of 60 km/h the measuring equipment is switched on and a manoeuvre is being prepared.

3. Upon entering the braking zone (crossing the first column with the front axle of the vehicle), extreme braking is started and at the same time steering wheel is being turned at an angle of 90–120°, an attempt is made to avoid a collision with an obstacle.
4. When the vehicle comes to a complete stop, the measuring instruments are stopped, the obstacle is inspected if it was avoided.

Two devices were used for the measurement of vehicle performance during braking in a turn: XL Meter PRO from *Inventure* (for longitudinal and lateral acceleration) and smartphone with MATLAB application (for yaw rate).

A systematic overview of the results obtained during the study is presented in Table 2, as well as graphs and their comparisons. In Table 2, tests 1–7 show the results of the obstacle avoidance manoeuvre, while test 8 shows the results of the braking in a turn manoeuvre with a constant 50 m radius.

Table 2. Summary of experimental research results.

Test no.	Vehicle	Rim size	Road surface	Braking distance, m	Braking time, s	MFDD, m/s^2	Obstacle avoidance
1	E46	R17	Slip	37.06	4.41	3.97	No
2	F30	R19	Slip	50.01	5.94	2.68	No
3	E46	R17	Dry	18.17	2.13	7.84	Yes
4	F30	R19	Dry	17.84	2.10	8.99	No
5	F30	R19	Dry	17.43	1.99	9.13	No
6	F30	R17	Dry	18.14	2.11	8.31	Yes
7	F30	R17	Dry	18.40	2.15	8.03	Yes
8	E46	R17	Dry	22.54	2.50	6.72	–

The Mean Fully Developed Deceleration (MFDD) shows the maximum deceleration a vehicle can achieve [13]. It is usually the deceleration between 80% and 10% of the trigger activation speed, the time at which the vehicle is loaded up and braking at its highest achievable level:

$$\mathrm{MFDD} = \frac{v_b^2 - v_e^2}{25.92(S_e - S_b)}, \tag{1}$$

where v_o – initial vehicle speed, km/h; v_b – vehicle speed at $0.8v_o$, km/h; v_e – vehicle speed at $0.1v_o$, km/h; S_b – distance travelled between v_o and v_b, m; S_e – distance travelled between v_o and v_e, m.

Tests 1–2 are performed on a very slip road surface. Figure 3 shows the longitudinal and lateral accelerations of both vehicles, and Fig. 4 shows the yaw rate. Second vehicle (F30) did not obey the driver's desired trajectory during the braking and steering manoeuvre on a slip road surface, as can be seen from lower lateral acceleration during cornering (around 2nd sec. in Fig. 3), which resulted a hitted obstacle; moreover, lower

deceleration (Fig. 3). In addition, second vehicle generated a higher angular velocity at a second stage of course change (around 3.5 s in Fig. 4), which resulted in an unstable driving (oversteering) and more challenging course change for the driver. All these factors mentioned in the presence of slippery road surfaces have resulted in poorer braking performance and handling of the second vehicle. This situation may have occurred because of heavier vehicle (140 kg) and a slipper stretch of road.

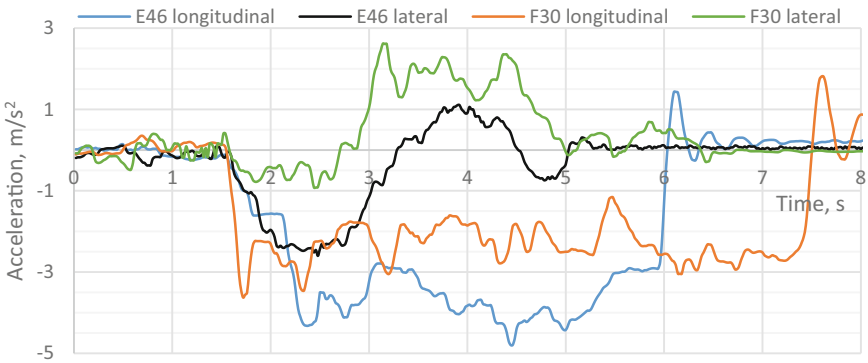


Fig. 3. Longitudinal and lateral accelerations (road surface slip).

The following is an overview of tests 3–7 when vehicles are braked on a dry road surface with cornering. Results of tests 3, 5, and 7 will be compared below. Figure 5 shows the results of the longitudinal accelerations, Fig. 6 – lateral accelerations, and Fig. 7 – yaw rate during the test. It was evaluated that the average stopping distance is 17.5–18 m, with an average stopping time of approximately 2 s. However, test 5 shows that second vehicle developed maximum mean deceleration MFDD = 9.3 m/s^2, the shortest stopping distance and time. Although the best braking performance was when the vehicle was not able to avoid the obstacle that was on a road course.

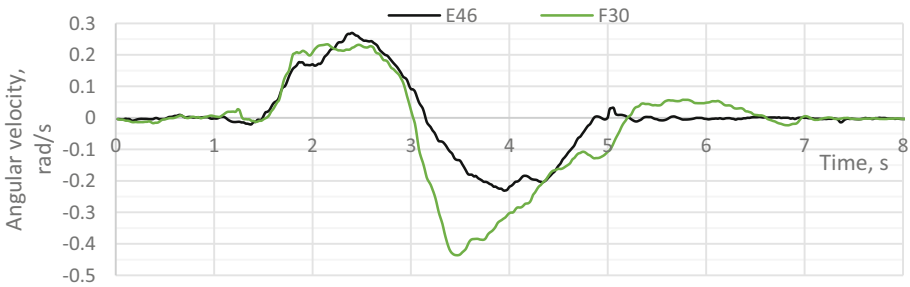


Fig. 4. Vehicle yaw rate (road surface slip).

Vehicle (F30) generated a longitudinal acceleration of 9.5–10 m/s^2 at the initial braking stage and maintained it for precisely the time (approximately 0.5 s). It is also

visible that no lateral acceleration is generated for second vehicle at the initial manoeuver stage (1st sec. in Fig. 6).

Fig. 5. Longitudinal accelerations (road surface dry).

One explanation for why vehicle did not generate lateral acceleration from the start of the manoeuvre may be that the driver, who experienced a sudden increase in rapid growing deceleration, failed to perform the turning manoeuvre. Only when the ABS ECU detected that vehicle's wheel tend to lock, the hydraulic fluid pressure in the hydraulic brake system was reduced, resulting in a reduction in longitudinal deceleration and according to that, the driver was able to perform a turning manoeuvre (thus increasing lateral acceleration). This is the reason to perform a second research stage for driver's behaviour during braking in a turn manoeuvre. Safety experts mostly argue that under good road conditions the driver with average driving skills can control the vehicle properly when braking at a deceleration of 0.47 G, and an experienced and well-skilled driver can control the car at 0.62 G [14].

In Fig. 7 it is seen that second vehicle (F30 with R19 wheels) generates angular velocity 0.5 s later than other cases. It is caused by the same reason mentioned in the paragraph before. From the graphs it could be seen that first vehicle's (E46) angular velocity characteristic is different, unfortunately this could be due to measuring error.

4 Driver Behaviour Influence for Emergency Braking in a Turn

One of the main objectives of this research is to identify specific possible profiles of driver behaviour that are used to improve and enhance various safety systems such as ABS, ESP, ACC, etc. Safety systems are constantly improved through real-time and computer-simulated research to deal with real-life accident scenarios [15]. Considering the research already presented in this paper and seeing the importance of the influence of driver behaviour during extreme braking with a turning manoeuvre, the impact of

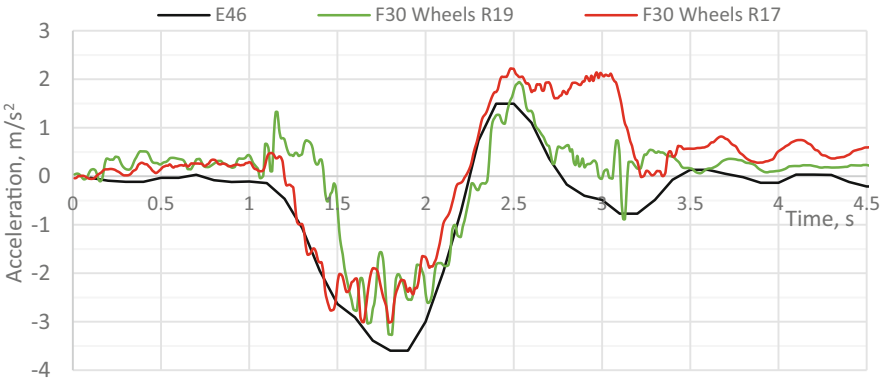


Fig. 6. Lateral accelerations (road surface dry).

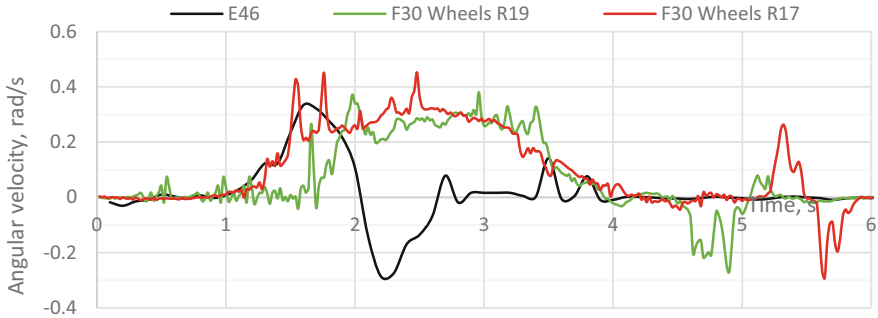


Fig. 7. Vehicle yaw rate (road surface dry).

driver actions are examined. The research aims to replicate several sequences of driver's behaviours that occur during extreme braking with a turning manoeuvre. The following driver behaviour profiles were selected for the study:

1. Braking with medium pedal force; an obstacle avoidance manoeuvre is performed.
2. Braking with the maximum pedal force; an obstacle avoidance manoeuvre is performed, and the brake pedal is released at the same time. The maximum force is applied again after the manoeuvre.
3. The average pedal force is applied without ABS activation; an obstacle avoidance manoeuvre is performed.
4. The maximum pedal force is applied without ABS activation; an obstacle avoidance manoeuvre is performed, and the brake pedal is released simultaneously. The maximum force is braked after the manoeuvre.

Figure 8 shows acceleration characteristic when at first vehicle is braked with maximum pedal force and driver makes an obstacle avoidance manoeuvre (cornering) and at the same time releases the brake pedal, after the manoeuvre a maximum braking force is reapplied. This test attempts to simulate the driver's behaviour in an emergency braking

event, were braking and steering is not an optimal option to avoid collision. It puts drivers and ABS system working together.

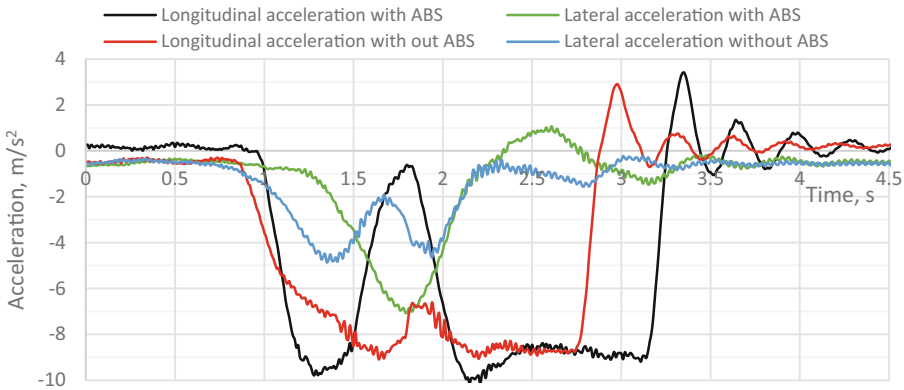


Fig. 8. Vehicle acceleration dependence on driver behaviour in a designed emergency braking in a turn event.

The Fig. 8 shows how the acceleration characteristics change with and without ABS. It is noticeable that vehicle achieved a higher lateral acceleration during the turning manoeuvre when the brake pedal was released. Looking at the lateral acceleration curve, when the vehicle without ABS has manoeuvred, "waves" are visible, indicating that the driver has made steering adjustments during braking without ABS to keep vehicle stable. However, although the case with ABS has developed a higher lateral acceleration (this results in better manoeuvrability of the vehicle during braking), this sequence of actions shows that vehicle with ABS stopping time is longer. This has happened because vehicle lost all longitudinal deceleration when the brake pedal was released. According to driver's sensation, it was difficult to dose the level of pedal release with ABS active. The loss of deceleration was not critical at the case without ABS when driver keeps tight control of brake pedal force all the braking time.

5 Conclusions

Summarising results from the conducted research it can be stated that the force applied to the braking pedal and its moment (according to moment of steering) affects the manoeuvring of the vehicle when ABS is engaged or disengaged. The efficiency of the ABS during braking with emergency cornering manoeuvre depends on the following factors:

1. Rapidly increasing longitudinal acceleration (around 8–9.5 m/s^2) directly affects vehicle lateral dynamics. Increased longitudinal acceleration resisted a change in vehicle's trajectory, even though the wheels were not locked, and ABS was working. It is suggested, that during an extreme braking manoeuvre, ABS should react to the steering angle if the driver seeks to avoid a collision by changing trajectory.

ABS ECU should take into account steering wheel angle as an input for ABS algorithm, which would make calculations and distribute braking forces in the wheels accordingly so that the higher braking force acts on the wheel contour that coincides with the direction of the driver's desired trajectory. This would cause the vehicle to rotate around a vertical axis and increase lateral acceleration, thus improving the manoeuvrability of the vehicle and improving active safety performance.

2. It's been observed that effectiveness of ABS depends on the sequence of actions that drivers makes in an emergency situation, and it is suggested that, studies that seek to make improvements to current ABS system need to include a wide range of different emergency braking scenarios when observing their experiments.
3. It is very important to consider the fact that each driver reacts differently to an emergency, so the human factor is an integral part of these studies. Active safety systems are additional measures designed to compensate for the lack of driver's skills, aiming to ensure that the driver has maximum control of the vehicle during an emergency.
4. Braking with ABS vehicle's lateral acceleration is up to 40% higher than braking without ABS control, because driver do not have to precisely dose the braking force (part of ABS), therefore he is more involved in course change (steering). However, from vehicle dynamics point of view the sequence of braking and steering actions is still important for safe obstacle avoidance during emergency braking.

References

1. Road Traffic Injuries and Deaths—A Global Problem. https://www.cdc.gov/injury/features/global-road-safety/index.html. Accessed 27 May 2022
2. Reif, K.: Brakes, Brake Control and Driver Assistance Systems. Function, Regulation and Components, pp. 74–89. Springer, Wiesbaden (2014). https://doi.org/10.1007/978-3-658-03978-3
3. Žuraulis, V., Chugh, A.: Vehicle ABS braking performance on road with pavement obstacles. In: Prentkovskis, O., Yatskiv (Jackiva), I., Skačkauskas, P., Junevičius, R., Maruschak, P. (eds.) TRANSBALTICA 2021. LNITI, pp. 221–229. Springer, Cham (2022). https://doi.org/10.1007/978-3-030-94774-3_22
4. Chen, W., Xiao, H., Wang, Q., Zhao, L., Zhu, M.: Integrated Vehicle Dynamics and Control, pp. 38–75. Wiley, Hoboken (2016)
5. Denton, T.: Automobile Electrical and Electronic Systems, p. 476. Elsevier, Amsterdam (2004)
6. Rajendran, S., Spurgeon, S., Tsampardoukas, G., Hampson, R.: Time-varying sliding mode control for ABS control of an electric car. IFAC-PapersOnLine **50**(1), 8490–8495 (2017)
7. Li, Y., Sun, W., Huang, J., Zheng, L., Wang, Y.: Effect of vertical and lateral coupling between tyre and road on vehicle rollover. Veh. Syst. Dyn. **51**(8), 1216–1241 (2013)
8. Meywerk, M.: Vehicle Dynamics, p. 360. Wiley, Hoboken (2015)
9. Žuraulis, V., Surblys, V.: Assessment of risky cornering on a horizontal road curve by improving vehicle suspension performance. Baltic J. Road Bridge Eng. **16**(4), 1–27 (2021)
10. Botero, J., Gobbi, M., Mastinu, G., Piazza, N., Martorana, R.: On the reformulation of the ABS logic by sensing forces and moments at the wheels. IFAC Proc. Vol. (IFAC Papers-OnLine) **40**(10), 265–272 (2007)

11. Guiggiani, M.: The Science of Vehicle Dynamics, p. 565. Springer, Dordrecht (2018). https://doi.org/10.1007/978-3-319-73220-6
12. BMW E46 3 Series 320d Specs. https://www.ultimatespecs.com/car-specs/BMW/4936/BMW-E46-3-Series-320d.html. Accessed 28 May 2022
13. Li, W.L., Zhou, W., Gao, L.: Vehicle braking efficiency on-line monitoring and evaluation with MFDD. In: Advanced Material Research, pp. 968–971 (2012)
14. McLaughlin, S.B.: Measurement of Driver Preferences and Intervention Responses as Influenced by Adaptive Cruise Control Deceleration Characteristics. Blacksburg (1998)
15. Najm, W., Smith, D.: Modelling driver response to lead vehicle decelerating. https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.225.5005&rep=rep1&type=pdf. Accessed 27 May 2022

Methodology of the Durability Tests of Semi-trailers on the MTS 320 Road Simulator

Arkadiusz Czarnuch[1](✉), Marek Stembalski[2], Tomasz Szydłowski[1], and Damian Batory[1]

[1] Department of Vehicles and Fundamentals in Machine Design, Łódź University of Technology, Lodz, Poland
arkadiusz.czarnuch@dokt.p.lodz.pl, {tomasz.szydlowski, damian.batory}@p.lodz.pl

[2] Department of Machine Tools and Mechanical Technology, Wrocław University of Technology, Wroclaw, Poland
marek.stembalski@pwr.edu.pl

Abstract. Modern vehicles more and more often have a specific life cycle, presented in years or with the possibility of going through a certain mileage without failure. For this purpose, manufacturers perform a series of tests, to confirm the reliability of their products. One of such tests is an accelerated durability test, with the use of modern simulation stands that imitate road conditions.

This article presents the methodology of durability tests for commercial vehicles, using the eight poster, inertia reacted, road simulator MTS 320. The first step is to collect reference road data. For this purpose, the vehicle is equipped with a set of sensors. Gathered data was recreated on the road simulator. Authors prove the convergence of the obtained results, in comparison to the data collected from the road, at the level of up to 99% of root mean square value of the reference signals to the reconstructed signals. Tests are performed for loaded and unloaded vehicles. The result of the test is to confirm the reliability of the manufactured vehicle. During the test, the supporting structure of the vehicle with suspension as well as the functional reliability of the vehicle are assessed. Moreover, the key issue is to correctly determine the duration of the test and to set test parameter values.

The development of this test technology is response to the need, to quickly and reliably check vehicles or their components, before implementing them into serial production.

Keywords: Road simulator · Durability tests · Mechanical engineering

1 Introduction

Before the vehicle is handed to the customer into operation, the vehicle manufacturer carries out a series of tests and examinations. Nowadays, a lot of emphasis during testing is placed on durability tests. The life cycle of the vehicle is referred by determining the reliability of individual vehicle components. In order to perform a reliable fatigue

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 236–246, 2023.
https://doi.org/10.1007/978-3-031-25863-3_22

analysis or the durability tests themselves, it is necessary to determine the conditions in which the vehicle will operate. Fu et al. [1] presented the process of estimating and determining the durability test mode based on a user survey.

The durability analysis and the tests themselves can be divided into three basic groups. The first is the theoretical analysis, where fatigue calculations are performed using standards or developed methods of durability estimation. Nasir [2] performed the fatigue analysis of the vehicle suspension component using three methods Coffin-Manson, Morrow and Smith-Watson-Topper (SWT). The analysis for the vehicle suspension spring was performed for three types of roads. Another way to confirm the fatigue strength of components is conducting tests on test tracks. Klepka et al. [3] presented bus tests on a special test track. In another paper Kosobudzki et. al. [4] presented the fatigue analysis of the suspension element in order to estimate the fatigue life on the basis of the fatigue accumulation index d. The last group of durability tests are bench tests with the use of simulators. Simulators are used to test vehicle components and whole vehicles, Doddsa et al. [5] reviewed the techniques for laboratory road simulations. Chindamo et al. [6] represents the recreation of real road conditions for vehicle suspension tests. Vehicle tests on four-poster stands are described in the paper Sharma et al. [7]. The road simulator recreates various road conditions. Czarnuch et al. [8] proved a very accurate representation of road conditions using a road simulator.

Durability tests are carried out not only on complete vehicles but also on selected components. At work Yongping et al. [9] present the experimental test of gas-tightness and electrical insulation of fuel cell stack reconstructing road vibration on the vibration table.

In this paper, authors present the methodology of conducting accelerated durability tests using the MTS 320 road simulator stand. The stand was described by Stembalski et al. [10], where the method of collecting road data, which was reconstructed on a road simulator, was also presented. On the simulator, a series of durability tests of semi-trailers in various designs as curtain, sideboard or box-type trailers were carried out. On the same stand semi-trailers for the transport of sea containers as well as tippers were also tested.

The MTS 320 road simulator is designed to test commercial vehicles such as semi-trailers and trailers. It is the second test stand for this purpose in Europe. The tests are performed for both unloaded and loaded vehicles, the mass of which reaches 39 t. Considering the weight of the vehicle and its dimensions, the dynamic simulation of such vehicles generates very high forces.

This paper presents research methodologies based on the mapping of road conditions, which are collected separately for each tested vehicle. This approach guarantees appropriately selected conditions for the tested vehicle, considering its specific purpose. The loads that will be transported and the regions in which the vehicle will be operated are taken into account. The methodology is presented on the basis of the conducted tests of large-size vehicles.

2 Description of the Stand for Durability Tests

The presented MTS 320 road simulator is a mechatronic device used by Wielton for durability tests of semi-trailers, trailers and trucks. The diagram of the stand is presented

in Fig. 1. The stand is equipped with eight independently working hydraulic cylinders. Six actuators are used to generate movements under the wheels of the vehicle (2), two actuators located in the coupling part are used to simulate the movements of the tractor fifth wheel (6). The actuators with the coupling part are placed on the seismic mass (4). The mass is 600 t, supported on 26 air bags (5). The task of seismic mass is to absorb vibrations occurring during the test, ensuring vibration isolation of the entire station.

The construction of the stand enables the adjustment of the position of each cylinder to the dimensions and construction of various vehicles. The cylinders under the wheels can be adjusted within the length of the seismic mass (3), around 8 m. The coupling part is adapted to simulate a tractor unit as well as to simulate a coupling for trailers with a drawbar (7). The stand can also work without the coupling part thus, enabling testing of self-propelled vehicles equipped with up to three axles.

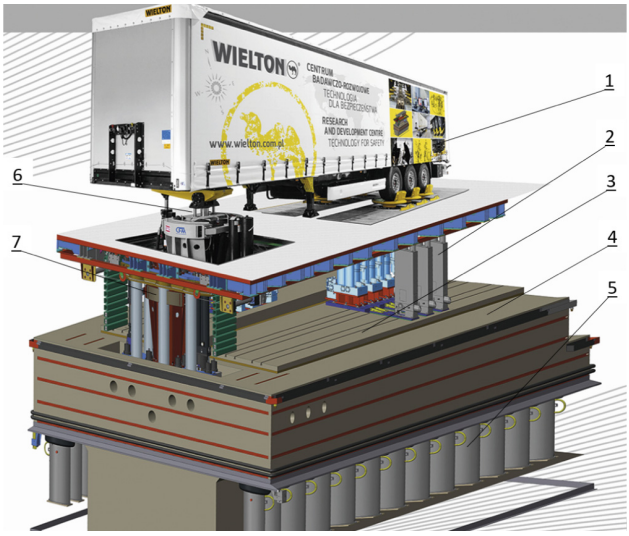


Fig. 1. Schematic diagram of the test stand. 1 – tested vehicle, 2 – actuators under the wheals, 3 – mounting plate, 4 – seismic mass, 5 – air bags, 6 – actuators of the coupling part, 7 – coupling part.

The permissible load of the tested vehicles is 9 t per axle and 12 t per coupling part. For semi-trailer vehicles, the permissible mass is 39 t. The stand therefore enables dynamic tests of both unloaded and fully loaded vehicles. Due to the fact that the stand is from the group of "inertia reacted", the vehicle must be loaded in order to test the vehicle load. This method also enables various vehicle loads such as partial concentrated loads to be tested.

3 Methodology of Bench Tests on a Road Simulator

3.1 Defining the Boundary Conditions for the Test Execution

In order to perform reliable tests, the first step is to define the boundary conditions for the test. In the case of durability tests of a commercial vehicle, the mileage assumed by the manufacturer of the vehicle should be determined as an assumption of durability of the vehicle and the road conditions on which the vehicle will be driven. For commercial vehicles, it is important to determine under what conditions the vehicle will be loaded and unloaded or what loads will be transported. The stage of assumptions for durability tests is very important due to the relatively long duration of tests in which defined conditions are repeated in sequence. Table 1 presents the averaged results from a survey conducted with several customers regarding the conditions of use of a three-axle curtain semi-trailer with a technical load capacity of up to 32 t.

Table 1. Reference mileage for a curtain semi-trailer in the annual settlement.

	Mileage of loaded trailer		Mileage of un-loaded trailer	
	[km]	[%]	[km]	[%]
Local roads (L)	9,500	12%	5,000	23%
National roads (G, GP)	26,000	33%	6,000	28%
Motorways roads (S, A)	43,500	55%	10,500	49%
Total annual mileage	**79,000**	**79%**	**21,500**	**21%**

The test has been performed in two variants, with the permissible load, and with an unladen vehicle. The roads on which the vehicle traveled were divided into three groups: - local roads (visible large surface defects, marked as L in Poland), - national roads (visible minor surface defects, referred as G and GP in Poland) and motorways (no visible surface defects, referred in Poland as S and A roads) [11]. A similar division was used in the work Prażnowski et. al. [12]. The author divided the roads into three categories in terms of the surface condition. Based on the information collected from customers, vehicles of this type are used in various ways as loaded and unloaded vehicles. In both cases, the predominant routes are on good-surfaced roads, classified as express roads. The annual mileage of the analyzed vehicles is around 100,000 km.

3.2 Preparation of the Vehicle for Testing

The vehicle designed for durability tests is after a series of functional and strength tests. Earlier tests eliminate possible defects that do not result from durability tests. The vehicle is being prepared to collect road data. For this purpose, a measuring installation is made from a number of sensors, the task of which will be to record data from the road and measurements during the mapping of these data on the test stand. Below is an example of a list of sensors that are installed on the vehicle:

– accelerometers ±300 m/s^2 with measurement in one vertical axis, located on each axle near the wheels and in the front part of the frame;
– distance sensors ±0.32 m located near every wheel, measuring the distance from the axle to the frame;
– half-bridge strain gauges located on the main beams at the places where the cross section changes, one direction measure;
– pressure sensor 0–200 MPa in every air bag of the suspension.

Quantum HBM series measurement cards are used for data acquisition. Data are recorded with the CX22 data logger. The installation is equipped with a power supply system that allows recording of road data for 48 h. No filters are used for data logging, the sampling frequency is 300 Hz [13].

The sensors are located near the axis of the vehicle and in the area of the coupling part. For vehicles with air suspension systems, pressure sensors located in the suspension bags are also used. Displacement sensors register the change in the position of the axle in relation to the vehicle frame. The acceleration sensors are installed near each wheel and in the area of the king pin, allowing the behavior of the fifth wheel truck, to be reproduced. In the front part of the frame, strain gauges are glued to record the change in tension in the stressed areas of the frame. The location of the sensors on an exemplary semi-trailer from the NS3 series is shown in Fig. 2.

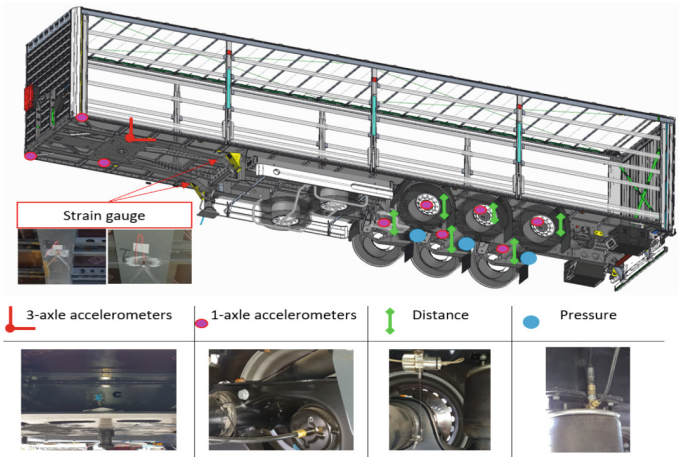


Fig. 2. Location of measurement sensors.

3.3 Collecting Road Data

In order to collect road data, the roads on which the vehicle will travel are defined. Reference routes are performed for both loaded and unloaded vehicles. The routes are determined on the basis of information from customers, on which roads the tested vehicle will ultimately drive on. Figure 3 shows an example of the classification of reference

roads along which road data for a curtain semi-trailer was collected. When traveling on the roads, data from the installed sensors are recorded, as well as the position and speed of the vehicle from the vehicle's on-board telematics [14]. It is important that the vehicle is equally configured to collect road data and during performing road reconstruction on the test bench.

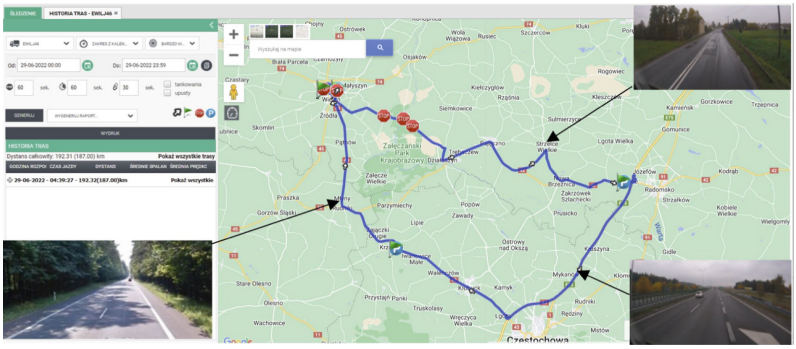


Fig. 3. Designated roads for collecting road data.

3.4 Installation of the Vehicle on the Test Stand

After collecting road data, the vehicle is installed on the test stand. The diagram of connecting the vehicle at the road simulator stand is presented in Fig. 4 (a), the real view of the installed test vehicle is presented in Fig. 4 (b). The stand is properly configured for the technical parameters of the vehicle, taking into account dimensions and axle loads. Measuring installation located on the tested vehicle is connected to the station through the CX27 HBM module (4) and the EtherCAT protocol [15]. The information from the sensors is transmitted to the station controller (3) and to the computer (5). The station controller allows you to control the actuators (2) in order to recreate road signals on the road simulator.

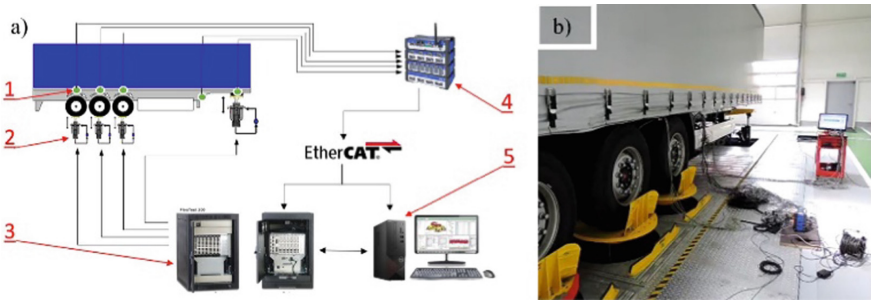


Fig. 4. The vehicle on the test stand. a) Connection diagram. b) Real view. 1 – set of sensors on the trailer, 2 – stand actuators, 3 – controller, 4 – measure cards with CX27 module, 5 – computer.

The presented connection and configuration system enables the reconstruction of road data recorded during road routes. The installation is also used during simulation tests to check the behavior of the vehicle. Limits are set on the recorded signals, if exceeded, the test process stops. Continuous recording of signals from sensors, allows to determine the trend, on the basis of which the wear process during the test can be predicted.

3.5 Data Processing on the Road Simulator

Recorded data in the form of time series are processed using the MTS RPC Pro software. The signal is filtered within a filter in the range from 0.6 to 50 Hz. Then signal is resampled, the inaccuracies so-called spikes and offset are removed. In order to select the appropriate signal, the formula for calculating the fatigue accumulation coefficient is used to create the control profiles. In this way, the time periods of the signal with the greatest accumulation of fatigue are selected. For example, in Fig. 5 is shown the signal in which the time periods with the highest accumulation of fatigue were selected. The signals are cut at the same time period for all analyzed signals. The cut-out sections are put together into one signal with a tapering time of 0.3 s. The signals edited in this way have a length of 40 to 300 s and these are the signals that will be used in the next steps to reconstruct the road data in the simulation.

In this way, several signals from the collected reference data are generated. In total it is about 1,200 s of the signal used for the simulation. The generated signals correspond to the range of the spectrum that was collected during reference routs. Signal processing is performed for the data with a laden and unladen vehicle.

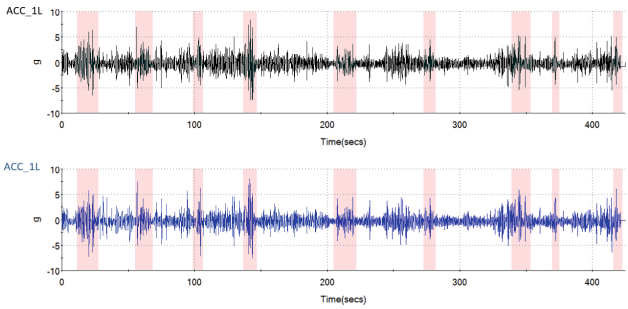


Fig. 5. Road signal processing, first and second axis of the left side.

3.6 Creating a System Model

The System Modeling step is associated with the launch of the station with an already configured vehicle. The purpose of the System Model is to define the relationship between input and output signals.

– The input signals are the station actuators controlling signals, referred to as “Drive”.

– The output signals are signals from sensors installed on the vehicle, called "Response".

System model, this is Frequency Response Function (FRF). It shows the relationship of outputs to inputs across the frequency band. In other words, for a given input it is possible to calculate the output. When the system model is created it became possible to reconstruct the drive data signal. The "Drive" signal of the actuator displacement is determined by multiplying the signals collected from the road by the inverse of matrix FRF. It is schematically presented in Fig. 6 [16].

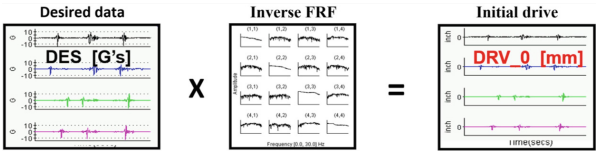


Fig. 6. Model of the system.

3.7 Road Data Simulation

Road data simulation consists of recreation of the prepared signals using the system model. The reconstruction of the runs takes place in several iterative steps. After each iteration step, the level of signal reconstruction, the level of frequency reconstruction and the measurement of the error are controlled by taking into account the root mean square (RMS) of the signal expected to the desired signal. An example of reconstructed acceleration signal of one of the axes to the given signal in the time domain is shown in Fig. 7 (a). The graph shows the desired signal (black line) and the response signal (blue line). Figure 7 (b) shows a reconstruction of this signal in the frequency domain. The level of the reproduction was achieved from 95 to 99%, in terms of RMS of the desired signal to the signal reconstructed. Achieved level is a very good result, due to the dimensions of the tested vehicle.

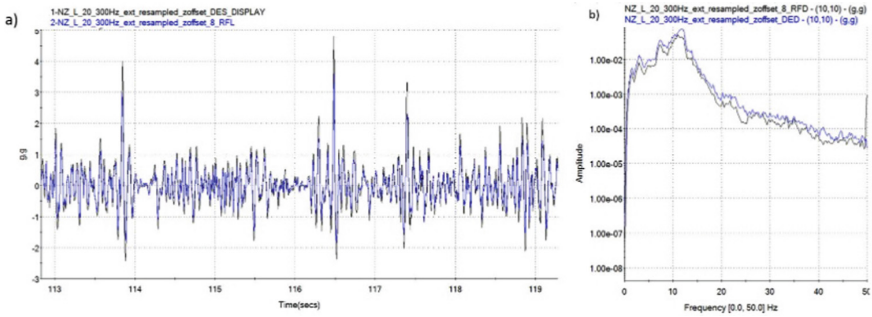


Fig. 7. Signal reconstructing on the road simulator stand, a) in the time domain, b) in the frequency domain. (Color figure online)

The ultimate goal of the simulation is to generate a drive signal, that is used to control the displacement of the simulator actuators during the test. Figure 8 and Fig. 9 present sample statistics of the drive signal of individual actuators, respectively for an unloaded and loaded semi-trailer. The drive signal represents the profile of the road with respect to the movement of the wheel contact point with the road ground.

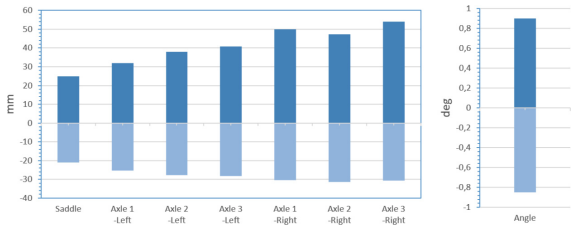


Fig. 8. The range of actuators displacement and angle change of the coupling part, for simulating an unloaded semi-trailer.

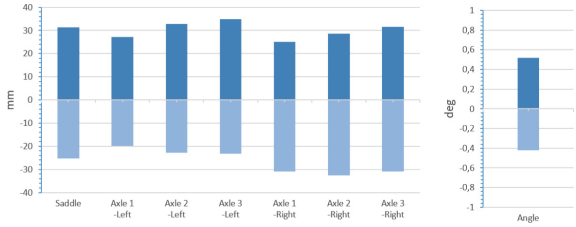


Fig. 9. The range of actuators displacement and angle change of the coupling part, to simulate a loaded semi-trailer.

The analysis of the actuator movement statistics shows, that the range is greater for an unloaded semi-trailer, than for a loaded semi-trailer. The difference is up to 20%. This is due to the characteristics of the vehicle suspension, which is designed for higher loads, up to 9 t axle load. Additionally, there is a noticeable difference in the displacements generated on the right side of the vehicle compared to the displacements on the left side of the vehicle. The difference is up to 15%, more noticeable on an unladen vehicle. The difference between the sides is the effect of greater damaged left side of the road.

4 Durability Tests

The final step is to perform the test. For this purpose, the generated drive data are arranged in a sequence that repeats in a loop. The number of repetitions is determined based on the calculation of the fatigue accumulation factor. The coefficient is estimated on the basis of readings from strain gauges located in the vehicle structure. It is calculated by comparing the data obtained from reference routes, appropriately multiplied by the assumed mileage in km. The coefficient is compared to the data obtained on the simulator in order to achieve the same fatigue accumulation coefficient as during the reference runs.

The Fig. 10 shows a diagram of the comparison of data obtained while driving with data from laboratory tests. The assumption for the tests of trailers is their life cycle defined in years or mileage. For standard semi-trailers, the assumed failure-free operation is the mileage of 500,000 km.

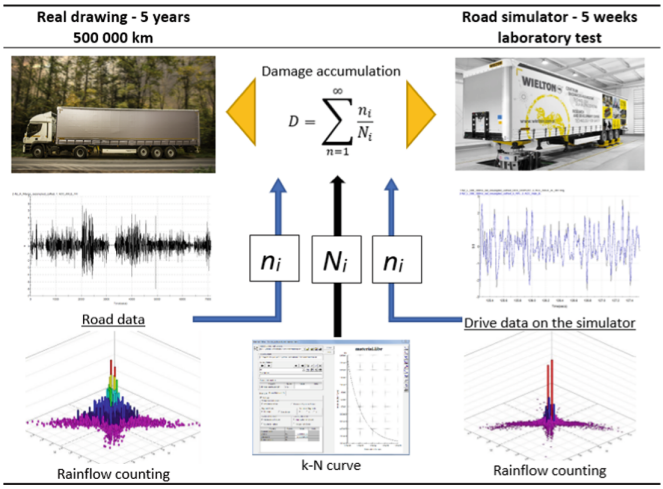


Fig. 10. Schematic diagram of the simulation test comparison.

During the test, signals from the installed sensors as well as from sensors controlling the stand are monitored. For the wheel coupled simulators, all loads come in through the suspension and a failure in the suspension is more severe than a failure in the body. Therefore, it is important to monitor loads in the suspension.

During the test, trend monitoring is also used. It allows for collection of statistics over the life of the test. Additionally, it enables to compare statistics to reference levels, to control test execution, to warn or to abort the test.

5 Summary

The presented methodology of accelerated durability tests with the use of a road simulator stand is successfully used in the Wielton company, producer of the commercial vehicles. The methodology efficiently defines how to check newly designed products before their serial implementation on the market. Several dozen vehicles have been tested since the launch of the stand. It enriched the knowledge of engineers about the durability of commercial vehicles. This allows the company to develop much faster by introducing new, proven products to the market.

The methodology is based on individual data collection for each structure, therefore it can be successfully used for various design of semi-trailers or other vehicles.

The obtained data from durability tests are also used during computer simulations using the finite element method (FEM). It also allows to eliminate construction errors

at the design stage. The methodology is also used in the optimization of the structure, where a very important parameter is the reduction of the curb weight of the vehicle.

The methodology is constantly verified and updated at the same time. Data to verify the correctness of performed tests are obtained from customers as well as from internal service databases.

References

1. Fu, H., Gao, J.: Vehicle durability test based on user survey. Comput. Model. New Technol., 479–483 (2014)
2. Nasir, N.N.M., Abdullah, S., Singh, S.S.K., Haris, S.M.: Risk-based life assessment of prediction models on suspension system for various road profiles. Eng. Fail. Anal. **114**, 104573 (2020)
3. Kepka, M., Kepka Jr., M., Václavík, J., Chvojan, J.: Fatigue life of a bus structure in normal operation and in accelerated testing on special tracks. Procedia Struct. Integr. **17**, 44–50 (2019)
4. Kosobudzki, M., Stańko, M.: Problems in assessing the durability of the selected vehicle component based on the accelerated proving ground test. Maint. Reliab. **21**(4), 592–598 (2019)
5. Doddsa, C.J., Plummer, A.R.: Laboratory road simulation for full vehicle testing a review. SAE Tech. Pap. (2001). https://doi.org/10.4271/2001-26-0047
6. Chindamo, D., Gadola, M., Marchesin, F.: Reproduction of real-world road profiles on a four-poster rig for indoor vehicle chassis and suspension durability testing. Adv. Mech. Eng. **9**(8), 1–10 (2017)
7. Sharma, B.R.: Feasibility of use of four-post road simulators for automotive modal applications. University of Cincinnati (2010)
8. Czarnuch, A., Stembalski, M., Szydłowski, T., Batory, D.: Method of reconstructing dynamic load characteristics for durability test of heavy semitrailer under different road conditions. Maint. Reliab. **23**, 548–558 (2021)
9. Yongping, H., Wei, Z., Caoyuan, S.: Experimental investigation of gas-tightness and electrical insulation of fuel cell stack under strengthened road vibrating conditions. Int. J. Hydrog. Energy, 13763–13768 (2011)
10. Stembalski, M., Czarnuch, A., Batory, D.: Collection of reference data for durability tests using a road simulator. Int. Bus. Inf. Manag. Assoc., 11352–11365 (2020)
11. https://www.gov.pl/web/infrastruktura/rodzaje-drog-w-polsce
12. Prażnowski, K., Mamala, J.: Classification of the road surface condition on the basis of vibrations of the sprung mass in a passenger car. Mater. Sci. Eng. **148**, 012022 (2016)
13. Tianshuang, Q.: Signal Processing and Data Analysis. De Gruyter (2018)
14. Wang, B., Panigrahi, S., Narsude, M., Mohanty, A.: Driver identification using vehicle telematics data. In: Conference Paper, Ford Motor Company (2017)
15. Seno, L., Zunino, C.: A simulation approach to a real-time ethernet protocol: EtherCAT. In: International Conference on Emerging Technologies and Factory Automation, pp. 440–443 (2008). https://doi.org/10.1109/ETFA.2008.4638431
16. User manual for the MTS road simulator station (2005)

An Engineering Design of a Frame of an Electric Bicycle

Ján Dižo(✉), Miroslav Blatnický, and Denis Molnár

University of Žilina, Univerzitná 8215/1, 010 26 Žilina, Slovak Republic
{jan.dizo,miroslav.blatnicky,denis.molnar}@fstroj.uniza.sk

Abstract. The article is a continuation of the ongoing research of an engineering design of a mini-electric bicycle. The previous outputs include the detailed legislation in individual countries and a historical overview of the development of bicycles. This current study is focused on the description of an engineering design of a frame of a bicycle with respect of the method of designing and safety as the most important requirement for any structure. The main goal of the authors is to design a bicycle with respecting all legislation demands in a particular country and to provide a possibility to assembly such a transport mean self-help in home conditions without lengthy information retrieval. Due to the range of the solved problem, this research presents a simulation of driving regime, namely sitting of a passenger on a bicycle without considering additional loads. The solved structural unit can be included to the competition environment, which is proven by calculated and analysed parameters needed for a proper choose of normalized components.

Keywords: Electric bicycle · Engineering design · Simulation · Analysis

1 Introduction

Electrification of a bicycle is not a new idea. The first patent for an electric bicycle comes from 1895. However, a concept has not been very successful. Even at the beginning of the 21st century, electric bicycles were relatively rare. For example, in the period of years 2006 to 2012, electric bicycles represented less than 1% of all sold bicycles in the USA. On the other hand, they produced in China 37 millions of electric bicycles in the year 2013 and they sold 32 million of them. In comparison with this, they sold only 1.8 millions of electric bicycles in Europe, 440,000 in Japan and 185,000 in the USA [1].

There are many categories of electric bicycles [2, 3]. However, there is one main aspect for categorization of electric bicycles. It is based on, whether an electromotor helps to a cyclist while pedalling or it has a possibility to control it by a regulator (it is usually controlled by a cycling computer) [4]. Hence, electric bicycles can be categorized based on this to three categories:

- a motor helps to a cyclist only while pedalling,
- a motor works only when using the controller,

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 247–257, 2023.
https://doi.org/10.1007/978-3-031-25863-3_23

- a motor is controlled either by pedalling or by a regulator.

The article presents a history of bicycles including breakthrough models. This is a continuation of the research [5] and it includes a design of a frame of the electric bicycle created in the Catia V5 R21 software. The electric bicycle has been modelled in the Catia software and the final model is depicted in Fig. 1. The Catia software is widely used tool for designers to create from simply to very large and parametrized models of many kind of transport means and it is used in many automotive, railway and other companies [6–8].

Fig. 1. A CAD model of the designed electric bicycle.

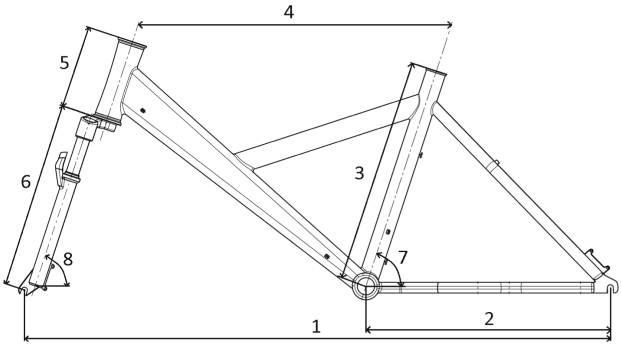


Fig. 2. Basic dimensions of the designed frame of an electric bicycle.

Figure 2 depicts the basic dimensions of the frame. These dimensions are marked by numbers and their particular values are listed in Table 1.

The introduced parameters are influenced by following dimensions:

- a wheel's diameter,
- a location and dimensions of a battery,
- a diameter of a seatpost,
- a diameter of an upper tube of a fork and
- a diameter of a pedal crank.

Table 1. Description of basic dimensions of the frame.

Number of a dimension (Fig. 1)	Parameter	Value
1	Wheelbase	1,193 mm
2	Length of a rear fork	497 mm
3	Length of a seatpost	463 mm
4	Horizontal distance between a head tube and a seatpost	628 mm
5	Length of a headtube	170 mm
6	Length of a front fork	389 mm
7	Seat angle	72°
8	Head angle	72°

2 Materials and Methods

When designing any bicycle, it is important to identify many factors such as for whom it is intended, where it will be used or for what purpose it will serve us. The competitive environment of bicycles is very diverse and it can be said that there is a bicycle for almost everyone and for every occasion. The designed bicycle is powered by an electromotor, which is practically maintenance free [9–11], it has sufficient power to transport a passenger for wanted distance at appropriate speed and it is able to overcome driving resistances, which can appear during operation of the bicycle [12–14].

Our design is designed especially for seniors, so it will focus on comfortable driving and ergonomic design. Sitting position is a very important aspect for a comfortable driving. The most comfortable sitting position is where the cyclist's back is as outstretched as possible and as perpendicular to the riding surface. Therefore, it is necessary that the handlebars are of sufficient height.

The design is designed for driving in the city, mostly on paved roads, but will also manage driving on mild terrain. For better driving quality, this design will be equipped with front suspension and disc brakes on the front and rear wheels. It will also be equipped with thicker wheels that will better absorb vibration caused by road irregularities and uneven terrain [15, 16].

The main advantages of our design compared with other mini-electric bicycles are, that this one is more comfortable for driving, it has better driving characteristics, higher stability, the possibility of driving in off-road conditions [17–19].

The most important material of the entire bicycle is the frame material. There are many different materials that are used for frame construction, but it can be said that there are four main options: aluminium, carbon fibre, titanium and steel. Each of them has its advantages and disadvantages, but depending on the application, we can find the right choice.

The place of use and the price play a role in our choice of the frame material. As our design is designed for driving mostly in the city on paved roads, the increased strength of titanium and carbon fibre will not be used. The remaining options are aluminium and steel. Of these two materials, aluminium suits us better because it is lighter (it will have a better effect on the range).

The following sections of the article are focused on the strength analyses of the main supporting part of the bicycle, i.e. the frame. Its CAD model is shown in Fig. 3.

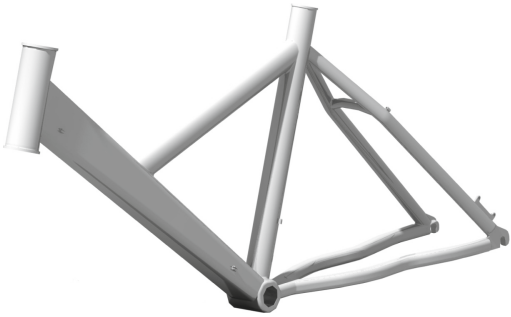


Fig. 3. Basic dimensions of the designed frame of an electric bicycle.

3 FEM Analysis of the Frame

This section includes a static analysis of the electric bicycle frame in the Ansys software. This is one of the most often used FE software for analysing structural properties of various structures [18]. In our case, the frame is analysed in term of distribution of stresses in under various loads and forces. These loads represent a common using of the bicycle. In addition to the frame, the front fork, handlebars, seat post and pedal crank simulation bar will be included in the simulation to more accurately determine the forces acting on the frame (Fig. 4). Analyses are focused on the load cease, namely for load during sitting on a seat and the load during braking the bicycle. Information about the input data to the FE frame model are listed in Table 2.

3.1 Analysis of the Frame for the Sitting Position

During the simulation of sitting, it was assumed that only the gravity of the cyclist who is at rest acts on the frame. Its weight was redistributed as a percentage into three parts

Table 2. The input data of the FE model of the frame.

Material	Aluminium alloy	Isotropic, homogenous
Parameter	Value	Unit
Young's modulus	71,000	[MPa]
Poissons ratio	0.33	[–]
Bulk modulus	69,608	[MPa]
Tensile ultimate strength	310	[MPa]
Tensile yield strength	280	[MPa]
Finite element size	5	[mm]

Fig. 4. Models of a frame together with other considered components.

where the cyclist contacts the bicycle: seat (70%), pedals (25%) and handlebars (5%) [20].

The model of the frame is created in the coordinate system, in which the *x*-axis represents the lateral direction, the *y*-axis is the longitudinal direction (driving direction) and the z-axis indicates the vertical direction. On the seat and pedals, the force will act in the negative direction of the *z*-axis and on the handlebars at an angle of 45°, i.e. it is distributed so that 50% acts in the negative direction of the *z*-axis and 50% in the negative direction of the *y*-axis (Fig. 5). The frame is attached at the point of contact with the rear wheel shaft by a rotating link which prevents movement in any direction and allows only rotation around the *x*-axis and at the point of contact with the front wheel shaft with a rotary-sliding link which also allows rotation around the *x*-axis but also allows movement in the direction of the *y*-axis (Fig. 5).

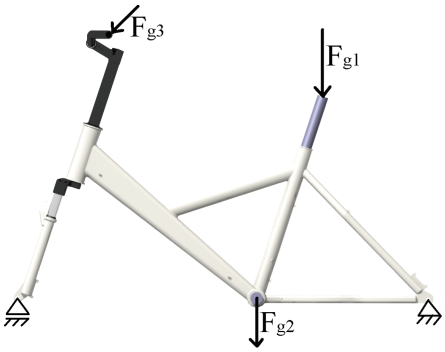


Fig. 5. Boundary conditions of the frame while cyclist sits on a seat.

Table 3. A distribution of the gravitational force acting on the frame for simulation of the cyclist sitting.

Force	Percentage [%]	Value [N]	Location of acting the force	Direction of acting
$\boldsymbol{F}_{g1}$	70	515.03	The top of a seatpost	Negative direction of the z-axis
$\boldsymbol{F}_{g2}$	25	183.94	Edge of the rod simulating pedal crank	Negative direction of the z-axis
$\boldsymbol{F}_{g3}$	5	36.79	Edge of the handlebars	50% negative direction of the z-axis 50% negative direction of the y-axis

The forces acting on the frame were calculated using Newton's second law (1), where the force is equal to the relevant mass multiplied by its acceleration. In this case, the cyclist's gravity is equal to the product of the cyclist's mass $m_c = 75$ kg and the gravitational acceleration $g = 9.81$ m·s^{-2}.

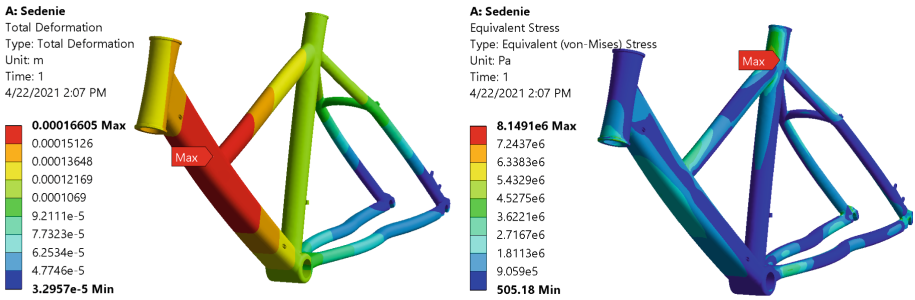
$$F = m_c.g. \tag{1}$$

According to the performed experiment, the result of the gravitational force will be divided into the places of contact of the cyclist with the bicycle according to Table 3.

According to the results of the simulation program, the place with the largest deformation displacement is located at the point of contact of the upper and lower tubes with max. Displacement 0.16605 mm (Fig. 6a). The place with the highest stress is located at the point of contact between the seat post and the seat tube with max. Stress of 8.1491 MPa (Fig. 6b).

3.2 Analysis of the Frame for the Braking

In this analysis, the all effects of braking by a front brake is considered. According to the bicycle braking analysis [21], the deceleration of a bicycle with disc brakes is approx.



a) b)

Fig. 6. Results of the analysed frame for the load while sitting: the maximal displacements of the frame (a), the maximal stress in the frame structure (b).

0.4·g to 0.71·g. Hence, it is assumed that the maximum deceleration is of 0.71·g, which is of 6.97 m·s^{-2}. In addition to the cyclist's gravity, the frame will now be subjected to a braking force F_b, which will act at the point of contact between the rear wheel shaft and the frame in the direction of travel, i.e. in the opposite direction of the y-axis. However, it must not forget the force of inertia of the cyclist F_z, which will act in the driving direction on the handlebars. The attachment of the frame will be the opposite direction in comparison with the seating simulation. Forces are depicted in Fig. 7.

The same as in the case of the sitting analysis, the braking force is calculated by means of the second Newton's law (Eq. 2), where the force F_b will equal to the product of the weight of the bicycle with the cyclist of $m = 99.56$ kg and deceleration of $a = 6.97$ m·s^{-2} while the force of inertia of the cyclist F_z will equal to the product of the cyclist's weight $m_c = 75$ kg and deceleration $a = 6.97$ m·s^{-2}:

$$F_b = m.a = 99.56\,\text{kg} \cdot 6.97\,\text{m} \cdot \text{s}^{-2} = 693.93\,\text{N}, \tag{2}$$

$$F_z = m_c.a = 75\,\text{kg} \cdot 6.97\,\text{m} \cdot \text{s}^{-2} = 522.75\,\text{N}. \tag{3}$$

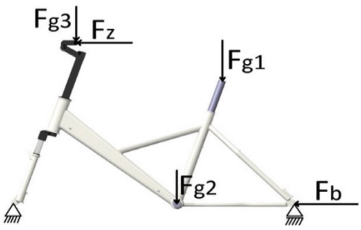
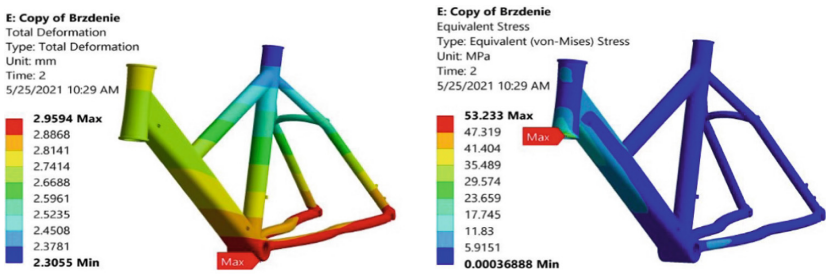


Fig. 7. Boundary conditions of the frame while braking.

In the first step, the frame is loaded by the gravity as in the previous simulation, which will act constantly throughout the simulation. In the second step, the frame is loaded by the forces F_b and F_z, which will grow linearly to the end, where they will have maximum values.

According to the results of the braking simulation, the place with the largest deformation displacement is located on the lower console tube with max. Displacement of 2.9594 mm (Fig. 8a). The location with the highest value of the stress is located at the bottom of the head tube with max. Stress of 53.233 MPa (Fig. 8b).



a) b)

Fig. 8. Results of the analysed frame for the load during braking: the maximal displacements of the frame (a), the maximal stress in the frame structure (b).

4 Discussion

The parameter required for an accurate numerical solution of the frame integrity is its weight. After the conceptual design of the frame, it was necessary to use the information presented by the authors in the article [21]. They methodically stated the choice of material from which the frame is constructed, stating its main advantages. The frame weight could then be obtained from the CAD model using the Measure Item function. Using this function, the program calculates the volume of the selected assembly. We then multiply the volume value by the density of the material from which the whole is made. In this way, the weight of the design has been determined. The results are shown in Table 4.

Table 4. Determined weights of individual bicycle components.

Structural unit	Volume [m^3]	Material	Density [$kg.m^{-3}$]	Mass [kg]
Frame	0.002480	Aluminium	2,700	6.696
Fork	0.000562	Aluminium	2,700	1.517
Head, handlebars	0.000462	Aluminium	2,700	1.247
Seatpost	0.000056	Aluminium	2,700	0.151
Seat	0.000012	Rubber	1,522	0.018
Pedal crank	0.000469	Aluminium	2,700	1.266

(*continued*)

Table 4. (*continued*)

Structural unit	Volume [m^3]	Material	Density [$kg.m^{-3}$]	Mass [kg]
Pedals	0.000078	Aluminium	2,700	0.211
Chain	0.000048	Steel	8,050	0.386
Rim of a front wheel	0.000819	Aluminium	2,700	2.211
Rim of a rear wheel	0.000522	Aluminium	2,700	1.409
Sprockets	0.000017	Steel	8,050	0.137
Brake discs	0.000046	Steel	8,050	0.370
Tyres	0.000870	Rubber	1,522	2.64
Battery	–	–	–	3
Electromotor	–	–	–	3.3
Cyclist	–	–	–	75
Total				99.559

Analysis of the frame in the case of a seating simulation showed that the frame is sufficiently rigid and strong for the given load for the sitting position of a cyclist as well as for braking of the bicycle.

The future research in this field will be focused on optimization of the bicycle structure. The objective will be to find out, whether it is possible to reduce the weight of the bicycle. As it is an electrical bicycle, the planned optimization process will not relate only with a frame, but also with other components, which can contribute to reduce the weight of bicycle and thus also to improve its driving properties. As authors have available modern simulation software for creation of a MBS models, the research will be also aimed at part setting-up a multibody model of a bicycle and at analysis of driving properties under various operational conditions including more types of road surface qualities.

5 Conclusion

The authors presented the continuation of the complex issues of the design of a mini-electric bicycle. The main novelty of this contribution is the design of a frame an original electric bicycle. They explained in detail the methodology of construction of the bicycle support frame and performed a numerical simulation in order to examine the integrity of the frame under the influence of human sitting on a bicycle. The designed electric bicycle is supposed for using on even roads with occasional trips to heavier off-road terrain. Therefore, the frame is designed for these purposes. The frame has been analysed for selected loads cases. The analyses have been performed by means of a numerical software. The simulations showed low von Mises stresses, which means high frame reliability. In the next solution of the problem, the authors focus on FEM simulations and calculations of loading forces during braking, pedal pedalling and also pedalling

in a position where the frame transmits the same load, but other parts of the structure will be more stressed. Static analyses have shown, that the frame structure is able to meet strength requirements of the frame. For practical application and production of the bicycle, some other needed activities will be performed. In term of research, dynamic analyses will be the most important. They will allow to reveal a level of comfort and driving safety of the bicycle. The overall goal is to design a reliable mini-electric bike that meets the requirements of legislation, which, according to the publication, can be made by any cycling enthusiast.

Acknowledgement. "This research was supported by the Cultural and Educational Grant Agency of the Ministry of Education of the Slovak Republic in the project No. KEGA 023ŽU-4/2020: Development of advanced virtual models for studying and investigation of transport means operation characteristics."

"This research was supported by the Cultural and Educational Grant Agency of the Ministry of Education of the Slovak Republic in the project No. KEGA 036ŽU-4/2021: Implementation of modern methods of computer and experimental analysis of the properties of vehicle components in the education of future vehicle designers."

References

1. Deloitte Insights. https://www2.deloitte.com/content/dam/Deloitte/at/Documents/technology-media-telecommunications/at-tmt-predictions-2020.pdf
2. Salmeron-Manzano, M., Manzano-Agugliaro, F.: The electric bicycle: worldwide research trends. Energies **11**(7), 1–16 (2018)
3. Kwiatkowski, M.A., Grzelak-Kostulska, E., Bieganska, J.: Could it be a bike for everyone? The electric bicycle in Poland. Energies **14**(16), 1–19 (2021)
4. Zhang, S.P., Tak, T.O.: Efficiency evaluation of electric bicycle power transmission systems. Sustainability **13**(19), 1–12 (2021)
5. Blatnický, M., Dižo, J., Molnár, D.: Analysis of the current state of the issue of an electric bicycle structural design. In: Proceedings of 26th International Scientific Conference Transport Means 2022, to be Published. Online Conference (2022)
6. Harusinec, J., Suchanek, A., Loulova, M., Kurcik, P.: Design of a prototype frame of an electrically driven three-wheel vehicle. In: 23rd Polish-Slovak Scientific Conference on Machine Modelling and Simulations (MMS2018), Rydzyna, Poland, pp. 1–9 (2018)
7. Harusinec, J., Suchanek, A., Loulova, M.: Creation of prototype 3D models using rapid prototyping. In: 23rd Polish-Slovak Scientific Conference on Machine Modelling and Simulations (MMS2018), Rydzyna, Poland, pp. 1–13 (2018)
8. Stastniak, P., Moravcik, M., Baran, P., Smetanka, L.: Computer aided structural analysis of newly developed railway bogie frame. In: 22nd Slovak-Polish Scientific Conference on Machine Modelling and Simulations (MMS2017), Sklene Teplice, Slovakia, pp. 1–10 (2017)
9. Gerlici, J., Shvedchikova, I.A., Nikitchenko, I.V., Romanchenko, J.A.: Investigation of influence of separator magnetic system configuration with permanent magnets on magnetic field distribution in working area. Electr. Eng. Electromech. **2**, 13–17 (2017)
10. Bazhinov, O., et al.: Development of a method for evaluating the technical condition of a cars hybrid powertrain. Symmetry **13**(2), 1–13 (2022)
11. Goolak, S., Tkachenko, V., Stastniak, P., Sapronova, S., Liubarskyi, B.: Analysis of control methods for the traction drive of an alternating current electric locomotive. Symmetry **14**(1), 1–18 (2022)

12. Evtimov, I., Ivanov, R., Staneva, G., Kadikyanov, G.: A study on electric bicycle energy efficiency. Transp. Probl. **10**(3), 131–140 (2015)
13. Hung, N.B., Lim, O.: A simulation and experimental study of dynamic performance and electric consumption of an electric bicycle. In: 10th International Conference on Applied Energy (ICAE2019), Hong Kong, Hong Kong, pp. 2865–2871 (2019)
14. Jajczyk, J., Slomczynski, K.: A dedicated battery for an electric bike. In: Conference on Computer Applications in Electrical Engineering (ZkwE), Poznan, Poland, pp. 1–2 (2019)
15. Leitner, B., Figuli, L.: Fatigue life prediction of mechanical structures under stochastic loading. In: 22nd Slovak-Polish Scientific Conference on Machine Modelling and Simulation 2017 (MMS 2017), Sklene Teplice, Slovakia, pp. 1–11 (2017)
16. Saga, M., Jakubovicova, L.: Simulation of vertical vehicle non-stationary random vibrations considering various speeds. Sci. J. Silesian Univ. Technol. Ser. Transp. **84**, 113–118 (2014)
17. Gerlici, J., Sakhno, V., Yefymenko, A., Verbitskii, V., Kravchenko, A., Kravchenko, K.: The stability analysis of two-wheeled vehicle model. In: 22nd Slovak Polish Scientific Conference on Machine Modelling and Simulations 2017 (MMS 2017), Sklene Teplice, Slovakia, pp. 1–10 (2017)
18. Sani, M.S.M., Nazri, N.A., Zahari, S.N., Abdullah, N.A.Z., Priyandoko, G.: Dynamic study of bicycle frame structure. In: International Engineering Research and Innovation Symposium (IRIS), pp. 1–8 (2016)
19. Huang, Y.C., Huang, T.S.: A study for adjustable riding position of the innovation bicycle design. In: International Conference on Sustainable Development and Green Technology (SDGT), Chiayi, Taiwan, pp. 1–8 (2018)
20. Carahalios, A.: An analysis of the bicycle-rider interface forces in stationary road cycling. Thesis, University of Portland (2011)
21. Famiglietti, N., Nguyen, B., Fatzinger, E., Landerville, J.: Bicycle braking performance testing and analysis. SAE Tech. Pap. (2020)

Environmental Problems Associated with Vehicle Braking and Their Solutions

Oleksandr Kravchenko[1(✉)], Dalibor Barta[2], Juraj Gerlici[2], Kateryna Kravchenko[2], Iwona Rybicka[3], and Andrej Zigo[2]

[1] Zhytomyr Polytechnic State University, Chudnivska 103, Zhytomyr 10005, Ukraine
avtoap@ukr.net
[2] University of Žilina, Univerzitná 8215/1, 01026 Žilina, Slovak Republic
{dalibor.barta,katreryna.kravchenko,andrej.zigo}@fstroj.uniza.sk
[3] Lublin University of Technology, Nadbystrzycka 36, 20-618 Lublin, Poland
i.rybicka@pollub.pl

Abstract. The article considers the problem of the reliability of semitrailer truck. The results of processing statistical data on the workability of semitrailer trucks due to a malfunction of the brake system are presented. Data processing was carried out according to the operating data of the world's leading companies VOLVO and MERCEDES - BENZ (truck), as well as Schmitz, Kögel, Krone (semitrailer). The results of processing the data on the brake pads wear of the truck's disc brakes are presented. The mass of friction material resulting from the wear of brake pads, calculated per millimeter of worn-out pads and kilometer run of a semitrailer truck, has been determined. An expert assessment and ranking of factors affecting the wear of the friction pair "brake dick - pad" of the road train was carried out. A technical solution for the abrasive particles capture that occurs during braking is proposed. This system can be used on all vehicles with disc brakes.

Keywords: Brake system · Vehicle · Statistic

1 Introduction

The optimization of transport systems focused primarily on economic issues [1–3]. In recent years, there has been a trend in action planning based on decision-making models that take into account the negative impact of transport on the environment, e.g. emission of pollutants [4], noise [5], or road safety [6]. The emphasis is also placed on customer satisfaction and proper quality of service [7, 8]. It is ensured by maintaining high readiness [9] and reliability of the entire transport system [10, 11], as well as its individual elements [12, 13]. Simulation models have been developed, which enable examination of systems different in scale and functions, as well as taking into account the issue of sensitivity [14] and flexibility [15, 16]. As a result, the number of disturbances in the system (side effects, caused e.g. by the failure of a means of transport) and the costs of its functioning are lower. The suitability of vehicles in terms of their basic safety systems, such as the braking system, reduces the probability of threats that may

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 258–267, 2023.
https://doi.org/10.1007/978-3-031-25863-3_24

interrupt the operation of the transport system [17–19]. The analysis of the influence of various factors on the wear of brake system components presented in the literature generally refers to the results of laboratory tests. It most often refers to the materials of which discs [20] and brake pads [21] were made [20], as well as mutual friction pair interactions under various operating conditions [7, 22].

The article [23–25] presents the results of experiments whose aim was to examine the interaction of model environmental conditions with the friction pair friction coefficient of a disc brake. The influence of various operating conditions (rotational speed of the brake disc, number of braking cycles) and external factors (appearance of water and brake fluid in the friction area) were analysed, confirming their significance. In turn, the subject of the research work [5] was the influence of factors resulting from their environment (humidity and temperature) on the friction elements of car brakes, resulting in a change in braking force. Also in the article [26] a significant influence of the temperature of friction steam on the friction coefficient was shown. Skrúcaný and others [27, 28] investigated dangers to traffic related to heavy goods vehicle traffic under different loads and in varying conditions of operating as well as during braking process. In order to increase vehicle transport safety complex mechatronic systems such as passive and active safety systems are implemented in all new vehicles. One of the most important safety systems in the vehicle is braking system, which has a decisive impact on the safety level of an active car. In the literature, there is a lot of work about the friction elements of the braking systems [29–33].

A significant increase in the number of rolling stock of motor vehicles aggravates the relevance of the issue of increasing the operational reliability of semi-trailer trucks [34]. In this regard, an important place is taken by the relationship between the theory of reliability and technical operation of cars, which determine the directions and research methods in the field of cars operational reliability. One of the characteristic indicators of the reliability theory are random values that drift even under stable conditions by obtaining results, and even more so in the field of car operation: traffic flow on the roads, the occurrence of failures and malfunctions, the time and complexity of eliminating them, the preventive actions frequency, etc.

During the road trains operation, the technical condition of the brake system significantly affects the operational properties, as well as the road safety of semi-trailer trucks. The causes of malfunctioning of the semitrailer trucks brake elements observed in operation can cause dangerous consequences: deterioration of road safety indicators, environmental safety, decrease in performance, low quality functioning, change in geometric parameters, emergency failures of parts, etc. In this regard, an urgent task is to study the workability, causes of failures and malfunctions of the brake system and determine methods to increase the reliability of its operation.

2 Analysis of the Impact of the Brake System Workability on the Semitrailer Truck Reliability

The methodology for solving the problems of processing the initial data on the reliability of semi-trailer trucks [35, 36] includes the processes of obtaining and processing data,

which are blocks: 1 - collection of data on operational reliability and their systematization; 2 - statistical processing of samples to determine the parameters and types of distribution laws; 3 - determination of the entire population parameters; 4 - development of conclusions and proposals.

Of the total number of semitrailer trucks carrying out international transportation, a significant part is foreign production of the world's leading firms VOLVO and MERCEDES - BENZ (trucks), as well as Schmitz, Kögel, Krone (semitrailers). In this regard, statistical information was collected on semitrailer trucks of these brands.

Information was collected for serial KRONE, SCHMITZ, and KÖGEL semi-trailers, which are operated as the semitrailer trucks combination with VOLVO and MERCEDES - BENZ trucks (Table 1), at LAA TRANS and TRANSPELE enterprises (Ukraine). Storage of semitrailer tracks is carried out in open areas; the operating conditions category - I - II; the maintenance is carried out in accordance with the manufacturer instructions [21, 37, 38].

Table 1. The basic operational indicators of semitrailer trucks.

Indicators	SCHMITZ	KRONE	KÖGEL
Semitrailer truck amount, units	50	50	50
Semitrailer truck run:			
• average, thousand km	98	166	300
• maximum, thousand km	118	198	342
• minimum, thousand km	23	123	266
The run at the start of observation:			
• average, thousand km	0	68	192
• maximum, thousand km	0	90	217
• minimum, thousand km	0	60	165
Usage coefficient of semitrailer truck run	0.95	0.95	0.95

The results of processing statistical data (Fig. 1, Table 2) show that a decrease in the workability of semitrailers due to malfunction of the ABS and the brake system is most likely for SCHMITZ semitrailers - by 40–50 thousand kilometers; for KRONE semi-trailers - for 160 thousand kilometers; for KÖGEL semi-trailers - 280 thousand kilometers.

The analysis of the main malfunctions and failures of the brake systems that lead to inefficient braking of the semitrailer truck are divided into two groups: the mechanical drive violations and malfunctions of the anti-lock system (ABS). The ingress of dust, dirt and moisture into the brake mechanism causes oxidation and jamming of the brake chamber rods, which causes the brake pads to fail and their wear to be uneven.

One of the reasons for the clogging of the brake system and other mechanisms of the semitrailer truck is the wear products in the friction pair: "brake disc-pad". In addition, deteriorate the appearance of the vehicle from the constant formation of plaque from the

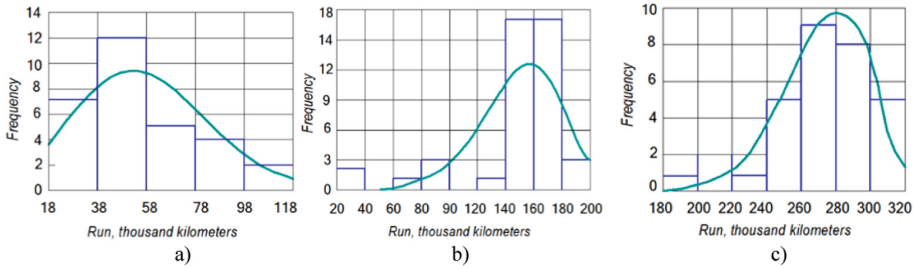


Fig. 1. Patterns of semitrailers violation workability due to brake system and ABS malfunction: a) – SCHMITZ semitrailers; b) – KRONE semitrailers; c) – KÖGEL semitrailers.

Table 2. Statistic characteristics of the semitrailers violation workability due to brake system and ABS malfunctions.

Semitrailer	$\bar{M}$, thous. km	σ, thous. km	α	β	The pattern
SCHMITZ	56.83	25.14	2.47	64.28	$0.77 \cdot \left(\frac{t}{64.28}\right)^{1.47} \cdot e^{\left(-\left(\frac{t}{64.28}\right)^{2.47}\right)}$
KRONE	150.55	35.7	6.175	162.1	$0.76 \cdot \left(\frac{t}{162.1}\right)^{5.175} \cdot e^{\left(-\left(\frac{t}{162.1}\right)^{6.175}\right)}$
KÖGEL	237.4	34.32	11.981	283.7	$0.845 \cdot \left(\frac{t}{283.7}\right)^{10.981} \cdot e^{\left(-\left(\frac{t}{283.7}\right)^{11,981}\right)}$

wear particles on its outer surfaces. Depending on the manufacturer and the brake pads composition, the wear products and their impact on mechanisms of the semitrailer truck and the environment are different.

According to a 2015 study, brakes alone are responsible for 20% of emissions. The brakes would release up to 30 mg/km of particles. In Europe, these emissions of particles during braking represent nearly 110,000 tones/year, of which 50,000 tones are distilled into the air [39].

3 The Results of Processing Statistical Data on the Brake Pads Semitrailer Trucks Wear

In further studies, the value of brake pad wear for the semitrailer truck group of "EMG TRANS" (Bulgaria) was estimated. Statistical data is collected for brake pads (Table 3), which are paired with brake discs with a diameter of 370 mm and 430 mm. In most cases, brake discs with a diameter of 370 mm are mounted on tracks, with a diameter of 430 mm on both semitrailers and trucks. The main road of semitrailer trucks, on which was tested brake pads, passed from Bulgaria through Romania (Calafat-Turnu Severin-Timisoara - Arad or Oradea), Vendria (Szeged-Budapešť-Győr or Szeged-Budapest - Šahy, or Artand-Debrecen-Miskolc - Seňa or Czech Republic). At the same time, the

workload of the vehicles was different, but within 34–38 tons. Brake pads were removed from the vehicle at the end of its life cycle, which amounted to 150–200 thousand km. It was also taken into account that the minimum thickness of the friction part of the block should be at least 5 mm. Accordingly, the life cycle of a brake pad with a thickness of 30 mm (the thickness of the metal part is 9.5 mm) will end with a wear of 15.5 mm of the friction material.

Table 3. Formatting sections, subsections and subsubsections.

Brake disc with a diameter of 370 mm	Brake disc with a diameter of 430 mm
Parameters of the new brake pad	
Total thickness – 30 mm	Total thickness – 30 mm
Metal thickness – 9.5 mm	Metal thickness – 9.5 mm
Weight – 2035 g	Weight – 3030 g

Processing of statistical data (Fig. 2, 3) showed that with a run of 150–200 thousand km from one pad, working in tandem with a brake disc with a diameter of 370 mm, 38–44 g/mm of wear products are produced, paired with a brake disc with a diameter 430 mm–86–146 g/mm. In terms of kilometres, 4.3–5.8 mg/km for pads working together with a brake disk with a diameter of 370 mm and 5.2–6.9 mg/km - paired with a brake disk with a diameter of 430 mm are output.

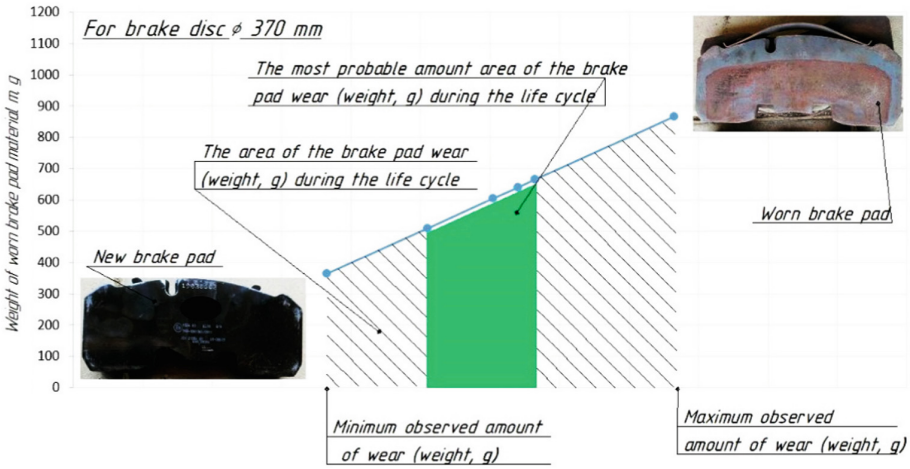


Fig. 2. The amount of wear of the brake pads working in tandem with the brake disc with a diameter of 370 mm.

According to the operation results (Fig. 2, 3), it was determined that the replacement of a brake pad, working in tandem with a brake disc with a diameter of 370 mm, is most

likely to occur at a time when its wear averages 500–670 g and 655–760 g - for a brake pad working in tandem with a brake disc with a diameter of 430 mm.

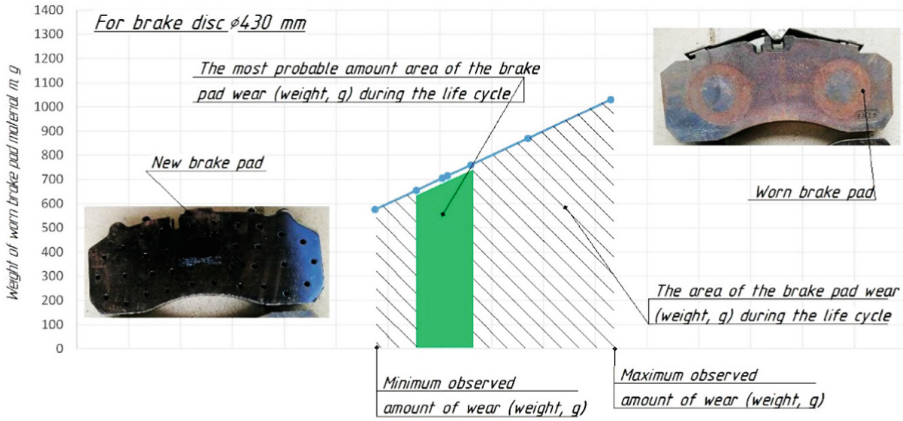


Fig. 3. The amount of wear of the brake pads working in tandem with the brake disc with a diameter of 430 mm.

The maximum amount of brake pad wear during the life cycle process observed during operation (Fig. 2, 3):

- when paired with a brake disc with a diameter of 370 mm, it amounted to 365 g;
- when working with a brake disc with a diameter of 430 mm was - 865 g.

The minimum brake pad wear during the life cycle process observed during operation (Fig. 2, 3):

- when paired with a brake disc with a diameter of 370 mm it amounted to - 575 g;
- when working with a brake disc with a diameter of 430 mm amounted to - 1,030 g.

4 Structural Solution for Collecting Brake Pad Wear Particles is Development

To reduce the impact of brake pad wear products on clogging of the brake system mechanisms, other mechanical parts of the semitrailer truck, as well as to reduce their emission into the atmosphere, a structural solution for collecting brake pad wear particles has been proposed.

The system is used to catch the solid parts of the brake pads and disk that are released during braking. It consists of (Fig. 4, 5):

- the brake dust collector which is mounted close to the brake pad in order to extract as effectively as possible the brake dust which is formed during the friction of the brake pad and the brake disc;

- the brake dust extraction pipes;
- the vacuum cleaner containing a paper filter, a propeller and an electric motor.

For the vacuum cleaner to work properly, the exhaust air vents must be large enough so that there is no high resistance to the flowing air. This increases the air flow through the filter, which traps more brake dust. The paper filter is removable and would be changed at the same service interval as the engine oil.

This system can be used on all vehicles with disc brakes. All that is required is to adjust the brick on which the vacuum cleaner is attached. The system is connected to a brake light sensor, through which the vacuum cleaner motor is also powered. Thus, it is only started when the brake pedal is depressed. If the driver does not act on the brake pedal, the vacuum cleaner is switched off, which prolongs the life of the device. The brake dust vacuum cleaner can filter brake dust without preventing the brake disc from cooling and is easy to maintain.

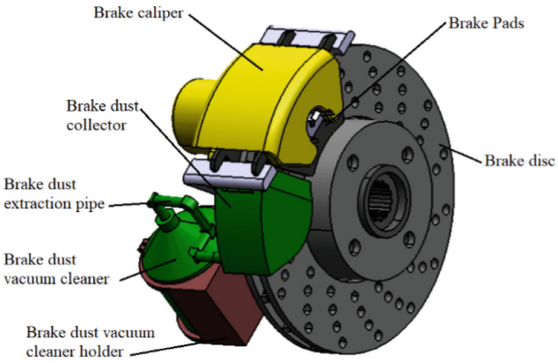


Fig. 4. Brake dust vacuum cleaner concept design.

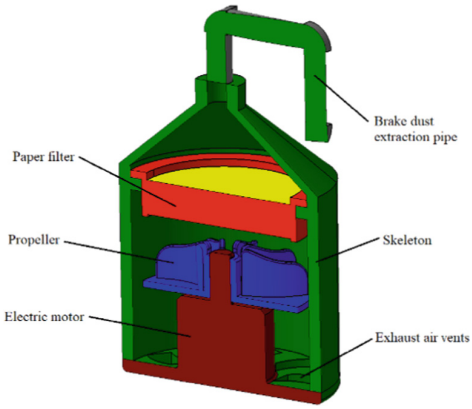


Fig. 5. Design of the internal arrangement of the parts of the vacuum cleaner.

The advantages of a vacuum cleaner for solid particles from brake pads are:

- captures brake dust.
- it does not limit the cooling of the brake disc.

Wide use for various types of vehicles.

5 Conclusions

Studies have shown that the reliability of semitrailer trucks largely depends on the brake system workability. Decrease in workability of semitrailers due to malfunction of ABS and brake system is most likely for SCHMITZ semitrailers - by 40–50 thousand km; for KRONE semi-trailers - for 160 thousand kilometres; for KÖGEL semi-trailers – 280 thousand kilometres. It was also found that the ingress of dust, dirt and moisture into the brake mechanism causes oxidation and jamming of the brake chamber rods, which causes the brake pads to fail and their wear to be uneven. The processing of operational data showed that significant wear of the vehicle mechanisms is caused by the wear products of the friction pair "brake disc-pad". With a run of 150–200 thousand km from one pad, 4.3–6.9 mg/km is produced. According to expert assessment, the vehicle weight and the driver's driving level have a significant impact on wear. To eliminate the negative impact of wear products of the friction pair "brake disc-pad", a device has been developed that allows to capture wear particles and, thereby, reduce the pollution of mechanical components of the vehicle.

Acknowledgements. This publication was issued thanks to support from the Cultural and Educational Grant Agency of the Ministry of Education of the Slovak Republic in the projects, "Implementation of modern methods of computer and experimental analysis of properties of vehicle components in the education of future vehicle designers" (Project No. KEGA 036ŽU-4/2021), "Development of advanced virtual models for studying and investigation of transport means operation characteristics" (Project No. KEGA 023ŽU-4/2020). This research was also supported by the Slovak Research and Development Agency of the Ministry of Education, Science, Research and Sport of the Slovak Republic in Educational Grant Agency of the Ministry of Education of the Slovak Republic in the project and VEGA 1/0513/22 "Investigation of the properties of railway brake components in simulated operating conditions on a flywheel brake stand".

References

1. Andrzejczak, K., Młyńczak, M., Selech, J.: Poisson-distributed failures in the predicting of the cost of corrective maintenance. Eksploatacja i Niezawodność Maint. Reliab. **20**(4), 602–609 (2018)
2. Andrzejczak, K., Selech, J.: Quantile analysis of the operating costs of public transport fleet. Transp. Probl. **12**(3), 103–111 (2017)
3. Wasiak, M., Jacyna, M., Lewczuk, K., Szczepański, E.: The method for evaluation of efficiency of the concept of centrally managed distribution in cities. Transport **32**(4), 348–357 (2017)

4. Merkisz-Guranowska, A., Pielecha, J.: Emisja zanieczyszczeń z pojazdów samochodowych a parametry ruchu drogowego. Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa (2014)
5. Borawski, A.: Suggested research method for testing selected tribological properties of friction components in vehicle braking systems. Acta Mechanica et Automatica **10**(3), 223–226 (2016)
6. Jacyna, M., Wasiak, M., Lewczuk, K., Karoń, G.: Noise and environmental pollution from transport: decisive problems in developing ecologically efficient transport systems. J. Vibroeng. **19**(7), 5639–5655 (2017)
7. Chłopek, Z., Suchocka, K., Zawistowski, A.: Comparative examination of disc brake friction pairs with brake pads of different types in respect of their tribological properties. Arch. Automot. Eng. Archiwum Motoryzacji **72**(2), 15–28 (2016)
8. Dižo, J., et al.: Evaluation of ride comfort in a railway passenger car depending on a change of suspension parameters. Sensors **21**(23), 8138 (2021)
9. Nowakowski, T.: Problems of reliability modelling of multiple-phased systems. Eksploatacja i Niezawodność Maint. Reliab. **4**, 79–84 (2011)
10. Niewczas, A., Koszałka, G., Wrona, J., Pieniak, D.: Chosen aspects of municipal transport operation on the example of the city of Lublin. Transport **23**(1), 88–90 (2008)
11. Nowakowski, T.: Niezawodność systemów logistycznych. Oficyna Wydawnicza Politechniki Warszawskiej, Wrocław (2011)
12. Karczewski, M., Szczęch, L.: Influence of the F-34 unified battlefield fuel with bio components on usable parameters of the IC engine. Eksploatacja i Niezawodność Maint. Reliab. **18**(3), 358–366 (2016)
13. Marzec, P.: An examination of vehicles at the brake-chassis test bed in the range of the partial engine load. Sci. J. Silesian Univ. Technol. Ser. Transp. **95**, 121–131 (2017)
14. Mattsson, L.G., Jenelius, E.: Vulnerability and resilience of transport systems–a discussion of recent research. Transp. Res. Part A Policy Pract. **81**, 16–34 (2015)
15. Alrabghi, A., Tiwari, A.: State of the art in simulation-based optimisation for maintenance systems. Comput. Ind. Eng. **82**, 167–182 (2015)
16. De Almeida, A.T., Cavalcante, C.A.V., Alencar, M.H., Ferreira, R.J.P., de AlmeidaFilho, A.T., Garcez, T.V.: Multicriteria and multiobjective Models for Risk, Reliability and Maintenance Decision Analysis, 1st edn. Springer, Cham (2015). https://doi.org/10.1007/978-3-319-17969-8
17. Figlus, T., Kuczyński, Ł.: Selection of a semi-trailer for the haulage of long oversize loads, taking into account an analysis of operational damage. In: 2018 XI International Science-Technical Conference Automotive Safety, Casta, pp. 1–5 (2018)
18. Zio, E.: The future of risk assessment. Reliab. Eng. Syst. Saf. **177**, 176–190 (2018)
19. Barta, D., Dižo, J., Blatnický, M., Vaňko, J.: Experimental investigation of the motorcycle braking properties when riding on different road surfaces. IOP Conf. Ser. Mater. Sci. Eng. **1002**(1), 012030 (2020)
20. Wojciechowski, A., Sobczak J.: Kompozytowe tarcze hamulcowe pojazdów drogowych. Instytut Transportu Samochodowego, Warszawa (2001)
21. Kravchenko, A.P.: Statistical researches of disturbances of working capacity of trailer structure of semitrailer trucks of the European production. Bull. East Ukrainian Natl. Univ. Sci. J. (Luhansk: V. Dal East Ukrainian Natl. Univ. **7**(101), 87–91 (2006)
22. Tokaj, P.: Zużycie par ciernych hamulców w wybranych typach pojazdów szynowych. Prace Instytutu Kolejnictwa **155**, 29–35 (2017)
23. Gajek, A., Szczypiński-Sala, W.: Wybrane własności tribologiczne okładzin ciernych hamulców tarczowych. Arch. Automot. Eng. Archiwum Motoryzacji **57**(3), 119–132 (2012)

24. Suchánek, A., Kurčík, P., Šťatniak, P.: Design of a testing equipment for experimental research of railway brake systems. In: AIP Conference Proceedings, vol. 2198, p. 0200159 20190 (2018)
25. Harušinec, J., Suchánek, A., Štastniak, P., Strázovec, P.: Brake actuator optimization of the brake test stand as a tool for improvement railway safety. MATEC Web Conf. **235**, 00028 (2018)
26. Krupa, M.: Wpływ temperatury na wartość współczynnika tarcia samochodowych hamulców ciernych. Politechnika Śląska, Gliwice (2008)
27. Skrucany, T., Gnap, J.: The effect of the crosswinds on the stability of the moving vehicles. In: 6th International Scientific Conference on Dynamic of Civil Engineering and Transport Structures and Wind Engineering. Applied Mechanics and Materials, vol. 617, pp. 296–301 (2014)
28. Skrucany, T., Šarkan, B., Gnap, J.: Influence of aerodynamic trailer devices on drag reduction measured in a wind tunnel. Eksploatacja i Niezawodność Maint. Reliab. **18**(1), 151–154 (2016)
29. Caban, J., et al.: The research on ageing of glycol-based brake fluids of vehicles in operation. Adv. Sci. Technol. Res. J. **10**(32), 9–16 (2016)
30. Indira, V., Vasanthakumari, R., Jegadeeshwaran, R., Sugumaran, V.: Determination of minimum sample size for fault diagnosis of automobile hydraulic brake system using power analysis. Eng. Sci. Technol. Int. J. **18**, 59–69 (2015)
31. Jegadeeshwaran, R., Sugumaran, V.: Fault diagnosis of automobile hydraulic brake system using statistical features and support vector machines. Mech. Syst. Signal Process. **52–53**, 436–446 (2015)
32. Pavlov, A.V., Kudelnikova, S.P., Vicharev, A.N.: On the corrosion resistance of half-metallic composite brake pads for railroad cars. J. Frict. Wear **36**(2), 123–126 (2015). https://doi.org/10.3103/S1068366615020130
33. Sergienko, V.P., Tseluev, M.Y., Kolesnikov, V.I., Sychev, A.P., Savonchik, V.A., Yanuchkovskii, V.I.: Studying thermal state of friction pairs of multidisc brake. J. Frict. Wear **34**(6), 421–428 (2013). https://doi.org/10.3103/S106836661306010X
34. Farobin, Y.E., Turspekov, M.Kh.: Trunk semitrailer trucks. Automot. Ind. **5**, 35–38 (2010)
35. Govorushchenko, N.Ya.: The main problems of ensuring the operational reliability of rolling stock of automobile transport. Knowledge, Kiev, pp. 3–4 (1978)
36. Kanarchuk, V.E., Levkovets, P.R., Levkivsky, O.P.: Formation of a systematic approach to the consideration of strategies to ensure the operational reliability of vehicles Visnyk. Coll. Science Work TAU and UTU. RVV UTU, Kiev, vol. 3, pp. 11–15 (1999)
37. Kramskoy, D.Y., Tereshchenko, E.N., Kramskoy, A.Y.: Models of resource allocation between innovative projects. Collection of scientific papers Vestnik NTU"KPI": Technical progress and efficiency, NTU"KPI", Kiev, vol. 5, pp. 142–149 (2009)
38. Kravchenko, A.P., Shkvarok, O.I., Glayboroda, A.A., Gayvoronsky, A.S.: The results of a statistical study of the operational reliability of the trailer composition of semitrailer trucks. In: Materials of the XII Scientific and Technical Conference "Transport, Ecology - Sustainable Development". TU, Varna, pp. 153–159 (2006)
39. Les Freins, Responsables De 20% Des Particules Du Trafic Routier. https://www.ompe.org/les-freins-responsables-de-20-des-particules-du-trafic-routier/. Accessed 05 Dec 2020
40. Gerlici, J., Gorbunov, M., Kravchenko, K., Prosvirova, O., Lack, T., Hauser, V.: Assessment of innovative methods of the rolling stock brake system efficiency increasing. Manuf. Technol. **18**(1), 35–38 (2018)

Friction Resistances in a Prototype Internal Gear Pump with Sickle Insert Made of Plastic

Krzysztof Towarnicki[1](✉), Michał Stosiak[1], Tadeusz Leśniewski[1], Adam Deptuła[2], Kamil Urbanowicz[3], and Paweł Śliwiński[4]

[1] Faculty of Mechanical Engineering, Department of Technical Systems Operation and Maintenance, Wrocław University of Science and Technology, Wrocław, Poland
{krzysztof.towarnicki,michal.stosiak, tadeusz.lesniewski}@pwr.edu.pl

[2] Faculty of Production Engineering and Logistics, Department of Management and Production Engineering, Opole University of Technology, Opole, Poland
a.deptula@po.edu.pl

[3] Faculty of Mechanical Engineering and Mechatronics, West Pomeranian University of Technology, Szczecin, Poland
kamil.urbanowicz@zut.edu.pl

[4] Faculty of Mechanical Engineering and Ship Technology, Gdańsk University of Tech, Gdańsk, Poland
Pawel.sliwinski@pg.edu.pl

Abstract. This paper presents the results on the modification in the areas of design and material of the internal gear pump sickle insert. The modification relies on making a cut in the sickle insert. As a result, the insert raceways are pressed against the tooth tips of the gear wheels. Due to the introduced radial compensation, the discharge flow rate falls less as the discharge pressure increases. The test stand and the measurement results are respectively presented. Friction resistances between the gear wheel material and the insert materials were measured for selected pump operating parameters. The tested materials were found to differ in their friction resistance. The differences were confirmed by shaft torque measurements taken while the pump was running. The results of the investigations indicate the direction for further research with an aim of creating an optimal insert which meets the requirements for a prototype pump with enhanced capacity at higher discharge pressures.

Keywords: Frictional resistances · Pump · Radial compensation · Capacity

1 Introduction

The main directions of development of micro-hydraulic systems is the reduction of noise generated by them and the minimization of their mass. It is achieved by making elements of plastic pipelines [1], pipes [2], pumps, actuators and valves [3]. The aim is to reduce the pressure pulsations generated by the pumps, which, consequently, leads

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 268–276, 2023.
https://doi.org/10.1007/978-3-031-25863-3_25

to noise reduction [4, 5]. Bearing in mind the growing pressure on environmental protection, measures are taken to increase the efficiency of devices [6–8]. Certain efforts are made to reduce energy and mass losses while increasing the transferred power, thus achieving a higher power-to-weight ratio. The adopted ratio is the main ratio used to compare different disk types. The advantage of hydrostatic drive units is their high power-to-weight ratio. As a result, hydraulic transmissions, i.e. pumps and motors, are often preferred by designers of hydraulic systems [9, 10]. Axial and radial compensations have been introduced to obtain a high discharge pressure in gear pumps. Many compensation solutions have been developed, but mainly for external gear pumps. The present study deals with internal gear pumps. Internal gear pumps are characterized by lower noise level, lower flow rate nonuniformity and a more compact design in comparison with external gear pumps. The greater teeth overlap results in smoother pump operation and lower pump filling losses and contributes to a reduction in flow rate and pressure fluctuations and in noise level. Due to the above-mentioned advantages, the research is underway to increase the capacity of such pumps and achieve higher discharge pressures. Axial compensations are commonly used as they are economical and relatively easy to make. However, as increasingly higher pressures are used in hydrostatic drive system, it becomes necessary to introduce a radial compensation to obtain higher discharge pressures and higher efficiency. Radial compensations are often complicated and expensive to make. A modification in the gate (sickle) insert is a radial compensation. The modification consists in introducing a partial-depth cut in the classic sickle insert, whereby two flexible tongues are obtained. When the discharge pressure increases, the tongues are elastically deformed, whereby the insert raceway is pressed against the gear tooth tips. Due to this solution, the efficiency of the hydraulic machine is possible to be increased. The efficiency depends on the losses stemming from the system elements' design and to a large extent also on the friction between the interacting elements [11, 12]. Friction significantly determines resistances to motion and also the wear and durability of the elements. The interdependence between the effect of the material on motion resistances, and changes in the friction coefficient with changing operating parameters is of key importance since changes in pump pressure and rotational speed are closely related to changes in the friction coefficient and this translates into the power losses of the hydraulic system. The aim of this research is to interrelate hydraulic and tribological parameters and to determine their influence on the further development of hydraulic pump designs.

2 Prototype Pump

The presented control measures for the prototype gear method with the meshing of the pump with the insert made of the crescent modification. To introduce a solution for setting the reformation, the insert, the insert of the elements is to introduce, introducing a partial incision in the classic crescent insert. Below is a preview of the patent solution No. P.431145 patented in the Patent Office of the Republic of Poland (Fig. 1).

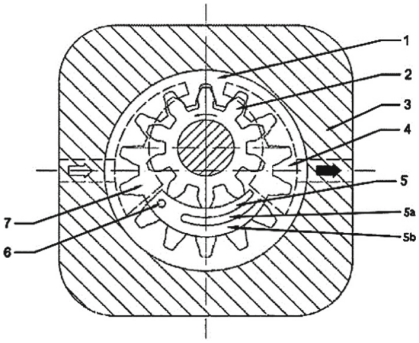


Fig. 1. Cross-section of a pump with a modified sickle insert on the patent study P.431145: 1 – toothed rim, 2 – gear wheel, 3 – pump bory, 4 – discharge space, 5 – sickle insert, 5a – bay inside the sickle insert, 5b – elastic tonque of the sickle insert, 6 – locating pin, 7 – suction space [13].

The above-presented radial compensation increases the volumetric efficiency of the hydraulic machine. The rear cover of the pump was made of transparent plastic, which allowed for taking photos during measurements with a high-speed camera. The modification of the insert concerned cutting a channel inside the insert with a size corresponding to ¼ of the insert's length. Pictures from measurements for the insert made of POM and PA plastic are presented below (Figs. 2, 3, 4 and 5).

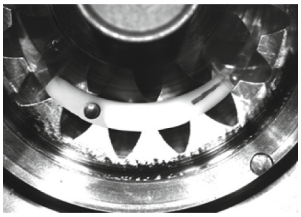


Fig. 2. View of the modified insert made of POM – first modification. The photo was taken when the pump drive shaft reached rotational speed n = 1,000 rpm

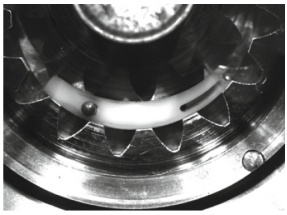


Fig. 3. View of the modified insert made of PA – first modification. The photo was taken when the pump drive shaft reached rotational speed n = 1,000 rpm.

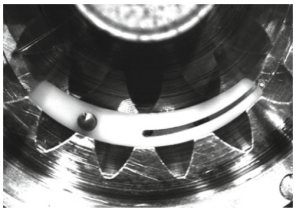


Fig. 4. View of the modified insert made of POM – second modification. The photo was taken when the pump drive shaft reached rotational speed n = 1,000 rpm.

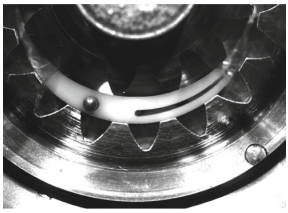


Fig. 5. View of the modified insert made of PA – second modification. The photo was taken when the pump drive shaft reached rotational speed n = 1,000 rpm.

3 Test Methods and Materials

The investigations were carried out in two stages. Firstly, the hydraulic parameters were determined depending on the compensating chamber size of the sickle insert and its material. Secondly, the effect of the insert material on the pump's motion resistance and efficiency was analysed.

The following materials were used in the tests:

- Material I – POM C (naturally white).
- Material II – PA6.

The choice of the materials was based on a analysis of the corresponding subject literature and research on any previous attempts to use such materials in hydraulic systems.

3.1 Hydraulic Tests

A special research stand (presented in detail in the [14]) was built in order to take the measurements. Prior to measurements the measuring system was turned on to assess whether the measuring instruments worked correctly. Then measurements were taken and on their basis characteristics were plotted. The rotational speed of the pump shaft was assumed to be 750 rpm and 1,500 rpm. The discharge pressure was varied from 6 to 20 bar in 1 bar increments. The temperature of the working liquid during the measurements is 333 K. Modification I is the implementation of the channel in the insert by ¼ of the length of the insert and modification II is the execution of a channel in the insert by 1/2 the length of the insert.

3.2 Tribological Tests

A standard T-11 tribotester manufactured by the Institute of Sustainable Technologies in Radom was used to carry out tribological tests. The main objective of the research was the preliminary selection of materials for sickle pads for a hydraulic cylinder. Additionally, it was necessary to quickly select a material for testing on a real object, and this method allows for a quick comparison of several materials and selection of the best one, i.e. the one with the best resistance to wear and the lowest friction coefficient. During the tests, a sliding association of the cooperating elements in a ball-disc system was used. The adopted testing method perfectly imitates machine elements working in sliding motion, which determined its selection. The method also allowed a straightforward production of the specimens. The specimens were discs of 1″ diameter and 6 mm height made of the tested materials. Balls made of 100Cr6 bearing steel with a diameter of 1/4″ were used as counter-samples.

The input values for the experiment were selected to take into account the actual working conditions of the hydraulic cylinders and to ensure the continuity of the experiment (eliminating the possibility of seizure) for all selected materials. The data was taken from hydraulic tests and the final test parameters were as follows:

– load - 9.81 N and 14.72 N,
– linear velocity - 0.26 m/s and 0.52 (corresponding to 750 rpm and 1,500 rpm),
– friction path - 250 m (corresponding to test duration of 962 s),
– lubricant - Renolin VG46,
– ambient conditions were controlled and remained constant during all the tests.

4 Presentation and Discussion of Test Results

4.1 Hydraulic Tests

The results of the hydraulic tests are presented in Fig. 6.

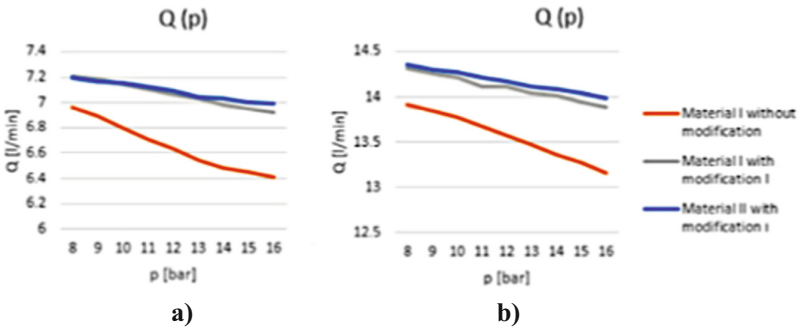


Fig. 6. Changes in the pump capacity depending on the discharge pressure for modification I at the speed of the pump rotating shaft: a) n = 750 rpm; b) n = 1,500 rpm. Source: [14, 15].

The measurement results presented in the Fig. 6 correspond to the cut located at up to 1/4 of the sickle insert length. The modification improved the capacity of the pump as shown by the diagram. As discharge pressure rises, the fall in the discharge flow rate is considerably smaller. Then measurements were taken for the cut located up to half of the sickle insert length (Fig. 7). All the measurements were carried out for the same pump, only sickle inserts were changed. Figure 7 shows exemplary pump capacity results for sickle insert modification II.

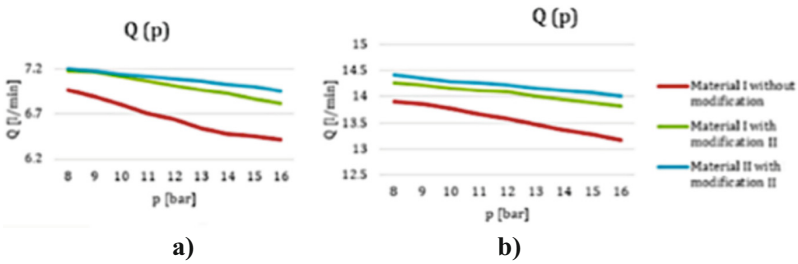


Fig. 7. Changes in the pump capacity depending on the discharge pressure for modification II at the speed of the pump rotating shaft: a) n = 750 rpm; b) n = 1,500 rpm. Source: [15].

During the pump flow rate measurements also the pump shaft torque was measured. Figure 8 and Fig. 9 show the pump shaft torque measurement results for the insert with modification I and II, respectively.

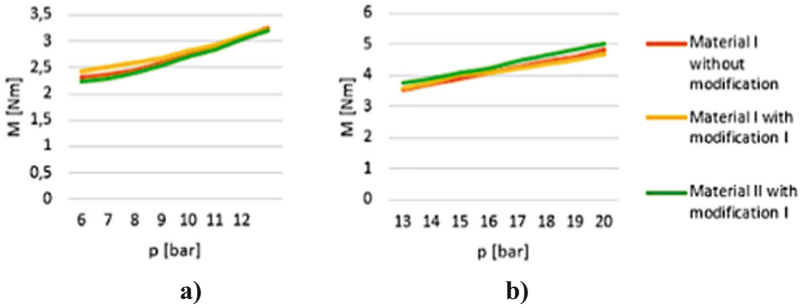


Fig. 8. Influence of pumping pressure changes on changes in pump shaft torque with modification I: a) n = 750 rpm, b) n = 1,500 rpm.

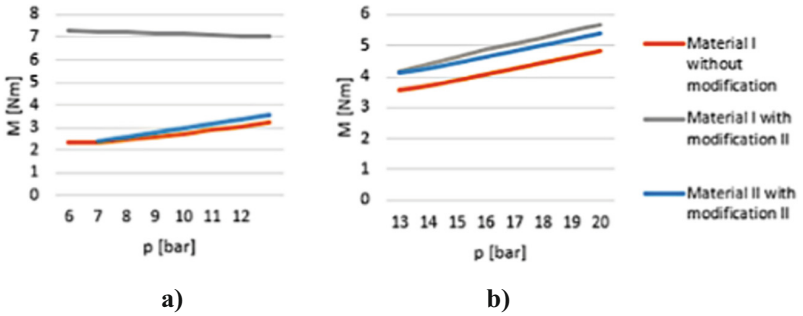


Fig. 9. Influence of pumping pressure changes on changes in pump shaft torque with modification II: a) n = 750 rpm, b) n = 1,500 rpm.

It appears from the above diagrams that at a lower rotational speed and a lighter load, material I is characterized by lower friction resistances in comparison with material II. However, when the speed and the force with which the insert (under rising pressure) is pressed against the gear wheel increase, the friction resistances of material I and II are similar. The reverse of the situation observed for modification I occurs for modification II – material I causes greater friction resistances than material II. This is certainly due to the fact that the materials differ in their coefficients of friction and E-modulus. Material I has a lower elastic modulus, whereby when the insert has a longer cut, the tongue is pressed against the gear wheel with a greater force than in the case of material II. This conclusion is confirmed by the friction coefficient measurement results presented below.

4.2 Tribological Tests

Figure 10 and Fig. 11 show the mean and maximum force of the friction of the steel mandrel against the samples.

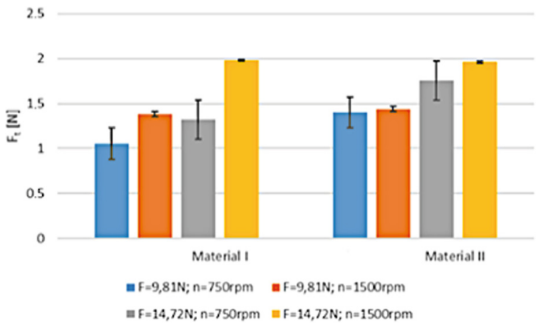


Fig. 10. Mean force of friction of steel mandrel against materials I and II.

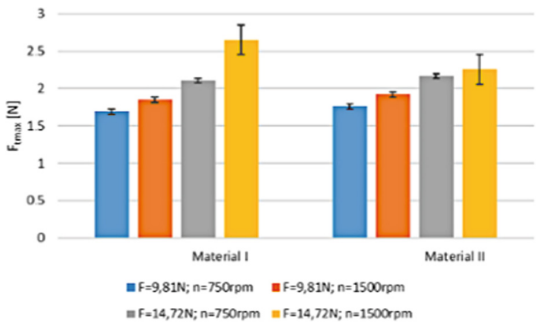


Fig. 11. Maximum force of friction of steel mandrel against materials I and II.

Material I exhibits lower mean friction force values in the major part of the selected range of excitations (loads and operating speeds) as presented in the Figs. 10 and 11. Therefore, it is confirmed that the material I is preferable for the sickle insert. However, at higher rotational speeds and greater loads, the material II, on the other hand, begins to exhibit lower mean friction force values. This is probably due to the limitations of plastics at higher temperatures. In the case of the tester used, this is a significant problem since because of the tester design the work takes place in very sparing lubrication conditions. At this preliminary stage of the investigations this finding indicates the direction for further research, but it needs to be corroborated and it should be assessed how inserts made of metals (e.g. bronze) or a composite behave in the given operating conditions.

The friction force traces shown in Fig. 12 further confirm the previous conclusions. However, in case of the material I, the friction force trace is less stable and the process of lubricating layer restoration is more turbulent.

5 Summary

Current development of technological production is manufactured to achieve considerably higher pressures. This allows the imposition of financial institutions and enables their creation. Therefore, it creates a need for manufacturing pumps with higher delivery

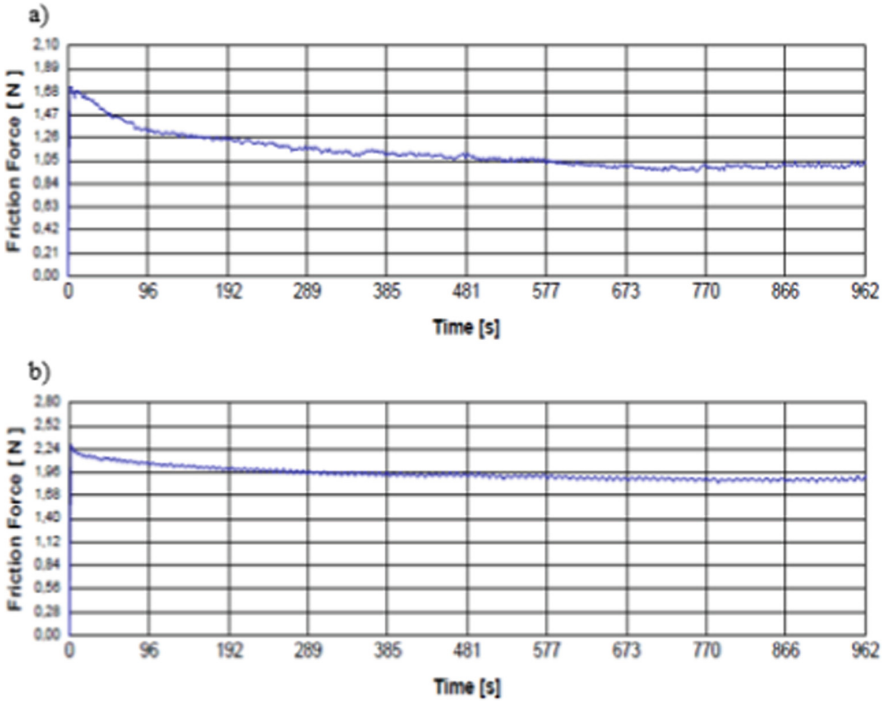


Fig. 12. Exemplary friction force traces recorded during measurement for: a) material I, b) material II.

pressures. The gerotor pumps described in [14] achieve low weight while maintaining high resistance to contamination. The paper [13] presents the preliminary measurement results for the pump with compensation meshing with radial compensation. Therefore, two different cuts were made in the sickle insert, named modification I and modification II, respectively. Due to the possible applications, the insert appearing in the role of C: POM (material I) and PA6 (material II). In the case of the modified inserts the pressure is greater, whereby the torque is higher than for the unmodified insert. The difference between the measured pump drive torques for the two different materials is due to the different coefficients of friction. This is confirmed by the results of measurements of friction resistance between steel and the insert material. Moreover, the differences are corroborated by the results of measurements carried out for static friction coefficients, presented in [17]. As a result of the comparative tribological studies a suitable material (plastic) was preliminarily selected for the next stages in the design process. Further research will focus on selection of another material with a lower friction coefficient and with the required elastoplastic parameters.

References

1. Bogdevičius, M., Karpenko, M., Bogdevičius, P.: Determination of rheological model coefficients of pipeline composite material layers based on spectrum analysis and optimization. J. Theor. Appl. Mech. **59**(2), 265–278 (2021)
2. Urbanowicz, K., et al.: Modeling transient pipe flow in plastic pipes with modified discrete bubble cavitation model. Energies **14**(20), 1–22 (2021)
3. Stryczek, J., Banaś, M., Krawczyk, J., Marciniak, L., Stryczek, P.: The fluid power elements and systems made of plastics. Procedia Eng. **176**, 600–609 (2017)
4. Woo, S., Vacca, A.: An investigation of the vibration modes of an external gear pump through experiments and numerical modeling. Energies **15**(3), 1–22 (2022)
5. Fiebig, W., Wróbel, J.: FEM – natural frequency analysis of different mounting arrangements of an external gear pump. Górnictwo Odkrywkowe **55**(4/5), 121–125 (2014)
6. Karpenko, M., Bogdevičius, M.: Investigation into the hydrodynamic processes of fitting connections for determining pressure losses of transport hydraulic drive. Transport **35**(1), 108–120 (2020)
7. Karpenko, M., Prentkovskis, O., Šukevičius, Š: Research on high-pressure hose with repairing fitting and influence on energy parameter of the hydraulic drive. Eksploatacja i Niezawodnosc Maint. Reliab. **24**(1), 25–32 (2022)
8. Kędzia, K.: A method of determining optimal parameters for the secondary energy source of a multisource hydrostatic drive system in machines working in closed spaces. Energies **15**(14), 5132 (2022)
9. Śliwiński, P.: The influence of water and mineral oil on volumetric losses in the displacement pump for offshore and marine applications. Pol. Marit. Res. **26**(2), 173–182 (2019)
10. Sliwinski, P.: The methodology of design of axial clearances compensation unit in hydraulic satellite displacement machine and their experimental verification. Arch. Civ. Mech. Eng. **19**(4), 1163–1182 (2019). https://doi.org/10.1016/j.acme.2019.04.003
11. Bednarczyk, S., Jankowski, L., Krawczyk, J.: The influence of eccentrity changes on power losses in cycloidal gearing. Tribologia **285**(3), 19–29 (2009)
12. Spałek, J., Kwaśny, M.: Analysis of the influence of basic constructional parameters on power losses in the meshing of a toothed cylindrical gear. Tribologia **227**(5), 171–178 (2009)
13. Towarnicki, K., Stosiak, M.: Internal gear pump with compensation of radial clerances, Patent PL431145A1 (2022)
14. Antoniak, P., Stosiak, M., Towarnicki, K.: Preliminary testing of the gear pump with internal gearing with modification of the sickle insert. In: Engineering Mechanics 2019: 25th International Conference, 13–16 May. Institute of Thermomechanics of the Czech Academy of Sciences, Svratka, pp. 33–36 (2019)
15. Antoniak, P., Stosiak, M., Towarnicki, K.: Preliminary testing of the internal gear pump with modifications of the sickle insert. Acta Innov. **32**, 84–90 (2019)
16. Stryczek, J., Stryczek, P.: Synthetic approach to the design, manufacturing and examination of gerotor and orbitral hydraulic machines. Energies **14**(3), 1–31 (2021)
17. Dobrowolska, A., Kowaleswki, P., Ptak, A.: Effect of one-stroke pressure on the static friction coefficient of selected metal-polymer sliding pairs. Tribologia **4**, 21–31 (2014)

Comparison of Same Aftermarket Monotube Shock Absorbers Manufactured by Different Brands

Paulius Skačkauskas[1](✉), Dominyka Norkūnaitė[2], Mykola Karpenko[1], and Vilius Mejeras[1]

[1] Vilnius Gediminas Technical University, Plytinės 27, 10105 Vilnius, Lithuania
{paulius.skackauskas,m.karpenko,vilius.mejeras}@vilniustech.lt
[2] Vilnius Gediminas Technical University, J. Basanavičiaus 28, 03224 Vilnius, Lithuania
dominyka.norkunaite@stud.vilniustech.lt

Abstract. Suspension keeps the wheels of the vehicle in contact with the road surface, dampens various vibrations that arise due to road surface irregularities and ensures adequate control of the vehicle. The performance of the suspension is directly related to shock absorbers, which are an integral part of the suspension. As there are many options of various aftermarket shock absorbers, quality and price are the main factors that define the driver's choice. However, the main question is how different can the same aftermarket monotube shock absorbers be, which were designed for a specific vehicle, but were manufactured by different brands? To answer this question, further described research presents the experimental analysis and comparison of damping characteristics of the same aftermarket monotube shock absorbers, which were manufactured by different brands. During the analysis, in total, 8 completely new shock absorbers manufactured by 4 different brands were compared, and the effects of the initial shock absorber temperature were also taken into account.

Keywords: Vehicle · Monotube · Aftermarket · Shock absorber · Damping force · Force vs. velocity · Graph · Knee-point · Comparison

1 Introduction and Literature Review

Active and passive safety systems are crucial to the safety of any vehicle; however, other factors, such as the general technical condition of vehicle, the quality of the used aftermarket parts or the performance of other vehicle systems also play a significant role. In terms of safety and performance, vehicle suspension is not an exception. Since the change of the shock absorber damping characteristics greatly affects ride and handling of the vehicle [1], it can be stated that the shock absorber damping characteristics is the main indicator that defines suspension performance. A shock absorber, which does not generate enough damping force or a shock absorber that is too stiff and generates too much damping force, is going to negatively affect the safety of any vehicle. According to [2], worn shock absorbers can reduce braking efficiency or they can directly affect

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 277–286, 2023.
https://doi.org/10.1007/978-3-031-25863-3_26

loss of handling and control of the vehicle. Therefore, the impacts of the shock absorber damping characteristics on the ride and handling of the vehicle is a relevant topic, frequently discussed by the researchers. This section further provides a concise review of how the relation between the performance of shock absorbers and the safety of the vehicle is analysed in various research works.

A number of scholars are analysing the relation between the performance of the shock absorber and the safety of the vehicle and, respectively, the relation between the performance of the shock absorber and its damping characteristics. The influence of the wear of the shock absorber on vehicle braking performance is analysed in [3]. On the basis of the performed analysis, the authors concluded that the shock absorber status has no influence on the vehicle's braking performance when the vehicle is moving on a smooth road profile. However, in the case of a rough road profile, the state of the shock absorber has a significant influence on the braking distance [3]. The influence of worn shock absorbers on the braking performance on a rough road was also analysed in [4]. In this reference it was shown that when the ABS is activated, the brake pressure fluctuations are affected by the changes in shock absorber damping capacity. After performing similar experimental tests with worn and new shock absorbers, it was determined that the braking distance obtained with the worn shock absorbers is approximately 21% longer than with the new shock absorbers [4]. Regarding the relation between the ABS braking and shock absorbers, in [5] the effects of variable shock absorber damping settings induced brake pressure oscillations on axle and wheel oscillations during the ABS braking are discussed. In their work, the authors showed that the brake pressure is distinctly changed by variable shock absorber damping settings and that it is possible to damp the axle and wheel oscillations by setting wheel load effect at high and low piston velocities of different shock absorber settings. The authors in [6] have shown that the performance of shock absorbers also adversely affects the handling and stability of the vehicle. Worn shock absorbers increase roll and pitch motions, leading to a less stable vehicle response. The possibility to increase vehicle stability by regulating the damping force characteristic, while vehicle is moving on a sharp road curve with deteriorated pavement edge, was analysed in [7]. It was determined by the authors that suspension with higher damping force characteristic showed better vehicle stability results. While further considering steerability and stability problems, an analysis of the influence of the worn shock absorbers on steerability and stability of the vehicle motion is presented in [8]. The presented analysis of the worn shock absorbers showed that: 1. The damage of the shock absorber increases the vehicle understeering phenomena; 2. The inefficiency of the worn shock absorber causes the wheels to disconnect from the road surface, thereby worsening the steerability of the vehicle. The author of [8] in one of his more recent works [9] once again supported the observation that the reduced damping of the shock absorber generally results in the understeering phenomena of the vehicle during various manoeuvres. What is more, similarly to the research works [3] and [4], the author of [8] also noted that the damage of the shock absorber influences the increase in the braking distance.

In relation to the fact that the damping characteristics of the shock absorber directly affect the safety and performance of the vehicle, scholars are paying quite a lot of attention to the diagnostics and failure analysis of the shock absorbers. In [10] the authors

analysed the failure characteristics of a twintube shock absorber and the proposed virtual prototyping technology, designed to investigate dynamic properties of shock absorbers. An application of the vibration test in order to evaluate the technical condition of shock absorbers built into the vehicle is described in [11]. In [12] a sound metric approach based on the Wigner–Ville distribution was developed to investigate the shock absorber rattling noises. It is also important to mention that, in the research works, the changes in shock absorber damping characteristics are being analysed from many different points of view. For example, in [13] a comparative analysis of monotube shock absorbers with different valve systems is performed. Investigation of the relation between the cavitation process in the monotube shock absorber and its damping characteristics is presented in [14]. In [15] a non-linear analysis of shock absorbers with amplitude-dependent damping characteristics is described. Based on the described research works it is clear that the importance of the shock absorber and the damping force generated by the shock absorber cannot be ignored when considering the safety of the vehicle.

This research work proposes to look at the damping characteristics of shock absorbers from a slightly different point of view. Currently there are more than 25 major shock absorber manufacturers [16]. According to the Global Industrial Hydraulic Shock Absorber Market Report [17], the global industrial hydraulic shock absorber market size is projected to reach USD 304.9 million in 2022 and is forecast to a readjusted size of USD 357.7 million by 2028. The passenger vehicle holds the largest share in the shock absorber market share, accounted for 74.6% in 2018, with a market value of USD 11,873.4 million [16]. Thus, while seeking to replace faulty shock absorbers, the consumer – the driver of the vehicle has a significant number of different options. The main question that arises is: if the driver should expect that the same shock absorber, designed for a specific vehicle, but manufactured by a different brand, can actually have different damping characteristics, which would differently affect the performance and safety of the vehicle? Due to this reason, the main aim of this work is to answer this question by comparing the damping characteristics of the same aftermarket monotube shock absorbers, designed for specific vehicles, but manufactured by different brands.

2 Experimental Research

In order to compare the damping characteristics of the same aftermarket monotube shock absorbers manufactured by different brands, an experimental research was performed. While seeking to obtain more reliable and detailed results, the experimental research was performed by testing entirely new shock absorbers, designed for two different specific light vehicles (the same class and year of manufacture). The exact brands and models of the light vehicles, for which the tested shock absorbers were designed, were selected randomly. In total, 8 shock absorbers, manufactured by 4 different brands, were tested, i.e., 4 shock absorbers manufactured by 4 different brands for vehicle No. 1 and 4 shock absorbers manufactured by the matching 4 different brands for vehicle No. 2 were experimentally tested. The tested shock absorbers were designed for the rear suspension of both vehicles. The rear suspension was selected due to the more simple mounting joints design. The brands of the tested shock absorbers were selected based on the price of the single shock absorber, from lowest to highest. Respectively, further in the work,

"Brand 1" represents the shock absorber brand with the lowest price and "Brand 4" represents the shock absorber brand with the highest price. It is important to note that when considering the price of the tested shock absorbers, in the cases of both vehicles, the actual brands of the tested shock absorber lined up in a similar order. All tested shock absorbers are shown in Fig. 1.

Fig. 1. Monotube shock absorbers, which were tested during the experimental research.

The experimental research was performed while using the *LABA*^{7} *Featherlight Shock Dyno* shock absorber test stand (Fig. 2). All shock absorbers were tested at a maximum compression/rebound velocity of 600 mm/s, i.e. the amplitude of the compression/rebound velocity was equal to 600 mm/s. The amplitude of compression/rebound strokes was 50 mm. When considering research work [18] and the importance of the shock absorber temperature, two-stage testing was used: 1. Testing with an initial shock absorber temperature of 25 °C; 2. Testing with an initial shock absorber temperature of 50 °C. Such values of the initial shock absorber temperature were selected as the "normal" and "relatively high" values, while taking into account that shock absorbers must be able to properly perform up to 100 °C temperature [18]. The initial temperatures of the shock absorbers were measured by using an IR temperature sensor, mounted on the test stand. A remark must be made that the specific initial temperatures (25 °C and 50 °C) of the shock absorbers were achieved by primarily performing compression/rebound strokes and warming up the shock absorbers in the test stand. The experimental testing of each shock absorber started only when the specific initial temperature was achieved accurately. During the experimental tests, the initial temperature was not maintained, as the shock absorbers continued to slightly warm up, while their damping characteristics were measured.

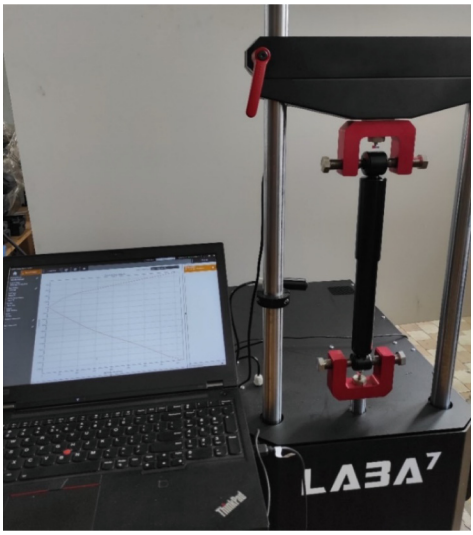


Fig. 2. The *LABA*^{7} *Featherlight Shock Dyno* shock absorber test stand used for the experimental research and the monotube shock absorber mounted in the test stand.

3 Analysis of the Results and Remarks

The results of the experimental research – damping force vs. average velocity graphs are provided in the Fig. 3 and Fig. 4 (vehicle No. 1 and vehicle No. 2 respectively). The generalised maximum damping force values and knee-point characteristics of each of the experimentally tested shock absorbers are provided in Tables 1, 2 and 3.

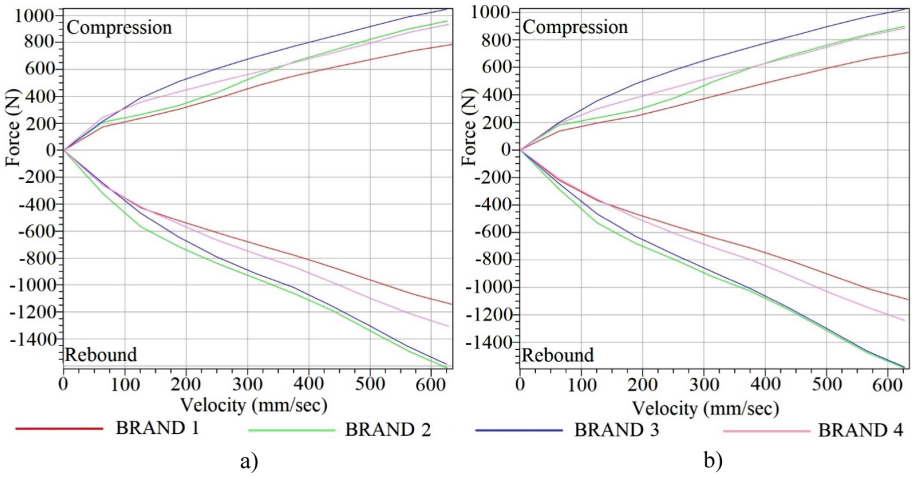


Fig. 3. Experimental results of the tested shock absorbers (vehicle No. 1): a) Initial shock absorber temperature of 25 °C; b) Initial shock absorber temperature of 50 °C.

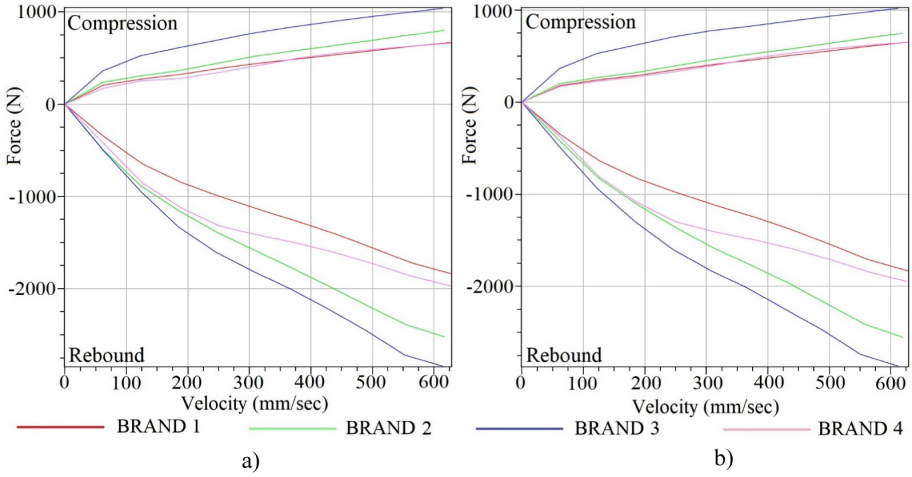


Fig. 4. Experimental results of the tested shock absorbers (vehicle No. 2): a) Initial shock absorber temperature of 25 °C; b) Initial shock absorber temperature of 50 °C.

Table 1. Maximum damping forces generated by the tested shock absorbers.

Vehicle	Vehicle no. 1		Vehicle no. 2	
Shock absorber brand	25 °C	50 °C	25 °C	50 °C
	Maximum damping force, N (Compression/Rebound)	Maximum damping force, N (Compression/Rebound)	Maximum damping force, N (Compression/Rebound)	Maximum damping force, N (Compression/Rebound)
Brand 1	785/−1,144	709/−1,088	667/−1,837	650/−1,832
Brand 2	959/−1,617	898/−1,580	799/−2,523	747/−2,502
Brand 3	1,046/−1,589	1,023/−1,587	1,038/−2,840	1,018/−2,837
Brand 4	935/−1,308	885/−1,240	661/−1,972	649/−1,949

Firstly, while comparing the damping force vs. average velocity graphs and the values of the generated maximum damping forces, a general tendency can be formulated; although in some of the cases there are similarities in the damping graphs, it can be seen that the shapes and slopes of the graphs, i.e., the changes of the damping force and maximum damping force values, which are generated by the same aftermarket monotube shock absorbers manufactured by different brands, differ quite significantly. In the case of vehicle No. 1, at the initial shock absorber temperature of 25 °C, during the compression of the shock absorbers, the largest difference observed between the damping forces was 28.5% (brands 1 and 3), the lowest difference observed between the damping forces was 2.5% (brands 2 and 4). During the rebound of the shock absorbers, the largest difference between the damping forces was 34.3% (brands 1 and 2), the lowest difference between the damping forces was 1.7% (brands 2 and 3). Respectively, in the case of vehicle No. 2, at the initial shock absorber temperature of 25 °C, during the compression of the shock absorbers, the largest difference observed between the damping forces was even

greater and reached 44.4% (brands 1 and 3), the lowest difference observed between the damping forces was 0.9% (brands 1 and 4). Similarly, during the rebound of the shock absorbers, the largest difference between the damping forces was also greater and reached 42.9%, the lowest difference observed between the damping forces was 7.1% (brands 1 and 4). The tendency can be seen that the differences between the maximum damping force values are higher during the rebound of the shock absorber and lower during the compression. What is even more important from the comparison point of view, as can be seen from the provided figures (Fig. 2 and Fig. 3), the increase of the initial shock absorber temperature up to 50 °C did not have any significant influence on the shape and slope of the damping force vs. average velocity graphs. Due to this reason the difference between the maximum damping force values, generated by the same aftermarket monotube shock absorbers manufactured by different brands, remained approximately the same as in the case of the initial shock absorber temperature of 25 °C.

Secondly, while further taking into consideration the effect of the initial shock absorber temperature increase up to 50 °C, it was observed that, in all of the tested different brand shock absorbers, the increase of the initial temperature affected the decrease of the generated maximum damping force. This remark can be easily explained by the fact that, as the temperature of the shock absorber increases, the viscosity of the shock absorber oil decreases, leading to a decrease of the generated maximum damping force [18, 19]. It should be noted that the decrease of the maximum damping force in the shock absorbers of different brands was approximately similar, but not entirely equal. After the increase of the initial shock absorber temperature up to 50 °C, the average decrease in the maximum damping force in each of the tested different brand shock absorbers was (based on the data provided in Table 1): in brand 1 for the compression 6.4% and for the rebound 2.6%; in brand 2 for the compression 6.6% and for the rebound 1.5%; in brand 3 for the compression 2.1% and for the rebound 0.1%; in brand 4 for the compression 3.7% and for the rebound 3.3%. Based on these results it can be stated that, although the changes in the maximum damping force of different brand shock absorbers are not entirely equal, these changes and differences in the maximum damping force, which emerged as a result of the temperature change, were not significant. Thus, a general remark can be made that all of the tested different brand shock absorbers react similarly to the change of the initial temperature.

Thirdly, while comparing the performance of the shock absorbers, it is important to consider the knee-point characteristics (location of the knee-point), i.e., the transition point from the low-velocity compression/rebound strokes range (piston valve system is closed) to the high-velocity compression/rebound strokes range (piston valve system is opened to a specific level). The location of the knee-point must be considered as an important characteristic because: 1. It shows at which point of the damping curve the piston valve system of the shock absorber actually starts to open; 2. It allows to make assumptions about the differences between the performance of the valve systems, used in different shock absorbers. The knee-point characteristics recorded during the experimental tests are provided in Table 2 and Table 3.

It is very interesting to note that actually, in most of the tested different brand shock absorbers, the knee-point appeared approximately at the same compression/rebound velocities: for the compression between the 60–64 mm/s and for the rebound between

Table 2. Knee-point characteristics of the tested shock absorbers (vehicle No. 1).

Shock absorber	Initial temperature of 25 °C		Initial temperature of 50 °C	
	Damping force (Compression) at velocity, N at mm/sec	Damping force (Rebound) and velocity, N and mm/sec	Damping force (Compression) and velocity, N and mm/sec	Damping force (Rebound) and velocity, N and mm/sec
Brand 1	173 N at 63.8 mm/s	−429 N at 126.7 mm/s	136 N at 63.3 mm/s	−219 N at 63.3 mm/s
Brand 2	206 N at 62.5 mm/s	−566 N at 125.3 mm/s	179 N at 62.7 mm/s	−531 N at 125.4 mm/s
Brand 3	*Not visible clearly*	−465 N at 125.1 mm/s	*Not visible clearly*	−465 N at 125.4 mm/s
Brand 4	242 N at 62.8 mm/s	−420N at 125.7 mm/s	189 N at 62.7 mm/s	−207 N at 62.7 mm/s

Table 3. Knee-point characteristics of the tested shock absorbers (vehicle No. 2).

Shock absorber	Initial temperature of 25 °C		Initial temperature of 50 °C	
	Damping force (Compression) and velocity, N and mm/sec	Damping force (Rebound) and velocity, N and mm/sec	Damping force (Compression) and velocity, N and mm/sec	Damping force (Rebound) and velocity, N and mm/sec
Brand 1	206 N at 62.7 mm/s	−646 N at 125.5 mm/s	181 N at 62.8 mm/s	−636 N at 125.5 mm/s
Brand 2	236 N at 61.7 mm/s	−886 N at 123.5 mm/s	201 N at 61.9 mm/s	−820 N at 123.9 mm/s
Brand 3	360 N at 61.4 mm/s	−943 N at 122.8 mm/s	354 N at 61.2 mm/s	−936 N at 122.3 mm/s
Brand 4	173 N at 62.7 mm/s	−852 N at 125.5 mm/s	172 N at 60.7 mm/s	−809 N at 125.4 mm/s

the 122–126 mm/s. What is more, during the experimental tests, the increase of the temperature also did not have any significant effect on the compression/rebound velocities at which the knee-point appeared. Noticed exception: in the case of vehicle No. 1, after the increase of the initial shock absorber temperature up to 50 °C, in the brand 1 and brand 4 shock absorbers the rebound velocity at which the knee-point appears decreased by 50%. This phenomenon was not noticed in the case of vehicle No. 2, while testing brand 1 and brand 4 shock absorbers. Thus, it can be assumed that the brand of the shock absorber and the temperature have no significant influence on the compression/rebound velocity at which the knee-point appears. However, the damping force at the knee-point in all of the tested different brand shock absorbers was noticeably different. In the case

of vehicle No. 1, at the initial shock absorber temperature of 25 °C, during the compression of the shock absorbers the largest difference observed between the damping forces at the knee-point was 33.3% (brands 1 and 4). In the case of vehicle No. 2, the largest difference observed between the damping forces at the knee-point was 70.2% (brands 3 and 4). Regarding the increase of the temperature – similarly to the already described effect of the temperature on the damping force, the increase of the initial shock absorber temperature affected the decrease of the damping force value at the knee-point. The largest noticed decrease of the damping force value at the knee-point during the compression was 25% (vehicle No. 1, brand 4 shock absorber). During the rebound the largest decrease of the damping force value observed at the knee-point was 67%, also in the case of the vehicle No. 1, brand 4 shock absorber. Nevertheless, in some of the cases the increase of the initial shock absorber temperature did not have any effect at all on the damping force value at the knee-point (vehicle No. 1, brand 3 shock absorber) or the effect was minimal (vehicle No. 2, brand 1 and brand 3 shock absorber). It can be generalized that the knee-point characteristics of the same aftermarket monotube shock absorbers, manufactured by different brands, are also different and react differently to the changes of the initial shock absorber temperature.

4 Conclusions

This research paper raised an important practical question, related to the safety and performance of any vehicle, which should be taken into consideration during the maintenance of the suspension – if the driver of the vehicle should expect that the same aftermarket shock absorber, but manufactured by a different brand, can actually have different damping characteristics? Based on the performed research an initial answer to this question can be proposed – it is highly possible that the same aftermarket shock absorber, manufactured by a different brand, is going to have relatively or even significantly different damping characteristics. After conducting an experimental research it was observed that, during the compression of the shock absorbers, the differences between the generated maximum damping force reached approximately 29% and during the rebound the differences between the generated maximum damping force reached almost 45%. It was also observed that the damping force values at the knee-point of the same aftermarket monotube shock absorbers, manufactured by different brands, can also be different and can even reach the difference of approximately 70%. It should be noted that this is only the initial research and comparison of the same aftermarket shock absorbers, manufactured by different brands, which could serve as a base for further investigation. To more thoroughly support the described observations, more detailed and sophisticated research should be performed.

References

1. Rusli, F.Z., Darsivan, F.J.: The effect of hydraulic damper characteristics on the ride and handling of ground vehicle. Int. J. Recent Technol. Eng. **7**(6), 113–118 (2019)
2. Monroe Homepage: how shocks and struts can affect safety. https://eu.monroe.com/en-gb/blog/safety-indicators.html. Accessed 23 Apr 2022

3. Calvo, J.A., Diaz, V., San Roman, J.L., Garcia-Pozuelo, D.: Influence of shock absorber wearing on vehicle brake performance. Int. J. Automot. Technol. **9**(4), 467–472 (2008)
4. Koylu, H., Cinar, A.: The influences of worn shock absorber on ABS braking performance on rough road. Int. J. Veh. Des. **57**(1), 84–101 (2011)
5. Koylu, H., Cinar, A.: Dynamical investigation of effects of variable damper settings induced brake pressure oscillations on axle and wheel oscillations during ABS-braking based on experimental study. Meccanica **48**, 1093–1115 (2013)
6. Guba, S., Ko, Y., Rizzoni, G., Heydinger, G.J., Guenther, D.A., Wittman, T.: The impact of worn shocks on vehicle handling and stability. SAE Techn. Pap. Ser., 1–11, 2006-01-0563 (2006)
7. Žuraulis, V., Surblys, V.: Assessment of risky cornering on a horizontal road curve by improving vehicle suspension performance. Balt. J. Road Bridge Eng. **16**(4), 1–27 (2021)
8. Parczewski, K.: Exploration of the shock-absorber damage influence on the steerability and stability of the car motion. J. KONES Powertrain Transp. **18**(3), 1–8 (2011)
9. Parczewski, K., Wnek, H.: Analysis of the impact of reduced damping in the suspension on selected vehicle steering characteristics. J. Syst. Control Eng. **233**(4), 392–399 (2019)
10. Guan, D., Jing, X., Shen, H., Jing, L., Gong, J.: Test and simulation the failure characteristics of twin tube shock absorber. Mech. Syst. Signal Process. **122**, 707–719 (2019)
11. Konieczny, L., Burdzik, R., Lazarz, B.: Application of the vibration test in the evaluation of the technical condition of shock absorbers built into the vehicle. J. Vibroeng. **15**(4), 2042–2048 (2013)
12. Huang, H.B., Li, R.X., Huang, X.R., Yang, M.L., Ding, W.P.: Sound quality evaluation of vehicle suspension shock absorber rattling noise based on the Wigner–Ville distribution. Appl. Acoust. **100**, 18–25 (2015)
13. Ferdek, U., Luczko, J.: A comparative analysis of mono-tube shock absorbers with different valve systems. AIP Conf. Proc. **2239**, 1–10 (2020)
14. Skrickij, V., Savitski, D., Ivanov, V., Skačkauskas, P.: Investigation of cavitation process in monotube shock absorber. Int. J. Automot. Technol. **19**(5), 801–810 (2018)
15. Luczko, J., Ferdek, U., Latas, W.: Nonlinear analysis of shock absorbers with amplitude-dependent damping. AIP Conf. Proc. **1922**, 1–10 (2018)
16. MzwMoto Homepage: Top 25 Shock Absorber OEM List. https://mzwmotor.com/shock-absorber-manufacturer/. Accessed 06 May 2022
17. Research Reports World Homepage: Global industrial hydraulic shock absorber market insights and forecast to 2028. https://www.researchreportsworld.com/global-industrial-hydraulic-shock-absorber-market-19924795. Accessed 06 May 2022
18. Pavlov, N.: Influence of shock absorber temperature on vehicle ride comfort and road holding. In: 9th International Scientific Conference on Aeronautics, Automotive and Railway Engineering and Technologies, EDP Sciences, Bulgaria, pp. 1–6 (2017)
19. Xie, F., et al.: Temperature rise characteristics of the valve-controlled adjustable damping shock absorber. Mech. Ind. **21**(111), 1–11 (2020)

Experimental Study of Flow Rate in Hydraulic Satellite Motor with the Rotating Case at a Low Constant Rotational Speed

Pawel Sliwinski[1](✉), Piotr Patrosz[1], Marcin Bak[1], Michal Stosiak[2], Kamil Urbanowicz[3], and Šarūnas Šukevičius[4]

[1] Gdansk University of Technology, Gdansk, Poland
{pawel.sliwinski,piotr.patrosz,marcin.bak}@pg.edu.pl
[2] Wroclaw University of Technology, Wroclaw, Poland
michal.stosiak@pwr.edu.pl
[3] West Pomeranian University of Technology, Szczecin, Poland
kamil.urbanowicz@zut.edu.pl
[4] Vilnius Gediminas Technical University, Vilnius, Lithuania
sarunas.sukevicius@vilniutech.lt

Abstract. In this article was described the methodology for the experimental study of flows in the prototype of a satellite hydraulic motor with a rotating body. The experimental tests of the motor were carried out at a low constant rotational speed in a wide range of pressure drop in this motor. The constant rotational speed of the motor was kept by a worm gear. Based on the test results, the leakage characteristics in the flat gaps of the curvature, satellites and in the commutation unit gaps were determined. The test results also allowed to evaluate the correct operation of the commutation unit and the compensation unit of axial clearances of the curvature and satellites in the working mechanism of the motor.

Keywords: Satellite motor · Flow rate · Leakage · Compensation unit · Commutation unit

1 Introduction

In hydraulic drive systems of machines and devices, pumps are the most important element [1–4]. Another very important element of the drive system is an executive element, i.e., the hydraulic motor. The parameters of the hydraulic motor affect the operating parameters of the entire hydraulic system [5–7]. Apart from the pump and the hydraulic motor, indispensable elements of the hydraulic system are control elements (valves) and hoses. The parameters of these elements also have a great influence on the operating parameters of the entire system and the efficiency of energy conversion [1, 6, 8].

The vast majority of hydraulic motors available on the market is characterized by the fact that the motor shaft is set in rotation. However, hydraulic motors with a rotating body can also be found on the market. One of the examples of such a hydraulic motor is the MF series radial piston motor offered by POCLAIN [9]. This motor is used especially in

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 287–299, 2023.
https://doi.org/10.1007/978-3-031-25863-3_27

trucks to drive the front wheels, as the so-called auxiliary drive. In such an arrangement, the vehicle wheel is mounted directly on the body of the hydraulic motor.

In addition to the auxiliary drive systems of trucks, hydraulic motors with a rotating body and a fixed shaft (rather a pin) can be used directly in:

1. belt conveyor drives (mining and transport industry);
2. winding machinery drives;
3. as interior cleaning heads for pipes (e.g. pipes in oil and gas wells).

It has been found that there is no alternative motor to the radial piston motor on the market. Therefore, it was undertaken to develop a completely new construction of the hydraulic motor with a rotating body based on a satellite working mechanism. This mechanism is shown in Fig. 1.

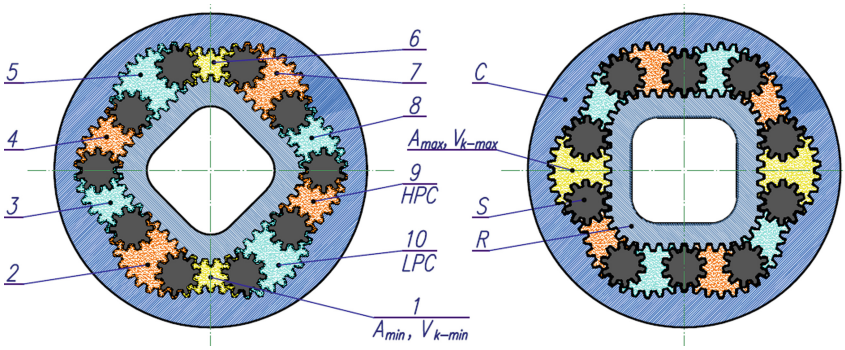


Fig. 1. Satellite mechanism type 4 × 6 [5, 10–13]: C – curvature, R – rotor, S – satellite, 1 ÷ 10 – working chambers, LPC – low pressure chamber, HPC – high pressure chamber, $V_{k\text{-}min}$ – chamber with minimal volume (death chamber) and with minimal area A_{min}, $V_{k\text{-}max}$ – chamber with maximal volume (death chamber) and with maximal area A_{max}.

So far, in the known satellite motors, the shaft and thus the rotor R, is set in rotation [14, 15]. In order to make the motor body rotate, the rotor R must be immobilized, the curvature C must be coupled to the motor body and thus the curvature C must be set in rotation [5, 16]. The construction of such motor is presented in the next chapter.

Comprehensive tests of a hydraulic motor include the following set of tests:

1. tests of unloaded motor in a wide range of rotational speed, tests of loaded motor in the entire range of load at low constant speed,
2. tests of loaded motor in the entire range of load at low constant speed,
3. tests of loaded motor in the entire range of load and entire range of rotational speed.

In this article, the results of the research on the flow rate in the motor at low constant speed are presented. The motor tests at low constant speed are the priority tests. The results of these tests allow the assessment of:

1. the correct operation of the motor commutation unit, i.e., the assessment of the correctness of the process of filling and emptying the working chambers;
2. the correct operation of the clearance compensation unit of the elements of the working mechanism,
3. internal leakage in the motor, i.e., flows in the gaps in the operating mechanism and in the commutation unit gaps.

The scheme of the measuring system for testing the engine at low constant speed is presented and described later in the article.

2 The Motor Construction

The construction of the prototype of the satellite motor, in which the curvature C and the body rotates, is shown in Fig. 2. This motor was marked with the symbol SWK. This motor uses a satellite mechanism type 4 × 6 (as shown in Fig. 1). The geometric working volume of the motor, and thus the mechanism (according to the mechanism documentation), is $V_g = 39.2$ cm^3/rev. The teeth of the satellite working mechanism have a module m = 1.5 mm.

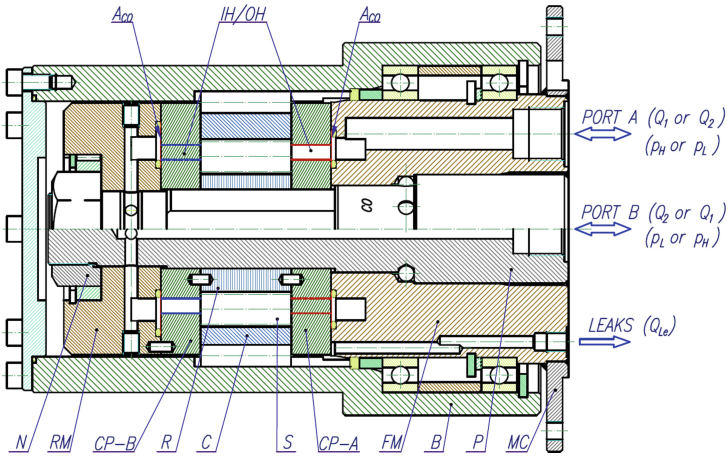


Fig. 2. Construction of the SWK satellite motor [17]: C – curvature, R – rotor, S – satellite, CP-A and CP-B – commutation (compensation) plates, IH – inflow channel, OH – outflow channel, A_{CO} – area of pressure action (in compensation chamber), P – pin, B – body (case), MC – mechanical connection, FM – front manifold, RM – rear manifold, N – nut, Q_1 – liquid stream (flow rate) supplying the motor, Q_2 – liquid stream (flow rate) flowing from the motor, Q_{Le} – external leaks, p_H – high pressure, p_H – low pressure.

The following factors were taken into account when designing the SWK motor:

a) the body 1 can be shaped freely, depending on the requirements of the machine, the motor of which is to be installed;

b) the motor can be loaded with radial forces (not only torque). The magnitude of the radial load is intended to affect only the type and size of the bearings. Radial forces must in no way be transferred to the working mechanism.

2.1 The Axial Clearance Compensation Unit

The motor commutation plates (CP-A and CP-B) are fixed relative to the rotor R.

(Fig. 2) [5, 17]. The commutation plates are also act as the compensation plates and are part of the so-called the axial clearance compensation unit for the satellites S and the curvature C. The axial compensation unit has been designed according to the diagram shown in Fig. 3.

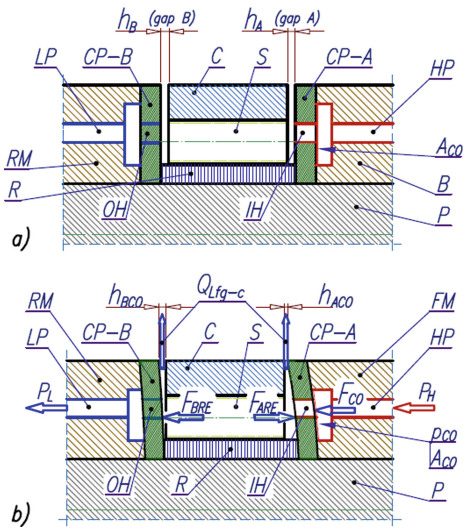


Fig. 3. The compensation unit of axial clearances of satellite S and curvature C: a) the unit is not under pressure; b) the unit under load; HP and LP – respectively: supply (high pressure p_H) and outlet (low pressure p_L) channel, F_{CO} – compensation force, F_{ARE} and F_{BRE} – forces due to pressure from working chambers, h_{ACO} and h_{BCO} – height of the gap between the curvature C and the commutation plate respectively CP-A and CP-B.

The task of the compensation unit is to effectively reduce the height of the flat gaps in the working mechanism under the load of the motor, and thus limit the leakage in these gaps. The effect of loading the motor with the torque is the increase in pressure p_H in the internal channels HP of the motor and in the compensation chamber A_{CO}. If the force F_{CO} from the compensation field A_{CO} is greater than the resultant force F_{ARE} from the working chambers, elastic deformation of the compensation plate CP-A will occur. The CP-B plate will behave in a similar way. Thus, the height of the curvature flat gaps will decrease from h_A and h_B to h_{ACO} and h_{BCO} (Fig. 3). Consequently, in a satellite machine, there is a very desirable reduction of leakage Q_{LfgC} in the curvature flat gaps and leakage Q_{LfgS} in the satellites flat gaps.

For the first laboratory tests, the satellite motor was prepared with very large axial clearances of the satellites and the curvature (at the level of 60 um). The reason for using such large clearances was the lack of information on the correct operation of the compensation unit in laboratory conditions. That is, in order to prevent unexpected damage to the surface of the compensation plates and satellites, it was decided to significantly increase the axial clearances.

At the moment of the occurrence of the motor load (increase in supply pressure), rotor R is clamped through the compensation plates CP-A and CP-B. Therefore, there is no leakage in the direction of pin P. A detailed description of the compensation unit is in [5, 13].

2.2 The Satellite Mechanism Commutation Unit

The commutation unit ensures the proper process of filling and emptying the working chambers of the satellite mechanism. The commutation unit consists of the satellites S and the inlet and outlet holes IH and OH in the plates CP (Fig. 2, Fig. 3 and Fig. 4). During the rotation of the curvature C, the satellites S move in relation to the rotor R and the curvature C, respectively covering and exposing the inlet holes IH or revealing the outlet holes OH in the plates CP.

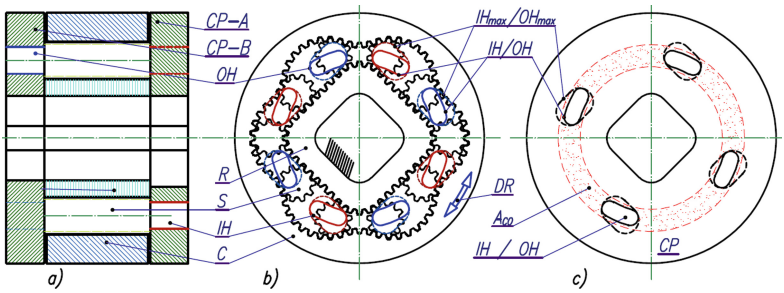


Fig. 4. The motor working mechanism [10, 11, 16]: a) axial section of the satellite mechanism, b) view of the satellite mechanism with the inflow and outflow holes, c) commutation (compensation) plate; A_{CO} – liquid contact area with the supply collector or the outflow collector (compensation area); IH/OH – inlet and outlet holes in the commutation plate (used in the construction), IH_{max}/OH_{max} – theoretical inlet and outlet holes (with a maximum permissible area); DR – direction of curvature rotation.

The inlet IH and OH outlet holes in the commutation plate CP are strictly located in relation to the hump of the rotor R [5, 16] (Fig. 4). Their size results from the position of the satellites in the mechanism corresponding to the field A_{min} and the field A_{max} (Fig. 1). It can be concluded from this that:

- the number of holes IH or OH in the commutation plate CP is equal to the number of the rotor's humps (Fig. 4);
- the shape of the holes IH and OH results from the position of the satellite for the case of a dead chamber ($V_{k\text{-}min}$) and a chamber with a maximum volume ($V_{k\text{-}max}$) (Fig. 4);

– the position of the holes IH in relation to the holes OH is a mirror image of the holes OH about any axis of the coordinate system (and vice versa);
– the length of hole IH and OH is greater than the diameter of the satellite tooth bases. Therefore, within a certain range of the angle of curvature rotation, two adjacent working chambers will be fed from one hole.

The holes IH_{max} and OH_{max} holes are the maximum area holes (Fig. 4). However, from a practical point of view, additional constraints arise as to the width of these holes. The first limitation is the construction of the collectors supplying and discharging liquid from the holes IH and OH in the plates CP (Fig. 2). The second is the construction of the compensation unit. In the motor construction, the collectors and the compensation unit form one cooperating unit (Fig. 2). The holes IH and OH are holes in the plates CP that conform to motor design constraints. More information on the methodology of designing commutation unit in satellite engines is provided in [5, 12].

In the presented motor, a zero overlap was used in the commutation unit. Nevertheless, depending on the purpose of the motor (low-speed or high-speed), it is possible to use positive or negative overlap, respectively (Fig. 5).

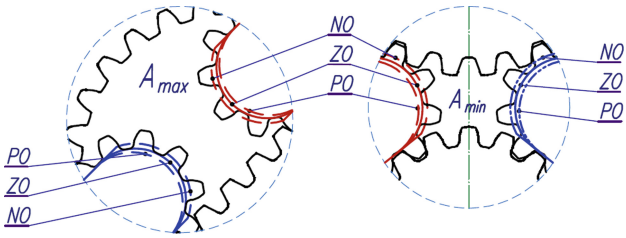


Fig. 5. Overlaps in the commutation unit of the satellite mechanism with a rotating curvature: ZO – edge of the inlet and outlet hole corresponding to the zero overlap; PO – edge of the inflow or outflow hole corresponding to the positive overlap; NO – edge of the inlet or outlet hole corresponding to the negative overlap; red color – inflow hole IF, blue color – outflow hole OH.

The value of the overlap affects the size of the peak flow Q during the appearance of the dead chamber $V_{k\text{-}min}$ and the chamber with the maximum volume $V_{k\text{-}max}$ [5, 12]. The flow rate peaks in the commutation unit gaps are a component of the volumetric losses. So they have an influence on the volumetric efficiency of the motor.

In high-speed motor, the existence of large flow peaks in the working mechanism is allowed for the following reasons [5, 12]:

a) the proportion of the flow peaks in the commutation unit gaps is small in the overall volumetric loss balance and has little effect on the volumetric efficiency;
b) a zero or a negative overlap is desirable to avoid unfavorable pressure peaks in the chambers $V_{k\text{-}min}$ and $V_{k\text{-}max}$.

Thus, a negative overlap can be used in high-speed motor.

In low-speed motor, high tightness of commutation unit is desirable because [5, 12]:

a) punctures in the commutation unit (flow peaks) affect the smooth running of the motor. With a small stream of feed liquid, the motor could stop;
b) an unfavorable increase in pressure in the chambers $V_{k\text{-min}}$ and $V_{k\text{-max}}$ may not occur, because at low rotational speed there will be a leak in the satellite gaps and the curvature gaps and thus the these pressure peaks will be discharged or significantly reduced.

Thus, a positive overlap can be used in low-speed motor. At the maximum value of this overlap, there will be no flow peaks in the commutation unit [5, 12].

The commutation unit, apart from ensuring the proper filling process of the working chambers, also influences the characteristics of the pressure drop Δp in the motor (of course, with a constant motor torque T as a parameter independent of this motor) [5, 12].

3 Balance of the Liquid Flow in the Hydraulic Motor

The flow rate balance in a hydraulic motor should be described by:

$$Q_1 = \underbrace{q_t \cdot n}_{Q_t} + \underbrace{\Delta Q_L + Q_{fc} + Q_{Lfg} + Q_C}_{Q_L} = Q_2 + Q_{Le}, \tag{1}$$

$$Q_2 = Q_t + \Delta Q_L + Q_{fc} + Q_{LfgS} + Q_C, \tag{2}$$

here Q_1 – the liquid flow rate in inflow port of the motor, Q_2 – the liquid flow rate in outflow port of the motor, Q_t – theoretical flow rate, Q_L – volumetric losses in the motor, ΔQ_L – the liquid flow rate caused by the cyclic elastic deformation of the working chambers, Q_{Lfg} – the liquid flow rate in flat gaps in satellite mechanism

$$Q_{Lfg} = \underbrace{\sum\nolimits_{i=1}^{2n} Q_{LfgS-i}}_{QLfgS} + \underbrace{\sum\nolimits_{k=1}^{m} Q_{LfgC-k}}_{QLfgC}, \tag{3}$$

where Q_{LfgS} – the liquid flow rate in flat gap of the satellite, Q_{LfgC} (= Q_{Le}) – the liquid flow rate in flat gaps of the curvature (external leakage), n – number of satellites, m – number of working chambers, Q_C – the liquid flow rate in clearances in commutation unit (short clearances) in satellite mechanism, Q_{fc} – the liquid flow rate depends on its compressibility.

For simplicity ΔQ_L and Q_{fc} may be omitted due to the very small values compared to the values of the other components of the Eq. (1).

4 The Results of the Tests of the Loaded Motor at Low Constant Speed

Testing the hydraulic motor at low constant speed, in addition to checking the correct operation of the commutation unit, allows to measure the size of leaks (so-called punctures) in this commutation unit. The size of these leaks depends on the magnitude of the

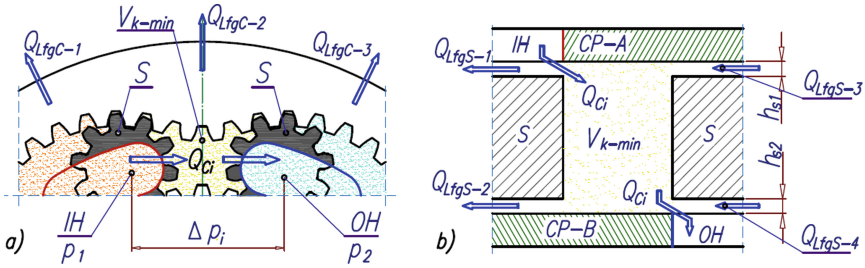


Fig. 6. Leaks in the flat gaps and in the commutation unit gaps.

axial clearance of the satellites and the type and size of the overlap in the commutation unit (Fig. 5) [5, 12].

During all experimental tests, the motor was powered with Total Azolla 46 mineral oil with a viscosity of 40 cSt.

The tests of the flow rate in the motor were carried out at a low constant speed (n = 1 rpm). This speed was kept constant by means of a worm gear WG driven by an electric motor E with a frequency converter (Fig. 7). In the test stand system, a specific motor supply pressure p_1 ($\approx p_H$) is set by setting the pump P capacity, and the motor M torque, measured with a force sensor FT located on the arm R, is a parameter depending on pressure losses and mechanical losses in the motor. The general view of the motor mounted on the test stand is shown in Fig. 8.

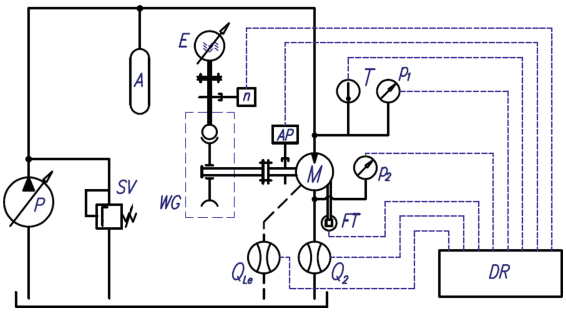


Fig. 7. Scheme of the measuring system: M – tested motor, P – pump, A – accumulator, E – electric motor with frequency converter, SV – safety valve, WG – worm gear, DT – measurement data recorder, Q_{Le} and Q_2 – flow meters, FT – force sensor (for torque measurement), p_1 and p_2 – pressure sensors, T – temperature sensor, n – rotational speed sensor, AP – shaft angular position sensor.

The test results of the loaded motor at n = 1 rpm and for selected pressure drops (6, 10 and 20 MPa) are shown in Figs. 9, 10 and 11.

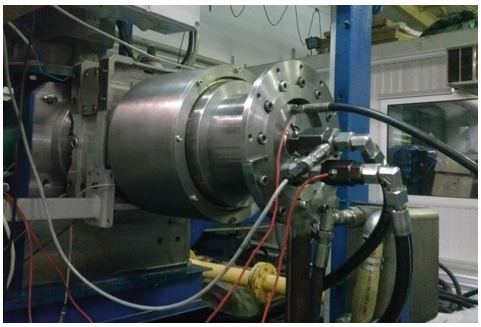


Fig. 8. SWK motor on the test stand – tests at n = 1 rpm.

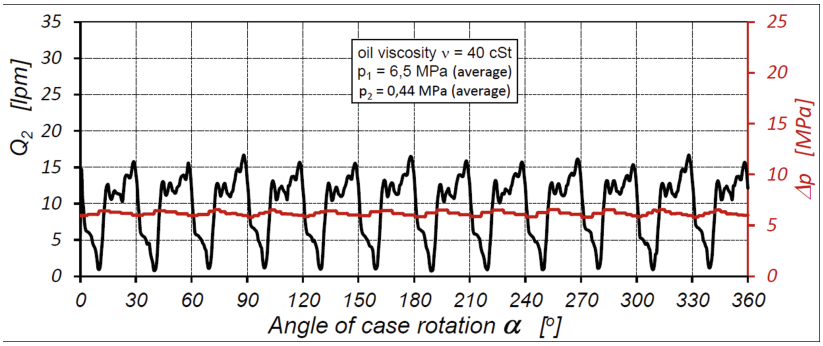


Fig. 9. Characteristic $Q_2 = f(\alpha)$ for $\Delta p = 6$ MPa.

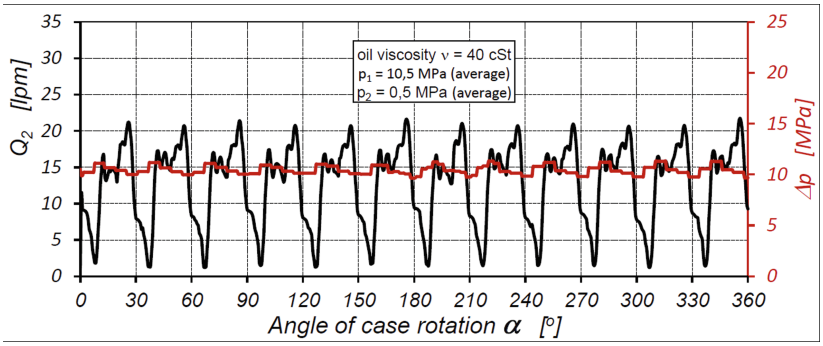


Fig. 10. Characteristic $Q_2 = f(\alpha)$ for $\Delta p = 10$ MPa.

5 Discussion

The results of the motor tests confirmed that the process of filling and emptying the working chambers of the motor is correct and the motor body rotates.

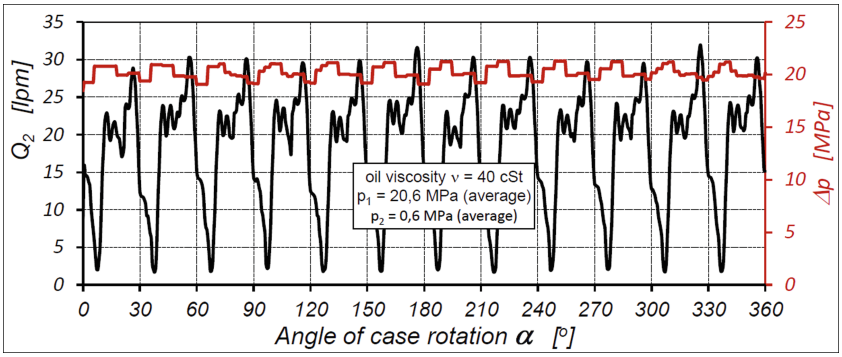


Fig. 11. Characteristic $Q_2 = f(\alpha)$ for $\Delta p = 20$ MPa.

Based on the characteristics presented in Figs. 9, 10 and 11, it can be concluded that the flow in the motor is periodically variable and is a function of the angle of rotation of the motor case B (curvature C, Fig. 2). In addition, there are punctures (large flow peaks) in the commutation unit, which is typical for zero overlap of the holes by satellites (the gap is similar to orifice, Fig. 6). Despite the used accumulator in the test system, there are fluctuations in the pressure drop Δp in the motor. These fluctuations are closely related to the punctures in the commutation unit.

The individual components of the flow rate Q_2, omitting Δ QL and Q_{fc}, are presented in Fig. 12.

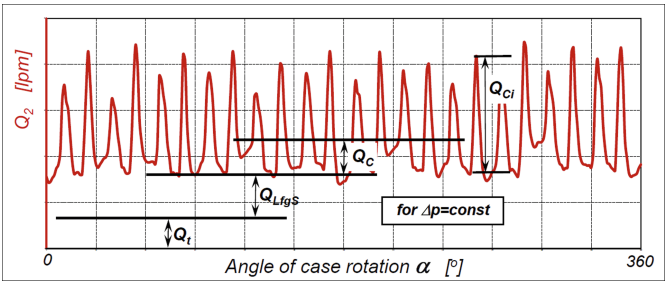


Fig. 12. Components of the flow rate against the background of the general experimental characteristic.

Based on the experimental data (Fig. 12), the average value of leaks in the curvature gaps Q_{LfgC}, the average value of leaks in the satellite gaps Q_{LfgS} and the average value of leaks in the commutation unit gaps Q_C were determined. The external leakage characteristics Q_{LfgC} $(= Q_{Le}) = f(\Delta p)$ (and thus the leakage in the gaps of the bypass) and the characteristics $Q_{LfgS} = f(\Delta p)$ of leakage in the gaps of flat satellites are shown in Fig. 13. Figure 14 presents the characteristics $Q_C = f(\Delta p)$ of the mean value of leakage in the commutation unit gaps. Q_C values were calculated after transforming the formula (2) and assuming that $\Delta Q_L = 0$ and $Q_{fc} = 0$.

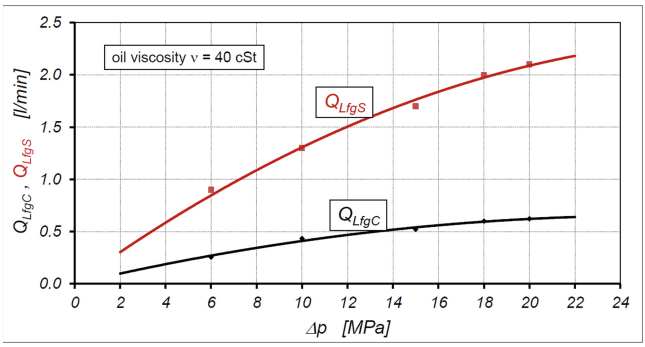


Fig. 13. Characteristics $Q_{LfgC} = f(\Delta p)$ and $Q_{LfgS} = f(\Delta p)$.

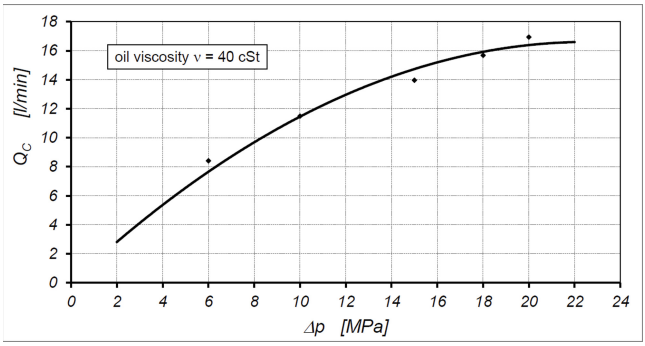


Fig. 14. Characteristic $Q_C = f(\Delta p)$.

Comparing the above characteristics (Fig. 13 and Fig. 14), it can be seen that the greatest leakage occurs in the gaps of the commutation unit. This leakage is almost eight times greater than the leakage in the flat gaps of satellites and almost 28 times greater than the leakage in the flat gaps of the curvature. Overall, the values of leaks in the motor are very high. The high value of leaks in the flat gaps of satellites is caused by the large axial clearance (total height of the gaps ($h_{s1} + h_{s2}$), Fig. 6) of the satellites amounting to as much as 60 um. However, large leakage in the commutation unit gaps is influenced by both the zero overlap in this unit (Fig. 5) and the large axial clearance of the satellites.

In order to simplify the considerations, it is assumed that the oil flow in the working mechanism flat gaps is laminar [18, 19].

Therefore, it can be seen from Fig. 13 that under the influence of the load, the axial clearances of satellites S and curvature C are reduced. Thus, the axial clearances compensation unit works correctly, in accordance with the assumptions presented in Fig. 3.

6 Summary

The motor described in this article is the first novel construction of a satellite motor in which the body rotates. Experimental studies have confirmed that the proper process of filling and emptying the working chambers takes place and that the engine is put into rotation. Thus, the tests confirmed the correctness of the commutation unit construction. In the presented construction of the motor a zero overlap in the commutation unit has been applied. This results in a large leakage in the commutation unit gaps. Such leakage may be acceptable if the motor is intended to be run at high rotational speeds, e.g., above 400 rpm. On the other hand, if the motor was to operate at low rotational speeds, e.g., below 100 rpm, then a positive overlap in the commutation unit should be used (Fig. 5) [5].

An advantage of the motor described in this article is that the body can be part of the machine being driven. For example, a motor without a casing can be mounted directly on the winch. Thus, it is possible to design drives without clutches, additional gears and bearing assemblies. The motor will have the features of a winch drum or a conveyor belt roller. So, the design of the machine that uses this motor will simplify and be competitive in terms of price.

Satellite motors are lighter than other motors of the same power. Moreover, they can be supplied with ecological, non-flammable liquids with poor lubricating properties, such as an oil-in-water emulsion of the HFA-E type, and even with water.

The satellite motor described in this article, due to its small dimensions and weight, will enable the construction of lighter and structurally simplified devices.

References

1. Karpenko, M., Bogdevičius, M.: Review of energy-saving technologies in modern hydraulic drives. Sci. Future Lith. **9**(5), 553–558 (2017). https://doi.org/10.3846/mla.2017.1074
2. Banaszek, A.: Methodology of flow rate assessment of submerged hydraulic ballast pumps on modern product and chemical tankers with use of neural network methods. Procedia Comput. Sci. **192**(4) (2021). https://doi.org/10.1016/j.procs.2021.08.195
3. Banaszek, A., Petrovic, R.: Problem of non proportional flow of hydraulic pumps working with Constant pressure regulators in big power multipump power pack unit in open system. Technicki Vjesnik **26**(2) (2019). https://doi.org/10.17559/TV-20161119215558
4. Zaluski, P.: Influence of fluid compressibility and movements of the swash plate axis of rotation on the volumetric efficiency of axial piston pumps. Energies **15**(1) (2022). https://doi.org/10.3390/en15010298
5. Sliwinski, P.: Satelitowe maszyny wyporowe. Podstawy projektowania i Analiza strat energetycznych (eng. Satellite displacement machines. Basic of design and analysis of power loss). Gdansk University of Technology Publishers, Gdansk, Poland (2016)
6. Karpenko, M., Prentkovskis, O., Šukevičius, Š.: Research on high-pressure hose with repairing fitting and influence on energy parameter of the hydraulic drive. Eksploatacja i Niezawodnosc – Maintenance and Reliability **24**(1), 25–32 (2022). http://doi.org/https://doi.org/10.17531/ein.2022.1.4
7. Jasinski, R.: Analysis of the heating process of hydraulic motors during start-up in thermal shock conditions. Energies **15**(1) (2022). https://doi.org/10.3390/en15010055

8. Stawinski, L., Kosucki, A., Cebulak, M., Gorniak vel Gorski, A., Grala, M.: Investigation of the influence of hydraulic oil temperature on the variable-speed pump performance. Eksploatacja i Niezawodnosc – Maintenance and Reliability **24**(2), 289–296 (2022). https://doi.org/10.17531/ein.2022.2.10
9. POCLAIN Homepage. http://www.poclain-hydraulics.com/en/products/motors/mf/mf-mfe08. Accessed 30 July 2022
10. Sliwinski, P., Patrosz, P.: Satelitowy mechanizm roboczy hydraulicznej maszyny wyporowej. (eng. Satellite operating mechanism of the hydraulic displacement machine). Patent PL 218888 (2015). https://ewyszukiwarka.pue.uprp.gov.pl/search/pwp-details/P.401821
11. Sliwinski, P.: Mechanizm satelitowy hydraulicznej maszyny wyporowej (eng. Satellite operating mechanism of a hydraulic displacement machine). Patent application P.437751 (2021). https://ewyszukiwarka.pue.uprp.gov.pl/search/pwp-details/P.437751
12. Sliwinski, P.: The basics of design and experimental tests of the commutation unit of a hydraulic satellite motor. Arch. Civil Mech. Eng. **16**(4), 634–644 (2016). https://doi.org/10.1016/j.acme.2016.04.003
13. Sliwinski, P.: The methodology of design of axial clearances compensation unit in hydraulic satellite displacement machine and their experimental verification. Arch. Civil Mech. Eng. **19**(4), 1163–1182 (2019). https://doi.org/10.1016/j.acme.2019.04.003
14. Szwajca, T.: Silnik hydrauliczny obiegowy (eng. Epicyclic hydraulic motor). Patent PL 200588 (2009)
15. SM-HYDRO Homepage: https://smhydro.com.pl/silniki-hydrauliczne/. Accessed 30 July 2022
16. Sliwinski, P., Patrosz, P., Osiecki, L.: Płynowa maszyna wyporowa z satelitowym mechanizmem roboczym o odwróconej kinematyce (eng. Displacement fluid machine with a satellite mechanism of reverse kinematics). Patent PL 223907 (2016). https://ewyszukiwarka.pue.uprp.gov.pl/search/pwp-details/P.403060
17. Sliwinski, P., Patrosz, P.: Hydraulic Positive Displacement Machine. European patent application 15003680.4/ EP15003680 (2015). https://patents.google.com/patent/EP3187733A1/zh
18. Kollek, W., Radziwanowska, U.: Energetic efficiency of gear micropumps. Arch. Civil Mech. Eng. **15**(1), 109–115 (2014). https://doi.org/10.1016/j.acme.2014.05.005
19. Borghi, M., Zardin, B., Specchia, E.: External gear pump volumetric efficiency: numerical and experimental analysis. SAE Tech. Pap. (2009).https://doi.org/10.4271/2009-01-2844

Determination of the Value of the Energy Equivalent Speed Parameter According to the Residual Deformations of the Finite Element Model

Tomas Pasaulis(✉) and Robertas Pečeliūnas

Vilnius Gediminas Technical University, Saulėtekis Av. 11, 10223 Vilnius, Lithuania
{tomas.pasaulis,robertas.peceliunas}@vilniustech.lt

Abstract. The work shall analyse the impact of the car body structure on passive safety. The methods for determining the Energy Equivalent Speed (EES) parameter and its relationship with the assessment of the impact velocity shall also be reviewed. Computer simulation of the LS DYNA programme according to the given conditions and calculations of the CRASH 3 software according to the resulting residual deformations shall be carried out to determine the values of the EES parameter. Simulations and calculations are performed using a speed of 50 km/h and a collision with 100% and 50% car body overlap.

Keywords: Automotive passive safety · LS DYNA · Frontal collision · Energy Equivalent Speed (EES)

1 Introduction

Speed is one of the most important factors in the rise of an accident. According to the World Health Organisation, the average speed is directly linked to the increase in the likelihood of an accident occurring and the severity of the consequences. For example, increasing the average speed by 1% the fatal accident risk increases by 4% [1]. It is therefore essential to ensure the passive safety performance of the car in the event of an accident. In the event of a collision between a vehicle and another vehicle or object, various vehicle deformations occur which are undoubtedly dependent on the speed of the collision. The speed at the time of the collision is also a very important parameter in analysing the circumstances of the accident and in determining the responsibilities of the road accident participants. There are a number of methods to determine the speed of the car in the event of a collision, taking into account the residual deformations caused by the car. Such methods are referred to as energy methods and describe the relationship between the energy equivalent speed (EES) and the vehicle's residual deformations after impact [2]. The purpose of this study is to analyze the methods of determining the vehicle's energy equivalent speed (EES) parameter and calculate this parameter using the CRASH 3 software according to the results of the LS DYNA simulation, and to compare the maximum depths of the vehicle's deformations with different overlaps of the vehicle during the collision.

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 300–308, 2023.
https://doi.org/10.1007/978-3-031-25863-3_28

2 Increasing the Energy Absorption of the Car Body by Improving Construction

The main purpose of the car body is to minimize the consequences of an accident, i.e., to increase the passive safety performance of the car. In the event of an accident, the ability of the driver and passengers to survive depends to a large extent on the overload of the human body during the accident and on a sufficient safety space for the car. In the event of an accident, the overload of the human body depends on the ability of the elements of the vehicle body deformation area to absorb kinetic energy [3]. In the design and development of vehicles, it is essential to have an appropriate strategy for selecting materials for the different parts of the car body. It is precisely the choice of materials for the parts of the car body that is the most important and, at the same time, the most difficult operation encompasses many areas and brings together manufacturing technologies, designers, material engineers, even managers and economists. The individual parts of the car body have a significant impact on the overall fuel consumption, ecology, vehicle handling, operation and, in particular, on driver and passenger safety [4]. Figure 1 illustrates the body structure of the Volvo XC90 car and the materials used in it.

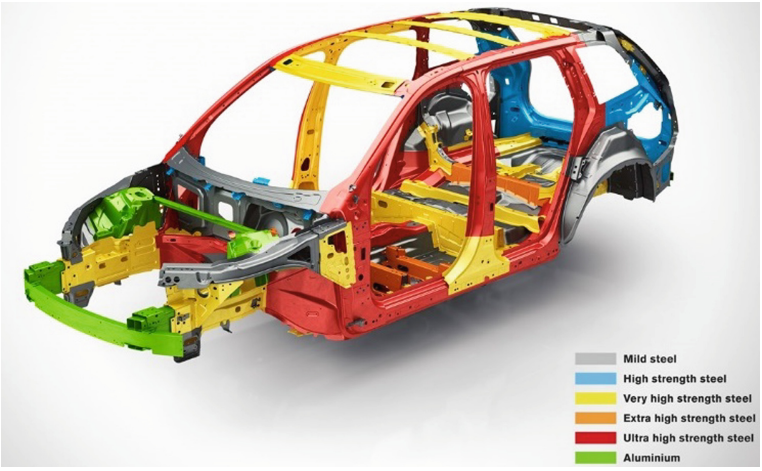


Fig. 1. Volvo XC90 body structure [5].

Figure 1 shows that the vehicle's deformable areas are made of more deformable materials, i.e., aluminum, medium steel. A car safety area in which passengers are located and the driver is made of stronger and deformically resistant materials such as very high-strength steel, extra high-strength steel and ultra-high strength steel to protect the driver and passengers in the event of an accident. According to EURONCAP, car collision tests are specifically designed to check that the structure of the bodywork is appropriate, that the deformation zones of the car absorb energy efficiently and protect the driver and passengers during the collision, in particular in the event of frontal collision, as the consequences in this case are the most serious [6]. It can therefore be said that only a

well-designed car body can protect the driver and passengers in the event of various collisions. Passengers inside the car and the driver are moving forward in the event of a collision at the same speed as the vehicle was moving shortly before the collision. Passengers shall stop only in contact with a particular object inside the car, such as the steering wheel, the dashboard or the front seat. The force produced by the impact on the object may cause fatal or very serious injuries [7]. According to the second Niuton law, the higher deceleration in the event of a collision, the greater the force exerted on the human body. Passive safety features such as airbags, seat belts or vehicle deformation areas are specifically designed to reduce the force applied to passengers and the driver in the event of a collision.

The idea of designing the structure of the car body is to identify in advance the deformation zones which, in the event of a collision, could absorb the resulting kinetic energy and possibly reduce acceleration in the event of a collision. The purpose of the bodywork development process is to control the emerging bodywork loads in the event of a collision by creating special deformation paths which can absorb the resulting energy (Fig. 2) in the event of a collision, thus minimizing the adverse effects on the driver and passengers [8].

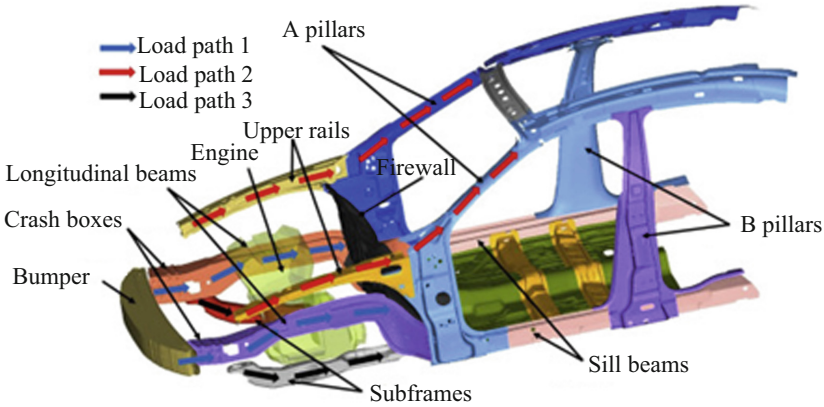


Fig. 2. Front body deformation paths [8].

Figure 2 shows three deformation paths which can absorb the energy of impact in the event of a collision. The first path may absorb more than 50% of the total impact energy in the event of frontal collision. Car longerons are the most energy-absorbing elements in the car [9]. However, the kinetic energy resulting from the collision is absorbed not only by the bodywork but also by other parts forming part of the car. An estimate of the energy absorption in the various components of the structure of the front part of the car in the event of a collision with an undeformable barrier at 56 km/h is shown in Fig. 3 [8].

The effective absorption of the impact energy resulting from the collision may increase the safety of the car in the event of an accident.

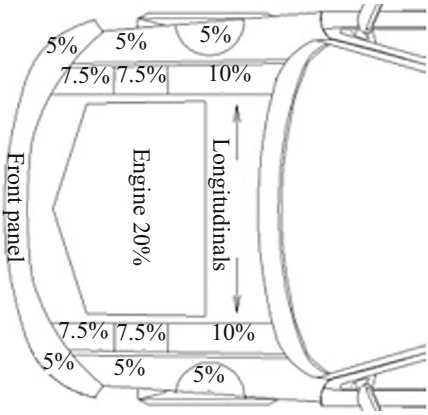


Fig. 3. Estimated energy absorption at the front of the car [10].

3 Methods for Determining the EES Parameter by Residual Deformations

One of the methods for determining the speed parameter of a vehicle's EES is to perform computer simulation in the software LS DYNA environment using automotive finite element models. However, the time costs for the calculations and the price eliminate the use of this technique for the conduct of examinations, but can be used very successfully by car manufacturers, since modelling the car body structure in finite elements can help reduce production costs and improve design processes [11].

PC CRASH software also allows the calculation of the EES through the CRASH 3 software, which provides simplified calculations. The EES calculation method using the CRASH 3 software is based on a linear relationship between the force applied and the plastic deformation [2]. This is a sufficiently convenient and user-friendly approach, but with some limitations.

The EES comparison method is one of the simplest and most commonly used methods in expert practice. In this case, vehicle deformations are compared to vehicle deformations from known EES catalogues. When comparing vehicle deformations visually, the difference in vehicle weights should also be assessed using the following formula [12]:

$$EES_{vehicle} = \sqrt{\frac{m_{etalon}}{m_{vehicle}}} \cdot EES_{etalon}. \tag{1}$$

Another method used to determine the EES value is the energy raster method. This method is based on the relationship between the impact velocity and the deformation depth [12] but is rarely used in expert practice.

4 Testing Model and Modelling Conditions

The simulation shall be used 2010 the Toyota Yaris finite element model developed by the Centre for Collision Safety and Analysis based at the University of George Mason

in the USA (Fig. 4). The model was approved by the NHTSA. This model is designed to perform impact simulations in the software LS DYNA environment. The model is freely accessible to all consumers [13].

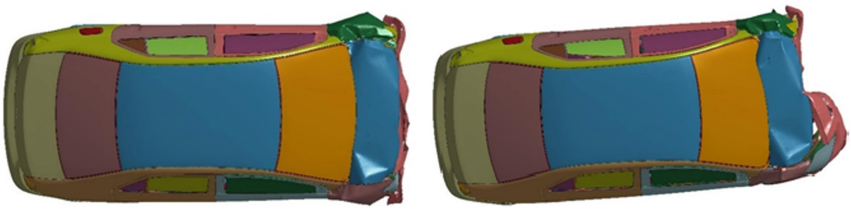
a) b)

Fig. 4. a) Toyota Yaris finite element model; b) Toyota Yaris representation [14].

The finite elements shall be modeled using the above-mentioned software in LS DYNA. The simulator shall use a speed of 50 km/h and a collision with a non-deformable wall at 100% and 50% overlap.

5 Modelling Results

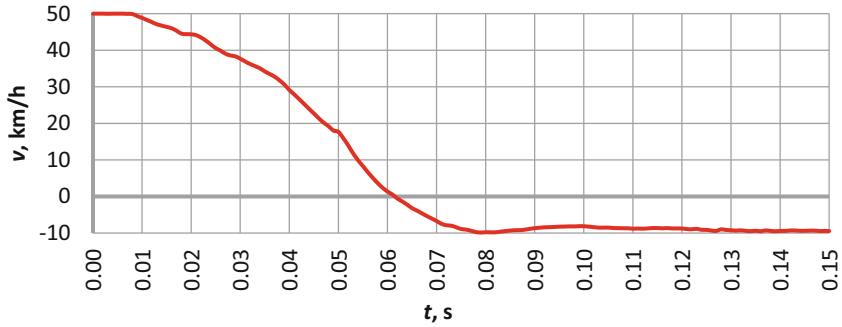
After computer simulation of the encounter against the non-deformable barrier, the LS DYNA programme resulted in the deformations of the Toyota Yaris car under the prescribed conditions. Deformation images are shown in Fig. 5.



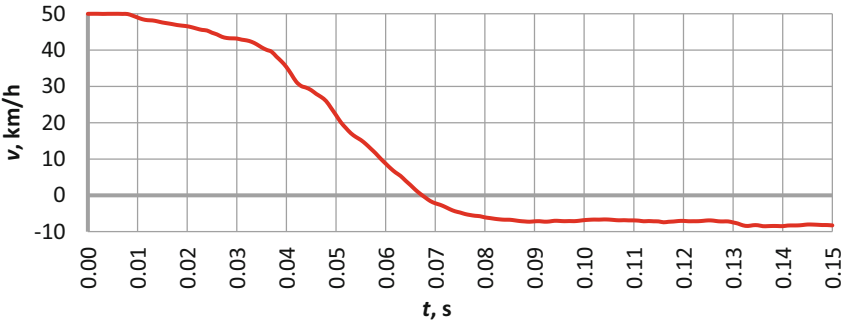
a) b)

Fig. 5. Visual view of Toyota Yaris vehicle deformations a) at 100% overlap; b) at 50% overlap.

The results of the simulation show that Toyota Yaris, after a collision with a non-deformable wall at 100% overlap, has crushed the front over the whole width from the front towards the rear. In the event of a collision with a non-deformable wall with a 50% overlap, the vehicle shall be crushed on the left side of the front in a direction from the front towards the rear. The simulations velocity variation schedules at the moment of impact are shown in Fig. 6. The graphs show the variation in velocity at the moment of impact from the initial simulation speed of 50 km/h.



a)



b)

Fig. 6. Changes in speed of Toyota Yaris in collision a) 100% overlap; b) 50% overlap.

Since the collision simulations were carried out with a non-deformable wall, then the simulated collision velocity corresponds to the EES value without an elastic recovery assessment [15]. According to THE AGU Zurich crash database, the initial impact velocity and the EES value may vary slightly (± 1 km/h) [16], which may be due precisely to the elastic recovery of the car after the impact, but such a small difference does not have a significant impact on the results.

6 Calculation of the ESS Value Using PC CRASH

The energy equivalent speed (EES) value can be calculated using PC CRASH program CRASH 3. Before the calculations are made, a car with appropriate parameters is uploaded into the PC CRASH environment from the existing database, in which case the Toyota Yaris car is considered. The DXF image of the car is then added. A top view of the Toyota Yaris car, deformed in the LS DYNA environment, shall be placed in the programme environment and compatible with its DXF image. A deformation line is drawn from which the programme automatically divides the deformed vehicle area into segments [17]. In this case, the deformation zone of the car is divided into 11 segments

according to the deformation line drawn. Figure 7 shows the deformation of the collision with the non-deformable wall at 100% and 50% overlap with the deformation line drawn.

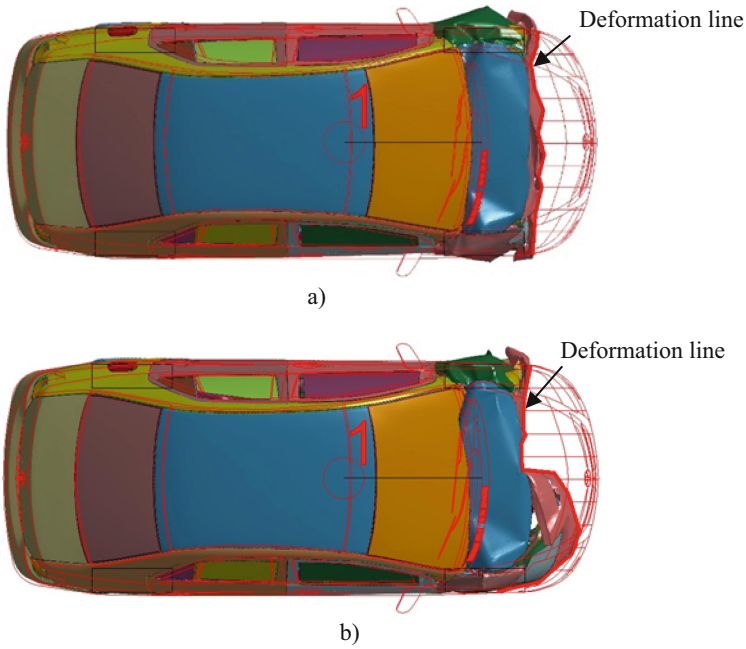


Fig. 7. Representation of the deformed car with a drawing of the deformation line: a) at 100% overlap; b) at 50% overlap.

The CRASH 3 EBS calculation window (Fig. 8) selects analyzed car or resembles the car to be analysed from the NHTSA database. Based on the data contained in the database, the stiffness parameters A, B, G are calculated for the calculation of the EES value of the car in question [17].

The application window (vehicle crush) automatically determine the deformation depth of the vehicle according to the drawn deformation line. The programme window (EBS) automatically calculate the value of the EES parameter (Fig. 9).

For the PC CRASH programme CRASH 3, the values of the EES parameters were obtained. For collisions with a non-deformable wall at 100% overlap, the EES value is 54.4 km/h, and by analogy with the CRASH 3 actions, the value of the EES for collisions with a non-deformable wall at 50% overlap is estimated at 50.7 km/h.

However, it is worth stressing that the CRASH 3 algorithm is based on impact tests with a non-deformable barrier. Based on the impact velocity and its corresponding deformation, the algorithm determines the input parameters used to calculate the EES. However, in the cases in question, where a barrier is deformed in the event of a collision or low overlap between two vehicles, then the EES calculation may be incorrect or sufficiently inaccurate [2].

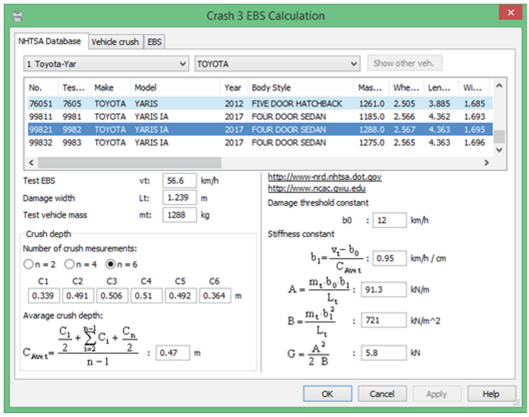
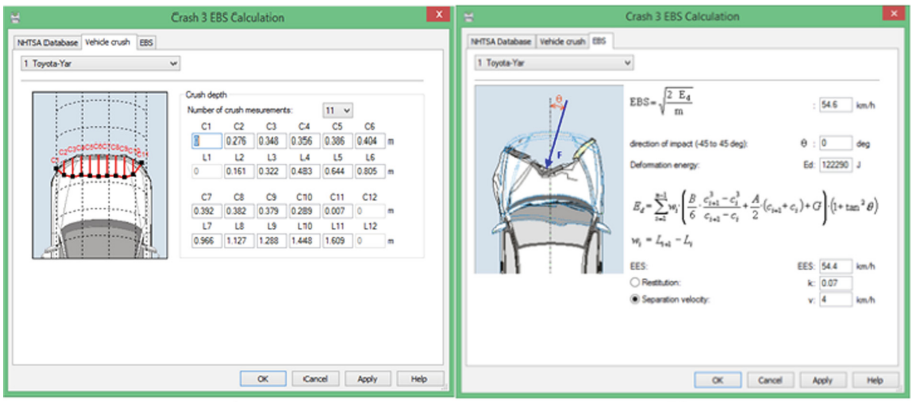


Fig. 8. CRASH 3 calculation window.



a) b)

Fig. 9. a) Automotive deformation depth parameters; b) Estimated EBS and EES values.

It can also be observed from the calculations and from the comparison of deformation depths that with 50% overlap the maximum deformation depth is 0.541 m and with 100% overlap the maximum deformation depth is 0.404 m. Consequently, the deformation depth dependence on the width of the deformation can be observed.

7 Conclusions

1. In the case of a vehicle collision with a non-deformable wall, the impact velocity be equal to the equivalent energy velocity (EES) value.
2. Using PC CRASH program CRASH 3, the resulting value of the EES parameter at 100% overlap is 54.4 km/h. This value is about 8.8% higher than the impact velocity of the LS DYNA simulation. With a 50% overlap, the EES value is 50.7 km/h, which is only about 1.4% higher than the impact velocity of the LS DYNA simulation.

It is noteworthy that, following the CRASH 3 calculation, the EES is greater than the specified impact velocity. It should be noted that the CRASH 3 calculations are primarily applicable in the event of collisions with a non-deformable wall. In cases where there is a low overlap, the deformation of the wall or collision between two cars may be incorrect.

3. Following the impact simulations and calculations, the CRASH 3 programme can be observed that the deformation depth depends on the width of the deformation, i.e., at 50% overlap, the maximum deformation depth is approximately 34% higher than at 100% overlap during the impact.

References

1. Road traffic injuries. https://www.who.int/news-room/fact-sheets/detail/road-traffic-injuries. Accessed 20 May 2022
2. Macurová, L., Kohut, P., Čopiak, M., Imrich, L., Rédl, M.: Determining the energy equivalent speed by using software based on the finite element method. Transp. Res. Procedia Procedia **44**, 219–225. LOGI 2019 – Horizons of Autonomous Mobility in Europe. Elsevier Ltd. (2020)
3. Evin, E., Tomáš, M.: Comparison of deformation properties of steel sheets for car body parts. Procedia Eng. **48**, 115–122. Elsevier Ltd. Selection and/or peer-review under responsibility of the Branch Office of Slovak Metallurgical Society at Faculty of Metallurgy and Faculty of Mechanical Engineering, Technical University of Košice (2012)
4. Fechová, E., Kmec, J., Vagaská, A., Kozak, D.: Material properties and safety of cars at crash tests. Int. Conf. Manufact. Eng. Mater. Proc. Eng. **149**, 263–268 (2016)
5. Volvo XC90 body structure. https://www.media.volvocars.com/global/en-gb/media/photos/148215/volvo-xc90-body-structure. Accessed 21 Apr 2022
6. Offset-Deformable Barrier-OBD. https://www.euroncap.com/en/vehicle-safety/the-ratings-explained/adult-occupant-protection/previous-tests/offset-deformable-barrier/. Accessed 21 Apr 2022
7. Nayak, R., Padhye, R., Kanesalingam, S., Arnold, L., Bahera, B.K.: Airbags, Textile Progress, pp. 209–301. Taylor & Francis(2013)
8. Vangi, D.: Vehicle Collision Dynamics: Analysis and Reconstruction. Elsevier Science (2020)
9. Griškevičius, P., Žiliukas, A.: The crash energy absorption of vehicles front structures. Transport XVIII(2), 97–101 (2003)
10. Witteman, W. J.: Improved vehicle crashworthiness design by control of the energy absorption for different collision situations. Technische Universiteit Eindhoven, Eindhoven (1999)
11. Burg, H., Moser, A.: Handbuch Verkehrsunfallrekonstruktion. Springer (2017)
12. Moravcová, P., Bucsuházy1, K., Bilík, M., Belák, M., Bradáč, A.: Let it crash! energy equivalent speed determination. In: VEHITS 2021 - 7th International Conference on Vehicle Technology and Intelligent Transport Systems, pp. 521–528. Science and Technology Publications, Lda (2021)
13. Toyota Yaris Finite Element Model Validation Coarse Mesh, https://www.ccsa.gmu.edu/wp-content/uploads/2016/11/2010-toyota-yaris-coarse-validation-v1.pdf. Accessed 22 Apr 2022
14. Toyota Yaris 2010. 2010 Toyota Yaris (iihs.org). Accessed 18 Apr 2022
15. Vangi, D.: Simplified method for evaluating energy loss in vehicle collisions. Accid. Analy. Prevent. **41**(3), 633–641 (2009)
16. AGU Zurich crash test database. Crashtest-Datenbank (agu.ch). Accessed 18 May 2022
17. Datentechnik, S.: PC Crash Version 12.0 Operating and Technical Manual. Linz (2018)

Finite Element Analysis of the Tank Semi-trailer‘s Frame on Road Irregularities and Liquid Sloshing Conditions

Tomas Smolskas and Romualdas Juknelevičius(✉)

Vilnius Gediminas Technical University, J. Basanavičiaus G. 28, 03224 Vilnius, Lithuania
romualdas.juknelevicius@vilniustech.lt

Abstract. The strict requirements in order to optimize the fuel consumption of vehicles thus reducing the emission of greenhouse gases, force manufacturers focus on structural optimization during the development of new type prototypes. The stresses and deformations of the main member of frame and tank which occur during operation under cyclic loads were researched. The review of scientific articles that examine the construction of truck semi-trailer frames and their research, the use of new materials in the automotive industry, and the phenomenon of liquid sloshing and researches done on this subject. The dual-phase 1.4162 (DUPLEX) steel was used for tank while the frame structure made of 1.4404 (316L) stainless steel, 1.4162 (DUPLEX) dual-phase steel, 6063-T6 aluminum alloy and S235JR black steel. The research methodology has been developed to assess the stresses, strains and critical points in the structure where is a high probability of cracking during operation. Results were gathered using ANSYS software and the most suitable material for the main member of frame was recommended.

Keywords: Tank semi-trailer · Frame · Road irregularities · Liquid sloshing · Finite element · Duplex steel · Von Mises stresses

1 Introduction

The requirement to reduce the mass of vehicles is getting stricter in order to reduce the fuel consumption of vehicles thus mitigate the emission of greenhouse gases. In order to meet this requirement, manufacturers focus on design optimization of prototypes. The main principle of such optimization is to reduce the number and mass of elements that make up the structure, while maintaining the stiffness and functionality.

The frame is one of the main parts of the semi-trailer, providing support for the other components of the unit. Frames usually have two functions: to provide support to the components of the semi-trailer, and to withstand the static and dynamic loads caused by loads, when moving through the unevenness of the road profile. In order to facilitate the suitable operation of the truck and semi-trailer, it is necessary to assess whether the selected frame construction is sufficiently rigid.

Few EU manufacturers of the tank semi-trailers faced with the problem of the cracks in the rear support of the main member of the frame. The chassis of the semi-trailer

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 309–326, 2023.
https://doi.org/10.1007/978-3-031-25863-3_29

during movement on road enters the pits and face various forces caused by acceleration, braking and curving. The whole structure of the tank semi-trailer needed to be studied in order to find the reasons of the cracks. The tank semi-trailer consists of these main components: tank, frame and chassis.

The object of this work is the main members of the frame (double beam) and the tank of liquid cargo semi-trailer.

The study intends to recommend the most suitable material to produce a reliable and light-weight main frame members of the tank semi-trailer. In order to achieve that aim, the critical locations at the supports where the highest stresses needs to be defined. Based on the obtained results, assess whether the chosen materials are suitable on road driven conditions and define the feasibility to decrease the mass of the frame in order to sustain the resistance to multi-cyclic loads.

2 Literature Overview

The tank semi-trailer is complex design unit and several researches has been done to determine the stresses and deformations with the aim to optimize the supports, structural units and the tank itself.

The study [1] examined the frame of a ladder-type truck made up of riveted parts. The main material used for the frame is high-strength, low-carbon steel - S600MC (DIN 1.8969). The SOLIDWORKS and ANSYS software packages were used for the numerical research, with the help of which the max. Stresses were defined in the middle of the frame structure with max. Value of 175 MPa. While ANSYS numerical study determined max. Stress of 186 MPa. The yield strength of this frame was 420 MPa, so it was concluded that the frame would be sufficiently rigid under static load.

The study [2] examined bus frame structures using ANSYS MECHANICAL 20.0 software. Bus frame was made of 6061-T6 and 7075-T6 aluminum alloys and low carbon steels. According to the results of the study, the max. Stresses in the frames of all materials did not exceed the strength limits of the materials, but comparing the maximum deformation values shows that aluminum frames deform significantly more than steel, so aluminum could be used to optimize vehicle weight.

A study [3] examines the frame of a dump truck model YJ3128 designed and manufactured by Inner Mongolia First Machinery Group Corporation and China North Mercedes-Benz Co. During the investigation, the construction of the truck frame was examined during operation and by the FEM using the ANSYS software package. Two critical locations were defined: at the end of the frame with max. Stress of 331 MPa, when wheel enters the pit and at the middle with max. Stress of 184 MPa. Although the value of the stresses does not exceed the strength limit of the material, cracks may occur during operation in these areas due to fatigue.

Two beam-type frames were investigated [4]: a U-shaped frame and a combined Z-shaped joint profile made of 7075 aluminum, stainless steel (SS304), DUPLEX 2101 (1.4162), and fiberglass with epoxy composite. Evaluating von Mises' stresses, stress energies and structural deformations, it can be stated that regardless of the shape of the profile, the most optimal results were obtained using DUPLEX 2101 steel and SS304 stainless steel.

The numerical study [5] was performed using the CATIA V5 and the ANSYS WORKBENCH software packages. In order to optimize the weight of the vehicle three frame materials were analyzed: low carbon steel and fiberglass with epoxy composite. The results showed that although the frames did not withstand the intended loads in the case of rotation, in order to optimize the weight of the vehicle, the frame can be made not only of steel but also fiberglass with epoxy composite.

The study [6] examined frames made of aluminum, steel, and carbon fiber to reduce the frame weight, and maintain the frame stiffness. ANSYS 15.0 WORKBENCH software was used to perform the numerical experiment. During the research, the frame was loaded with a distributed load of 10 kN and the front part of the frame with 6 kN. In order to design a rigid truck frame structure and optimize the mass, the frames can be made of steel or aluminum alloys. The stresses at the carbon fiber made frame also do not exceed the strength limit, but the construction deformations were severe.

During the study [7] on material optimization of the EICHER E2 TATA stiffening elements of various shapes, made of ASTM A710 and A302 steels and 6063-T6 aluminum alloy were examined. The frame FEM model was loaded with 100 kN over the upper surface of the frame. It was observed that the structure of the rectangular beam is stiffer in compare to other shaped beams. The results allow to conclude that all construction options are possible, but practical experiment needs to be performed.

The study [8] examined steel and aluminum frames consisting of a U-shaped profile beams of the SX360 truck using ABAQUS software. The study proposed to use aluminum alloys to reduce the mass of the structure. Similarly, concluded study [9] on an aluminum alloy heavy-duty frame. The final weight of the heavy-duty vehicle was reduced by 1,500 kg by using aluminum, while such optimization allowed to increase the amount of cargo and reduced fuel consumption by 3%.

At the article [10] was proposed to optimize not only the elements of the frame structure, but also the materials of the elements, to use lower density steels, in order not only to reduce the mass of the product, but also to maintain its rigidity. According to the authors, elements of the frame structure could be made from DUPLEX steel alloys, characterized by a lower density compared to austenitic and ferritic steel. Despite the fact that two-phase steels are characterized by twice the strength compared to austenitic steels [11], they are also superior at a lower price.

Research [12] analyzed the mechanical properties of single-phase austenitic steel alloy AISI 316L and several DUPLEX steel alloys. Results presented, that elasticity of DUPLEX steel alloys is almost 3 times higher than the austenitic steel alloy.

The study [13] on the material properties considered 3 steel alloys: two dual-phase and one austenitic steel. The tests revealed that strength properties of the material depend on the amount of ferrite structure in the alloy, because the measured strength of sample with the highest amount of ferrite was the highest.

The overview of the presented studies allows us to conclude that the behavior of austenitic stainless steel tank semi-trailers due to the loads caused by road irregularities and fluid sloshing is sufficiently well studied and known. However, the studies conducted on DUPLEX LDX 2101 (1.4162) have mainly focused on the mechanical properties of the material, and the stresses and deformations occurring in the main frame and its members are not sufficiently investigated. Even if these studies have been done, they

are not readily available. Therefore, there is a lack of knowledge about the stresses and deformations of a tank semi-trailer made of 1.4162 steel due to road irregularities and liquid sloshing.

Two-phase DUPLEX LDX 2101 (1.4162) is a steel with lower density, higher corrosion and higher strength limit (especially under cyclic loads) in compare to austenitic steel. Since the objectives of this study are to recommend a material for the production of light main frame elements of a tank semi-trailer, to reduce its mass and to solve the problem of cracks, using DUPLEX steel for the study of this work would fulfill the research objective, the results should interest researchers and manufacturers and expand the scientific knowledge in this field.

In order to study the frame of the semi-trailer with focus on main members and brackets, the tank material used to be DUPLEX steel while the frame structure would be made of various materials.

3 Methods and Materials of the Study

3.1 Calculation Model and Finite Element Mesh

Using SOLDIWORKS software, a simplified model of the tank truck suitable for calculations was drawn. The model consists of: 2.5 mm thick cylindrical tank bodies with an inner diameter of 2 m and conical partitions of the same thickness dividing the tanks into 3 parts of different volumes: 11,000 l/7,500 l/14,500 l. Torospheric covers are welded to the ends of the tank, the dimensions of which comply with the DIN 28011 standard [14]. In order to ensure the rigidity of the container, rigidity rings are used, rolled from u-shaped profiles with an edge thickness of 3 mm. The container is reinforced with a double-beam profile frame using 3 mm thick brackets. The geometry model used for calculations shown at the Fig. 1.

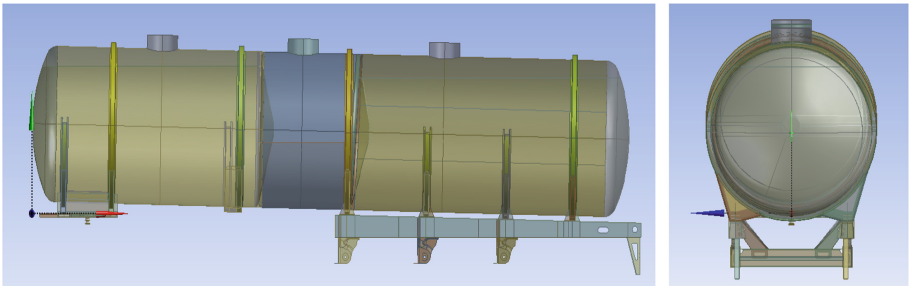


Fig. 1. Tank semi-trailer model used for calculations.

The simplified geometry model was saved in.step format and loaded into the ANSYS software package for calculations. The model consists of 175 elements and 185 parts [15, 16]. In order to be able to perform the finite element analysis, the model was divided into a finite element mesh shown at the Fig. 2.

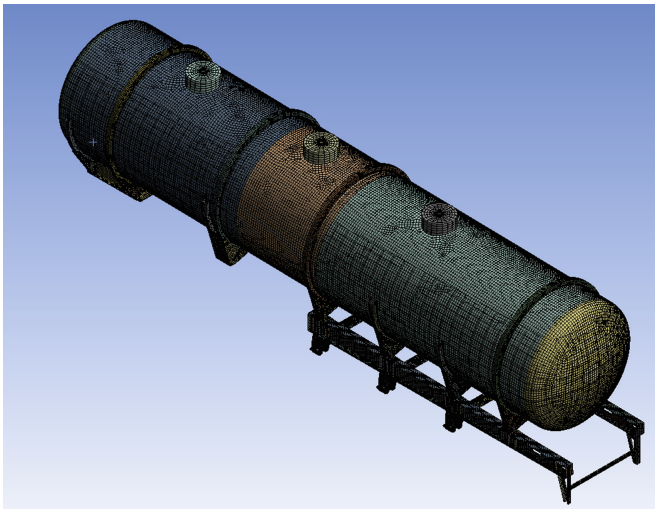


Fig. 2. Tank finite element mesh.

The finite element mesh consists of 378,525 nodes and 201,141 elements [17]. In order to optimize the calculations as much as possible, the size of the finite elements of the body cylinders and ends is 40 mm; stiffness rings - 25 mm; brackets - 30 mm; frame beams and stiffness plates 20 mm, and the volume of liquid cargo is divided into 100 mm finite elements.

3.2 Loads Caused by Vertical Displacement of Axis

The ultimate loads acting on the structure of a tanker semi-trailer can arise when the structure overcomes a step-shaped road pit. The ultimate loads acting on the structure of a tanker semi-trailer can arise when the structure overcomes a step-shaped road pit. The influence of road irregularities (amplitude and frequency) are damped by the suspension elements. However the calculation model and FEM includes only the structural elements of the frame and tanks, but the suspension elements were not included. In order to evaluate the loads and vertical displacements, stresses and deformations occurring in the main frame and its members, one axis was rigidly fixed, while other axis can move vertically. The results obtained in this way show the maximum amplitude of movement of the unrestrained axis, which is possible due to such a frame construction and the stress in the frame and members. This situation was simulated in 3 modes:

1. The tank semi-trailer enters a pit at the coupling device. In other words the truck rear axle enters the pit, and an unrestrained vertical displacement is created at the coupling device.
2. The tank semi-trailer’s front axis enters a pit, an unrestrained vertical displacement is created at the front axle of the semi-trailer.
3. The tank semi-trailer’s rear axis enters a pit, an unrestrained vertical displacement is created at the rear axle of the semi-trailer [18].

The boundary conditions used in simulation presented at the Fig. 3.

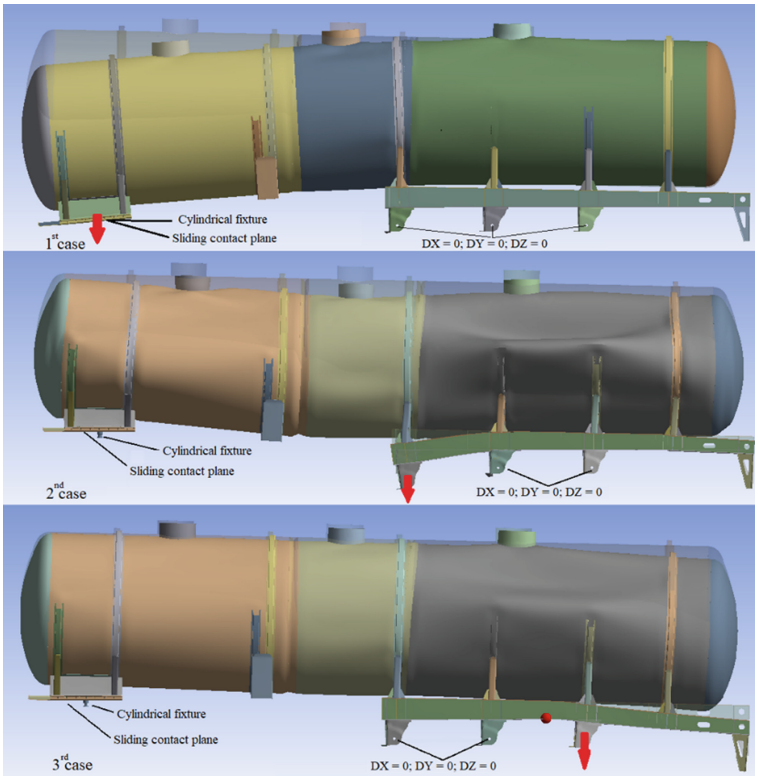


Fig. 3. Boundary conditions of the tank semi-trailer.

At the all three cases considered that tank semi-tanker are filled with a liquid with a density of 997 kg/m^3.

Stresses and deformations occurring in the main frame member and in all elements of the tank semi-trailer were calculated with the four materials presented at the subchapter 3.4 using the ANSYS WORKBENCH software.

3.3 Loads Caused by the Sloshing of Liquid Cargo

When the vehicle brakes, due to inertia, the liquid cargo in its tanks moves forward, and thus pressure is created on the walls of the tanks. Due to the pressure created by the fluid flow, the structure is deformed and this deformation continues until the liquid returns to the equilibrium position [19, 20, and 21]. The analysis of the effect of fluid flow on the tank semi-trailer was performed using the *fluent* and *transient structural* sub-programs.

One of the boundary conditions is braking, which causes the liquid cargo to surge. Assuming that a tank semi-trailer moves at 90 km/h (25 m/s), the total mass of the vehicle with liquid cargo is 32,500 kg and performs moderate braking with truck & semi-trailer

wheels friction coefficient of 0.6 on dry asphalt, the calculated braking acceleration – 5.88 m/s^2. However in order to study the extreme braking situation, a braking acceleration of 10 m/s^2 used for the calculations.

The fluid flow during braking was analyzed using the *Fluid flow* analysis method in the ANSYS software package. Computational model tanks are fulfilled at the following levels: 80%/40%/80%.

3.4 Tank and Frame Materials

All the elements that make up the semi-trailer tank model (body cylinders, cones, stiffness rings and brackets) are chosen to be manufactured from DUPLEX 1.4162 two-phase steel. The tank and a frame consisting of a main member of the frame (double beam) and stiffness plates was examined. The model of the tank and frame construction shown at the Fig. 4.

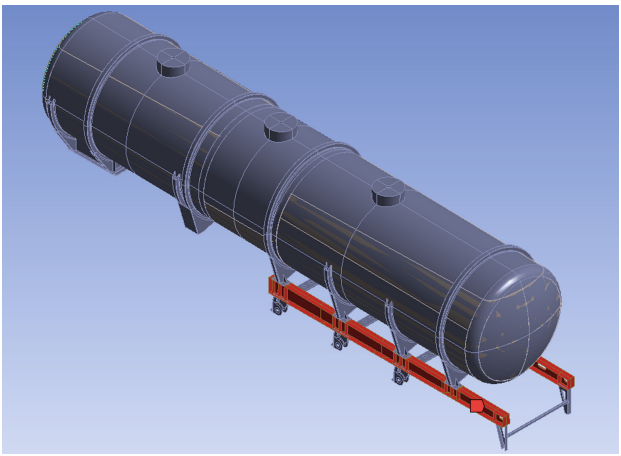


Fig. 4. Main frame members (marked in red) whose material has been changed.

During the study, four variants of the main frame members of the same design, made of 1.4404 (316L) stainless steel, 1.4162 (LDX 2101) dual-phase steel, 6063-T6 aluminum alloy and S235JR black steel [22–24], were examined. The material was changed only for the construction elements, which are shown in Fig. 4 marked in red. The mechanical properties of these materials are shown in Table 1.

According to the calculations of the SOLIDWORKS program, which was used to create the geometry of the calculated model, the structure of the austenitic steel frame and its stiffness elements weighs 560 kg. The frame of the same construction made of two-phase DUPLEX steel weighs 539 kg, aluminum alloy - 189 kg, and black steel - 546 kg.

Table 1. Mechanical properties of frame materials [25].

Material	Density, kg/m3	Young's modulus, GPa	Tensile strength, MPa	Poisson's ratio	Fatigue limit, MPa
S235JR	7,800	210	360	0.3	140
6063-T6	2,700	68	240	0.33	70
1.4404	8,000	200	530	0.3	260
1.4162	7,700	195	780	0.3	410

4 Results and Discussion

4.1 Stresses and Deformations Caused by Road Unevenness

The Tank Semi-Trailer Enters a Pit at the Coupling Device. The minimum and maximum values of von Mises stresses, which occur in the structure of the main frame members and its stiffness elements made of different materials, were calculated (Fig. 5).

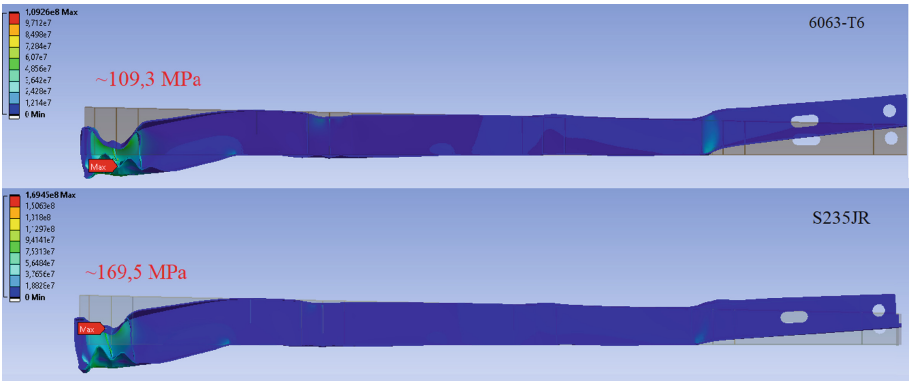


Fig. 5. Stresses at the main frame members when tank semi-trailer enters a pit at the coupling device.

The highest stresses were determined in the frame construction made of black steel (S235JR) - 169.5 MPa, and the lowest - in the frame construction made of aluminum alloy (6063-T6) - 109.3 MPa. The stress and deformation at the frame and tank produced of various materials used in the study presented at the Table 2.

The largest deformations occurred at the front axle of the semi-trailer-tank, almost at the same place where the highest stress values are concentrated. The maximum deformation was determined in the aluminum frame - 0.409 mm, and the lowest maximum deformation was determined in the black steel (S235JR) frame construction - 0.245 mm.

The stress values of the tank, when frame made of various materials, are shown at the Fig. 6.

Table 2. Von Mises stress and deformation at the main frame member and tank semi-trailer when tank semi-trailer enters a pit at the coupling device

Material	Max. Von Mises stress, MPa		Max. Deformation, mm	
	Main member of frame	Tank semi-trailer	Main member of frame	Tank semi-trailer
S235JR	169.5	182.6	0.245	6.26
6063-T6	109.3	203.3	0.409	6.74
1.4404	161.1	184.9	0.250	6.22
1.4162	164.5	183.6	0.252	6.28

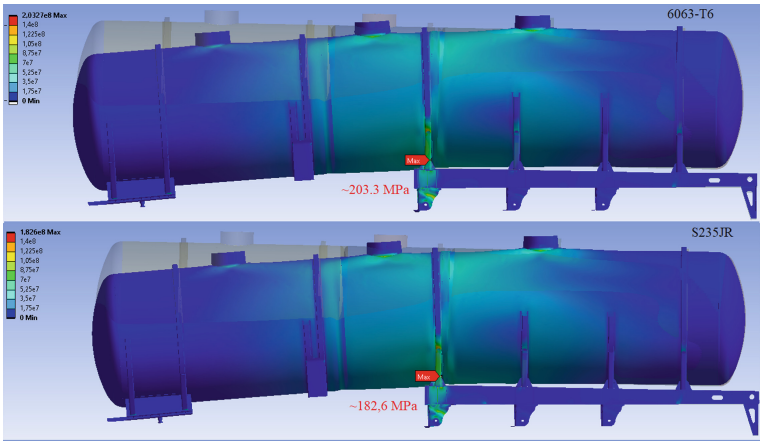


Fig. 6. Stresses at the tank when tank semi-trailer enters a pit at the coupling device.

In all cases, regardless of the material of the frame structure, the highest stresses are found in the brackets located above the front axle of the semi-trailer while the maximum deformations are determined at the end of the first tank.

The Tank Semi-TRAiler’s Front Axis Enters a Pit. Determined the minimum and maximum values of von Mises stresses and deformations that occur in the structure of the tank and frame made of different materials. The results are presented at the Table 3.

Table 3. Von Mises stress and deformation at the main frame member and tank semi-trailer when tank semi-trailer’s front axis enters a pit

Material	Max. Von Mises stress, MPa		Max. Deformation, mm	
	Main member of frame	Tank semi-trailer	Main member of frame	Tank semi-trailer
S235JR	52.0	84.4	0.564	1.41
6063-T6	38.6	86.7	0.605	1.49
1.4404	51.3	84.8	0.547	1.39
1.4162	50.9	84.7	0.551	1.41

As in the first mode, the highest stresses occurred in the frame structure made of black steel (S235JR) - 52.0 MPa, and the lowest - in the frame structure made of aluminum alloy (6063-T6) - 38.6 MPa (Fig. 7). Slightly higher stresses were determined in the two-phase (1.4162) and austenitic (1.4404) steel structures: 50.9 MPa and 51.3 MPa respectively. The critical structural point where the highest stress values coincide for austenitic, dual-phase and black steels is over the front axle of the semi-tanker, but when the frame is made of aluminum alloy, the critical structural point is over the rear axle.

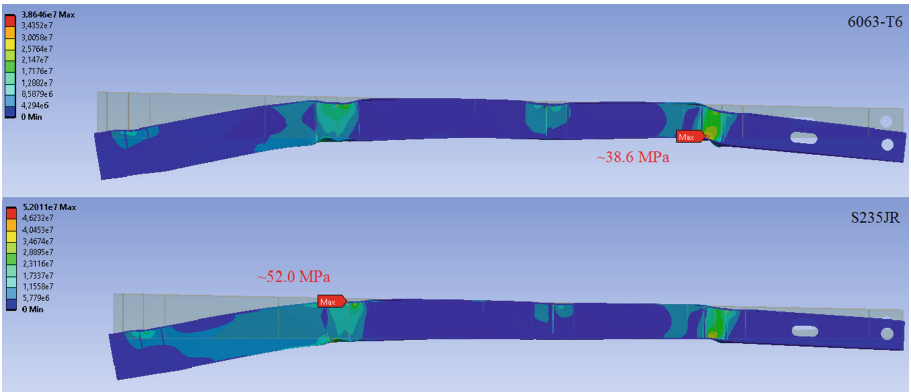


Fig. 7. Stresses at the frame elements when tank semi-trailer's front axis enters a pit.

Both in the first mode and in this one, the maximum deformations occurred in the frame and element structure made of aluminum alloy (6063-T6) - 0.605 mm, and the smallest maximum deformation was determined in the frame structure made of black steel (S235JR) - 0.546 mm. Slightly larger deformations were found in the structures of austenitic (1.4404) and dual-phase (1.4162) steel: 0.547 mm and 0.551 mm respectively. In all cases, regardless of the material of the frame structures, the maximum deformation values were obtained at the ends of the frames. The maximum and minimum values of the stresses of the tank, when the frame made of various materials, shown at the Fig. 8.

The highest values of von Mises stresses were determined when the aluminum alloy (6063-T6) frame was used –86.7 MPa, the lowest values of the maximum stresses were determined when black steel (S235JR) was used for the frame construction - 84.4 MPa. In all cases, regardless of the material of the frame and tank, the maximum stresses are determined in the brackets located above the front axle of the semi-trailer, in the place where the bracket is connected together with the tank stiffness ring.

The highest deformation values of the tank were determined when the frame made of aluminum alloy was used (1.49 mm), the lowest - when the austenitic steel frame was used (1.39 mm). In all cases, regardless of what material the frame structure is made of, the largest deformations are found in the cylinder of the third tank.

The Tank Semi-TRAiler's Rear Axis Enters a Pit. Determined the minimum and maximum values of von Mises stresses and deformation that occur in the structure of the tank and frame made of different materials. The results are presented at the Table 4.

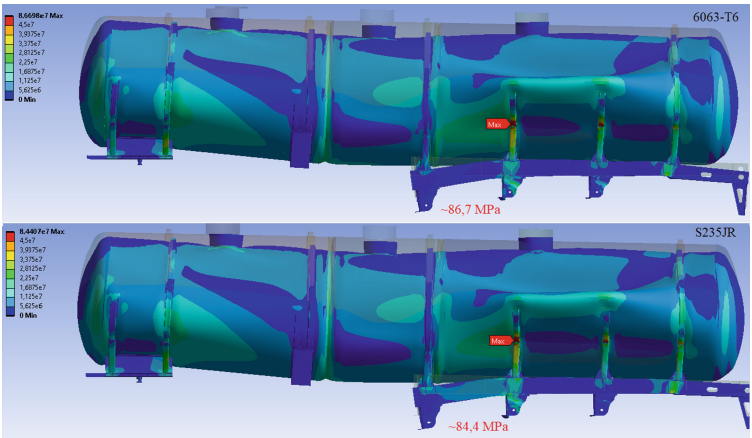


Fig. 8. Stresses of the tank when tank semi-trailer’s front axis enters a pit.

As in the first and second modes, the highest stresses occurred in the frame structure made of black steel (S235JR) - 96 MPa, and the lowest - in the frame structure made of aluminum alloy (6063-T6) - 67.6 MPa. The same trend as before was noticed with slightly higher stresses with two-phase (1.4162) and austenitic (1.4404) steel structures: 94.0 MPa and 94.4 MPa respectively. The critical point of the structure, where the stress values are the highest, regardless of the material of the frame structure, is above the rear axle of the tank semi-trailer. In the same case, when the rear axle of the semi-trailer enters the pit, the deformations occurring in the main member of the frame shown at the Fig. 9.

Table 4. Von Mises stress and deformation at the main member of frame and tank – frame when tank semi-trailer’s rear axis enters a pit

Material	Max. Von Mises stress, MPa		Max. Deformation, mm	
	Main member of frame	Tank semi-trailer	Main member of frame	Tank semi-trailer
S235JR	96.0	96.0	1.055	1.50
6063-T6	67.6	75.4	1.223	1.68
1.4404	94.4	94.4	1.057	1.51
1.4162	94.0	94.0	1.069	1.52

The largest deformations occurred in the structure of the main member of the frame made of aluminum alloy - 1.22 mm, and the smallest maximum deformation was determined in the structure of the frame made of black steel - 1.055 mm. Slightly larger deformations were found in the structures of austenitic (1.4404) - 1.057 mm and dual-phase (1.4162) steel - 1.069 mm. In all cases, regardless of the material of the frame structures, the maximum deformation values were obtained at the ends of the frames.

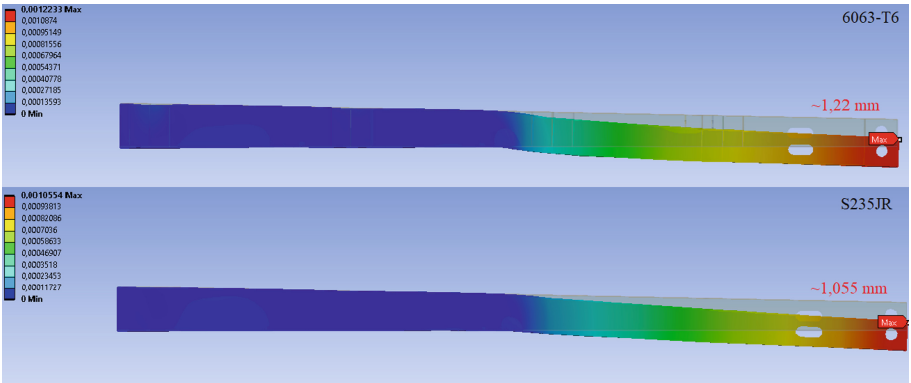


Fig. 9. Stresses at the main member of the frame when tank semi-trailer's rear axis enters a pit.

The maximum and minimum values of the stresses in the tank structure, when the rear axle enters the pit and the frames are made of various materials, shown in Fig. 10.

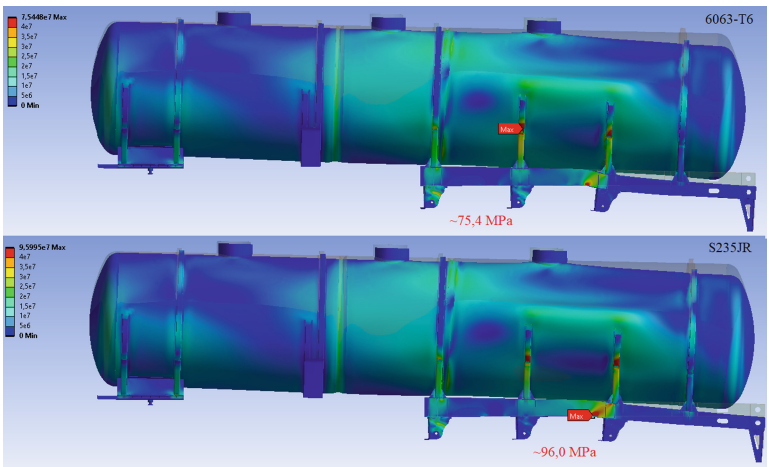


Fig. 10. Stresses of the tank when tank semi-trailer's rear axis enters a pit.

The lowest von Mises stress values were determined when the aluminum alloy (6063-T6) frame was used - 75.4 MPa. The highest stress values were determined when black steel (S235JR) was used for the frame construction –96.0 MPa. In all cases, except when the frame is made of aluminum alloy, the maximum stresses are determined in the frames above the rear axle of the semi-trailer. In the case of an aluminum alloy frame, the highest stresses are generated by the bracket located above the middle axle of the semi-trailer.

The highest deformation values were determined when using the frame made of aluminum alloy - 1.68 mm, the lowest - when using the black steel frame 1.50 mm. In all cases, regardless of the material of the frame structure, the maximum deformations were determined in the cylinder of the third tank.

The highest stresses in the frame occurred when the tank semi-trailer entered the pit at the coupling device. The highest stresses are determined using the black steel frame and reach 169.5 MPa. Slightly lower stresses are generated when two-phase DUPLEX and austenitic steels were used, with maximum stress values of 164.6 MPa and 161.1 MPa respectively. The lowest maximum stresses occur in the aluminum alloy frame - 109.3 MPa.

According to the results, all the four materials could be used for the frame, since the maximum values of the resulting stresses do not exceed the strength limit, but the fatigue limit must be taken into account in order to evaluate the optimal frame material. The maximum stresses developed in the aluminum frame exceed the fatigue limit of the alloy used, which would result in fatigue cracking and loss of stiffness during service. The optimal frame material to avoid fatigue cracks is dual-phase steel. Although in this frame, the values of the resulting stresses are not the lowest compared to the frames of other materials, but dual-phase steel is characterized by the highest fatigue resistance.

It can also be seen from the obtained results that the frames were deformed the most when the rear axle of the tank semi-trailer enters the road pit. The highest deformation value was determined in the aluminum alloy frame - 1.223 mm, slightly less deformed frames made of two-phase and austenitic steel - 1.069 mm and 1.057 mm. The black steel frame was the least deformed, with a maximum deformation of 1.055 mm.

4.2 Stresses and Deformations Caused by the Sloshing of Liquid Cargo

The stresses and deformations in the structural elements caused by the floating of the liquid cargo are studied by giving the semi-trailer-tanker braking acceleration. Due to the fact that the modeled reservoirs are not completely filled (80%/40%/80%), the liquid load due to inertia moves in a direction opposite to the direction of the braking force and interacts with the structural elements. This dynamic interaction between the fluid

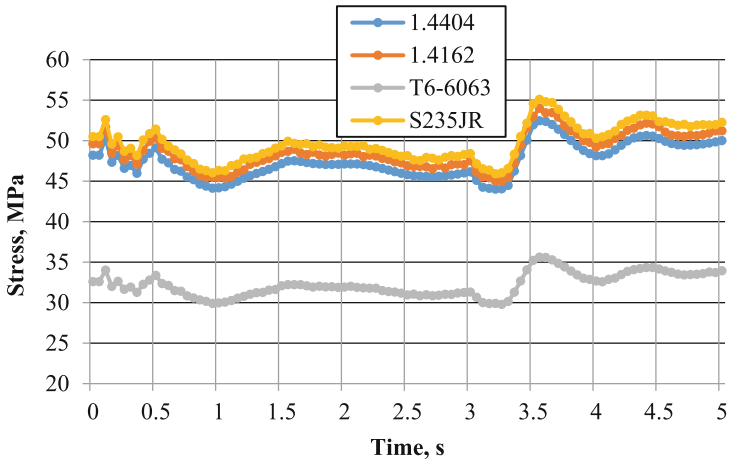


Fig. 11. Stress of the main member of frame at the braking.

flow and the structural elements continues until the fluid flow returns to equilibrium and the structure is subjected to only static pressure. The values of the maximum stresses generated in the pressure frames due to the undulation of the liquid cargo are shown in Fig. 11.

As can be seen from the presented results, the highest stresses occurred in the frames of all materials after 3.55 s from the start. The highest stresses occurred in the frame made of black steel - 55.1 MPa. Lower maximum stress values were obtained in two-phase and austenitic steel frame constructions and reach 54.0 MPa and 52.4 MPa. The lowest stresses occurred in the frame, which is made of aluminum alloy - 35.6 MPa. The highest concentration of stresses in the frame structures occurs at the part located above the front axle of the semi-trailer-tanker, regardless of the material the frames are made of.

Due to the pressure caused by the surge of the liquid cargo, the maximum deformations occurring in the frames are shown in Fig. 12.

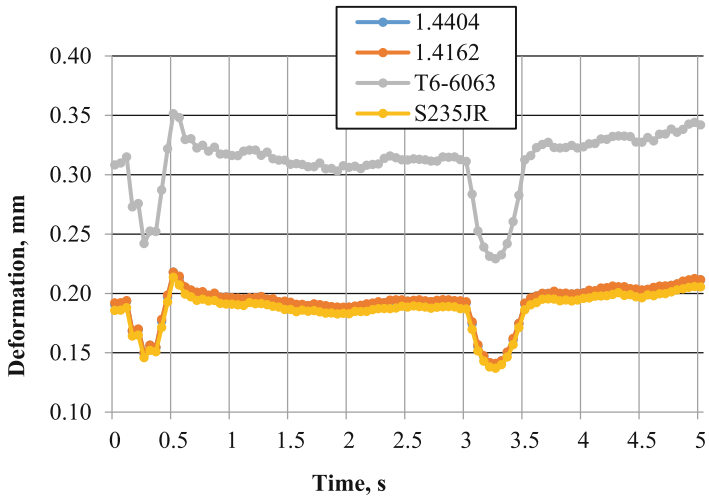


Fig. 12. Deformation of the main member of frame at the braking.

As can be seen from the presented results, the maximum deformations in the frames occur at the start of braking, 0.5 s after the start of the simulation. The main member of the frame made of aluminum deforms the most - 0.351 mm. Lower maximum deformation values were obtained in the austenitic and two-phase steel frame constructions and reach 0.218 mm and 0.217 mm. The smallest maximum deformations occurred in the frame, which is made of black steel −0.213 mm. The largest deformation in frame structures occurs at the free end of the frame, which is the furthest from the semi-trailer-tank, regardless of the material the frames are made of.

Due to the pressure caused by the surge of the liquid cargo, the maximum stresses generated in the structure of the tank are shown in Fig. 13.

The highest stresses in the tank structure occur half a second after the start of the simulation, at the time when the model is given braking acceleration. The highest stress

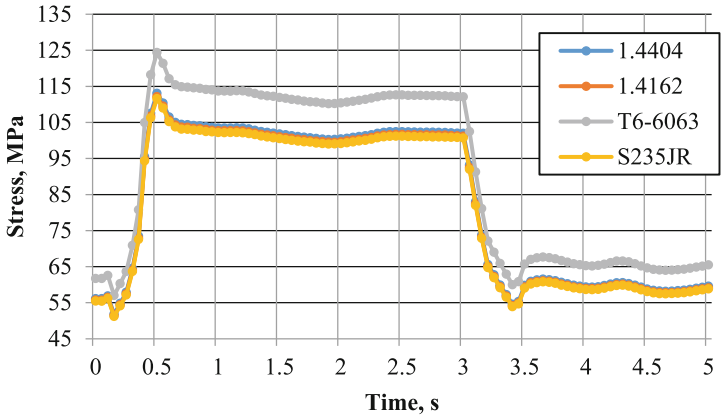


Fig. 13. Max. Stresses of the tank of semi-trailer at the braking.

values occur when an aluminum alloy frame is used and reach 124 MPa. Slightly lower stresses occur when using frames made of austenitic and dual-phase steel, their numerical values: 113 MPa and 112 MPa. The lowest maximum stresses occur when the structural elements of the semi-trailer-tank frame are made of black steel - 111 MPa. The critical point of the structure where the generated stresses are the highest are the brackets located above the front axle of the semi-trailer, but in none of the investigated cases, the obtained numerical values of the stresses do not exceed the strength limit of the materials.

During braking, the maximum values of the deformations occurring in the structure of the tank of semi-trailer are shown in Fig. 14.

From the obtained results, it can be seen that the deformation values when the frame is made of austenitic, dual-phase and black steel almost coincide, only the deformation of the tank when the frame is made of aluminum alloy stand out. Like the maximum stresses, the maximum deformation also occur at the braking acceleration of 0.5 s after the start simulation. The structure of the tank of semi-trailer is most deformed when

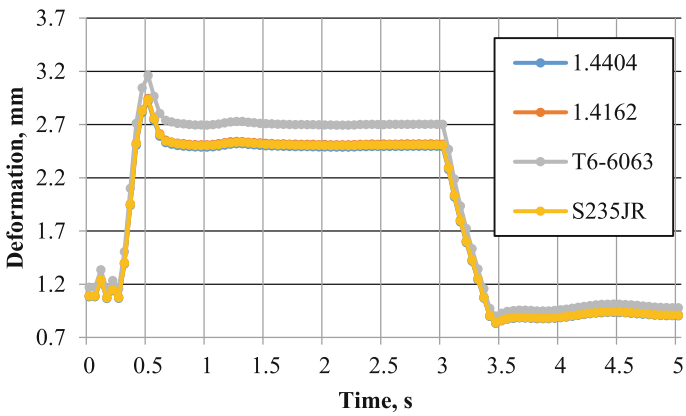


Fig. 14. Deformation of the tank semi-trailer at the braking.

the aluminum alloy frame is used, the maximum numerical value of the determined deformation –3.16 mm. Smaller deformations were determined using dual-phase and black steel frames, resulting in deformation of 2.94 mm and 2.93 mm respectively. The smallest maximum deformations of the tank occurs when an austenitic steel frame is used and equal to 2.92 mm. The critical area of the tank structure that deforms the most is the container's rigid ring located above the front axle of the tank semi-trailer.

As in the study of the influence of the unevenness of the road profile, in the analysis of the fluid sloshing during braking, it was found that the highest stresses in the frames occur when the black steel frame structure is used, and the lowest when the aluminum alloy frame is used. The maximum deformations occur in the opposite way - the largest when aluminum alloy is used, and the smallest when black steel is used. The determined maximum stress values do not exceed the strength limit of the materials in any case, so the frames of all materials are suitable for use.

5 Conclusions

1. The highest stresses in the construction consisting of the frame and the tank occurred when tank semi-trailer enters the pit at the coupling device (1st case).
2. The highest stresses are determined with the S235JR steel frame and reach 169.5 MPa. The lowest maximum stresses occur with the 6063-T6 aluminum frame −109.3 MPa. The highest stresses (of all 3 cases) were obtained in the front part of the main member of the frame.
3. The main member of the frame were deformed the most when the rear axle of the semi-trailer enters the road pit (3rd case).
4. The maximum deformation was determined with the 6063-T6 aluminum frame − 1.223 mm. The lowest deformed was the S235J steel frame, with a maximum deformation of 1.055 mm. The rear part of the main member of frame was the most deformed. However, tank of the semi-trailer was most deformed when the semi-trailer enters the pit at the coupling device (1st case).
5. All four researched materials: austenitic steel AISI 316L (1.4404), two-phase DUPLEX steel (1.4162), aluminum alloy (6063-T6) and black steel (S235JR) are capable to withstand the simulation loads.
6. Design of main members and frame can be optimized with the aim to decrease the whole mass of semi-trailer, however fatigue resistance must be considered.
7. Considering the simulation results obtained during the simulation, the cracks in the frame structure occurs due to fatigue, so the optimal material for the main member of the frame is two-phase DUPLEX steel, with the highest fatigue resistance.

References

1. Savkin, A.N., Gorobtsov, A.S., Badikov, K. A.: Estimation of truck frame fatigue life under service loading. In: International Conference on Industrial Engineering, pp. 318–323. Elsevier (2016)

2. Nandhakumar, S., Seenivasan, S., Saalih, A.M., Saifudheen, M.: Weight optimization and structural analysis of an electric bus chassis frame. Mater. Today Proc. **37**(2), 1824–1827 (2021). https://doi.org/10.1016/j.matpr.2020.07.404
3. Yanhong, C., Feng, Z.: The finite element analysis and the optimization design of the YJ3128-type dump truck's sub-frames based on ANSYS. Procedia Earth Planet. Sci. **2**, 133–138 (2011). https://doi.org/10.1016/j.proeps.2011.09.022
4. Ramesh Kannan, C., Stalin, B., Ravichandran, M., Sathiya Moorthi, K.: Performance analysis of SS304 steel hat stringer on the chassis frame. In: Hiremath, S.S., Shanmugam, N.S., Bapu, B.R.R. (eds.) Advances in Manufacturing Technology. LNME, pp. 289–296. Springer, Singapore (2019). https://doi.org/10.1007/978-981-13-6374-0_34
5. Siraj, A., Babu, N.R., Reddy, K.S.: Static analysis of dump truck chassis frame made of composite materials. Int. J. Eng. Sci. Technol. **11**(2), 21–32 (2019). https://doi.org/10.4314/ijest.v11i2.2
6. Kiran, L., Kakkeri, S., Deshpande, S.: Proposal of hybrid composite material for light commercial vehicle chassis. Mater. Today Proc. **5**(11), 24258–24267 (2018). https://doi.org/10.1016/j.matpr.2018.10.221
7. Kumar, H.A., Deepanjali, V.: Design and analysis of automobile chassis. Int. J. Eng. Sci. Innov. Technol. **5**(1), 187–195 (2016)
8. Ren, Y., Yu, Y., Zhao, B., Fan, C., Li, H.: Finite element analysis and optimal design for the frame of SX360 dump trucks. Procedia Eng. **174**(1), 638–647 (2017). https://doi.org/10.1016/j.proeng.2017.01.201
9. Karita, K., Kohiyama, Y., Kobiki, T., Ooshima, K., Hashimoto, M.: Development of aluminum frame for heavy-duty trucks. Tech. Rev. Japan **15**(1), 81–84 (2003)
10. Rana, R., Liu, C., Ray, R.K.: Evolution of microstructure and mechanical properties during thermomechanical processing of a low-density multiphase steel for automotive application. Acta Mater. **75**(1), 227–245 (2014). https://doi.org/10.1016/j.actamat.2014.04.031
11. Lagnebor, R.: New steels and steel applications for vehicles. Mater. Des. **12**(1), 3–14 (1991). https://doi.org/10.1016/0261-3069(91)90086-J
12. Chail, G., Kang, P.: Super and hyper duplex stainless steels: structures, properties and applications. Procedia Struct. Integrity **2**(1), 1755–1762 (2016)
13. Toor, I., Hyun, P.J., Kwon, H.S.: Development of high Mn–N duplex stainless steel for automobile structural components. Corros. Sci. **50**(2), 404–410 (2008)
14. DIN 28011 Torosperical dished ends (1993)
15. Biglarbegian, M., Zu, J.W.: Tractor–semitrailer model for vehicles carrying liquids. Veh. Syst. Dyn. **44**(11), 871–885 (2007). https://doi.org/10.1080/00423110600737072
16. Rumold, W.: Modeling and simulation of vehicles carrying liquid cargo. Multibody Sys. Dyn. **5**(1), 351–374 (2001). https://doi.org/10.1023/A:1011425305261
17. Nicolsen, B., Wang, L., Shabana, A.: Nonlinear finite element analysis of liquid sloshing in complex vehicle motion scenarios. J. Sound Vib. **405**(10), 208–233 (2017). https://doi.org/10.1016/j.jsv.2017.05.021
18. Ranganathan, R., Rakheja, S., Sankar, S.: Kineto-static roll plane analysis of articulated tank vehicles with arbitrary tank geometry. Int. J. Veh. Des. **10**(1), 89–111 (1989). https://doi.org/10.1504/IJVD.1989.061565
19. Sankar, S., Ranganathan, R., Rakheja, S.: Impact of dynamic fluid slosh loads on the directional response of tank vehicles. Int. J. Veh. Mech. Mob. **21**(1), 385–404 (1992). https://doi.org/10.1080/00423119208969017
20. Abramson, N.H.: Dynamic behaviour of liquids in moving containers. Natl. Aeronaut. Space Adm. (1966)
21. Ranganathan, R., Yang, Y.S.: Impact of liquid load shift on the braking characteristics of partially filled tank vehicles. Int. J. Veh. Mech. Mobil. **26**(3), 223–240 (1996). https://doi.org/10.1080/00423119608969310

22. Cole, G.S., Sherman, A.M.: Light weight materials for automotive applications. Mater. Charact. **35**(1), 3–9 (1995). https://doi.org/10.1016/1044-5803(95)00063-1
23. Komatsu, Y., Arai, T., Abe, H., Sato, M., Nakazawa, Y.: Application of aluminum for automobile chassis parts [pranešimas konferencijoje]. In: International Congress & Exposition Conference, Detroit, Michigan, USA (1991). https://doi.org/10.4271/910554
24. Shin, J., Kim, T., Kim, D., Kim, D.K., Kim, K.: Castability and mechanical properties of new 7xxx aluminum alloys for automotive chassis/body applications. J. Alloy. Compd. **698**(1), 577–890 (2017). https://doi.org/10.1016/j.jallcom.2016.12.269
25. Makeitfrom Material properties database. https://www.makeitfrom.com/. Accessed 21 Mar 2022

Methodology for Calculating the Load of Petroleum Products Emissions on the Soils of the Roadside Space Created by the Operation of Highways

Oksana Melnikova[1](✉), Valentina Iurchenko[1], and Mykola Mykhalevych[2]

[1] Kharkiv National University of Civil Engineering and Architecture, 40, Sumskaya Street, Kharkiv, Ukraine
mikhoksana82@gmail.com

[2] Kharkiv National Automobile and Highway University, 25, Petrovskoho Str., Kharkiv, Ukraine

Abstract. The development of the road and transport network is an extremely powerful source of various environmental hazards for natural environments and people in particular. The paper considers the problem of determining the load of petroleum products (PP) on the roadside space soil, which is created by the operation of the road. This indicator is necessary for the search and design of highways taking into account environmental consequences, namely, determination of their maximum carrying capacity, monitoring of urban areas, ecological studies of technologically loaded roadside areas and formalization of the results of these studies in mathematical models, etc. The calculation method was developed on the basis of laboratory and field research data. The procedure for determining the real load of PP on the roadside space involves taking two soil samples in the roadside area to determine the current concentration of PP in one sample and establishing the self-cleaning characteristics of this type of soil during the incubation of the second sample in an ecologically clean zone free from the technogenic influence of the highway. The obtained experimental data are used to calculate the real load on the soil of the roadside space of the PP, which is created by the operation of the highway, with the help of which a balance equation was developed.

Keywords: Road · Man-made load · Emissions of petroleum products · Roadside soil · Self-cleaning · Calculation method

1 Introduction

Soil ecosystems are the most vulnerable environment exposed to the influence of the road and transport network. The soil is the main accumulator, sorbent and destroyer of pollutants. It protects adjacent environments from the influence of technical objects. But the soil, unfortunately, is an exhaustible resource, and its quality directly affects the quality of food consumed by humans. That is why the issue of ecological safety of soils is a primary issue for the population of urbanized areas [1].

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 327–335, 2023.
https://doi.org/10.1007/978-3-031-25863-3_30

By the multiple of exceeding the maximum permissible concentration (MPC), the greatest ecological danger for roadside soils is created by petroleum products (PP) pollution [2–4]. Moreover, especially high concentrations of PP are reached in the soils of roadside areas of country roads. PP disrupts not only the ecological balance in the soil environment, but also change the morphological, physical and chemical properties, and water-physical characteristics of soil horizons, thereby disrupting the ratio of some organic substances and thus reducing land productivity [5–7].

The concentration of PP in the soil, which is under man-made load from highways, is the resulting sum of 2 processes: the arrival of PP and self-cleaning of the soil. The entry of PP from the highway into roadside soils occurs in two ways: gas-air (mainly emissions of exhaust gases and dust dispersion) and water - with washes from the road surface [2, 8, 9]. Soil pollution in the first way covers a much larger area of roadside space. Based on the analysis of scientific and technical materials, it is possible to distinguish the following mechanisms of the entry of PP into the soils of the roadside space by gas-air route: absorption of gaseous compounds by the soil; condensation of aerosols; atmospheric precipitation with adsorbed PP dispersed in atmospheric air; dust deposition of solid PP particles blown by the wind from the road surface; the fall of plant biomass that absorbed PP [2, 10].

Three ecological factors interact with PP soil pollution and its self-cleaning [11]: polycomponent composition of PP; heterogeneity of the composition and structure of the soil ecosystem; diversity and variability of external factors (temperature, humidity, state of the atmosphere, etc.) [12–14]. The following [4] general stages of PP destruction can be distinguished, which can proceed either sequentially or simultaneously:

- physical-chemical and partially microbiological destruction of aliphatic explosives;
- microbiological destruction of low-molecular structures of various classes, new formation of resinous substances;
- transformation of high-molecular compounds - resins, asphaltenes, polycyclic UVs.

There are three possible ways of splitting n-alkanes (a common component of PP) [12, 15, 16]: monoterminal oxidation of the methyl group with the formation of alcohol, aldehyde, and monocarboxylic acids; monoterminal oxidation with the formation of the corresponding methyl ketone through a secondary alcohol; diterminal oxidation with the formation of fatty dicarboxylic acids. On the basis of experimental data, the authors [2, 17, 18] established the general features of the hydrocarbon destruction process and its use of the energy of enhanced oxidation of soil organic substances, primarily carbohydrates. End products of PP metabolism in the soil [17, 19]: alcohols, acids, aldehydes, ketones, which are partially included in the soil humus, partially dissolved in water and removed from the soil profile; solid insoluble products of metabolism (products of compaction of high molecular weight products or their binding to organo-mineral complexes); hard crusts of highly mineral PP on the soil surface [4]. At the stage of primary contamination, PP move deep into the soil mechanically as a separate phase, and then further spread by their transfer in the aqueous phase.

Thus, the concentration of PP in soils, which is determined by chemical analysis, is the resulting value of two simultaneous processes occurring in roadside soils: pollution and self-cleaning. It is somewhat lower than the true load of PP on soils. For ecological

studies, formalization of their results in mathematical models, search and design of highways, the characteristics of the true load on the roadside territories created by the flow of PP from this technical object are necessary.

The purpose of the research is to identify the real load on the soils of the roadside space due to the pollution of PP, which is created by the operation of highways, based on the determination of the content of the concentration of PP in the soils of the roadside territories.

2 Objects and Research Methods

The object of the study was the soil of the roadside space belonging to the man-made object - Highway R-46 of the Kharkiv region (Ukraine). Soil samples were taken by the envelope method at a depth of 1–5 cm. Determination of PP content in soil samples was carried out gravimetrically according to the method recommended by the regulatory documents of Ukraine [20].

Research on soil self-cleaning processes was carried out in field and laboratory conditions. When conducting a study of self-cleaning processes of soils from PP in field conditions, soil samples (1 kg) were transferred to a zone free from man-made influence without destroying the structure of the soil lump. At the same time, the climatic conditions were identical to the section that remained under the man-made load of the road. After certain intervals of time, soil samples were taken and examined for residual PP content.

The laboratory experiment was conducted in isolated conditions on “clean” soils. A fixed amount of PP was artificially added to the “pure” soils and incubated in laboratory conditions, excluding the introduction of any other pollutants, periodically determining the concentration of PP in them.

The calculation and experimental method was used to determine the real load of PP on roadside soils. The formulas of the calculation part of the method were formed using the apparatus of analytical geometry.

3 Results and Discussion

The dynamics of soil self-cleaning from PP, determined by the results of laboratory and field experiments, is presented in Fig. 1. The relative content of PP in soils was expressed as a ratio of the current concentration of PP (C_i) to the initial value of the content of PP in soil samples (C_0). As can be seen, the process of soil self-cleaning from PP in laboratory experiments is divided into two stages according to the speed of the process:

– slow cleaning from PP – a_0;
– quick cleaning from PP – b_0.

Similar dynamics of soil self-cleansing from PP were observed during field experiments (sites a and b).

Such dynamics correlates with ideas about the initial phase of PP destruction by microorganisms, namely, the splitting of the light fraction of PP and the gradual splitting of long-chain alkanes into organic acids. After that, in the next phase of self-cleaning

of the soil from PP, a more violent oxidation of the products of the first phase occurs, to which is added the increase in the mobility of these products in aqueous solutions, i.e., an increase in water migration.

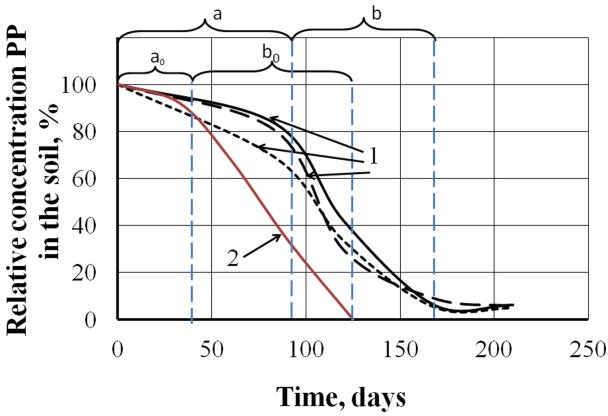


Fig. 1. Dynamics of the process of soil self-cleansing from PP: 1 – self-cleaning of soils based on the results of a field experiment with soils selected from different sections of the R-46 highway; 2 – the results of a laboratory experiment on self-cleaning of soil from PP, (a, b, a_0; b_0. – notation in the text).

However, the arrival of PP in field conditions does not occur once, as in a laboratory experiment, but continuously during the operation of a man-made object - a road. Due to the fact that the man-made load on road infrastructure objects is distributed throughout the entire period of operation, each portion of PP that enters the soil undergoes both stages of cleaning regardless of other portions. Therefore, the totality of self-cleaning can be presented in the form of separate processes for each portion of PP (see Fig. 2).

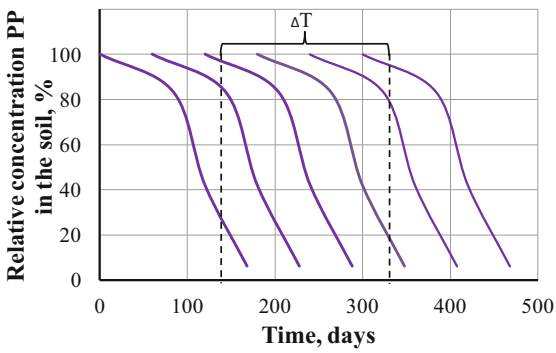


Fig. 2. Hypothetical illustration of the process of soil self-cleaning in real conditions.

Using the superposition method, it can be noted that the self-cleaning process in two stages is observed simultaneously in the soil. It can be assumed that the change in PP

concentration dC/dt over time for each portion of PP and the corresponding stage of self-cleaning is a constant and the same value. Then this process can be represented in the form of horizontal lines (see Fig. 3).

The positive value dC/dt indicates that the PP intake prevails over the processes of self-purification of grants from this pollutant. The negative value dC/dt indicates the predominance of self-cleaning activity over PP input. A zero value dC/dt indicates mutual compensation of these processes.

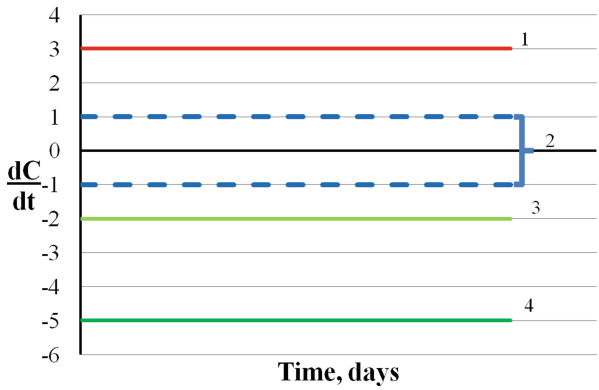


Fig. 3. Correlation between changes in concentrations of PP during their transformation in soil ecosystems of the roadside space: 1 – arrival of PP to the roadside space; 2 – hypothetical zone of change in PP concentration during real measurements; 3 – the first (slow) stage of soil self-cleansing from PP; 4 – the second (quick) stage of soil self-cleaning from PP.

According to the purpose of the study, a calculation scheme was developed to determine the real load of PP on the soils of the roadside space. This calculation can be carried out by measuring soil self-cleaning indicators and the real state of soil ecosystems that are under man-made load from the road. In Fig. 4 presents a calculation scheme that illustrates the formulated hypothesis and allows determining the real load on the soils of the roadside space.

In Fig. 4 marked: 1 – the process of receipt of PP (conditionally linear, monotonic); 2 – available concentration of PP in the soil, which is measured at the site of load determination; 3 – a set of processes of the slow stage of soil purification from PP; 4 – a set of processes of the rapid stage of soil purification from PP; C_1 –the concentration of PP in the soil at the beginning of the study, mg/kg; C_4 – the concentration of PP in repeatedly selected samples that are under technogenic influence at the time point t_4, mg/kg; C_5 – calculated-hypothetical concentration of PP in soils in the absence of self-cleaning processes, mg/kg; t_4 – the term of re-sampling of soils under technogenic load (C_4), days; $C_{2,4}$ – the concentration of PP, at the moment of time t_4, which characterizes the total self-cleaning of soils during the stage of slow cleaning, mg/kg; $C_{3,4}$ – the concentration of PP, at the moment of time t_4, which characterizes the total self-cleaning of soils during the stage of rapid cleaning, mg/kg.

According to the hypothesis, the real load of PP (site IV) on road infrastructure objects is the sum of PP removed from the soil as a result of two stages (sites I and II) of

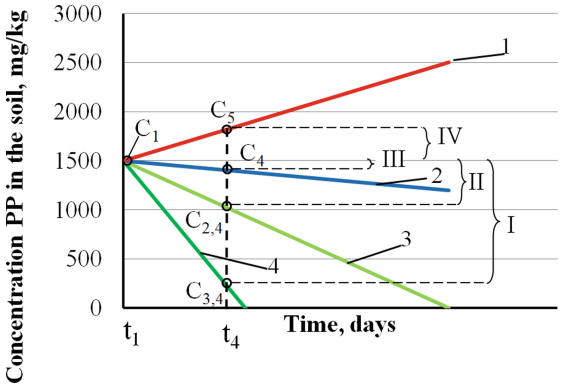


Fig. 4. Scheme illustrating the hypothesis regarding the calculation of the real load of the PP on the roadside space (notation in the text).

soil self-cleaning, and PP determined as the difference in concentrations of two samples of C_4- C_1 (section III), at the beginning (C_1) and at the end (C_4) of the specified term.

The procedure for determining the real load of PP on the roadside space is illustrated by the diagram in Fig. 5 and involves taking two soil samples (C_1 and C_4) directly at the road infrastructure object to determine the current concentration of PP.

Part of the C_1 sample is used to establish the self-cleaning characteristics of this type of soil. For this, a certain amount of the selected sample (C_1) is transferred to a conditionally clean zone free from man-made influence of the road. In the course of such a study to establish the characteristics of soil self-cleaning, samples are taken periodically (10 days) and the time (t_2) of a characteristic change in the stages of soil self-cleaning (C_3) is determined - the so-called breakdown or transition from the stage of slow cleaning to the stage of fast cleaning.

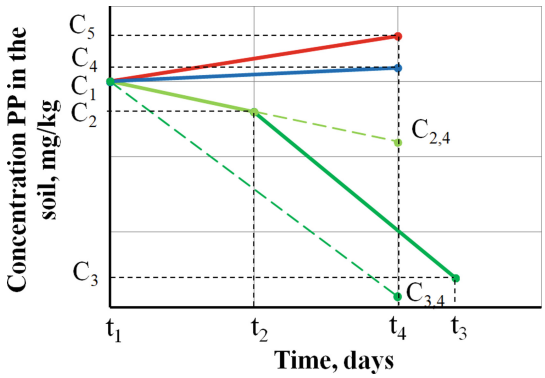


Fig. 5. Scheme for the experimental determination of the input parameters of the equation for determining the real load of the PP on the roadside space (notations similar to Fig. 4).

The experimental point (C_3, t_3) is determined arbitrarily, taking into account the possibility of determination dC/dt (values acquire a linear dependence) for this area.

According to the diagram in Fig. 4, we determine the concentrations of $C_{2,4}$ and $C_{3,4}$, taking into account the values dC/dt for the corresponding section of the soil self-cleaning curve from PP. Using the canonical equation of a straight line, we determine the necessary parameters. The concentration of $C_{2,4}$ is determined by formula 1:

$$C_{2,4} = \frac{(t_4 - t_1) \cdot (C_2 - C_1)}{t_2 - t_1} + C_1 \tag{1}$$

The concentration of $C_{3,4}$ is determined by formula 2:

$$C_{3,4} = \frac{(t_4 - t_1) \cdot (C_3 - C_2)}{t_3 - t_2} + C_1 \tag{2}$$

The real load of PP on the soil of the roadside space is determined by the formula 3:

$$\Delta C = C_5 - C_1 = (C_4 - C_1) + \left(C_1 - C_{2,4}\right) + \left(C_1 - C_{3,4}\right) \tag{3}$$

Analyzing the current state of the soil according to samples C_4 and C_1, it is possible to determine the balance between the load and self-cleaning of the soil of the roadside space from the PP.

In this way, three states can be identified:

- $(C_4 - C_1) > 0$ there is a gradual pollution of the soil ecosystems of PP, since the self-cleaning processes do not compensate for the flow of PP entering the roadside space from the highway (can be local in time);
- $(C_4 - C_1) < 0$ the processes of self-cleaning of the soil prevail over the flow of PP entering the roadside space from the highway, the process of self-restoration of the soil ecosystem is observed (it can be local in time);
- $(C_4 - C_1) \approx 0$ the limit state of the balance between the entry of PP into soils and their self-cleaning. Based on this condition, the maximum load on the soil ecosystem can be determined.

4 Conclusions

On the basis of the performed experimental studies, a methodology was developed for calculating the real load on the soils of the roadside space of the PP, which is created by the operation of the highway. The given experimental and calculation method has three practical results:

- the possibility of determining the maximum carrying capacity of the road according to the criterion of maintaining a balance between the man-made load of PP on the roadside soil and the self-cleaning of the soil from them;
- the possibility of identifying the unauthorized entry of PP to the adjacent soils, under the conditions of the pre-established man-made load of this highway on the roadside space in accordance with the existing traffic flow and regular monitoring studies of this road network object;

– the possibility to trace the dynamics of soil self-cleaning from PP arriving by air (analysis of samples taken at different distances from the road surface) and self-cleaning of soils located in the immediate vicinity of the highway, where there is an arrival of PP not only by air but also by water with road washes;
– on the basis of laboratory and field studies, a calculation methodology and practical recommendations for conducting a chemical analysis of soils for the content of PP were developed.

References

1. Li, G., Sun, G.-X., Ren, Y., Luo, X.-S., Zhu, Y.-G.: Urban soil and human health: a review. Eur. J. Soil Sci. **69**(1), 196–215 (2018). https://doi.org/10.1111/ejss.12518
2. Mykhailova, L., Fischer, T., Iurchenko, V.: Microbial activity and decomposition of soil organic matter in roadside soils contaminated with petroleum hydrocarbons clean - soil, air, water (2018)https://doi.org/10.1002/clen.201800132
3. Iurchenko ,V., Melnikova, O., Mikhaylova, L., Lebedeva, E.: Contamination and "self-cleaning" of soils, boarded on the objects of automobile and road complex, from petroleum products. TRANSBALTICA 2017. Procedia Eng. **187**, 783–789 (2017). https://doi.org/10.1016/j.proeng.2017.04.438/
4. Lisovickaya, O.: Hydrocarbon contamination of soils under the conditions of complex technogenic impact: dis. ... candidate of biological sciences: Moscow (2008)
5. Liang, Y., Zhang, X., Zhou, J., Li ,G.: Long-term oil contamination increases deterministic assembly processes in soil microbes. Ecol. Appl. **25**(5), 1235–1243 (2015). https://doi.org/10.1890/14-1672.1
6. Borowik, A., Wyszkowska, J., Kucharski, M., Kucharski, J.: Implications of soil pollution with diesel oil and BP petroleum with ACTIVE technology for soil health. Int. J. Environ. Res. Public Health **16**(14) (2019). https://doi.org/10.3390/ijerph16142474
7. Salam, L.B., Obayori, S.O., Nwaokorie, F.O., Suleiman, A., Mustapha, R.: Metagenomic insights into effects of spent engine oil perturbation on the microbial community composition and function in a tropical agricultural soil. Environ. Sci. Pollut. Res. **24**(8), 7139–7159 (2017). https://doi.org/10.1007/s11356-017-8364-3
8. Iurchenko, V., Melnikova, O., Mykhailova, L., Lebedeva, E., Mikhalevich, N.: Supporting of ecological safety of run-off from the territory of objects of road infrastructure, contaminated by petroleum products. In: Gopalakrishnan, K., Prentkovskis, O., Jackiva, I., Junevičius, R. (eds.) TRANSBALTICA 2021. LNITI, pp. 10–17. Springer, Cham (2020). https://doi.org/10.1007/978-3-030-38666-5_2
9. Ugnenko, E., Iurchenko, V., Sorochuk, N., Melnikova, O., Viselga, G.: Study of treatment efficiency of wastewater collected from the surface of roads by natural zeolite. TRANSBUD-2019 IOP Conf. Series: Materials Science and Engineering 708 (2019). https://doi.org/10.1088/1757-899X/708/1/012035
10. Buno, L., Tsvilyniuk, O., Karpyn, O., Terek, O.: Enzymatic activity of oil-contaminated soil in the root zone of plants Carex Hirta L. Gruntoznavstvo **14**(3–4), 43–51 (2013)
11. Sofinskaya, O.: Modeling of self-purification of leached chernozem from oil n-alkanes on the example of n-tridecane: abstract dis. ... candidate of biological sciences Kazan' (2006)
12. Ablieieva, I., Pliatsuk, L., Trunova, I., Yakhnenko, O., Berezhna, I.: The influence of biostimulants on the microbiological state of oil-contaminated soils. Environ. Saf. Balanced Resource Use **1**(23) (2021). https://doi.org/10.31471/2415-3184-2021-1(23)-73-83

13. Erkenova, M., Tolpeshta, I., Trofimov, S.: Changes of the content of oil products in the oil-polluted peat soil of a high-moor bog in a field experiment with application of lime and fertilizers. Eurasian Soil Sci. **49**(11), 1310–1318 (2016)
14. Shevchyk, L., Romaniuk, O.: Analysis of biological methods of restoration of oil-contaminated soils. ScienceRise: Biol. Sci. **1**(4), 31–39 (2017)
15. Dzhura, N., Tsvilyniuk, O., Terek, O.: The effect of oil pollution on the content of macro- and microelements in plants Carex hirta L. Ukrainian Botanical J. **64**(1), 122–131 (2007)
16. Mohsenzadeh, F.: Evaluation of oil removal efficiency and enzymatic activity in some fungal strains for bioremediation of petroleum-polluted soils. Iranian J. Environ. Health Sci. Eng. (2012). https://jehse.biomedcentral.com/track/
17. Fallgren, P., Jin, S.: Biodegradation of petroleum compounds in soil by a solid-phase circulating bioreactor with poultry manure amendments. J. Environ. Sci. Health A Tox. Hazard Subst. Environ. Eng **43**(2), 125–131 (2008)
18. Filiak, O., Sybirnyi, A., Yurym, M.: Biodegradation of petroleum products in the natural environmentю Bulletin of Lviv University. Biol. Ser. **47**, 89–95 (2008)
19. Stankevych, V., Kostenko, A., Kakura, I., Dubrova, O.: Hygienic aspects of the introduction of the latest methods of liquidation of soil oil pollution using the example of "DUKATm" biotechnology. Hygiene Populated Areas **59**, 107–113 (2012). https://doi.org/10.1186/1735-2746-9-26?site=jehse.biomedcentral.com
20. Soil quality. Sampling. Part 2 2006 Guidelines for Sampling Methods (ISO 10381–2: 2002, IDT): DSTU ISO 10381–2: Kyiv State Consumer Standard of Ukraine (2004)

Prospects for the Production of Recycled Hot Mix Asphalt with Plastic Fiber

Volodymyr Ilchenko[1](✉), Alla Kariuk[1], Roman Mishchenko[1], and Anna Shevchenko[2]

[1] National University "Yuri Kondratyuk Poltava Polytechnic", Poltava, Ukraine
ab.ilchenko_vv@nupp.edu.ua
[2] Ukrainian State University of Railway Transport, Kharkiv, Ukraine

Abstract. One of the advanced research directions to reduce the cost of road construction is the production of hot recycled asphalt concrete mixes based on milled asphalt concrete, which is formed by cutting off layers of asphalt concrete pavement, with the addition of plastic fibers obtained from household plastic waste. This combination of recycled materials enables not only to obtain an economic effect from reducing the cost of purchasing new road construction materials, but also to improve the environmental situation through household waste disposal.

Keywords: Asphalt pavement · Hot recycled · Milled asphalt · Plastic fiber · Recycled hot mix asphalt (RHMA)

1 Introduction

The cost of construction of one kilometer of a highway of the highest category is more than 6 million €, reconstruction and roadway overhaul cost for one kilometer road - almost 4 million € and 2 million €, respectively. The road construction cost depends on many factors (road category, infrastructure, relief, etc.), but on average it has the following structure: materials, products and structures –60% (20% of the asphalt concrete cost is on bitumen, which in the composition of asphalt concrete is only 6-8%), the operation of construction machines and mechanisms –20%, wages –10%, other expenses –10%. Due to limited funding for the road industry, almost 90% of the length of Ukrainian roads have not been repaired over the past decades, thus they do not meet modern requirements both in terms of strength (39.2%) and equality (51.1%) [1]. One of the ways to reduce the road construction cost can be the use of old asphalt concrete and plastic waste for the recycled asphalt mixtures manufacture.

2 Defining the Problem

The impetus for the old asphalt concrete reuse was the global energy crisis of the 70s of the last century, which prompted the search for ways to replace the deficient (in those times) organic binder for the asphalt mixtures preparation [2–6].

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 336–343, 2023.
https://doi.org/10.1007/978-3-031-25863-3_31

To date, the following methods of reusing old asphalt concrete are common in road construction, usually formed when cutting layers of the road surface with self-propelled road cutters during repair work [5–7]:

– subgrade roadsides and slopes strengthening;
– pavement underlying and lower layers arrangement;
– crushed stone layers wedging;
– cold organohydraulic mixtures production;
– hot asphalt mixes preparation.

The choice of one or another method of reusing old asphalt concrete depends on technical, environmental and economic factors [8–16].

The most rational way to use milled asphalt concrete can be considered the preparation of hot asphalt mixes with a partial or complete content of recycled material. For example, in most European countries, subject to the technological requirements, it is allowed to add up to 10% of milled asphalt concrete to the composition of new hot mixes intended for the upper layers; 30–50% - for the lower layers of the road surface; up to 100% for base layers.

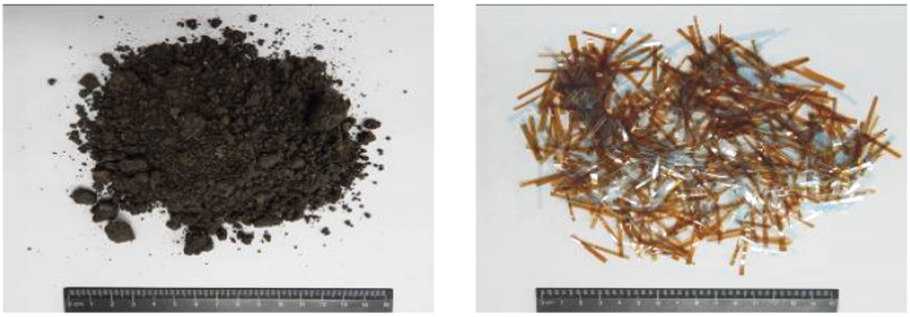
Since in Ukraine the milled asphalt concrete reuse for the new asphalt concrete mixtures preparation has not become as widespread as in America and Europe [8–16], there is a need to conduct research on the feasibility of manufacturing hot recycled asphalt concrete mixtures based on milled asphalt concrete with the addition of household plastic waste. Such a combination of recycled materials enables not only to obtain an economic effect from a reduction in the cost of purchasing new road construction materials, but also to improve the environmental situation through the old asphalt concrete reuse and the household waste disposal.

3 Research Results

To achieve this goal in the laboratory, a number of experimental studies were carried out [17, 18] on the production of hot recycled asphalt concrete mixes by the standard method [19, 20] based on milled and reshaped asphalt concrete with the addition of plastic fiber made from household plastic waste of various sizes and quantities from base material weight.

The first stage of experimental studies [17] involved the production of test series of hot recycled asphalt concrete mixtures based on milled asphalt concrete (Fig. 1a) with the addition of plastic fibers (Fig. 1b) in different amounts by base material weight, in particular: a control series of samples of asphalt concrete without impurities and several series of samples based on milled asphalt concrete with the addition of plastic fibers in the amount of 0.75%, 1.5% and 3.0% by weight of the base material.

Analysis of the physical and mechanical properties of test samples of the first stage of the study of hot asphalt mixes based on milled asphalt concrete with the addition of plastic fibers, given in [17], confirmed the possibility of using plastic fibers in an amount of 0.75–1.5% by weight of the base for recycled asphalt concrete reinforcement.



a) b)

Fig. 1. General view of raw materials: a – milled asphalt; b – plastic fiber (photo made by the author).

The second stage of experimental studies [18] involved the production of test series of test samples of hot recycled asphalt mixes based on milled asphalt concrete with the addition of plastic fibers of different sizes, in particular: a control series of samples from milled asphalt concrete without impurities and several series of samples based on milled asphalt concrete with the addition of plastic fibers of size 50 × 2 mm and 25 × 4 mm in the amount of 0.75% and 1.5% by weight of the base material.

Analysis of the physical and mechanical properties of test samples of the second stage of the study of hot asphalt mixes based on milled asphalt concrete with the addition of plastic fibers, given in [18], confirmed the feasibility of using plastic fibers with a size of 50 × 2 mm in an amount of 0.75% and 1.5% by weight of the main material for reinforcing recycled asphalt concrete.

The next stage of experimental studies involved the production of trial series of test samples of hot recycled asphalt concrete mixtures based on reformed asphalt concrete with the addition of plastic fibers 50 × 2 mm in size in different quantities from the mass of the base material, for which three series were made under laboratory conditions.

(Fig. 2) with the following composition:

- An series – reformed asphalt concrete without impurities (control series);
- Am0.75 series – reformed asphalt concrete with the addition of plastic fiber 50 × 2 mm in size in the amount of 0.75% by weight of the base material;
- Am1.50 series – reformed asphalt concrete with the addition of 50 × 2 mm plastic fiber in the amount of 1.50% by weight of the base material.

a) b)

Fig. 2. General view of test samples: a – after formation; b – after the test (photo made by the author).

Grain size of milled asphalt concrete, determined by sifting through standard sieves with openings from 40 to 0.071 mm, is most consistent with the regulatory requirements [19, 20] for type B hot fine-grained asphalt mixes (Fig. 3).

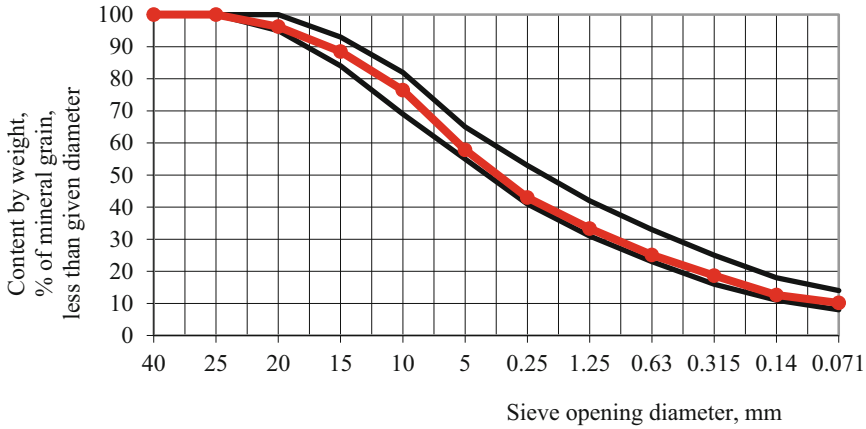


Fig. 3. Comparison of reformed asphalt concrete grain size with regulatory requirements for type B hot mix asphalt [16].

The production and testing of test samples of hot recycled asphalt mixes based on reformed asphalt concrete with the addition of plastic fibers were carried out to determine the average material density, water saturation, and compressive strength using standard methods in accordance with the requirements of regulatory documents [19, 20]. The results of determining the test samples physical and mechanical properties are shown in Table 1 and in Fig. 4, 5 and 6.

The dependence of the average density index of the test samples on the presence and content of the plastic fiber additive in the composition of hot recycled asphalt concrete mixtures based on reformed asphalt concrete is shown in Fig. 4.

Table 1. Physico-mechanical properties of test samples.

Property name	Sample series		
	An	Am0.75	Am1.5
Average density, g/cm^3	2.33	2.29	2.23
Water saturation, %	4.7	6.7	15.3
Ultimate compressive strength, MPa, dry at temperature: + 20 °C + 50 °C	5.1 1.1	5.4 1.1	6.6 1.6

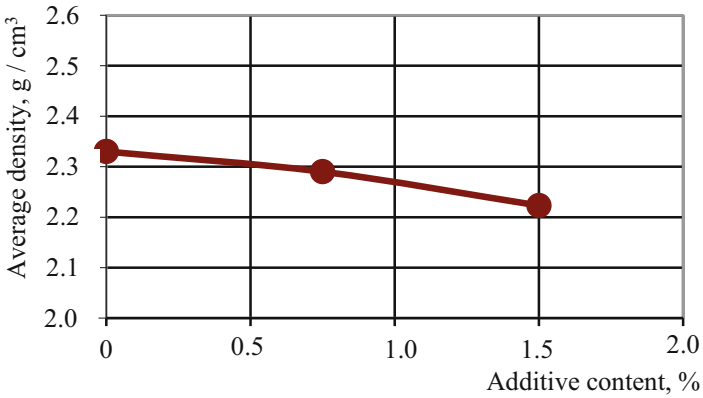


Fig. 4. Graph of the dependence of the average density of test samples on the presence and content of the fiber additive.

An analysis of the dependence of the average density index of the test samples on the presence and content of the plastic fiber additive in the composition of hot recycled asphalt concrete mixtures (see Fig. 4) shows that the average density of the samples with an increase in the content of plastic fibers in the composition of the asphalt concrete mixture decreases due to a gradual decrease of the roadstone part and increasing the content of lighter plastic fibers.

The dependence of the water saturation index of the yest samples on the presence and content of the plastic fiber additive in the composition of hot recycled asphalt concrete mixes based on reformed asphalt concrete is shown in Fig. 5.

An analysis of the dependence of the water saturation index of the test samples on the presence and content of the plastic fiber additive in the hot recycled asphalt concrete mixes composition (see Fig. 5) shows that the water saturation of the samples with an increase in the content of plastic fibers in the asphalt concrete mixture composition increases due to a gradual increase in porosity. Thus, the content of plastic fibers in an amount of more than 1% by weight of the base material can be harmful to asphalt concrete.

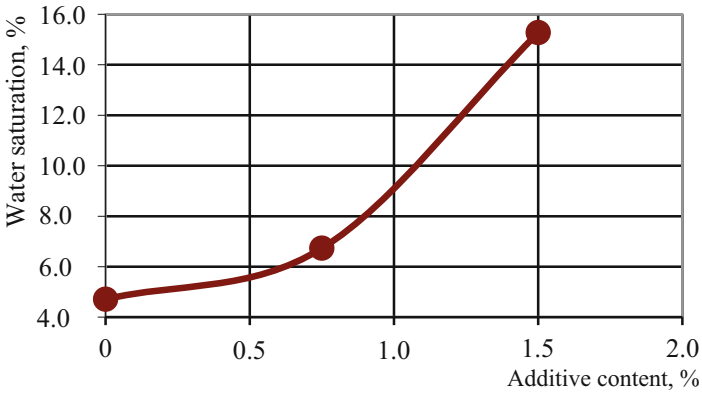


Fig. 5. Graph of the dependence of the water saturation index of the examine samples on the presence and content of the fiber additive.

The dependence of the compressive strength index of test samples on the presence and content of the plastic fiber additive in the composition of hot recycled asphalt concrete mixes based on reformed asphalt concrete is shown in Fig. 6.

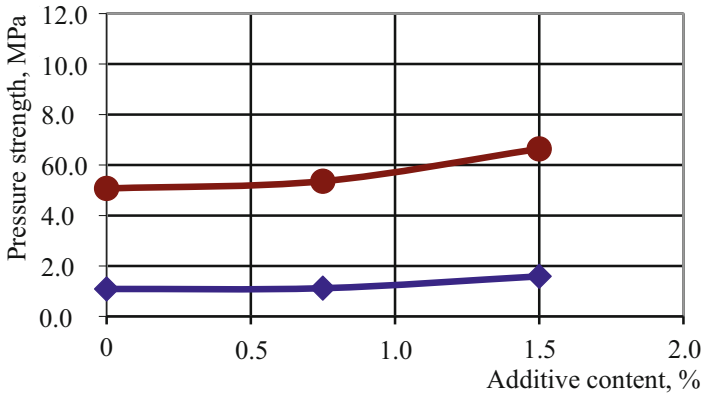


Fig. 6. Graph of the dependence of the compressive strength index of examine samples on the presence and content of the fiber additive: round markers - in a dry state at T = + 20 °C; square markers - dry at T = +50 °C.

An analysis of the dependence of the compressive strength index of test samples on the presence and content of plastic fiber additives in the composition of hot recycled asphalt concrete mixes (see Fig. 5) shows that the strength of samples in a dry state at temperatures of + 20 °C and + 50 °C with an increase in the content of plastic fiber in the composition of the asphalt concrete mix increases due to the effect of reinforcing the asphalt concrete with plastic fiber.

Thus, the physical and mechanical properties of test samples of hot recycled asphalt mixes based on reformed asphalt concrete with the addition of plastic fiber 50 × 2 mm

in size in an amount of up to 1.5% of the mass of the base material generally meet the regulatory requirements [19, 20] and are suitable for coatings of various categories or for top coatings layers of category III-IV with the obligatory thin-layer protective wear layers to prevent moisture penetration.

4 Conclusions

The results of the experimental studies of hot recycled asphalt mixes based on milled and reformed asphalt concrete with the addition of plastic fibers indicate the promising feasibility of their use in road construction, since they enable not only to obtain an economic effect from reducing the cost of purchasing new road building materials. But also to improve the environmental situation through the old asphalt concrete reuse and the household waste disposal.

References

1. The technical condition of roads of general usestry of Infrastructure of Ukraine. https://mtu.gov.ua/content/tehnichniy-stan-avtomobilnih-dorig-avtomobilnih-dorig-zagalnogo-vikoristannya.html
2. Bass, M., Faynberg, E., Usmanov, K.: Problemy povtornogo ispolzovaniya regenerirovannogo asfaltobetona v dorozhnom stroitelstve bolshih gorodov. Moscow (1976)
3. Syuni, G., Usmanov, K., Faynberg, E.: Regenerirovannyy dorozhnyy asfaltobeton. Moscow (1984)
4. Recycling Hot-Mix Asphalt Pavements // National Asphalt Pavement Association (NAPA). Information Series 123. Lanham (1996)
5. Zhdanyuk, V., Sibilskiy, D.: Рециклювання дорожніх одягів [Pavement Recycling]. Avtoshliakhovyk Ukrayiny. **4**(192), 32–35 (2004)
6. Golovko, S.: Відновлення несучої здатності нежорстких дорожніх одягів за методами холодного та гарячого ресайклінгу [Restoration of the Bearing Capacity of Non-rigid Pavements by Cold and Hot Recycling Methods]. Avtoshliakhovyk Ukrayiny. **5**, 44–46 (2011)
7. RV.3.2-218-02070915-204-2003: Recommendations for regeneration and reuse of milled asphalt. Kyiv [in Ukrainian] (2003)
8. Copeland, A.: Reclaimed Asphalt Pavement in Asphalt Mixtures: State of the Practice / Federal Highway Administration (FHWA). Report No. FHWA-HRT-11–021. McLean (2011)
9. Hansen, K., Copeland, A.: Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage: 2014 / National Asphalt Pavement Association (NAPA). Information Series 138 (5th edition). Lanham (2015)
10. Lizárraga, J.M., del Barco-Carrion, A.J., Ramírez, A., et al.: Mechanical performance assessment of half warm recycled asphalt mixes containing up to 100 % RAP. Materiales de construccion. **67**(327) (2017)
11. Lopes, M., Gabet, T., Bernucci, L., Mouillet, V.: Durability of hot and warm asphalt mixtures containing high rates of reclaimed asphalt at laboratory scale. Mater. Struct. **48**(12), 3937–3948 (2014). https://doi.org/10.1617/s11527-014-0454-9
12. Kim, M., Mohammad, L.N., Jordan, T., Cooper, S.B.: Fatigue performance of asphalt mixture containing recycled materials and warm-mix technologies under accelerated loading and four-point bending beam test. J. Clean. Prod. **192**, 656–664 (2018)

13. Kandhal, P., Mallick, R.: Pavement Recycling Guidelines for State and Local Governments: Participant's Reference Book [Electronic resource] / Federal Highway Administration (FHWA). Report No. FHWA-SA-98–042
14. Nosetti, A., Pérez-Madrigal, D., Pérez-Jiménez, F., Martínez, A.H.: Effect of the recycling process and binder type on bituminous mixtures with 100 % reclaimed asphalt pavement. Constr. Build. Mater. **167**, 440–448 (2018)
15. The Asphalt Paving Industry: A Global Perspective // European Asphalt Pavement Association (EAPA), National Asphalt Pavement Association (NAPA). Global Series 101. Brussels - Lanham (2011)
16. Zaumanis, M., Mallick, R.B., Frank, R.: 100% recycled hot mix asphalt: a review and analysis. Resour. Conserv. Recycl. **92**, 230–245 (2014)
17. Ilchenko, V., Tymoshevskyi, V., Mishchenko, R., Lyashko, D., Riznyk, V.: The prospects manufacture of recycled hot mix asphalt with fiber plastic reinforcement. Ind. Mach. Build. Civil Eng. **1**(48), 258–264 (2017)
18. Ilchenko, V., Demchenko, O., Mishchenko, R.: Physical and mechanical properties recycled hot mix asphalt based on milled asphalt with the plastic fiber addition. Roads Bridges **23**, 76–85 (2021). https://doi.org/10.36100/dorogimosti2021.23.076
19. DSTU B.V.2.7-119-2011: Mixes asphalts and asphalt of road and airfield. Kyiv [in Ukrainian] (2011)
20. DSTU B.V.2.7-319-2016: Asphalt concrete mixtures, road and airfield asphalt concrete. Test methods. Kyiv [in Ukrainian] (2016)

Realtime Measurements of the Relation Between the Acting Force, Unsprung and Sprung Masses on a Road Simulator Test Stand for Large-Size Vehicles

Marek Stembalski[1](✉), Arkadiusz Czarnuch[2], Tomasz Szydłowski[2], and Damian Batory[2]

[1] Faculty of Mechanical Engineering, Department of Machine Tools and Mechanical Technology, Wrocław University of Science and Technology, Wrocław, Poland
marek.stembalski@pwr.edu.pl

[2] Department of Vehicles and Fundamentals in Machine Design, Łódź University of Technology, Łódź, Poland
{arkadiusz.czarnuch,Tomasz.szydlowski,damian.batory}@p.lodz.pl

Abstract. The article presents the results of measurements obtained during durability tests of large-size vehicles. During the durability tests, the correlation between the acceleration obtained under the semi-trailer wheel, on the axis and on the suspension of the bracket and at the place of attachment of the pneumatic suspension cushion was checked. Measurements were carried out using single-axle induction accelerators. The tests were carried out for an unloaded and fully loaded semi-trailer with a load of 26 tons. For analysis of the results, in each test three road profiles controlling the operation of pneumatic actuators were generated at the MTS durability stand. The statistical and Auto Spectrum Density (ASD) frequency analysis were carried out. The presented results indicate 10 times greater accelerations registered under the semi-trailer wheel on the unsprung actuator plate. Acceleration obtained on the axis accounts for 30–65% of the acceleration value registered under the semi-trailer wheel. Basic frequencies for the semi -trailer axis and other suspension elements have been determined. As a result of the frequency analysis in the range up to 50 Hz, no frequencies characteristic of the plate under the semi-trailer wheel were found. The obtained results will be used to build an analytical model of the semi -trailer suspension specifying the damping coefficients for its individual elements.

Keywords: MTS road simulator · Sensor · Analytical model · Durability tests · Mechanical engineering

1 Introduction

Presently, one of the most commonly used means of transport of goods and passenger is road transport. According to the data of the Central Statistical Office [1] only in Poland, the share of transport in 2019 was 6% greater than in 2018.

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 344–353, 2023.
https://doi.org/10.1007/978-3-031-25863-3_32

One of the key stages of the production of vehicles traveling on the road is the stage of durability tests. Manufacturers of commercial vehicles, from the automotive industry [2–4], and large-size vehicles [5], can determine the lifetime of the product at the stage of prototype research. Thanks to this type of research, it is possible to check the reliability of the entire product and its individual components before entering the market. For example, in works [6, 7] the Authors described the methodology of feather springs tests. Thanks to this, manufacturers can avoid costly warranty or post-warranty repairs in the event of any construction errors. Users, in turn, can enjoy a reliable vehicles.

There are several methods of conducting durability tests of vehicles. One of them are durability tests on special test tracks with different road surfaces [8, 9]. This kind of test was described by Authors of work [10], where a bus was the tested object. A comparison of road test results with simulation results is described in the work [11]. Whereas, in ref. [12] the authors assess the fatigue durability of the components of the examined vehicle based on the type of road on which the vehicle moves. An example methods of determination of the road type and data acquisition are presented in [13, 14].

Another way to carry out durability tests are the road simulators. These are test stands aimed at reproducing the "behavior" of the examined vehicle under forces created by the actuators. Depending on the axis of the tested vehicle, they may be more or less complex. A review work on this subject presents Ref. [15]. Whereas the authors of Ref. [16] described the method of calculating the input data for such a simulator. Examples of 4-poster road simulators were shown in [17–19].

In addition to durability tests of passenger cars or vans in the literature, there are many examples of this type of research on e.g., motorcycles [20–22] or agricultural vehicles [23]. The proposition of the methodology of agricultural vehicles tests was presented in Ref. [24].

Not only entire vehicles but also selected components are subjected to durability tests [25–27].

In the presented paper the authors do not describe typical durability test. The aim of the work is to determine the influence of the tire dumping and suspension on the structure of the semi-trailer frame. In the studied structural system there is a hydraulic actuator, which generates forces acting on the semi-trailer. A plate is attached to the actuator and there is a semi-trailer tire on it. The tire is the first dumping element in the system. The semi-trailer wheel is mounted on the axis, which is the unsprung mass. The semi-trailer suspension system consists of an oil or gas shock absorber and a pneumatic suspension cushion. This type of suspension is an active system. After setting the driving height, which is constant, the system controls the pressure in the cushion to keep the height on an ongoing basis. A trailer frame with a chassis is mounted to the suspension. It is a sprung mass. In order to measure the dumping level in the unsprung and sprung mass in the proximity of the first axis, on its right side, induction accelerometers were installed in selected places. Measurements were carried out for an unloaded semi-trailer and the one fully loaded with a cargo of 26 tons. The semi-trailer suspension system diagram is shown in Fig. 1.

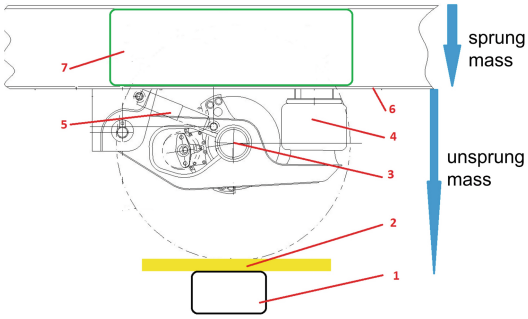


Fig. 1. A diagram of the suspension system with sprung and unsprung masses: 1) hydraulic actuator, 2) wheel plate, 3) axle, 4) air suspension cushion, 5) shock absorber, 6) semi-trailer frame, 7) chassis.

2 Road Simulator

The road simulator described in the paper is used for durability tests of large-size vehicles. The view of the simulator is shown in Fig. 2. A seismic mass was used to dampen the vibrations generated during durability tests (1). The mass is moved in the range of 0–50 mm above the foundation level (7) thanks to the use of several dozen pneumatic accumulators (2). Moreover, the entire station is placed on a separate foundation (7). This solution ensures effective active vibration isolation. The vibrations generated during the tests are not transferred to nearby buildings. The actuators are hydraulic cylinders (3) located under each wheel and the main cylinder (4). The lateral tilt cylinder (5) is responsible for the actual side tilts. For the safe operation of the test stand, if the difference between the main cylinder and the side tilt cylinder is greater than or equal to 2 degrees, the station will automatically turn off. This limitation protects against an excessive and uncontrolled twisting of the frame, which in an extreme case could lead to irreparable damage. All actuators move along one vertical axis. Therefore, maneuvers such as braking and acceleration and wheel rotation can't be simulated. The system is constructed in an open loop and the acting force control is done by the force generated by the actuators and their displacement. The software enables the free commissioning of each actuator independently. For this reason, 1, 2 or 3 axle vehicles can be tested. In addition, it is possible to change the position of the actuators in relation to each other. Thanks to this, it is possible to test vehicles with a distance between the axle and the coupling mechanism from 3 to 12 m. In order to increase the dynamics of the operation of hydraulic cylinders, hydro accumulators were used. The maximum operating frequency of the actuators is 102 Hz. In addition to the tests of large-size vehicles coupled to a truck tractor using the so-called king pin, a coupling for trailers with a drawbar can be mounted on the coupling device (8), which enables testing of trailer-type vehicles, e.g., an agricultural trailer.

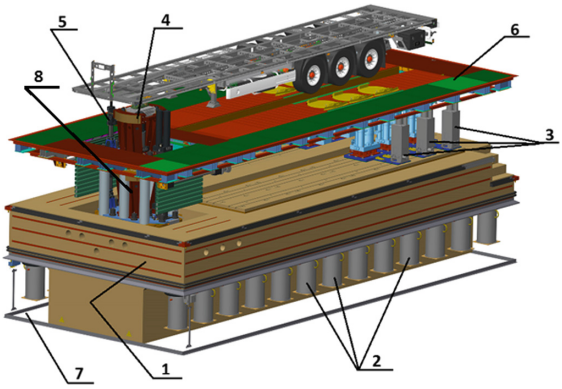


Fig. 2. Test stand: 1) seismic mass, 2) pneumatic accumulators, 3) axle hydraulic cylinders, 4) main king pin cylinder, 5) king pin side tilt cylinder, 6) top plate, 7) foundation, 8) device coupler.

3 Location of the Measuring Sensors on the Analyzed Semi-trailer

As a standard, when conducting durability tests of large-size vehicles at the MTS stand, several measuring sensors are placed on the vehicle. The installation includes acceleration sensors in selected places on the frame. In addition, displacement sensors measure the relative displacement between the axle of the semi-trailer and the top chord of the semi-trailer frame. Strain gauges measuring stress in selected places of the structure are also placed at selected points. In addition, there is a speed sensor with a GPS signal measurement function to measure the speed of the trailer and its position correlated with the data from the measuring sensors. The measurement system of the HBM company is used to record the measured physical quantities, e.g., measuring amplifiers for accelerometers, pressure displacement sensors and strain gauges. Data recording and communication with the user is ensured by the CX22 recorder. The sampling frequency of the measured signals was 300 Hz. An anti-aliasing filter (50 Hz) was used. In the described research, one of the accelerometers was placed on a plate supporting and separating the trailer wheel from the hydraulic cylinder (Acc_Wheelpan). In the design system, it is the last element of the MTS Road Simulator having direct contact with the tested vehicle. Another sensor was a uniaxial induction accelerometer placed on the trailer axle (ACC_Axle_R) - unsprung mass. Additionally, in order to check the level of vibrations transferred during durability tests to the semi-trailer frame, i.e., the unsprung mass, the accelerometers were placed on the lower web flange (Acc_Web_1R), near the suspension bracket (Acc_Bracket_1R) and the air suspension cushion (Acc_Airspring_1R). The location of the individual sensors is shown in Table 1.

Table 1. Location of the measurement sensors.

Description	Placement	View
ACC_Wheelpan_1R _864	A plate supporting the wheel - part of the MTS test stand	
ACC_Axle _1R_865	Above the first right axis near the beam spring - vertical direction	
ACC_Web_1R_866	Bottom web flange above the axis - vertical direction	
ACC_AirSpring_1R_ 861	Above the air suspension cushion - vertical direction	
ACC_Bracket_1R_8 68	Above the suspension bracket - vertical direction	

4 Analysis of the Results

Using RPC software, an iteration was carried out which resulted in obtaining a road profile. Road profiles are properly selected fragments of measurement signals collected during real road journeys. Thanks to the generated road profiles, it is possible to move the hydraulic cylinders of the test stand in such a way as to reproduce the measured physical quantities obtained during real journeys. An example of the methodology for determining such a road profile is described in [27]. The tests were carried out for the unloaded vehicle and the one loaded with a cargo of 26 tons. For each case, three road profiles were developed, denoted as profile 1, 2 and 3. The data for obtaining the road profiles were recorded on local roads. The literature [28] shows that these roads are characterized by the highest values of the obtained amplitudes of displacement, acceleration and stress in relation to national roads or highways.

4.1 Unloaded Semi-trailer

Figure 3 shows the time courses obtained as a result of measuring acceleration in selected places of the semi-trailer suspension structure whereas Fig. 4 summarizes the results of acceleration measurements in selected places in the structure and on the wheel supporting plate. The analyzes show that for all three profiles, the greatest acceleration was measured on the wheel supporting plate. As for the average value of the acceleration on the axle (unsprung mass), it is 70% lower than for the plate. The values measured on the lower web flange, above the air suspension cushion and on the bracket (sprung mass) are very similar and almost 10 times smaller than for the plate.

When analyzing the frequency spectrum for accelerometers (Fig. 5), it should be noted that for the plate under the wheel in the range of 0–50 Hz, no characteristic

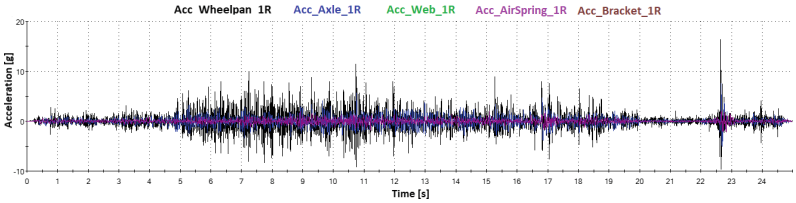


Fig. 3. Acceleration time waveforms for the selected profile no. 1.

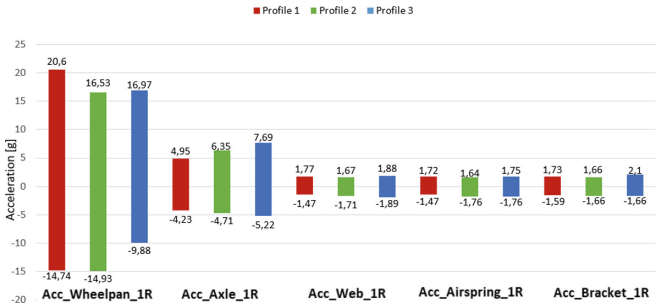


Fig. 4. Time courses of acceleration for the selected profile no. 1.

frequencies can be distinguished. The axle has a low frequency of 0.2 Hz, while the rest of the suspension has characteristic frequencies in the range of 2, 8, 18 and 30 Hz.

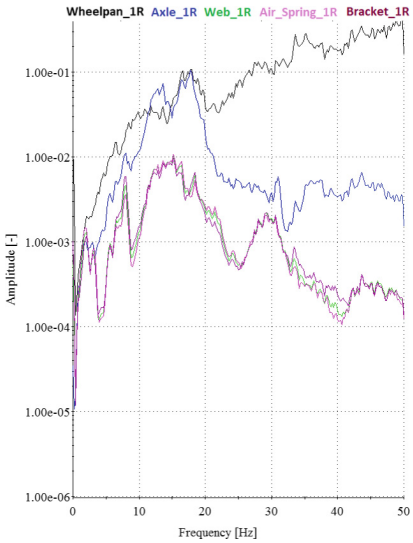


Fig. 5. ASD frequency comparison for unloaded semi-trailer.

4.2 Loaded Semi-trailer

Similar measurements as for the unloaded semi-trailer were carried out with a full load of 26 tons. Figure 6 shows the time courses of the measured acceleration, while Fig. 7 and.

Figure 8 compare the measuring ranges of acceleration and frequency (ASD), respectively. The forcing signal under the trailer wheel were the road profiles 1, 2 and 3.

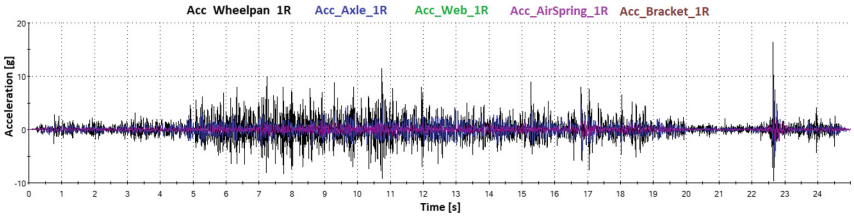


Fig. 6. Time courses of acceleration for the selected profile no. 1.

Similarly to the unloaded semi-trailer for the loaded one the greatest acceleration was measured on the wheel support plate. On the other hand, two times greater ranges of acceleration were observed on the unsprung mass (on the axle of the semi-trailer). The difference in average values between the plate under the wheel and the accelerations on the axle is 37%.

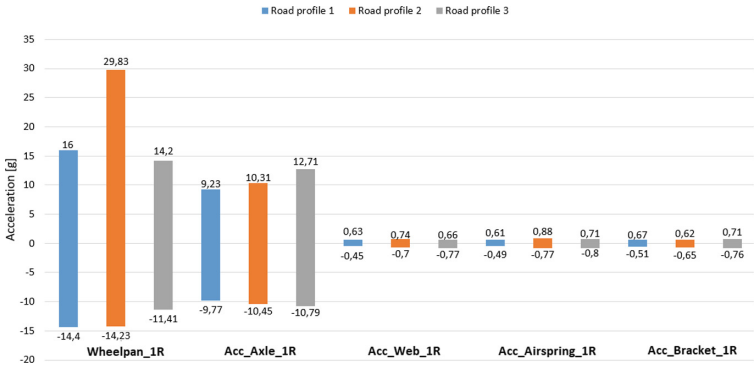


Fig. 7. Comparison of acceleration for different road profiles for a loaded semi-trailer.

Other sensors measuring acceleration on the bracket and on the lower web flange (sprung mass) registered accelerations twice as low for a loaded semi-trailer as compared to the unloaded one. The levels of acceleration on the bracket and on the lower web flange are similar to each other. When analyzing the frequency spectrum for accelerometers, it should be noted that, similarly to a semi-trailer without a load, in this case also the plate under the wheel has no characteristic frequencies in the range of 0–50 Hz. However, for the entire suspension, the basic frequencies are slightly higher, around 1.5 Hz. Moreover,

there are two dominant frequencies (11.8 Hz and 20 Hz) with the highest amplitude for the accelerometer placed on the axle of the trailer.

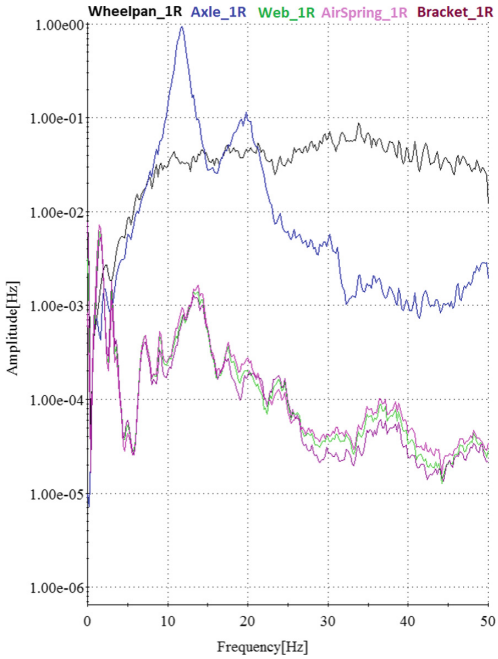


Fig. 8. ASD frequency comparison for a loaded semi-trailer.

5 Conclusions

The plate under the wheel is directly attached to the hydraulic cylinder, therefore it has no structural damping, only the material one. The acceleration ranges for the loaded and unloaded vehicle for the plate under the wheel are 10 times greater than for the structure with suspension. The frequencies characteristic for the plate are much higher than those taken into account in the tests up to 50 Hz.

The performed measurements and their analysis may be used in the future to create an analytical model in Matlab. The input data for the model will be the results obtained during the tests, while the result of the model will be the damping coefficients of individual suspension elements such as the axle, air suspension cushion or lower web flange.

References

1. https://stat.gov.pl/obszary-tematyczne/transport-i-lacznosc/transport/transport-drogowy-w-polsce-w-latach-2018-i-2019,6,6.html

2. Spickenreuther, M., Bersiner, F., Fricke, E.: Realistic driving experience of new vehicle concepts on the BMW ride simulator. In: Proceedings of the 7th International Styrian Noise, Vibration and Harshness Congress, The European Automotive Noise Conference (SNVH 2012), Graz, Austria, 13–15 June (2012)
3. https://www.nissan-global.com/EN/QUALITY/STORY/THENEVERENDINGROAD
4. http://www.saginomiya.co.jp/en/dynamic/jidousha/road/road01.html
5. Januszka, M., Kaczor, M.: A method to optimise semi-trailers with the use of FEM analysis and durability tests with a road simulator. In: IOP Conference Series: Materials Science and Engineering, vol. 1190, no. 1, p. 012021 (2021)
6. Kong, Y.S., Abdullah, S., Schramm, D., Omar, M.Z., Haris, S.M., Bruckmann, T.: Mission profiling of road data measurement for coil spring fatigue life. Measurement **107**, 99–110 (2017)
7. Ozmena, B., Altiok, B., Guzel, A., Kocyigit, I., Atamer, S.: A novel methodology with testing and simulation for the durability of leaf springs based on measured load collectives. Procedia Eng. **101**, 363–371 (2015)
8. Mysior, M., Pietruchab, G., Koziołek, S.: Strength testing of a modular trailer with a sandwich platform. Eksploatacja i Niezawodnosc – Maintenance Reliabil. **24**(2) (2022)
9. Gorges, C., Öztürk, K., Liebich, R.: impact detection using a machine learning approach and experimental road roughness classification. Mech. Syst. Signal Process. **117**, 738–756 (2019)
10. Kepkaa, M., Kepka, M., Jr., Václavík, J., Chvojan, J.: Fatigue life of a bus structure in normal operation and in accelerated testing on special tracks. Procedia Struct. Integrity **17**, 44–50 (2019)
11. Lu, Y., Yang, S., Li, S., Chen, L.: Numerical and experimental investigation on stochastic dynamic load of a heavy duty vehicle. Appl. Math. Model. **34**, 2698 (2010)
12. Nasir, N.N.M., Abdullah, S., Singh, S.S.K., Haris, S.M.: Risk-based life assessment of prediction models on suspension system for various road profiles. Eng. Fail. Anal. **114**, 104573 (2020)
13. Imine, H., Benallegue, A., Fridman, L.: Experimental validation of unknown inputs estimation via high order sliding mode observer. In: 12th IFAC Symposium on Transportation Systems Redondo Beach, CA, USA, 2–4 September (2009)
14. Levulytė, L., Žuraulis, V., Sokolovskij, E.: The research of dynamic characteristics of a vehicle driving over road roughness. Eksploatacja i Niezawodnosc – Maintenance Reliabil. **16**, 518–525 (2014)
15. Doddsa, C.J., Plummer, A.R.: Laboratory road simulation for full vehicle testing a review. SAE Tech. Pap. 487−494 (2001). https://doi.org/10.4271/2001-26-0047
16. Burger, M.: Calculating road input data for vehicle simulation. Multibody Sys. Dyn. **31**(1), 93–110 (2013). https://doi.org/10.1007/s11044-013-9380-9
17. Raath, A.D., Waverena, C.C.V.: Time domain approach to load reconstruction for durability testing. Eng. Fail. Anal. **5**, 113–119 (1998)
18. Chindamo, D., Gadola, M., Marchesin, F.P.: Reproduction of real-world road profiles on a four-poster rig for indoor vehicle chassis and suspension durability testing. Adv. Mech. Eng. **9**, 1–10 (2017)
19. Fricke, D., Frost, M.: Development of a full-vehicle hybrid-simulation test using hybrid system response convergence (HSRC). SAE Int. J. Passeng. Cars-Mech. Syst. **5**. https://doi.org/10.4271/2012-01-0763
20. Chindamo, D., Gadola, M., Armellin, D., Marchesin, F.: Desine of a road simulator for motorcycle application. Appl. Sci. **7**(12), 1220 (2017)
21. Nehaoua, L., Hima, S., Arioui, H., Seguy, N., Espié, S.: Design and modeling of a new motorcycle riding simulator. In: Proceedings of the IEEE American Control Conference, New York, NY, USA, 11–13 July, pp. 176–181 (2007)

22. Cossalter, V., Lot, R., Maso, M., Massaro, M., Sartori, R.: A motorcycle riding simulator for the improvement of the rider safety. In: Proceedings of FISITA World Automotive Congress: Munich, Germany (2008)
23. Mattetti, M., Molari, G., Vertua, A.: New methodology for accelerating the four-post testing of tractors using wheel hub displacements. Biosys. Eng. **129**, 307–314 (2015)
24. Azrulhisham, E., Asri, Y.M., Dzuraidah, A.W., Nik, N.M., Shahrom, A.: Application of road simulator service loads in automotive component durability assessment. Open Ind. Manufact. Eng. J. **4**, 1–7 (2011)
25. Coutinho, I., Landre, J.: Enhanced tailored durability test specification for multiaxial dynamically excited structures attached to a single input base under off-road loading environment. Eng. Struct. **219**, 110768 (2020)
26. Hou, Y., Zhou, W., Shen, C.: Experimental investigation of gas-tightness and electrical insulation of fuel cell stack under strengthened road vibrating conditions. Int. J. Hydrogen Energy **36**, 13763–13768 (2011)
27. Patel, C.B., Gohil, P.P., Borhade, B.: Modelling and vibration analysis of the road profile measuring system. Int. J. Autom. Mech. Eng. (IJAME) **1**, 13–28 (2010)
28. Czarnuch, A., Stembalski, M., Szydłowski, T., Batory, D.: Method of reconstructing dynamic load characteristics for durability test of heavy semitrailer under different road conditions. Eksploatacja i Niezawodność - Maintenance Reliabil. **23**, 548–558 (2021)

Possibilities of the Using of Drilling Mud in Road Construction

Oksana Demchenko[1](✉), Volodymyr Shulhin[1], Volodymyr Ilchenko[1], and Elena Uzhviieva[2]

[1] National University «Yuri Kondratyuk Poltava Polytechnic», Pershotravnevyj Ave. 24, Poltava, Ukraine
ab.demchenko_ov@nupp.edu.ua
[2] Ukrainian State University of Railway Transport, Kharkiv, Ukraine

Abstract. Drilling cuttings are toxic for the environment (III-IV hazard class) due to the drilling mud used and initial properties of the drilled rock. One of the promising areas is the processing of drilling cuttings to obtain a mixture that is non-toxic and can be used for road construction. Road design requires calculation of a number of parameters which provide durability, reliability, and frost resistance. The road layers made of drilling cuttings must efficiently resist shear stress and fractures in the pavement.

One of the main indicators that must be met in the road design is water consumptions. This indictor is closely related to the frost resistance of road pavement. The less water consumption is the more cycles of freezing and thawing the road pavement will endure. In this study, by mixing the drilling cuttings and special additives, the mixture of drilling slime-cement was obtained which after curing successfully endures the atmosphere influence. In this paper, the most optimal compositions of slime-cement with the use of lime and hydrophobic additives for the layers of pavement are presented. The influence of cement, lime, and hydrophobic additives on the strength and water absorption of slime-cement was investigated experimentally. Using the STATISTICA software package, the values of the factors when the maximum strength and minimum water absorption are achieved are specified. The conclusions provide quantitative indicators based on the results of these studies.

Keywords: Road pavement · Slime-cement · Drilling cuttings · Water sorption · Compression strength · Influence surface · Drilling waste management

1 Introduction

Drilling waste disposal is an integral part of well construction. Very often the work on neutralization of drilling cuttings is carried out carelessly, and sometimes not carried out at all. Unfortunately, this is the reality of the modern oil and gas industry. Unscrupulous companies, in order to make extra profits, neglect the proper disposal of drilling waste. As a result, this has a negative impact on the ecology of the development area. It should be noted particularly dangerous drilling waste, namely drilling wastewater [1].

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 354–364, 2023.
https://doi.org/10.1007/978-3-031-25863-3_33

These substances, when leaked into rivers, cause damage to regions far removed from construction sites. Therefore, the issue of drilling waste disposal is open and requires special attention from the state [2].

The proper state of the environmental aspect of well construction is questionable. The issue of utilization of drilling waste, namely drilling cuttings, is acute [3]. This is a large tonnage product that accumulates in large quantities and has in its structure hazardous reagents that have a detrimental effect on the environment. Given the current state of roads in Ukraine, the area of processing drilling cuttings for road construction is promising. In addition, many technologies have now been developed that involve the use of drilling cuttings in the building industry [4].

The main purpose of these studies is to develop a composition of drilling slime-cement that would meet the requirements of GBN V.2.3–37641918-554:2013 [5].

The main objectives of this study are the selection of the optimal ratio of components and analysis of factors that affect the properties of drilling slime-cement for the arrangement of pavement layers.

The study was planned on the basis of a plan using a three-factor experiment on three levels. The cement consumption, the amount of hydrophobic additive, and the consumption of lime were chosen as variable factors to determine the effect on the strength and water sorption of the samples.

2 Defining the Problematics

A promising direction of drilling cuttings utilization involves obtaining a universal mixture that is non-toxic and can be used for road construction.

There are many studies in the public domain that describe the processing of drilling cuttings into construction material. The most common [6] proposed technologies for processing drilling cuttings (in order to obtain a safe mixture for construction purposes), which involves mixing drilling cuttings with additives such as pre-foamed urea, calcium, and organic additives, cement, oxides.

Given the current state of Ukraine's roads, the use of drilling cuttings in road construction is an important area [8]. In addition, the use of drilling cuttings in the construction of roads solves two important issues: the safe disposal of hazardous waste and the arrangement of the road surface.

3 Research Methodology

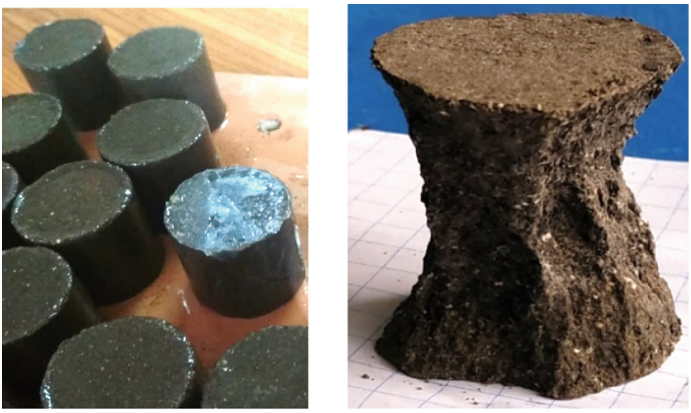
The mass of drilling cuttings was taken as a basis for making samples at one point of the plan (9 samples), which was 50 g. The content of lime and cement was determined as a percentage of the mass of one sample of drilling mud. The content of the hydrophobic additive Nanoalps® System SAFE was determined as a percentage of the mass of cement. The following component consumption was selected: cement (7%, 10%, 13%); hydrophobic additive (0.5%, 0.6%, 0.7%); lime (4%, 7%, 10%).

The optimal amount of water required for one batch was determined experimentally. The optimal water content was selected, which was 12.5% by weight of one sample of

drilling cuttings. The mixture turned out balanced, did not spread during pressing, and was not overdried.

Samples-cylinders with a diameter of 30 mm and a height of 30 mm (dimensions were selected taking into account the presence of additives) were made by pressing under load according to [9]. Since the drilling slime-cement was based on a mineral binder, a load of 15 MPa was chosen for pressing. Pressing the samples was performed using a plunger and a cylinder with a removable bottom. The pressing time was 3 min. The molded samples were stored in a normal curing chamber (moist curing). A day later, half of the samples were placed in water for further curing (water-saturated curing). Materials' properties determination and samples of slime-cement were carried out according to standard methods. The analysis of research results was carried out using the STATISTICA 10 software.

Each sub-item of the subsection is divided into 2 parts, which include an analysis of the samples study results of moist and water-saturated curing. The tests of the samples were performed after 7 and 28 days after molding. A comparative description of the studied values and the tendency of their variation over time is presented in Fig. 1.



a) b)

Fig. 1. General view of experimental samples of drilling slime-cement: a) after removal from the water-saturated environment; b) after the test.

Tests of samples for strength were performed according to the guidelines [9], the strength was determined immediately after molding, after 7 and 28 days, the test results are shown in Table 1.

According to the study (Table 1), the samples steadily gained strength throughout the curing period. For further analysis, the strength values of the samples after 7 and 28 days were used. It should be noted that the series of samples 1, 2, 3, 5, 7, 9, and 11 gained the greatest strength. This can be explained by the high content of the mineral binder in the working mixtures.

Table 1. The test results of the samples for strength after water-saturated curing.

Sample series number	Water-saturated curing samples strength, MPa		
	Raw (after molding)	7 days	28 days
1	1.83	5.12	8.05
2	2.44	4.21	7.01
3	2.13	5.24	7.68
4	2.13	4.33	5.92
5	1.34	4.51	7.50
6	2,26	3.23	4.97
7	1.95	4.76	6.77
8	1.89	4.27	5.79
9	2.13	4,82	7.87
10	2.01	4.33	5.89
11	1.71	4.14	6.89
12	2.01	4.70	6.22
13	2.07	3.78	6.19
14	1.77	4.09	5.67
15	1.77	3.78	5.00
16	1.76	3.45	4.85
17	1.75	3.43	4.76

To visually reflect the relationship between the cement content and the strength of the samples, it is advisable to determine the correlation coefficients [11]. The correlation coefficient can take values from −1 to + 1. The factors' values are presented in Table 2.

Table 2. Correlation of factors.

Factor	Strength	
	7 days	28 days
Cement consumption, g	0.654104	0.705222
Additive consumption, g	−0.175701	0.173713
Lime consumption, g	0.292738	0.352611

Table 3. The test results of the samples for strength after moist curing.

Sample series number	Samples' strength after moist curing, MPa		
	Raw	7 days	28 days
1	1.83	5.06	7.29
2	2.44	4.09	5.73
3	2.13	5.49	6.65
4	2.13	4.57	6.16
5	1.34	4.88	5.95
6	2.26	3.35	5.00
7	1.95	4.57	6.40
8	1.89	4.15	5.24
9	2.13	5.12	6.80
10	2.01	3.90	5.06
11	1.71	4.39	5.73
12	2.01	4.57	5.66
13	2.07	4.45	6.56
14	1.77	4.39	5.00
15	1.77	4.15	5.40
16	1.76	4.2	5.50
17	1.8	4.1	5.35

As Table 2 shows, the strength of the samples is most affected by the quantitative content of cement. Lime consumption has a medium correlation and therefore has a slight positive effect on the strength of the samples.

Surfaces of influence are built in the STATISTICA software complex for visual display of the variation factors' influence on durability.

Over time, the dependence of the lime consumption and cement on the strength remains, the main dependences can be observed on the influence surfaces of the cement and lime consumption on the strength of drilling slime-cement at water-saturated curing after 28 days.

As is seen from Fig. 2, the highest strength is obtained at the maximum consumption of cement and the maximum consumption of lime.

From the graphical dependence in Fig. 3 of the effect of cement and additive consumption on the values of the strength of drilling slime-cement, it is seen that the additive has a slight positive effect on the strength of the samples.

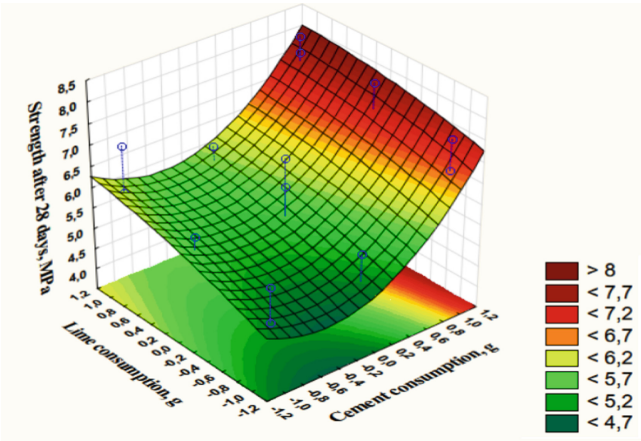


Fig. 2. The influence surface of cement and lime consumption on the strength values of drilling slime-cement after 28 days.

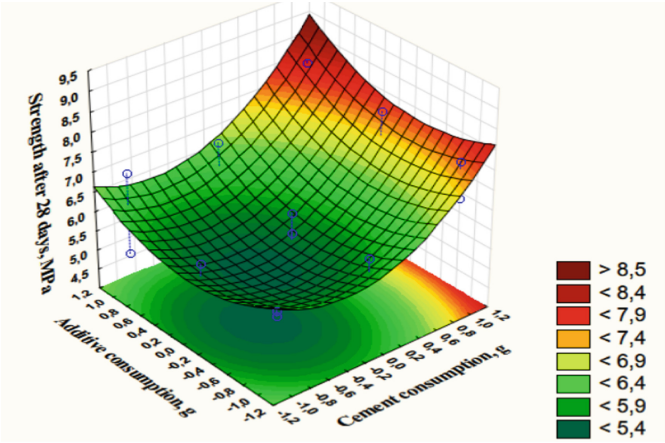


Fig. 3. The influence surface of cement and additives consumption on the strength values of drilling slime-cement after 28 days.

To analyze the effect of the additive during the entire curing period, the surface of the cement and the additives' effect on the strength of samples after 28 days was constructed.

The results of the dependence study of the compressive strength of samples that gained strength in the chamber of standard curing are shown in Table 2.

To study the effect of components on the strength of the drilling slime-cement mixture, the influence surface of cement and lime on the strength of samples after 7 and 28 days was constructed at first, as over time the strength dependence on the consumption of lime and cement remains. The influence surface of the cement and lime consumption on the curing strength after 28 days is seen in (Fig. 4).

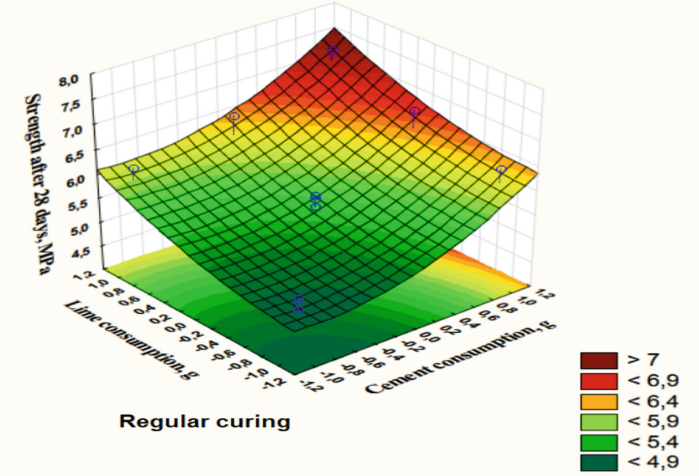


Fig. 4. The influence surface of cement and lime consumption on the values of the drilling slime-cement's strength after 28 days.

To explain the obtained results of the consumption of cement and lime and additives on the strength of the samples, the correlation coefficients are shown in Table 4.

The expected consumption of cement has the highest correlation. Increasing the consumption of lime has a positive effect on the strength, as evidenced by the average values of the correlation. According to [12], burnt lime increases the strength and hygroscopic properties of concrete, this is also true for the mixture of drilling slime-cement.

According to Table 4, the additives show a slight negative correlation after 7 days of samples' curing.

Table 4. Correlation of factors.

Factor	Strength	
	7 days	28 days
Cement consumption, g	0.805565799	0.716110
Additive consumption, g	−0.252329175	−0.025993
Lime consumption, g	0.368810599	0.540574

After 28 days, the additive has no effect on the strength of the samples, as evidenced by the lack of correlation.

Analyzing the influence surfaces presented in Fig. 5, it can be concluded that during the curing period the negative effect of the additive on the strength of the samples declines, and over time may have a positive trend.

One of the important studies of slime-cement for the arrangement of pavement layers is the study of water sorption of the material. The samples' water-saturated curing results analysis for water absorption is given in Table 5 in the study of correlation factors.

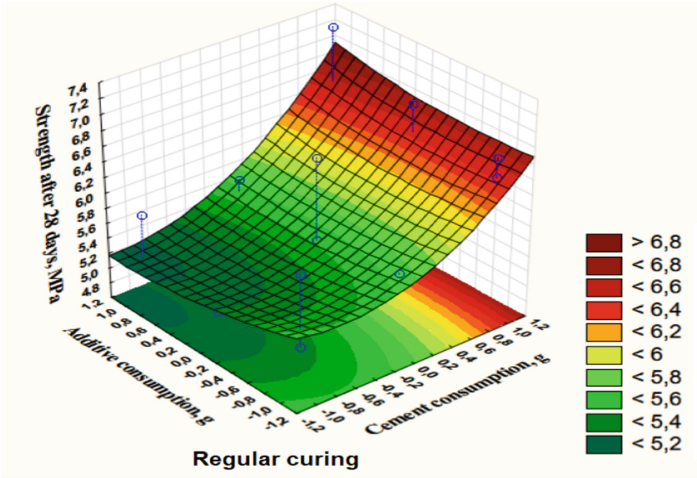


Fig. 5. The influence surface of cement and additive consumption on the strength values of the drilling slime cement after 28 days.

As is seen from Table 5 data, water sorption depends on all factors of variation. Consumption of additives is the most significant influence factor. According to [12], the additive plasticizer reduces the porosity of concrete, which in turn reduces water sorption. As it can be seen, this statement is true for a mixture of drilling slime cement. To visualize the dependencies, let's construct the influence surface of the components' consumption on the water sorption of the samples.

Table 5. Correlation of factors.

Factor	Water sorption
Cement consumption, g	−0.388626387
Additive consumption, g	−0.742439425
Lime consumption, g	−0.300870576

Analyzing Fig. 6–7, it is easy to see that the maximum consumption of cement and additives reduces water sorption. This fact confirms the effectiveness and feasibility of using an additive-water repellent because in the construction of roads an important factor is frost resistance, which directly depends on water absorption. Based on the obtained data, it was assumed that optimal component compositions of mixtures in which water sorption takes the acceptable values was obtained.

The analysis of slime-cement samples with lime and additive, which cured in the regular curing chamber, was also performed. Visually, the samples appeared wet, so it was decided to determine the water sorption percentage without direct contact of the samples with water. The samples were weighed under normal conditions and after drying.

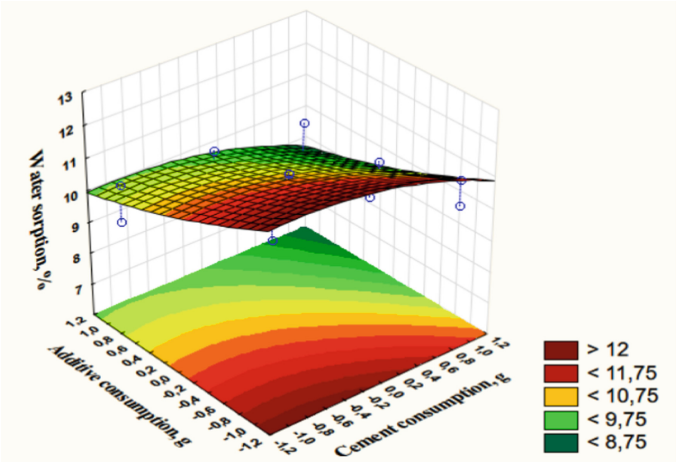


Fig. 6. The influence surface of additive and cement consumption on the values of water sorption of drilling slime-cement.

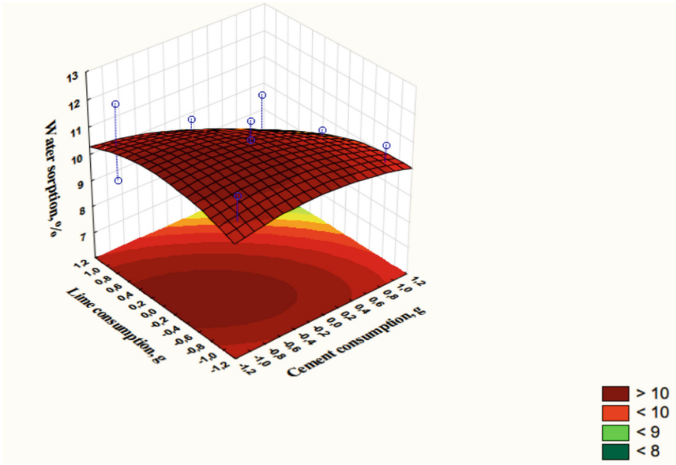


Fig. 7. The influence surface of lime and cement consumption on the values of water sorption of drilling-slime cement.

As evidenced by Table 6, the additive has the greatest effect on water sorption. This is due to its plasticizing effect. As a result of curing the dense structure of drilling slime-cement with the minimum number of pores is formed.

The moist curing samples showed similar correlation coefficients to the water-saturated curing samples. The main difference is the amount of moisture gained. Having investigated the dependence of the samples' consumption of cement, additives, and lime on the water sorption, the influence surfaces of the components on the values of water sorption were built. As can be seen from Fig. 8–9, the lowest value of water sorption is obtained at the highest consumption of lime, cement, and additives.

Table 6. Correlation of factors.

Factor	Water sorption
Cement consumption, g	−0.331266257
Additive consumption, g	−0.662035415
Lime consumption, g	−0.198938709

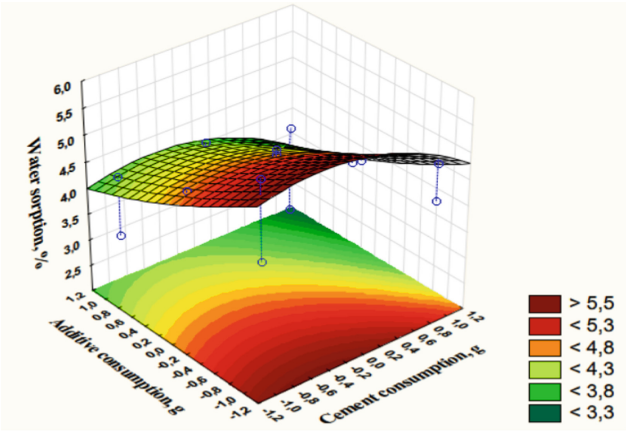


Fig. 8. The influence surface of additive and cement consumption on the values of water sorption of drilling slime-cement.

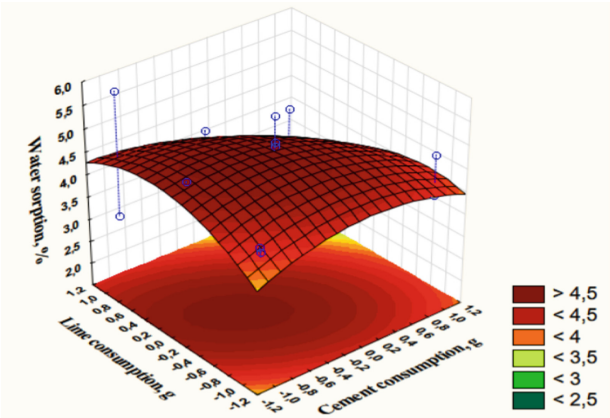


Fig. 9. The influence surface of the lime and cement consumption on the values of water sorption of drilling slime-cement.

4 Conclusions

After 7 days of water curing the sample's strength reached approximately 68% of that of 28 days. The maximum strength after 28 days of water curing was 8.05 MPa. The strength of samples that cured in water-wet conditions 28 days is 10% less than that of water curing. Water consumption of slime-cement ranges from 2.5% to 4%.

As a result of the conducted studies, we established the prospects of preparation of building material of drilling slime cement without its additional processing with the use of cement, lime, and additive Nanoalps®System SAFE. The optimal ratios of components that influence the properties of drilling slime cement for the arrangement of pavement layers are selected. The obtained material according to is suitable for use in the upper layer of pavement of temporary roads to drilling rigs.

The obtained material met the standard requirements and is suitable for usage in construction of the top layers of road pavement of temporary roads to the rig sites.

References

1. Knez, D., Gonet, A., Fijai, J., Czekaj, L.: Trends in the drilling waste management. Acta Montanistica Slovaca. **11**, 80–83 (2006)
2. Khodadadi, M., Moradi, L., Dabir, B., Nejad, F.M., Khodaii, A.: Reuse of drill cuttings in hot mix asphalt mixture: A study on the environmental and structure performance. Constr. Build. Mater. **256**, 119453 (2020)
3. Mironov, N.A., Usmanov, I.R.: The use of drilling cuttings in road construction. Electron. J. Cloud Sci. **2**, 33–36 (2013)
4. Foroutan, M., Hassan, M., Desrosiers, N., Rupnow, T.: Evaluation of the reuse and recycling of drill cuttings in concrete applications. Constr. Build. Mater. **164**, 400–409 (2018)
5. GBN V.2.3–37641918–554:2013. Roads. Layers of pavement made of stone materials, industrial waste, and cement-reinforced soils. Design and construction. Kyiv: Ministry of Regions [in Ukrainian] (2013)
6. Ponomarenko, D., Perevalov, S., Yashchenko, V.: Pat. 2387689. Composition for inerting drilling waste. Kyiv (2010)
7. Veil, J., Dusseault, M.: Evaluation of slurry injection technology for management of drilling wastes. Final Report. Argonne, Illinois (2003)
8. Kosulina, T., Kononenko, E., Tsokur, O.: Utilization of oil well cuttings by the reagent method and the use of waste products as secondary material resources. Altern. Energy Ecol. **2**, 187–192 (2012)
9. Demchenko, O., Shulgin, V., Petrash, R.: Experimental study on light concrete properties using bottom ash of thermal power stations. Int. J. Eng. Technol. **7**(3.2), 1–5 (2018)
10. Bondar, V., Shulgin, V., Demchenko, O., Bondar, L.: Experimental study of properties of heavy concrete with bottom ash from power stations. In: MATEC Web of Conferences, vol. 116, p.02007 (2017)
11. DSTU B V.2.7–309:2016. The soils reinforced with binder. Test method. Kyiv: Ministry of Regions [in Ukrainian] (2016)
12. Zhdanyuk, V., Sibilskiy, D.: Рециклювання дорожніх одягів [Pavement Recycling]. Avtoshliakhovyk Ukrayiny, 4(192), 32–35; 5(193), 27–30; 6(194), 23–25 [in Ukrainian] (2004)

New Design of Axial Piston Pump with Displaced Swash Plate Axis of Rotation for Hydro-Mechanical Transmissions

Paweł Załuski(✉), Piotr Patrosz, and Marcin Bąk

Gdansk University of Technology, Gdansk, Poland
{pawel.zaluski,piotr.patrosz,marcin.bak}@pg.edu.pl

Abstract. This paper presents a prototype design of an axial piston pump with displaced swash plate axis of rotation in two directions of discharge with electronic control intended for installation on a hydraulic-mechanical gearbox dedicated to working machines. The effect of displacement of the swash plate rotation axis on dead space volume and volumetric efficiency is presented. The construction and principle of operation of the capacity change mechanism and the delivery direction change mechanism are described. The design and hydraulic diagram of the pump are presented.

Keywords: Hydraulic transmission · Piston pump · Efficiency

1 Introduction

The increasing use of work vehicles, such as articulated and telescopic loaders and tractors in building and agricultural work, creates the need for work aimed at improving their design, improving operator comfort and achieving ever higher efficiencies, resulting in lower fuel consumption [1]. The gearboxes of slow-moving vehicles are among the most intensively developed components of these machines. Transmission using a hydraulic drive system enables low travel speeds and stepless ratio changes. This gives the vehicle operator the chance to adapt the optimum movement speed to the work being performed. Mechanical gearboxes, in contrast, provide higher efficiencies than hydraulic transmissions without requiring expensive hydraulic components such as pumps and motors [2]. The disadvantage of these gears is the strictly defined ratio value between the mating gears. As part of the LIDER project at the Gdansk University of Technology, a design for a hybrid gearbox combining the presented advantages of both hydraulic and mechanical gears was developed. The kinematic diagram of the designed gearbox is shown in Fig. 1. The gearbox consists of eight gears, a variable displacement main hydraulic pump with a secondary pump, a variable capacity hydraulic motor and two friction clutches [3, 4]. The used hydraulic motor has freewheel capability, i.e. it allows the shaft to rotate without causing movement of the working elements that cause the liquid to be pumped. The shown gearbox allows 4 gear ratios. The ratio when driving in gears *I* and *II* is due to the closed-circuit hydraulic transmission, where the *PM* pump feeds the *HM* hydraulic

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 365–374, 2023.
https://doi.org/10.1007/978-3-031-25863-3_34

motor. For both of these ratios, the main pump's displacement can change continuously from a minimum value of zero to a maximum displacement of q_{pmax}, so that the vehicle's speed can be varied smoothly. Gear *I* is implemented when the hydraulic motor has a maximum displacement q_{smax}, while for gear *II* the motor's displacement is reduced, denoted as q_{smin}. In contrast, the transmission in gears *III* and *IV* is carried out using a mechanical transmission only, for these gears the capacity of the main pump is set to a minimum value of q_{pmin}. The selection of gears *III* or *IV* depends on the clutch C_1 or C_2 being engaged. During the grant, a prototype gearbox-dedicated, two-directional axial piston pump with electronic control was designed. This pump, compared to market solutions, has a displaced axis of rotation of the swash plate which results in a reduction in dead space volume and an increase in volumetric efficiency at small swash plate swing angles.

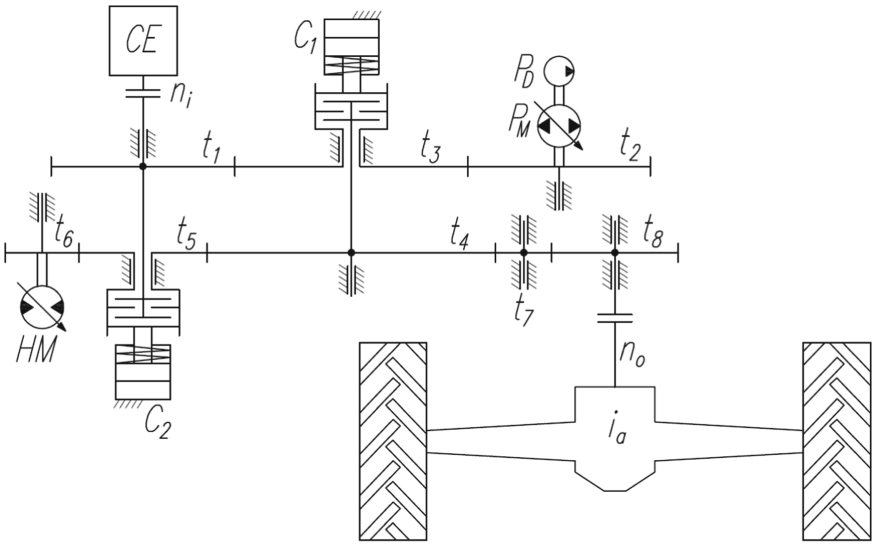


Fig. 1. Hydraulic-mechanical gearbox kinematic diagram: *CE* – combustion engine; C_1,C_2 – hydraulic couplings; *HM* – hydraulic motor; t_1-t_8 – gears; P_M – main pump; P_D – secondary pump; n_i – input speed; n_o – output speed; i_a – drive axle ratio.

1.1 Operation of the Axial Piston Pump with Swash Plate

The principle of the axial piston pump is illustrated in Fig. 2. The pump shaft (1) is connected by a spline to the cylinder drum (2), in which the cylinder chambers contain pistons (3) ending in slippers (7). The slippers slide on a swash plate (4). The swash plate is mounted in the pump housing and can swing relative to the centre of rotation (5). The contact of the slippers with the swivelling by an angle γ swash plate causes reciprocating movement of the pistons [5]. Each piston extends out of the cylinder chamber by a value of *s* for half a revolution of the drive shaft, and retracts into the cylinder chamber by the same distance for the second half revolution. The rotating cylinder drum (2) is pressed

against the fixed timing plate by a spring (9) and forces from the pressures acting on the drum surfaces. The timing plate, fixed in the pump housing, has kidney-shaped openings separated from each other by a timing bridge (13). The cylinder chambers from which the pistons extend are connected through a window (11) to the suction port of the pump, while the cylinder chambers into which the pistons insert are connected through a window (12) to the pressure port in the pump housing. In all standard pumps available on the market, the axis of rotation of the swash plate (5) intersects with the axis of rotation of the drive shaft and the plane on which the centres of the piston joints (3) are located.

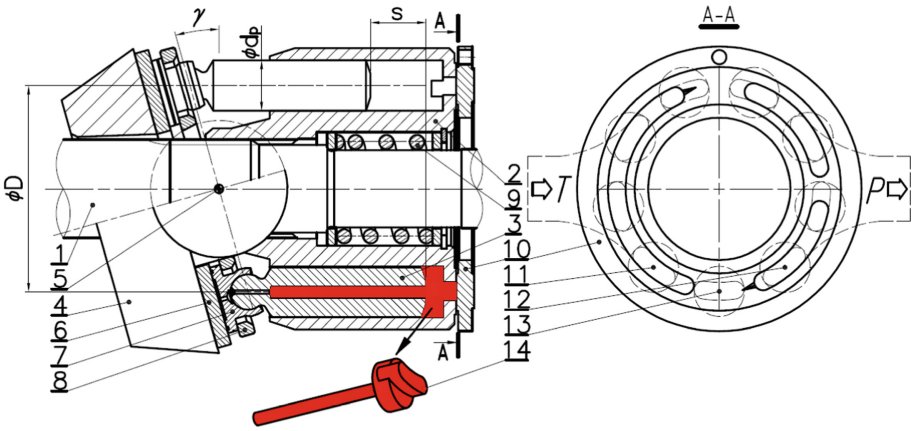


Fig. 2. Working mechanism of the axial piston pump: 1 – shaft; 2 – cylinder drum; 3 – piston; 4 – swash plate; 5 – swash plate axis of rotation; 6 – insert of swash plate; 7 – slipper; 8 – slippers separator; 9 – spring; 10 – timing plate; 11 – suction channel; 12 – delivery channel; 13 – timing bridge; 14 – dead space volume; γ – swing angle of swash plate; s – piston stroke; d_p – piston diameter; D – pitch diameter of drum; T – suction port; P – delivery port.

2 Dead Space Volume and Its Influence on the Volumetric Efficiency

The displacement volume of the pump, which depends on the swing angle of the swash plate, is:

$$V_s = \frac{\pi d_p^2}{4} \cdot D \cdot tan(\gamma). \tag{1}$$

The dead space volume, shown in Fig. 2 as (14), is the volume occupied by the working fluid in the cut-off cylinder chamber when the piston is in the extreme position at the end of the pressing phase [6, 7]. If the axis of rotation of the swash plate intersects the axis of rotation of the drive shaft, as in classical pumps of this type, the dead space volume is a function of the swash plate swing angle. For the maximum swing angle

of the swash plate γ_{max}, the dead space volume is the smallest and is V_{Dmin}. With decreasing swash plate swing angle, the dead space volume V_D increases according to the relationship:

$$V_D = V_{Dmin} + \frac{\pi d_p^2}{8} \cdot D \cdot \left[tan(\gamma_{max}) - tan(\gamma)\right]. \tag{2}$$

The relative dead space volume, i.e. the dead space volume related to the stroke volume at a specific moment [8], is:

$$\varepsilon_D = \frac{V_D}{V_s} = \frac{4 \cdot V_{Dmin}}{\pi \cdot d_p^2 \cdot D \cdot \tan(\gamma)} + \frac{1}{2}\left(\frac{\tan(\gamma_{max})}{\tan(\gamma)} - 1\right). \tag{3}$$

During pump operation, there is a pressure change cycling in the cylinder chambers. Analysing the operating conditions of one chamber, during the discharge phase this chamber is connected to the pressure port of the pump and a high pressure is there. When the cylinder chamber window passes through the dead point and timing bridge, when the piston is in its extreme position of maximum insertion into the cylinder drum, the fluid trapped in the dead space volume is cut off. Then there is a high pressure in the cylinder chamber. With further rotation of the shaft, this fluid expands into the suction collector window, thus affecting the volumetric efficiency of the pump. This phenomenon, due to the high pump shaft speeds, is influenced by the isentropic bulk modulus of the working fluid defined as [9]:

$$K_S = -V\left(\frac{dp}{dV}\right), \tag{4}$$

where V is the initial volume of the liquid, dV the change of volume under a change of pressure dp. The increase of the volume of the liquid ΔVc expanding from the dead space can be described as [10]:

$$\Delta V_c = V_D \cdot \frac{\Delta p}{K_s - \Delta p}. \tag{5}$$

Depending the volume of the dead space on the swing angle of the swash plate, we obtain:

$$\Delta V_c = \left[V_{Dmin} + \frac{\pi d_p^2}{8} \cdot D \cdot (tan(\gamma_{max}) - tan(\gamma))\right] \cdot \frac{\Delta p}{K_s - \Delta p}. \tag{6}$$

The volumetric losses caused by this phenomenon will depend on the pump speed n_r and the number of working chambers z:

$$\Delta Q_s = \Delta V_c \cdot n_r \cdot z. \tag{7}$$

When the suction manifold window is opened, there is no suction of liquid at the first moment, but a return flow of Q_s is created, which has the effect of reducing the amount of suctioned liquid and therefore limits the volumetric efficiency of the pump.

This phenomenon depends on the pressure and the relative volume of the dead space and is most evident at discharge pressures above 30 MPa and for swing angles of the swash plate less than 10°. The relative volume loss caused by this phenomenon is described by the relationship:

$$\Delta Q_{sw} = \left[\frac{4 \cdot V_{Dmin}}{\pi \cdot d_t^2 \cdot D \cdot tan(\gamma)} + \frac{1}{2}\left(\frac{tan(\gamma_{max})}{tan(\gamma)} - 1 \right) \right] \frac{\Delta p}{K_s - \Delta p}. \tag{8}$$

The volumetric efficiency of a pump is the ratio of the actual flow rate Q_r to the theoretical value Q_t [11, 12]. The actual flow rate is reduced from the theoretical value by leakage and the effect of fluid compressibility in the dead space:

$$\eta_v = \frac{Q_r}{Q_t} = \frac{Q_t - \Delta Q_l - \Delta Q_s}{Q_t}. \tag{9}$$

For improving the volumetric efficiency of a swash plate axial piston pump, leakage can be reduced, but these are necessary for the normal operation of the hydrostatic supports under the piston slippers and between the cylinder barrel and the timing plate. The second way is to reduce fluid compressibility losses in the dead space. In order to reduce the dead space volume, hollow pistons can be replaced by solid pistons. However, the specificity of the design of these pumps related to the position of the axis of rotation of the swash plate influences the fact that the dead space volume increases when the swing angle of the swash plate is reduced. In monograph [13], there was the idea of displacing the axis of rotation of the swash plate in such a way that the dead space volume was independent of the swash plate swing angle. This idea was developed in [14] which resulted in the design of prototypes of a pump with a displaced axis of rotation of the swash plate and the analytical and experimental confirmation of the effect of displacement of the axis of rotation on the increase of pump efficiency. As part of the work on the closed-circuit pump in the hydraulic-mechanical transmission, the problem was encountered. Changing the pumping direction with the same direction of rotation of the drive shaft involves swinging the swash plate to the other side from the neutral position. In classic pump designs, this is done as shown in Fig. 3.

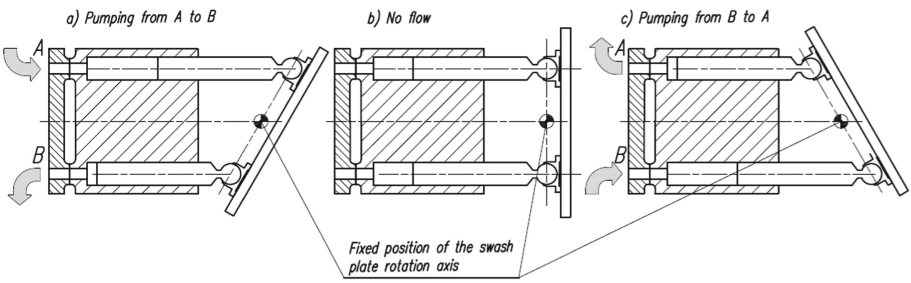


Fig. 3. Change of the pumping direction by change the swing angle of the swash plate in a piston pump of classic design, i.e., the axis of rotation of the swash plate intersecting with the axis of rotation of the shaft.

The method of changing the capacity in a pump with a displaced swash plate axis of rotation is shown in Fig. 4. In order to obtain a constant dead space volume in the pump,

independent of the swing angle of the swash plate, the swash plate rotation axis must be moved to position "*a*". With this position of the swash plate rotation axis, however, pumping is only possible in one direction. It is technically impossible to swing the swash plate in the opposite direction, as there is a danger of the swash plate colliding with the cylinder drum and the pistons colliding with the bottom of the cylinder chamber. This generates a serious design problem, since for one direction of discharge the swash plate rotation axis should be at one position, while for the opposite direction of discharge the swash plate rotation axis should be at a different position - rotated from the original by 180° relative to the shaft rotation axis (position "*b*"). This requires the design of a swash plate swing mechanism in which the swash plate rotation axis changes position at pump output '0', i.e. with the swash plate perpendicular to the shaft axis. Another design problem is that the load on the swash plate swing mechanism is much higher than with the traditional solution.

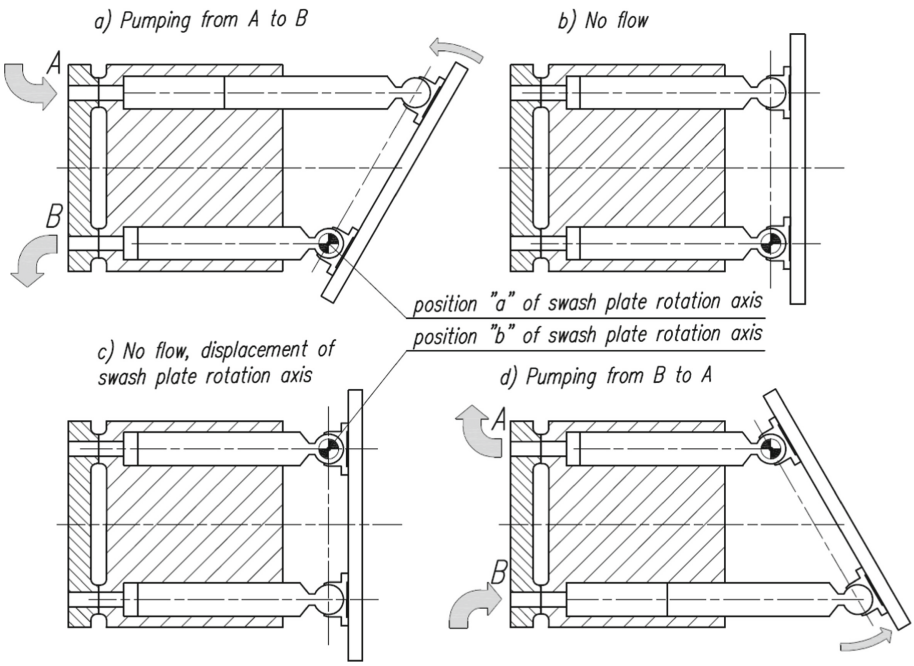


Fig. 4. Change of pumping direction by change of swing angle of the swash plate in a piston pump with a displaced axis of rotation of the swash plate.

A comparison of the relative dead space volume for a pump of classic design with a displaced swash plate axis pump is shown in Fig. 5. Clear differences are apparent for small swash plate swing angles, and clear increases in volumetric efficiency are expected there. Both characteristics apply to a pump with a displaced volume of 40 cm^3/rev and a minimum dead space volume of $V_{Dmin} = 3.24$ cm^3.

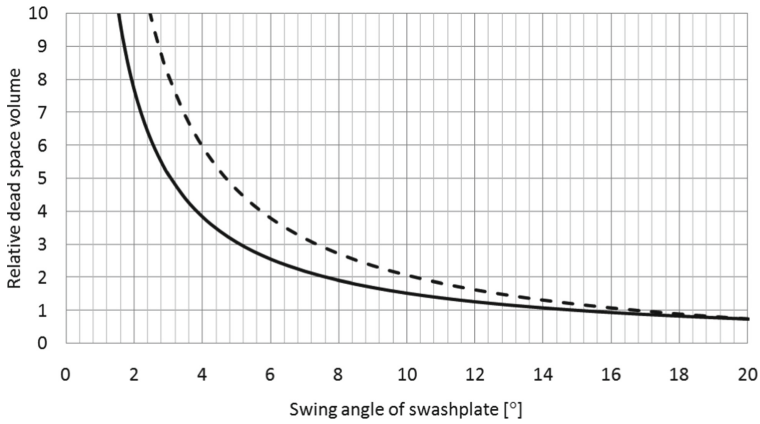


Fig. 5. Comparison of the relative dead space volume for a pump with the swash plate rotation axis intersecting with the shaft rotation axis (dashed line) and for a pump with the swash plate rotation axis displaced (solid line).

3 New Construction of the Pump

The main parameters of the designed pump with a displaced axis of rotation of swash plate for closed circuits with two discharge directions are shown in Table 1.

Table 1. Main parameters of pump.

Parameter	Value	Unit
Displacement q	40	cm^3/rev
Pistons spacing D	67	mm
Piston diameter d_t	15.17	mm
Number of pistons z	9	–
Dead space volume V_D	3.244	cm^3
Max. Swash plate swing angle γ_{max}	20	deg
Nominal pressure p	35	MPa

The cross-section of the pump operating mechanism is shown in Fig. 6. The innovation in relation to known designs is the support of the swash plate (10) on supports (5) moved by hydraulically powered pistons (13). When the swing angle of the swash plate is zero, the pistons (13) turn the supports (5) through the frame (14), which changes the position of the swash plate rotation axis (12) and enables pumping in the other direction. The pump is supplied with two displacement changing pistons (11), which are connected to a swash plate via connectors (9). Each piston is responsible for a given discharge direction. To change the pump's discharge direction, the capacity must be reduced to zero, then the swash plate supports (5) are overridden and the second piston is supplied. The

tracking mechanisms (15) controlled by stepper motors are responsible for controlling the flow of fluid to the pistons.

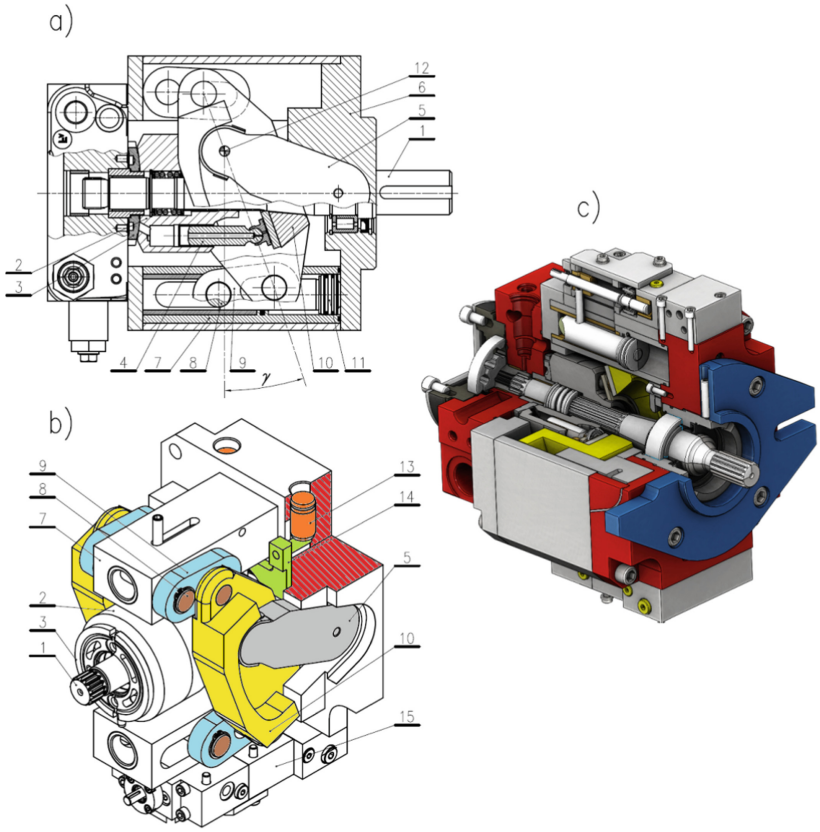


Fig. 6. Cross-section of the pump operating mechanism. a) main section, b) view of the working mechanism, c) view of the pump. 1 – shaft; 2 – cylinder drum; 3 – timing plate; 4 – piston; 5 – swash plate support; 6 – housing; 7 – cylinder of capacity change mechanism; 8 – pin; 9 – connector; 10 – swash plate; 11 – piston of capacity change mechanism; 12 – swash plate axis of rotation; 13 – support pivot piston; 14 – frame; 15 – valve tracking mechanism.

The hydraulic diagram of the pump is shown in Fig. 7. The main pump (1) with a fixed direction of rotation of the drive shaft is able to discharge in both directions. This is responsible for the capacity change pistons (14) controlled by valve tracking systems (9). The tracking system consists of a screw (12) screwed into a feedback pin (13), driven by a stepper motor (15) connected to a control plate (11) and a set of 4 check control valves (10). The valves control the flow to the respective chambers of the capacity change actuator. Connected to the main pump is a booster pump (2) protected by a relief valve (3), which limits the pressure in the line circuit of this pump to 20bar. The purpose of the booster pump is to create a suitable overpressure in the low-pressure line of the main pump. The main pump is protected by two relief valves (5). The capacity

change mechanisms are supplied from the high pressure line of the main pump via the alternate valve (4). The pivot mechanism of the swash plate supports (7) is supplied via a directional control valve (6) from the booster pump circuit. The pump is designed for closed-loop operation, i.e., a hydraulic motor mounted between the A and B branches is connected to the gearbox in Fig. 1.

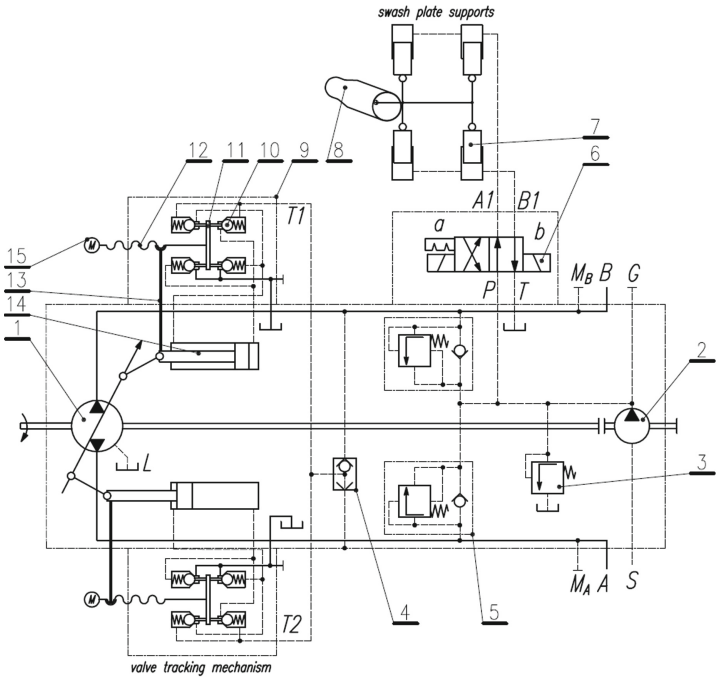


Fig. 7. Hydraulic diagram of the pump: 1 – main pump; 2 – secondary pump; 3 – relief valve; 4 – alternate valve; 5 – check-relief valve; 6 – directional valve 4/2; 7 – support pivot piston; 8 – swash plate support; 9 – valve tracking mechanism; 10 – check valve; 11 – control plate; 12 – screw; 13 – feedback pin with nut; 14 – capacity change actuator; 15 – stepper motor.

4 Conclusion

As part of the work on the LIDER project, a new pump design with a displaced swash plate axis of rotation was developed. This pump is dedicated to work in a closed circuit and, together with a hydraulic motor and mechanical gearbox, is part of a hydro-mechanical transmission dedicated to driving working machines such as telehandlers. Tests carried out on the prototype showed high efficiency and correct operation of the capacity-shifting system. Further work is planned to improve the dynamics of the capacity control and to increase the technology and reliability of the design.

Funding. This research was funded by The National Centre for Research and Development within the framework of program LIDER, grant number: LIDER/22/0130/L-8/16/NCBR/2017.

Project title: Hydro-mechanical automatic gearbox for agricultural vehicles and heavy machinery. Funding value: 1,197,500.00 PLN.

References

1. Soma, A.: Trends and hybridization factor for heavy-duty working vehicles. Hybrid Electr. Veh. 3–32 (2017)
2. Xiong, S., Wilfong, G., Lumkes, J.: Components sizing and performance analysis of hydro-mechanical power split transmission. Appl. Wheel Loader. Energ. **12**, 1613 (2019)
3. Patrosz, P., Bąk, M.: Metodologia badania skrzyni biegów z wykorzystaniem układu hydraulicznego jako hamowni. Napędy i Sterowanie, nr **11**, 95–101 (2020)
4. Bąk, M.: Torque capacity of multidisc wet clutch with reference to friction occurrence on its spline connections. Sci. Rep. **11**, 1–18 (2021)
5. Patrosz, P.: Influence of properties of hydraulic fluid on pressure peaks in axial piston pumps' chambers. Energies **14**, 3764 (2021)
6. Osiecki, L.: Wpływ przestrzeni martwej na straty energetyczne w pompach wielotłoczkowych. Hydraulika i Pneumatyka 3/2007 (2007)
7. Załuski, P.: Influence of fluid compressibility and movements of the swash plate axis of rotation on the volumetric efficiency of axial piston pumps. Energies **15**, 298 (2022)
8. Cho, J., Zhang, X., Manring, N.D., Nair, S.: Dynamic modeling and parametric studies of an indexing valve plate pump. Int. J. Fluid Power **3**, 37–48 (2002)
9. Gholizadeh, H.: Modeling and Experimental Evaluation of the Effective Bulk Modulus for a Mixture of Hydraulic Oil and Air. Ph.D. Dissertation, University of Saskatchewan, Saskatoon, Canada (2013)
10. Osiecki, L.: Wpływ przestrzeni martwej na straty energetyczne w pompach wielotłoczkowych. Hydraulika i Pneumatyka **27**, 12–15 (2007)
11. Patrosz, P.: Influence of gaps' geometry change on leakage flow in axial piston pumps. In: Stryczek, J., Warzyńska, U. (eds.) Advances in Hydraulic and Pneumatic Drives and Control 2020. NSHP 2020. Lecture Notes in Mechanical Engineering. Springer, Cham (2021). https://doi.org/10.1007/978-3-030-59509-8_7
12. Śliwiński, P.: The influence of water and mineral oil on volumetric losses in the displacement pump for offshore and marine applications. Pol. Marit. Res **26**, 173–182 (2019)
13. Osiecki, L.: Mechanizmy rozrządu hydraulicznych maszyn wielotłoczkowych osiowych. Wydawnictwo Politechniki Gdańskiej, Gdańsk, (2006)
14. Załuski, P.: Wpływ położenia osi obrotu wychylnej tarczy na sprawność objętościową pomp wielotłoczkowych osiowych. Ph.D. Dissertation, Gdańsk University of Technology (2017)

Identification of Specific System Parameter Space in Initial Research Stage

Andrius Macutkevičius and Raimundas Junevičius(✉)

Vilnius Gediminas Technical University, Vilnius, Lithuania
{andrius.macutkevicius,raimundas.junevicius}@vilniustech.lt

Abstract. High fidelity models are a good point to start investigation or design process. These models can be used to determine main parameters, to state its ranges ant to set an equilibrium between the parameters. Using these type models together with sensitivity analysis it is possible to make a clear picture about the problem on which the research is focussing. An application of such analysis presented in this paper. Some specific four input parameters of simplified physical system are selected to show variation of a few system outputs. Input parameter set is generated using Monte Carlo method. Article is summarized with the results and conclusions, which shows method and parameters influence to simulation results.

Keywords: Electric vehicle · Sensitivity analysis · Monte Carlo method

1 Introduction

1.1 Sensitivity Analysis

Electric vehicles on road simulation models have a number of electrical components which increases the complexity of analysis. Creating models to calculate system parameters, mathematically described physical processes are not needed. As a result of modelling, system features should be obtained and that not always can be to describe scientifically [5]. Information extracted form model can state a view about system parameters and help to make decisions in early stages of engineering. In some cases patterns can't be noticed without any mathematical methods [4]. Also, mathematical analysis method makes results more unbiased. Sensitivity analysis are essential Earth and environmental systems modelling paradigm [3]. This method makes accurate parameters ranking in interdisciplinary models and helps to define system parameters and characteristics dependencies. But sensitivity analysis also correlates with uncertainties in the model, if model is analysed and parameters do not match properly to it, uncertainties arise. That mean parameters sensitivity evaluation can't be done properly. Sensitivity analysis consist of: question or task formulation, suitable model for parameters changing analysis choose, before analysis need to know what to expect from model [6]. Sensitivity analysis analyse different simulation results with changed model parameters.

Results can be presented in different types of graph, but most convenient hypothetic characteristics surface. Example shown in Fig. 1. There is the surface which colored according to characteristic "y" value depends on model parameters value "x_1" and "x_2".

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 375–382, 2023.
https://doi.org/10.1007/978-3-031-25863-3_35

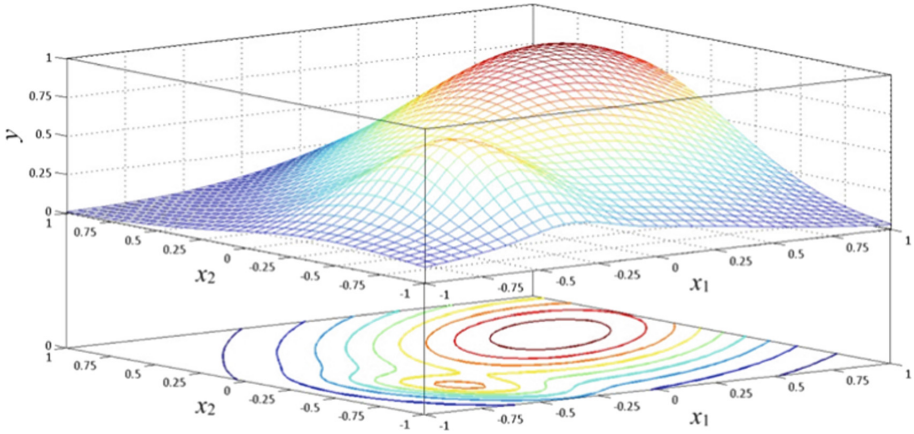


Fig. 1. Hypothetic characteristics surface, shows model characteristic values y according to different x_1 and x_2 values [3].

1.2 Monte Carlo Method

Monte Carlo method will be used for parameters sampling. This method based on random parameter generating. Only parameters that can be set is rage of possible parameters and probability density function. Range settings use to make realistic for parameters values. Probability density function can be used different according to parameters. In Fig. 2 shown three types of function, but in Monte Carlo method mainly used C type. In mentioned type probability density is the same in all range. This means that all values can be generated with the same probability.

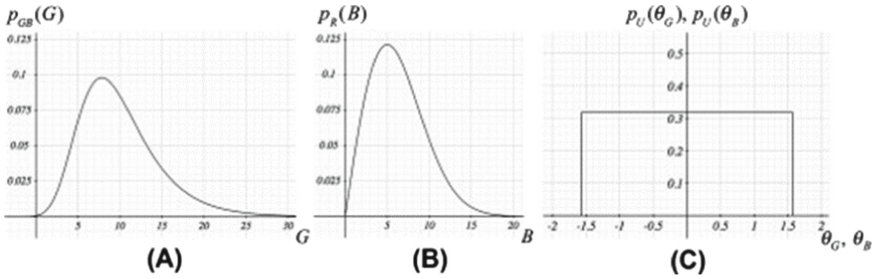


Fig. 2. Different probability density function in range of parameters values [2].

Data set is made as a result of this sampling. In this data are stored all dependencies from model and can be analyzed using sensitivity analysis or other data mining methods.

2 Modelling of Electric Vehicle

This section explains how the performance of each system component is calculated by assuming that electric vehicle overcome by road loads.

Acceleration force is needed to overcome vehicle inertia and make vehicle to move with acceleration. This acceleration can be positive to gain the speed or negative to stop.

$$F_{acc} = ma, \tag{1}$$

where m is the vehicle mass, a is acceleration.

Rolling resistance is produced in tire contact with the road. This force correlate with normal load force and act to wheel in opposite to rolling direction:

$$F_{roll} = C_0\, mg\ \cos(\beta), \tag{2}$$

where C_0 is rolling resistance coefficient, g is the acceleration due to gravity, β is hill angle gradient.

Aero-Dynamic drag force is the viscous resistance of air working against speed vector of vehicle. This force appears in front vehicle body surface.

$$F_{aero} = 0.5v^2\, C_D \gamma A, \tag{3}$$

where v is vehicle speed, C_D is the drag coefficient according to vehicle body, γ is the air density and A is the front cross-sectional area of the vehicle.

Gravity force acting the vehicle in situations when road goes uphill or downhill. This gradient force depends on the slope of the road and weight of the vehicle.

$$F_{grad} = mgsin(\beta). \tag{4}$$

The total load to vehicle

$$F_l = F_{acc} + F_{roll} + F_{aero} + F_{grad}. \tag{5}$$

To compute torque occurring at the vehicle engine it is necessary to include tire diameter and transmission ratio

$$M_{en} = F_l r_{wheel}\, i_{trans}, \tag{6}$$

where r_{wheel} is wheel tire radius, i_{trans} is transmission ratio.

Power can be obtained as:

$$P_{veh} = vF_l \tag{7}$$

In case of electric vehicle, braking power it can be produced from regeneration. During regeneration, energy is transmitted from the wheels through motor to the battery. Therefore, in experiment there are three scenarios: power consumption, power regeneration and then power is equal to 0.

By integrating the total power over time, is calculated the total energy consumption E

$$E_{veh} = \int P_{veh} dt. \tag{8}$$

Battery energy usage is calculated by,

$$E_{bat} = \frac{E_{veh}}{t}, \tag{9}$$

where t is time.

System current calculated from electrical energy expression as,

$$I_{en} = \frac{E_{bat}}{U_{bat}}, \tag{10}$$

where U_{bat} is voltage of the battery. In addition, it is calculated from data provided by battery cell or battery pack producer. In this paper battery cell, information presented in Fig. 3.

To know used up energy from battery pack in every time step, battery state of charge is calculated using data from Fig. 3 as

$$SOC = SOC_0 - \int \frac{I_{en}}{Q_{bat}} dt, \tag{11}$$

where SOC battery state of charge, SOC_0 initial state of charge Q_{bat} is battery capacity.

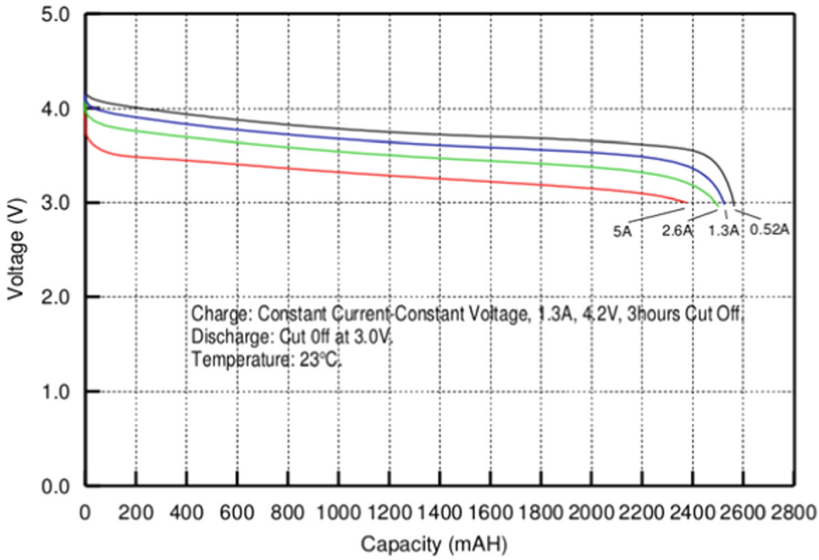


Fig. 3. Battery voltage chart according to capacity and system current [1].

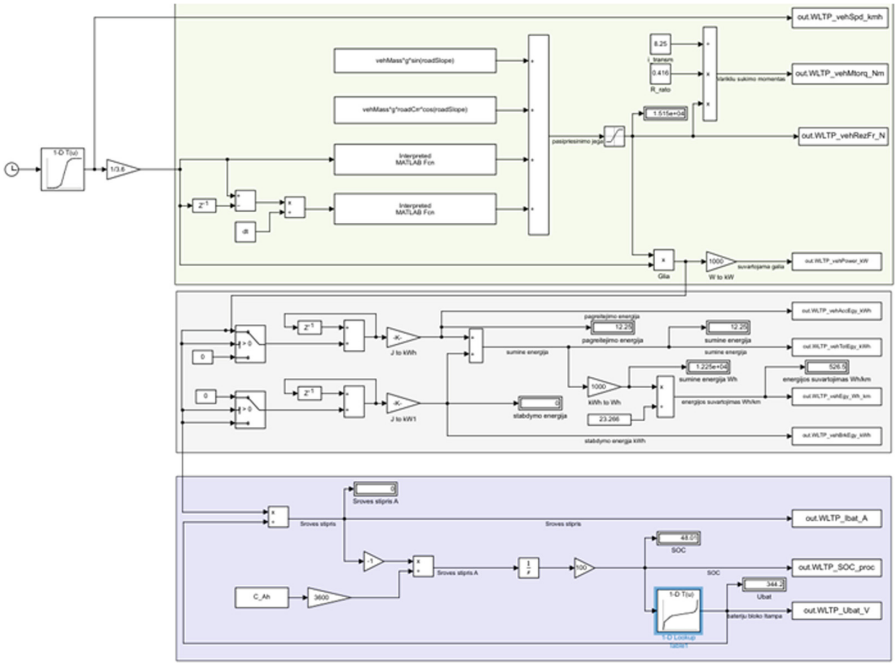


Fig. 4. Electric vehicle model Simulink scheme: vehicle loads (green block), power distribution (grey block), battery parameters calculation (blue block).

All specified parameters framework is used to compose MATLAB model. Model scheme shown in Fig. 4. As model, input used WLTP driving cycle vehicle speed. WLTP cycle is divided in different parts of driving scenarios from city to highway, this makes synthetic drive cycle close to real driving.

3 Results

Sensitivity analysis aims to determine interdependencies between parameters. Also, possible range of parameters for the final vehicle should be identified. Initial electric vehicle range of parameters for sampling shown in Table 1. Vehicle mass with full equipment could be from 3,000 kg up to 5,000 kg. Such a big range of vehicle mass is selected taking into account influence of the battery pack. Battery mass can add up one third of vehicle mass. Coefficient of drag and road profile slope angle are changeable on purpose of different road conditions. Those parameters also useful when choosing battery parameters. Generated results of 100 samples given in Fig. 5. Energy consumption form batteries correspond with vehicle mass, coefficient of drag and slope angle values. These parameters plays big influence to vehicle loads. From the charts in Fig. 5 can be noticed that energy consumption correlates with battery voltage and current. Meanwhile state of charge depends on battery capacity and vehicle mass. In simulation, all results received using the same WLTP driving cycle.

Table 1. Electric trips used for sensitivity analysis.

Parameter	Value	
	Min	Max
Vehicle mass, kg	3,000	5,000
Coefficient of drag	0.3	0.6
Slope angle, rad	0	0.6
Battery capacity, kWh	40	200

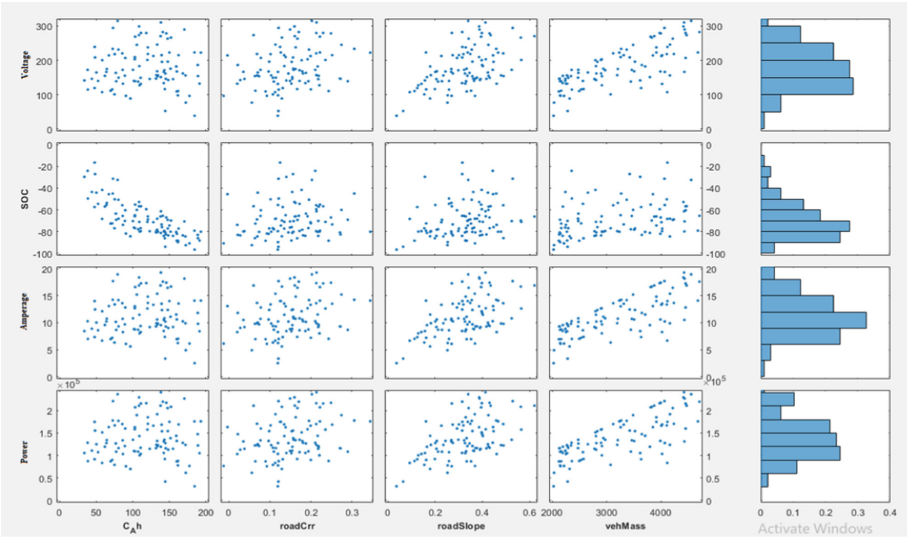


Fig. 5. Sampled using Monte Carlo method data plots/

Vehicle characteristics sensitivity results to model parameters validates the trends of parameters that was identify before. Characteristics such as power consumption, battery current and voltage have similar influence on the system. In selected ranges, battery parameters mostly affect vehicle mass, secondly coefficient of drag and road slope. Battery capacity less correlates with vehicle load parameters. State of charge mainly affects battery capacity, and it is a limitation of the model because battery mass variation is not reflected in data set.

To determine best set of the parameters hypothetic characteristic surfaces are used. From results, it is seen that main parameters that affect all vehicle characteristics and do not have clear correlation are vehicle mass and battery capacity (Fig. 7). Certainly, battery mass affect vehicle very significantly, and it shows that input parameters should be selected carefully for the analysis.

From the results, it is seen main model parameters and its relationship with each other or output parameters. For example, it is necessary to determine vehicle size, weight and

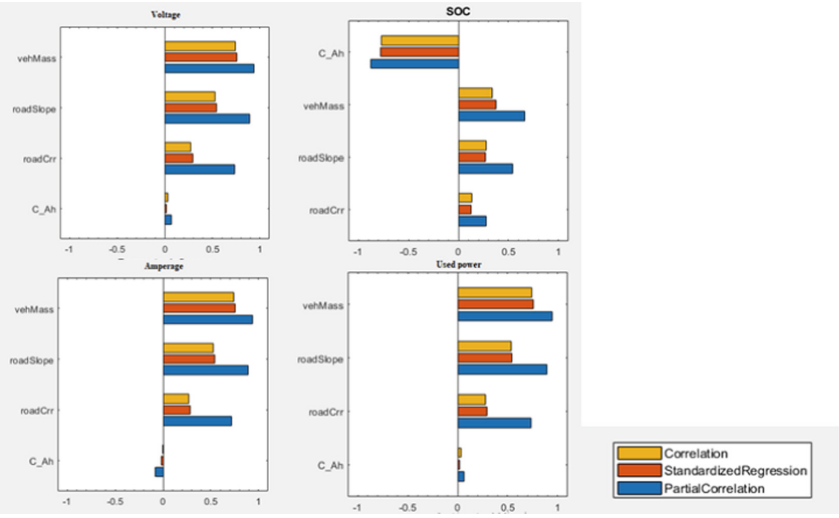


Fig. 6. Vehicle parameters influence on characteristics.

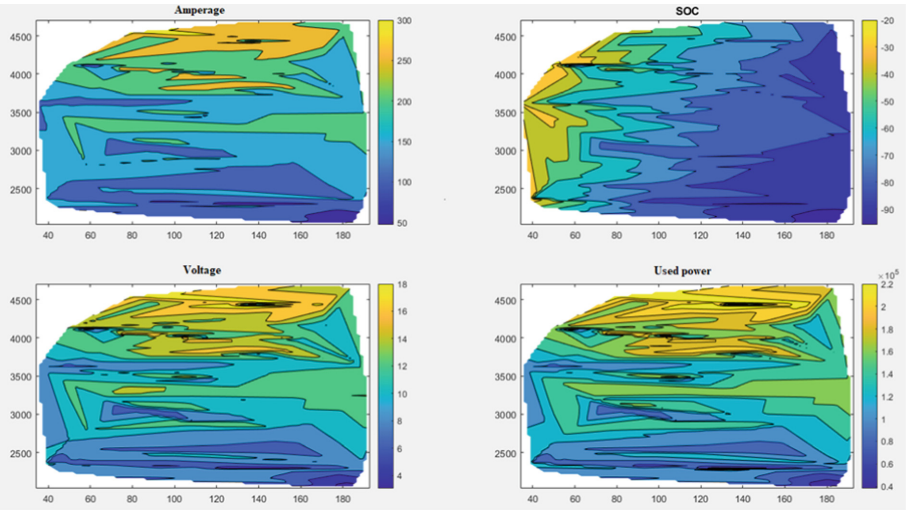


Fig. 7. Hypothetic characteristics surface of battery capacity and vehicle mass influence on characteristics.

to forecast necessary battery pack size, motor parameters or to set other parameter value range. This kind of simulation can help to do that. In Fig. 5, 6 and 7 it is shown how these parameters variation affects vehicle concept. Having these data researcher or product developer can see more precisely with what vehicle concept he is working with. In this particular example, power was taken as output value together with four inputs. In Fig. 7 it is seen how vehicle mass and battery SOC variates when vehicle drives one WLTC cycle. From the visualised data some specific range of parameters pops up with extremely

changing values. So, these intervals can be used as research targets to understand better system behaviour.

4 Conclusion

1. Results shows that for initial simulation and system analysis it is possible to use in general simple models. It saves time and forces to focus on the problem but not on system model. In addition, it helps better understand the problem and to save time in the next research steps.
2. Input parameters and output parameters for the analysis should be selected carefully. It affects results so recommendation is to set parameter interaction with each other before selecting final set.
3. To understand system response to input parameters all hypothetic characteristic surfaces should be used in analysis. These helps to identify specific parameter space for future analysis and product development.

References

1. EV design – battery simulation | ESI Group. (n.d.). https://www.scilab.org/ev-design-battery-simulation. Accessed 11 Sept 2022
2. Kabe, A.M., Sako, B.H.: Chapter 7—Probability and statistics. In: Kabe, A.M., Sako, B.H., (eds.), Structural Dynamics Fundamentals and Advanced Applications, pp. 513–653. Academic Press. (2020). https://doi.org/10.1016/B978-0-12-821615-6.00007-1
3. Razavi, S., Gupta, H.V.: What do we mean by sensitivity analysis? The need for comprehensive characterization of global sensitivity in Earth and environmental systems models. Water Resour. Res. **51**(5), 3070–3092 (2015). https://doi.org/10.1002/2014WR016527
4. Rodríguez, S.S.: Advance data mining for Monte Carlo simulation in project management. Procedia Technol. **9**, 705–711 (2013). https://doi.org/10.1016/j.protcy.2013.12.078
5. Rosen, R.: Life itself: a comprehensive inquiry into the nature, origin, and fabrication of life. 104334. https://repository.library.georgetown.edu/handle/10822/545203 (1991)
6. Saltelli, A., Ratto, M., Tarantola, S., Campolongo, F.: Sensitivity analysis practices: strategies for model-based inference. Reliab. Eng. Syst. Saf. **91**(10), 1109–1125 (2006). https://doi.org/10.1016/j.ress.2005.11.014

Comparison of Mathematical Models of Torque Transmitted by Multi-disc Wet Clutch with Experimental Results

Marcin Bąk[1](✉), Piotr Patrosz[1], Paweł Śliwiński[1], Paweł Załuski[1], and Mykola Karpenko[2]

[1] Gdansk University of Technology, Gdansk, Poland
marcin.bak@pg.edu.pl
[2] Vilnius Gediminas Technical University, Vilnius, Lithuania

Abstract. In the paper results of experimental tests on a multi-disc wet clutch are presented. Typical, single-sided multi-disc wet clutch was analysed. Experimentally obtained data present torque capacity of the clutch with varying number of friction surfaces. The results are also compared to characteristics obtained based on several known mathematical models. It was found that differences between most of known models describing torque transmitted by clutches and experimental results are considerable. The best correspondence between model and experiment was reached for Bąk's model. Nevertheless, differences between the model and data gained via experiment might differ substantially i.e., characteristic of proposed model are mostly shifted upwards in relation to experimental characteristics. The paper also includes a brief description of a test stand and its scheme. The article presents also a figure which contains diagrams presenting all characteristics as functions of average contact pressure on friction surfaces.

Keywords: Multi-disc clutch · Friction · Mathematical models · Experiments

1 Introduction

As a result of observable growth of application of semi and full powershift transmissions in heavy machinery like tractors, military vehicles or telescopic handlers, it is critical to gain knowledge about effects occurring in a wet clutch [1, 2]. It is especially important due to a number of clutches applied in those types of transmissions and their critical role in power transmission. Powershift transmission might have even more than ten wet clutches [2]. Therefore, a properly designed clutch with its dimensions and number of discs matching requirements is important. It might enhance design of assembly that correctly fulfils vital requirements such as sufficient torque capacity, minimalized number of discs of a clutch. Moreover, it is also required that slippage of the clutch will not occur. Unwanted slippage of engaged clutch would reduce efficiency of a vehicle. It would be extremely undesirable in relation to current trend, because many scientists concentrate on enhancing efficiencies through novel devices or improvements of already existing devices [2–6].

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 383–392, 2023.
https://doi.org/10.1007/978-3-031-25863-3_36

Multi-disc wet clutch is a clutch with multiple friction surfaces. It transmits torque due to friction occurrence on contacting discs. Increased number of friction surfaces, which is equivalent to increased number of discs comprising a clutch, allows to transmit higher torque compared to a clutch with only one friction surface. Typically applicable multi-disc is shown in the Fig. 1. Clamping force exerted on friction and separator discs causes engagement of the clutch. Therefore, torque is transmitted between two elements (input and output shafts) due to aforementioned friction. Disadvantages of multi-disc clutches relate to deformation of friction and separator discs, as well as blocking and pressure plates. Those effects might lead to non-uniform pressure distribution on contact surfaces [7–9].

In this paper, selected known mathematical models describing multi-disc clutches are presented. Characteristics obtained from those models are compared to experimental results. The results are presented for a clutch with defined dimensions, for a varying number of friction surfaces.

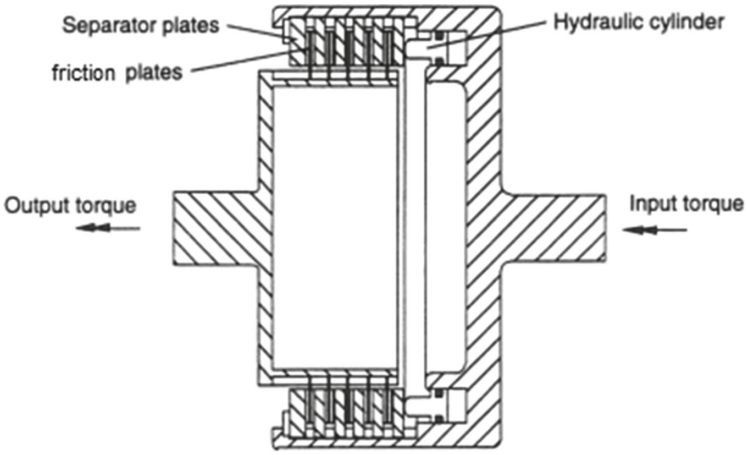


Fig. 1. Multi-disc wet clutch [10].

2 Mathematical Models

A typical model of a multi-disc clutch with a single-sided clamping of the plate pack is shown in Fig. 2. Friction discs with an internal spline e are connected to the shaft d, while discs f with an external spline are connected to the hub b. The clutch transmits torque to the hub from the shaft or in reversed direction, depending on the direction of transmission. This package is clamped by the axial force F_a exerted by the pressure plate c on the first plate. According to the model shown, the first disc is the separator disc. The blocking plate a restricts movement of clutch package in axial direction.

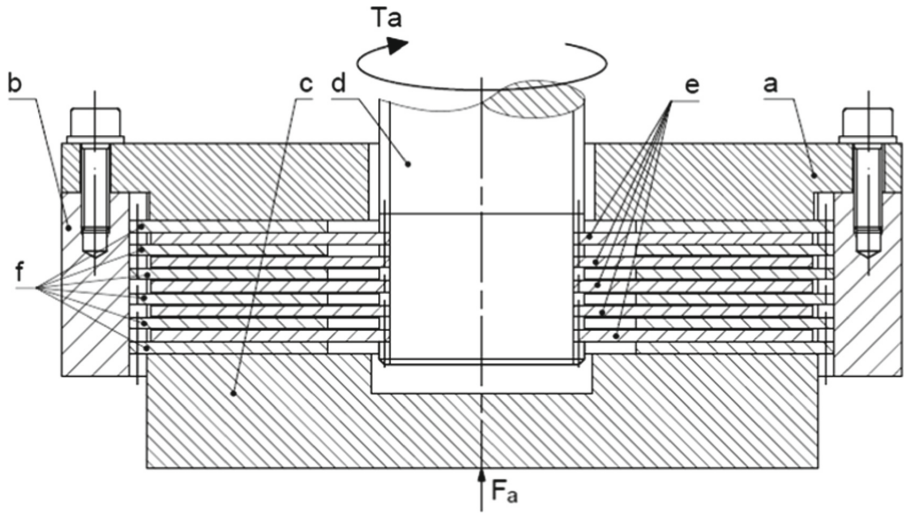


Fig. 2. Simplified sectional view of clutch assembly: a – blocking plate, b – hub, c – pressure plate, d – shaft, e – friction discs, f – separator discs, F_a – axial force, T_a – torque transmitted by a clutch [11].

In an engaged multi-disc clutch alternately mounted discs rotate at the same angular velocities. Therefore, in the models presented in this section, viscous friction is ignored [12]. In this case, the torque to be transmitted can be determined from widely known formula [10]:

$$T_a^{n_{pow}} = n \cdot T_t, \tag{1}$$

where n and T_t refer to number of friction surfaces and theoretical torque transmitted by single friction surface while friction forces appearing on splines are neglected. Theoretical torque T_t might be calculated with following equation:

$$T_t = \mu \cdot r_m \cdot F_a, \tag{2}$$

where μ is friction coefficient for a pair of clutch discs and r_m refers to a mean radius defined as:

$$r_m = \frac{2}{3} \frac{R_o^3 - R_i^3}{R_o^2 - R_i^2}. \tag{3}$$

Radius R_o and R_i are illustrated in Fig. 3.

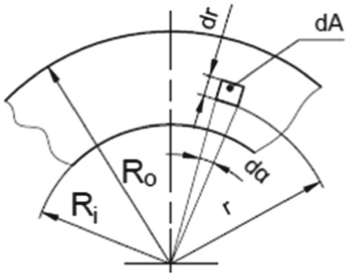


Fig. 3. Dimensions of friction surface [13, 14].

Formula (1) does not take into account friction in spline connections. These forces are considered in a model developed by Osinski [15]:

$$T_{os} = k_{os} \cdot n \cdot T_{\mathrm{t}}, \tag{4}$$

where k_{os} is a coefficient defining torque reduction depending on the number of friction surfaces n of the clutch. Values of the k_{os} coefficient are shown in Table 1.

Table 1. Values of coefficient k_{os} [15].

Number of friction surfaces	2	3	4	5	6	7	8	9	10
Coefficient k_{os}	1	0.97	0.94	0.91	0.88	0.85	0.82	0.79	0.76

Unfortunately, model proposed by Osinski applies arbitrarily assumed values of k_{os} coefficient. Influence of spline types or their standards is not taken into consideration in this model. Therefore, application of Eq. (4) might cause significant errors and faulty performances of wet clutches.

A mathematical model proposed by Bąk describing torque transmitted by multi-disc clutch is shown below (Eq. (5)) [14]. According to the model, torque T_t^a is a sum of elementary torque transferred by each of i_{pc} friction surfaces.

$$T_t^a = F_a \cdot C \cdot \frac{d_{po}}{2} \cdot cos\alpha_o \cdot \sum\nolimits_{i_{pc}=1}^{n} \left[\left(\frac{\frac{d_{pin}}{2} \cdot cos\alpha_{in} - C \cdot \mu_{in}}{\frac{d_{pin}}{2} \cdot cos\alpha_{in} + C \cdot \mu_{in}} \right)^{\frac{i_{pc}}{2}} \cdot \frac{\left(\frac{d_{po}}{2} \cdot cos\alpha_o - C \cdot \mu_o \right)^{\frac{i_{pc}-1}{2}}}{\left(\frac{d_{po}}{2} \cdot cos\alpha_o + C \cdot \mu_o \right)^{\frac{i_{pc}-1}{2}+1}} \right], \tag{5}$$

where α, d_p refer to pressure angle and pitch diameter of a spline, respectively. Subscripts o and in relate to external and internal splines. The same applies to μ_o and μ_{in}, which describe friction coefficient appearing on external and internal splines. Constant C is described by equation:

$$C = r_m \cdot \mu. \tag{6}$$

It is common that average contact pressure is applied in Eqs. (2) and (4) instead of axial force F_a. Average contact pressure p appearing on a friction surface might be

calculated with expression:

$$p = \frac{F_a}{\pi(R_o^2 - R_i^2)}. \tag{7}$$

3 Experiments

3.1 Test Stand

In order to carry out research on multi-disc clutches a test stand was designed. The test stand gives opportunity to study torque capacity and durability of the clutch, hence versatility of the device is its main advantage. It allows also to conduct other tests of clutches, such as time of an engagement and disengagement or drag torque.

Test stand is presented in the Fig. 4. The torque transmitted by the clutch is measured by torque transducer. The torque transducer also connects hydraulic motor shaft with the apparatus shaft. The device during torque capacity tests works as a multi-disc brake. During those tests the hub is stationary, connected to test stand foundation, while the shaft rotates with friction discs. Separator discs are mounted in the hub, alternately with friction discs.

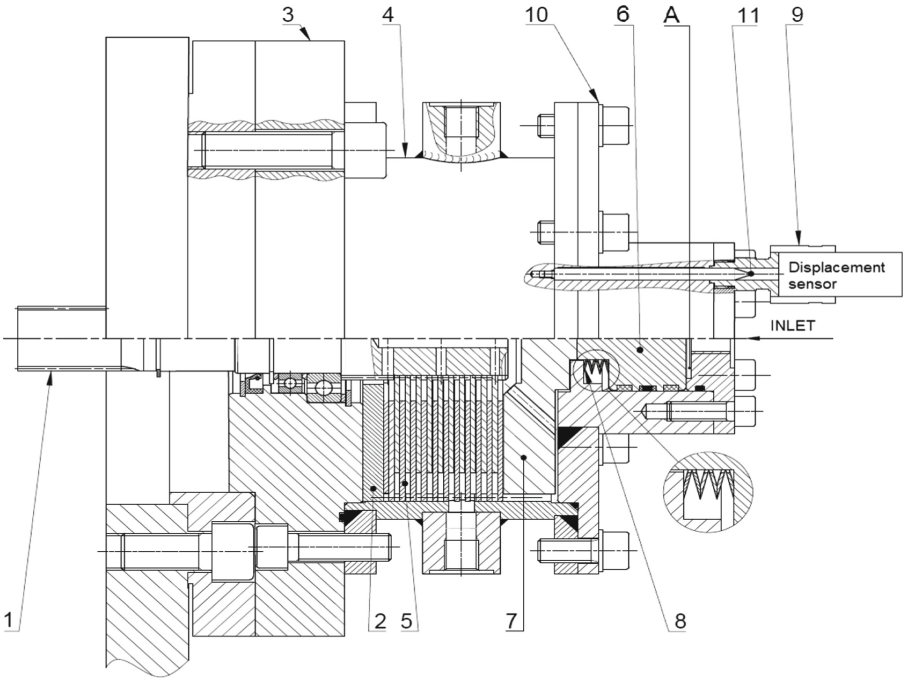


Fig. 4. Test stand: 1 – shaft, 2 – blocking plate, 3 – cover, 4 – hub, housing, 5 – clutch plates, 6 – piston, 7 – pressure plate, 8 – package of disc springs, 9 – displacement sensor holder, 10 – cover, 11 – position sensor tappet, A – actuator chamber [14].

As previously stated, the test stand allows conducting experiments for different combinations of number and dimension of friction and separator discs. Torque capacity of the clutch depends on axial force generated by the hydraulic actuator and the clutch itself. The axial force depends on pressure in the actuator chamber *A*. Axial force is applied by the piston to the pressure plate. Occurrence of axial force causes clamping of the clutch discs, hence engagement of the clutch.

Hydraulic circuit that supplies hydraulic actuator and motor is shown in the Fig. 5. For research on torque capacity tests a procedure was established. First, pressure p_1 was adjusted by valve ZP_1. Then, set-up of ZP_3 valve was slowly increasing, up to the moment when slippage occurred, which meant that torque capacity of the clutch had been exceeded. After the described cycle, the process continued further but with increased adjustment of ZP_1 valve. Between subsequent cycles force was not exerted on the pressure plate and shaft of hydraulic motor rotated at low rotational velocity for at least several seconds. An aim of the actions was to provide lubrication of every part of friction surfaces.

Axial force applied to the discs package is determined by pressure in actuator S_z chamber (A in Fig. 4) and varies as a function of pressure p_z adjusted by relief valve ZP_1. Rotational velocity of hydraulic motor SH is set by two-port adjustable flow control valve RP. The valve set-up was adjusted to ensure rotational speed n of motor during disengagement of the clutch that does not exceed a hundred rpm. Maximum torque appearing on hydraulic motor shaft depends on adjustment of pressure p_3. All the signals from the sensors were recorded by Hydac HMG 4000.

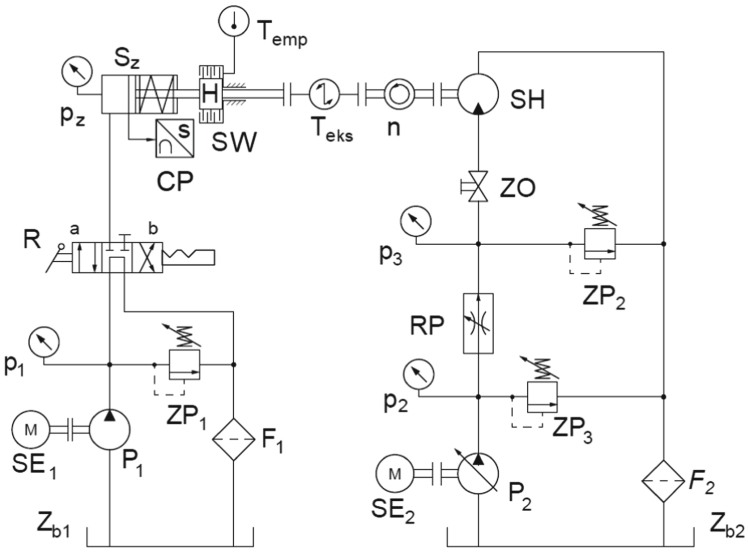


Fig. 5. Hydraulic system supplying actuator and motor: P – pumps, ZP – relief valve, ZO – ball valve, RP – flow control valve, p – pressure transducers, R – 4/3 directional valve, CP – displacement sensor, F – filters, SH – hydraulic motor, S_z – actuator, T_{emp} – temperature transducer, SW – clutch, T_{eks} – torque transducer, n – angular velocity sensor, SE – electric motor, Z_b – oil reservoir.

3.2 Object of Research

The subject of the study was a clutch consisting of steel discs. The discs were made of relatively soft S355 steel. The faces of the discs were ground and their roughness was less than Ra < 1.25 at the start of the research. Splines were manufactured according to DIN 5480 standard. The friction discs had 22 teeth and their module were 1.5 mm, while separator discs had 45 teeth and module equal to 3 mm. The internal diameter of separator discs were equal to 80 mm ($R_i = 40$ mm), while external diameter of friction discs were

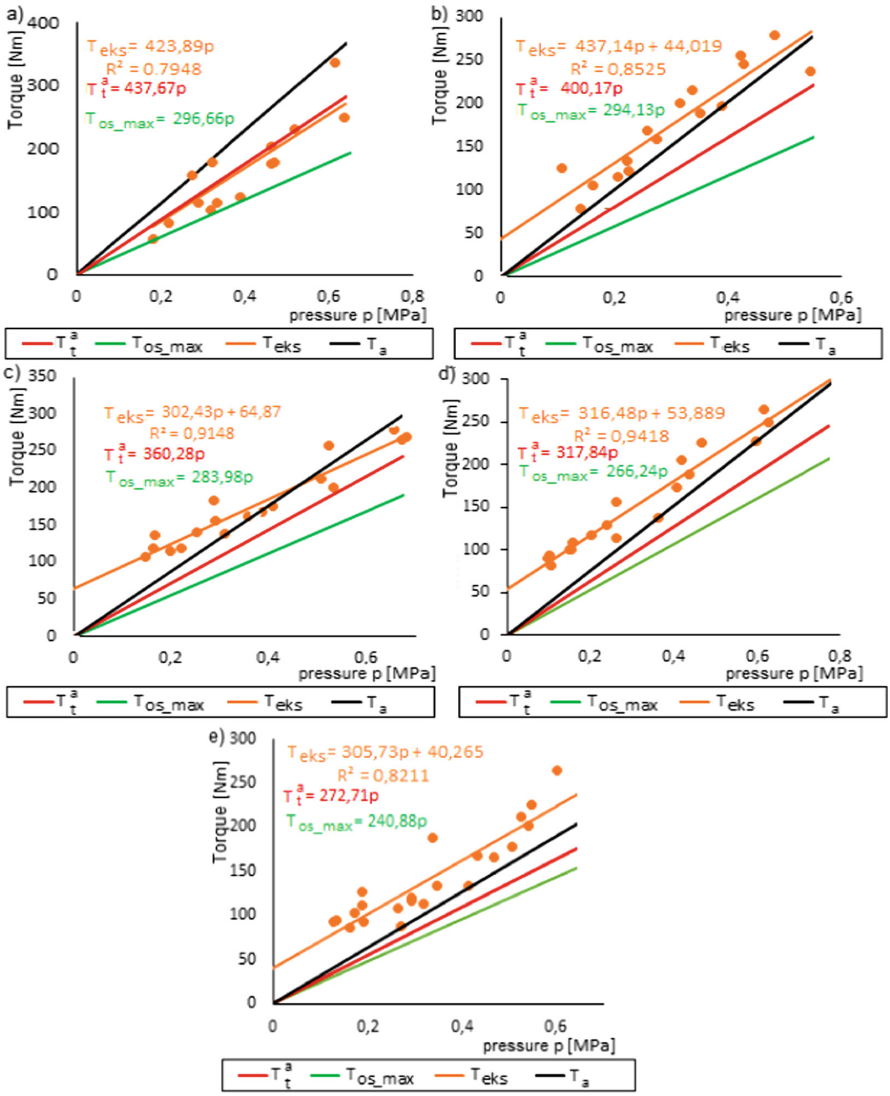


Fig. 6. Characteristics of torque transmitted by multi-disc wet clutch: $R_i = 40$ mm, $R_o = 57.5$ mm. Number of friction surfaces: a) 18; b) 16; c) 14; d) 12; e) 10.

115 mm ($R_o = 57.5$ mm). Therefore, alternately mounted separator and friction discs formed annular friction area between of internal diameter 80 mm and outer diameter 115 mm. Thickness of all discs were equal to 2 mm.

3.3 Results

Results of experiments T_{eks} and characteristics obtained based on Eqs. (1), (4) and (5) are shown in Fig. 6. The characteristics are illustrated as functions of average pressure p (Eq. (6)). The Fig. 6 includes also equations describing characteristics T_{eks}, T_{os_max}, T_t^a. Characteristics T_{os_max} were calculated with Eq. (4). For analysis purposes it was assumed that value of friction coefficient was maximum i. e. $\mu = 0.12$ [15]. The same value of friction coefficient was assumed for coefficients μ_o and μ_{in}. The lowest value of correlation coefficient is 0.89 (Fig. 6a). It indicates very strong correlation between results of experiments and trend line T_{eks}.

4 Discussion

All characteristics shown in Fig. 6 are linear. It can be seen in all figures that the T_{eks} torque reach significantly higher values than the T_{os_max}. Therefore, it is indisputable that design of clutch based on Osinski model (Eq. (4)) might lead to significantly oversized multi-disc clutch. It might happen even if the highest values of friction coefficient μ are assumed. Similarly, the T_t^a functions reach noticeably higher values compared to the T_{os_max} characteristics. Figure 6a shows that the T_{eks} and T_t^a functions have similar values. It demonstrates a very good correlation between the mathematical model (Eq. (5)) and the experimental results.

It can be seen in other diagrams that differences between slope angle of the T_t^a and T_{eks} characteristics are minimal. However, the T_{eks} functions are shifted upwards with respect to T_t^a. Despite a noticeable scatter of measurement points for low values of pressure p, which difference reach several tens of Nm, a very good agreement between the T_{eks} characteristic and the experimental results is obtained.

It is presumed that positive values of T_{eks} for $p = 0$ MPa (Fig. 6b–e) are caused by roughness of adjacent discs and adhesive forces between discs [11].

5 Conclusion

The article includes mathematical models which describe torque capacity of a clutch. The paper also involves graphs showing both experimentally and analytically obtained characteristics of torque transmitted by mutli-disc wet clutch. The test stand and methodology of experiments are briefly described in chapter 3.

Every configuration of tested multi-disc clutches indicate that the model proposed by Bąk gives better accuracy than previously known models (Eq. (1), Eq. (4)). Therefore this model ought to be taken into account during clutch design process.

Nevertheless, it is necessary to conduct further tests in order to verify correspondence between the model and results of experiments. Deformations of discs should be

taken into consideration, as well as their thickness. In order to reduce torque T_{eks} for $p = 0$ MPa which reach significant values it is recommended to assess and replace all clutch discs after each serie of an experiment. As a result of such actions wear of discs should be minimalized. Consequently, differences between results of experiments for approximately the same contact pressure p should be reduced as well.

Acknowledgments. The article includes the research conducted in PhD thesis of the corresponding author and a project funded by The National Centre for Research and Development within the framework of program LIDER:

Project no.: LIDER/22/0130/L-8/16/NCBR/2017

Project title: Hydro-mechanical automatic gearbox for agricultural vehicles and heavy machinery

References

1. Patrosz, P., Bąk, M., Załuski, P., Śliwiński, P., Karpenko, M.: Methodology of experimental research on efficiency of hydro-mechanical automatic gearbox. In: Lecture Notes in Intelligent Transportation and Infrastructure; publication status: in Process (2022)
2. Renius, K.T.: Fundamentals of Tractor Design; Springer International Publishing: Cham (2020)
3. Banaszek, A.: Identification of optimal efficiency exploitation conditions of axial-piston hydraulic motor A2FM type using artificial neural network algorithms. Procedia Comput. Sci. **192**, 1532–1540 (2021)
4. Załuski, P.: Influence of fluid compressibility and movements of the swash plate axis of rotation on the volumetric efficiency of axial piston pumps. Energies **15**(1), 298 (2022)
5. Molari, G., Sedoni, E.: Experimental evaluation of power losses in a power-shift agricultural tractor transmission. Biosys. Eng. **100**, 177–183 (2008)
6. Hamilton Ross Group internet site. https://www.hamiltonrossgroup.co.uk/the-revolutionary-jcb-536-70-dualtech-vt-telehandler-has-arrived-at-hamilton-brothers/
7. Yang, L., Ma, B., Ahmadian, M., Li, H., Vick, B.: Pressure distribution of a multidisc clutch suffering frictionally induced thermal load. Tribol. Trans. **59**, 983–992 (2016)
8. Abdullah, O., Rasham, A., Jobair, H.: The influence of frictional facing thickness on the contact pressure distribution of multi-disc dry clutches. FME Transaction **46**, 33–38 (2018)
9. Zagrodzki, P.: Numerical analysis of temperature fields and thermal stresses in the friction discs of a multidisc wet clutch. Wear **101**, 255–271 (1985)
10. Holgerson, M.: Wet Clutch Engagement Characteristics. PhD thesis, Lulea University of Technology
11. Bąk, M.: Torque capacity of multidisc wet clutch with reference to friction occurrence on its spline connections. Sci. Rep. **11**(1), 21305 (2021)
12. Davis, C.L., Sadeghi, F., Krousgrill, C.M.: A simplified approach to modeling thermal effects in wet clutch engagement: analytical and experimental comparison. J. Tribol. **122**, 110–118 (2000)
13. Bąk, M., Patrosz, P., Śliwiński, P.: Torque transmitted by multi-plate wet clutches in relation to number of friction plates and their dimensions. In: Stryczek, J., Warzyńska, U. (eds.) NSHP 2020. LNME, pp. 367–376. Springer, Cham (2021). https://doi.org/10.1007/978-3-030-59509-8_33

14. Bąk, M.: Wpływ Parametrów Konstrukcyjnych Sprzęgieł Mokrych i Ich Sterowania Na Zmiany Wybranych Wielkości Fizycznych w Trakcie Zmiany Przełożenia Przekładni Mechanicznej (Influence of design parameters and control of wet clutches on selected physical quantities' changes during gear change of a gearbox). PhD thesis, Gdansk University of Technology: Gdańsk (2022)
15. Osiński, Z.: Sprzęgła i Hamulce (Clutches and Brakes); PWN (2000)

Methodology of Experimental Research on Efficiency of Hydro-Mechanical Automatic Gearbox

Piotr Patrosz[1(✉)], Marcin Bąk[1], Paweł Załuski[1], Paweł Śliwiński[1], and Mykola Karpenko[2]

[1] Gdansk University of Technology, Gdansk, Poland
{piotr.patrosz,marcin.bak,pawel.zaluski, pawel.sliwinski}@pg.edu.pl
[2] Vilnius Gediminas Technical University, Vilnius, Lithuania
mykola.karpenko@vilniustech.lt

Abstract. The article shortly describes the design and principle of operation of the hydromechanical gearbox and presents the methodology and design of test stands used for testing hydromechanical prototype gearbox developed at Technical University of Gdansk. The article presents an approach according to which, in order to obtain reliable measurement data, it is necessary to separate the tests of the hydraulic and mechanical parts of the gearbox. For this reason, the tests of the pump and the hydraulic motor are also presented. To validate this approach sample test results are included and discussed.

Keywords: Gearbox · Hydraulics · Efficiency

1 Introduction

The gearboxes of slow-moving vehicles are one of the most intensively developed components of these machines. The growing use of working machines such as telescopic loaders or rough terrain forklifts in construction and agricultural works, results in works aimed at improving their design, operator's comfort and achieving higher efficiency, which leads to lower fuel consumption. For many years, the driving systems of these machines included mechanical, hydraulic and CVT transmissions. Hydraulic transmission allows low driving speeds and a stepless change of gear ratio [1–3]. Thanks to this, an operator has the opportunity to adjust the optimal speed of movement to the work performed. On the other hand, the mechanical transmission provides higher efficiency, without requiring expensive components of the hydraulic system such as pumps and motors. The disadvantage of these gears is the precisely defined value of the gear ratio between the mating gears resulting from the number of teeth of these gears. CVT transmissions combine the best of both worlds, but are very expensive at the same time. As part of the LIDER project at the Gdansk University of Technology, a design of a hybrid gearbox was developed that combines the advantages of both a hydraulic and a mechanical gearbox, while maintaining a relatively simple design, compared to CVT.

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 393–403, 2023.
https://doi.org/10.1007/978-3-031-25863-3_37

Comprehensive research has to be conducted to determine the efficiency at every point in the gearbox operation. The obtained characteristics will make it possible to determine the influence of the torque and the rotational speed on the efficiency. In order to create the discussed characteristics, a methodology for carrying out tests on a test stand that uses a hydraulic system as a load generator was developed. The test stand of the Hydraulics and Pneumatics Team of the Gdansk University of Technology was adapted to carry out tests of the mechanical transmission in the full range of its target operating parameters, in accordance with the developed procedure.

2 Design and Principle of Operation

As mentioned earlier, the tested gearbox is a hybrid of a hydraulic and mechanical transmission, which work interchangeably. Low gear ratios are realized with the use of a mechanical transmission, high gears with the use of a hydraulic and mechanical transmission. The kinematic diagram and a photo of the gearbox is shown in Fig. 1. The transmission consists of eight gears, a main hydraulic variable displacement pump with and a charge pump on the same shaft, a hydraulic double-motor and three wet clutches. Two clutches are necessary for gear shifting and disengagement of the mechanical transmission while using hydraulic transmission. The third clutch is only an auxiliary element used during the preliminary tests. The hydraulic motor used could work in the so-called freewheeling conditions. It means, it allowed the shaft to rotate freely without supplying the motor with hydraulic fluid.

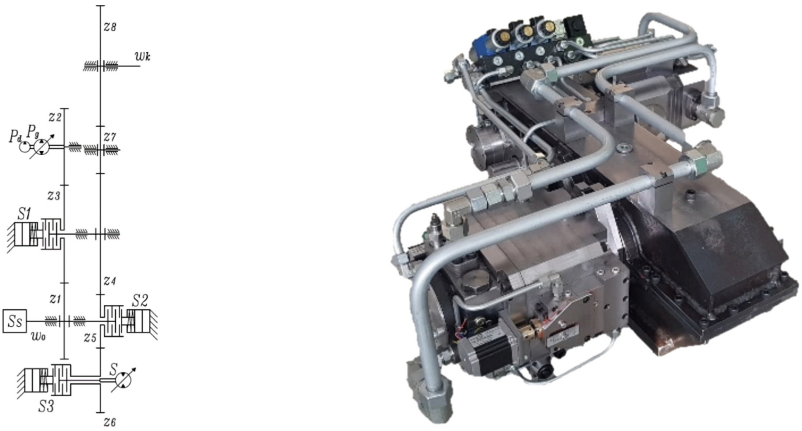


Fig. 1. Kinematic scheme and photo of hydromechanical gearbox.

The gearbox shown above allows you to choose one of the four forward gears and one reverse. The selected ratio results from: engagement of relevant clutches and setting of hydraulic machines (main pump and hydraulic motor) displacement. Table 1 shows the gearbox component configurations and settings for each gear.

The drive from the engine is transferred to the main shaft of the gearbox. In gears I and II, the drive is transmitted from the main shaft to the pump, which pumps oil to

the hydraulic motor. The hydraulic motor drives the gearbox output shaft. In gear I, the setting of the hydraulic motor displacement is higher than in gear II, which changes the range of available gear ratios. For both of these gears, the displacement of the main pump can vary smoothly from zero to maximum. Thanks to this, it is possible to smoothly change the vehicle speed without the need to change the engine speed. The drive transmission in gears III and IV utilizes only a mechanical gear. For these gears the displacement of the main pump is set to zero in order not to pump hydraulic fluid and generate losses. In addition, the hydraulic motor must either be mechanically disengaged from the gearbox using the S3 clutch or actuated to a freewheeling setting. The motor, which is not disconnected from the transmission, would work as a pump, pumping oil and generating large energy losses. In order to avoid this, it's displacement is set to a zero and thus, even without disengaging the S3 clutch, the motor does not generate significant losses. The choice of gear ratio III or IV depends on which clutch S1 or S2 is engaged. The S1 clutch is responsible for coupling the gear z3 with the output shaft ω_k, setting the drive transmission to gear III, while the clutch S2 engages the gear z5 with the input shaft $\omega_{0,}$ connected to the shaft of the engine, and sets the transmission to gear IV.

Table 1. Configurations and settings of gearbox components at specific gear.

Gear	Gear ratio	S1 clutch	S2 clutch	Pump displacement	Motor displacement
I	3.25–∞	Disengaged	Disengaged	0–40 cm^3	71 cm^3
II	1.73–∞	Disengaged	Disengaged	0–40 cm^3	38 cm^3
III	1.385	Engaged	Disengaged	0 cm^3	0 cm^3
IV	1.025	Disengaged	Engaged	0 cm^3	0 cm^3
Reverse	3.25–∞	Disengaged	Disengaged	0–40 cm^3 (reversed)	71 cm^3

3 Methodology of Efficiency Testing

Preliminary tests have shown that the research of the entire assembly, which is a hydro-mechanical gearbox, is not only inaccurate, but also does not represent a great cognitive value, because they do not provide information on the location of the main energy losses, but only allow quantitative estimation of their values. In addition, these estimates are highly error-prone, as a large number of components do not allow the stabilization of influencing factors such as, among others, hydraulic fluid temperature or residual friction in the clutches [4, 5]. For this reason, it was decided to carry out separate tests of the hydraulic transmission and the mechanical transmission. This approach does not limit the combination of the obtained results and the calculation of the total efficiency of the gearbox, but at the same time allows precise energy studies under steady-state conditions.

3.1 Tests of Hydraulic Drive

For the aforementioned reasons, the tests of the hydraulic transmission were also divided into: pump tests and hydraulic motor tests. Thanks to this approach, it was ensured that

the two prototypes did not influence each other. The pump and motor are assumed to operate in a closed-loop hydraulic system in which a relatively small volume of working liquid circulates. As a result, the temperature of the oil changes rapidly with the changing load, and the temperature stabilization system becomes very difficult to design, if not impossible. Measurements in such conditions would be burdened with a large error. Therefore, it was decided to separately test the pump and the motor connected to an open-loop system but with fluid pre-supply. About 2,000 dm^3 circulated in an open-loop system. This amount of oil heats up for a relatively long time, thanks to which the system equipped with water-oil coolers allows to maintain a stable temperature with an accuracy of ±2 °C.

Pump Tests. Scheme and photo of pumps test stand is presented in Fig. 2.

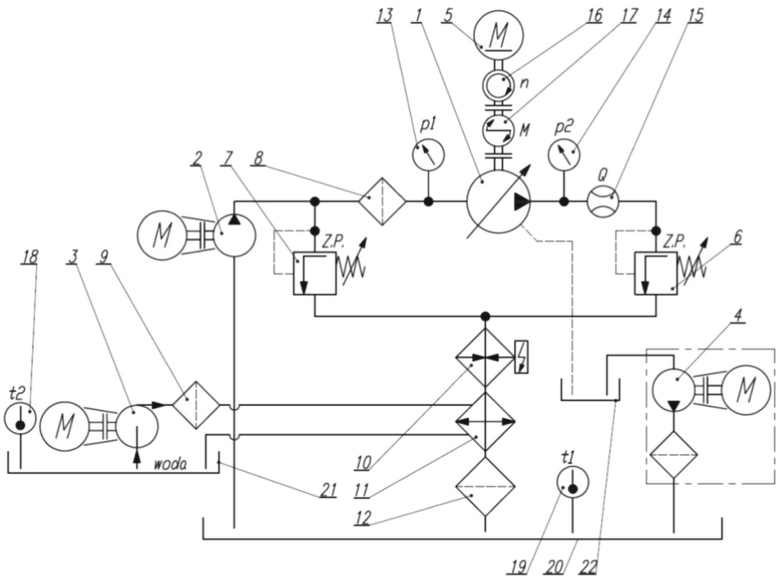


Fig. 2. Test stand for pump efficiency research.

The test stand consisted of the equipment listed in the Table 2. It allowed to conduct the test within specified ranges:

- Load pressure 0–35 MPa.
- Rotational speed 500–2,000 rpm.
- Displacement setting 0–100%.
- Oil temperature stable settings: 25–60 °C.

The tests were performed according to the following procedure:

1. Oil heating or cooling to the required temperature.

Table 2. Pump test stand measurement equipment.

No.	Measured parameter	Equipment	Range	Class	Max. error
1	Suction pressure	Manometer MPS-02	0–1.6 MPa	0.2	0.006 MPa
2	Pumping pressure	Manometer KFM	0–40 MPa	0.6	0.25 MPa
3	Oil temperature	Thermocouple	0–70 °C	1	1.7 °C
4	Flow rate	Piston flowmeter PT-200	0.3–200 dm^3/min	0.2	0.4 dm^3/min
5	Torque	Torquemeter HBM T1	0–500 Nm	0.2	1.01 Nm
6	Rotational speed	Incremental encoder	0–3,000 obr/min	nd.	1 obr/min

2. Stetting of the pump displacement.
3. Setting the required pressure in the suction channel of the pump.
4. Pre-setting the speed of the pump shaft.
5. Setting the pumping pressure with the pressure relief valve.
6. Verification and possible correction of the rotational speed of the pump shaft.
7. Verification and possible correction of pumping pressure and pressure in the suction channel.
8. Readout of measured parameter values.
9. Repeat the entire procedure for changed parameters.

Based on the obtained results the firstly the theoretical displacement is calculated using the methods presented in [6, 7]. The accurate value of theoretical displacement is necessary to correctly calculate the values of efficiency. The pumps efficiency consists of two partial efficiencies [8, 9]: hydromechanical efficiency, which includes the pressure losses in pumps channels and mechanical losses due to friction and volumetric efficiency [10–12], which includes losses caused by leakage and fluid compressibility.

The pump's hydromechanical efficiency η_{phm} is calculated using Eq. (1):

$$\eta_{phm} = \frac{\Delta p \cdot q_{tp}}{M_p \cdot 2 \cdot \pi}, \tag{1}$$

where Δp – pressure difference measured between the inlet(suction) and outlet(pumping) channel; q_{tp} – pump's theoretical displacement; M_p – torque measured at pumps shaft.

The pump's volumetric efficiency η_{pv} is calculated using Eq. (2):

$$\eta_{pv} = \frac{Q_p}{n_p \cdot q_{tp}}, \tag{2}$$

where Q_p – flow rate measured at the outlet; n_p – rotational speed of pumps shaft, the overall efficiency of the pump η_p is given by Eq. (3):

$$\eta_p = \eta_{phm} \cdot \eta_{pv}. \tag{3}$$

Hydraulic Motor Tests. Test stand for hydraulic motor is much more complicated than the pump test stand. The motor requires to be supplied with oil under high pressure, additionally it has to be loaded with external torque source. Therefore the test stand consists of two hydraulic systems. One is responsible for oil supply for motor and the second is a loading system in which the pump is connected to hydraulic motors shaft. Scheme and photo of hydraulic motors test stand is presented in Fig. 3. The test stand consisted of the equipment listed in the Table 3. It allowed to conduct the test within specified ranges:

- Load torque 0–350 Nm.
- Rotational speed 100–1,600 rpm.
- Displacement setting 100% and ~50%.
- Oil temperature stable settings: 25–60 °C.

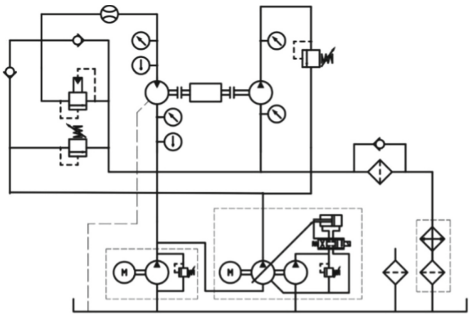


Fig. 3. Scheme of hydraulic motor test stand.

Table 3. Hydraulic motor test stand measurement equipment.

No.	Measured parameter	Equipment	Range	Class	Max. error
1	Return pressure	Transducer Trafag NAH	−0.1–1.0 MPa	0.6	0.01 MPa
2	Supply pressure	Transducer Trafag NAH	0–40 MPa	0.3	0.2 MPa
3	Oil temperature	Stauff PCC-04	−25–125 °C	1	1.4 °C
4	Flow rate	Piston flowmeter PT-200	0.3–200 dm^3/min	0.2	0.4 dm^3/min
5	Torque	Torquemeter HBM T1	0–500 Nm	0,2	1.01 Nm
6	Rotational speed	Incremental encoder	0–3,000 obr/min	nd.	1 obr/min

The tests were performed according to the following procedure:

1. Oil heating or cooling to the required temperature.
2. Setting the motor displacement.
3. Pre-setting the rotational speed of the motor shaft.
4. Pre-setting the pumping pressure in the loading system.
5. Verification and possible correction of the rotational speed of the motor's shaft.
6. Verification and possible correction of pumping pressure in loading system.
7. Readout of measured parameter values.
8. Repeat the entire procedure for changed parameters.

Based on the obtained results the firstly the theoretical displacement is calculated using the methods presented in [6, 7]. Similar the pump the accurate value of theoretical displacement is necessary to calculate the value of motor's efficiency.

The motor's hydromechanical efficiency η_{mhm} is calculated using Eq. (4):

$$\eta_{mhm} = \frac{M_m \cdot 2 \cdot \pi}{\Delta p \cdot q_{tm}}, \tag{4}$$

where Δp – pressure difference measured between the inlet and outlet channel; q_{tm} – pump's theoretical displacement; M_m – torque measured at motor's shaft.

The motor's volumetric efficiency η_{mv} is calculated using Eq. (5):

$$\eta_{mv} = \frac{n_m \cdot q_{tm}}{Q_m}, \tag{5}$$

where Q_m – flow rate measured at the inlet; n_m – rotational speed of motor's shaft, the overall efficiency of the motor η_m is given by Eq. (6):

$$\eta_m = \eta_{mhm} \cdot \eta_{mv}. \tag{6}$$

3.2 Tests of Mechanical Gearbox

The determination of the complete characteristics of the mechanical part of the gearbox required various configurations of the test stand. The full scale tests were carried out only on gears III and IV and the efficiency of the energy transfer between the input shaft and the output shaft was tested using the configuration presented in Fig. 4. For gears I and II only a partial tests were needed to research the efficiency of energy transfer:

- Transfer of energy between the input shaft and pump's shaft using configuration presented in Fig. 5a.
- Transfer of energy between the hydraulic motor shaft and output shaft using configuration presented in Fig. 5b.

The external load was generated using the hydraulic system acting as a load generator. The torque on the output shaft depended on the pumping pressure of the loading pump, set with pressure relief valve.

During the experimental tests, several different transducers were used to record: rotational speed of machine shafts, torque on the input shaft, torque on the output shaft, temperature of the lubricating liquid and pumping pressure of the loading pump.

Table 4 lists the relevant measuring instruments along with the measurement class and ranges. As part of the research, two identical torquemeters were used - one connecting the electric motor with the gear, the other connecting the load pump with the gear.

The detailed test procedure is presented in [13].

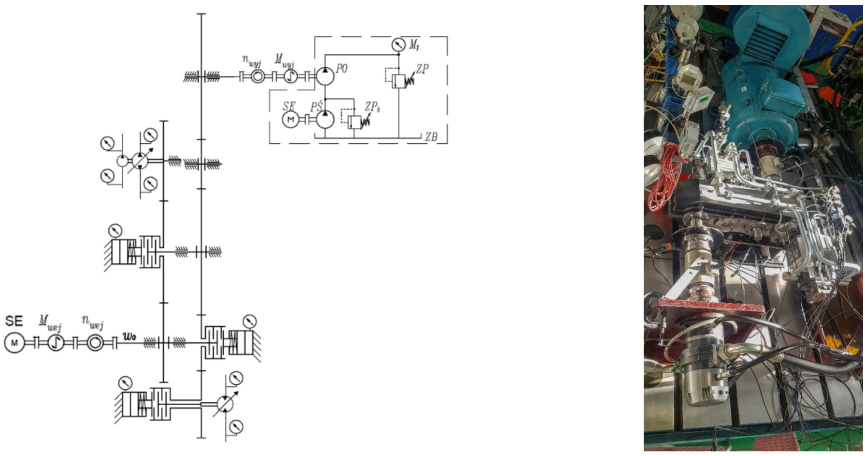


Fig. 4. Mechanical gearbox test stand in configuration for tests on III and IV gear.

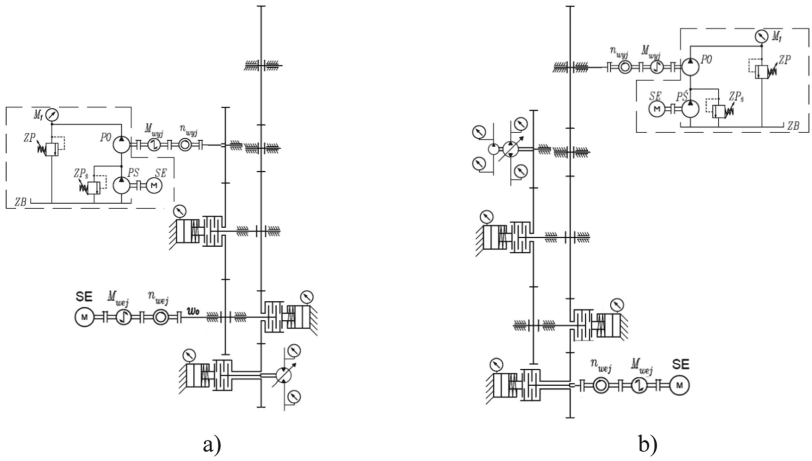


Fig. 5. Mechanical gearbox test stand in configuration for tests on I and II gear. Measurement energy transfer between: a) input shaft and pump shaft, b) motor shaft and output shaft.

Table 4. Gearbox test stand measurement equipment.

No.	Measured parameter	Equipment	Class	Range	Max. error
1	Pressure	Manometer	0.5	0–40 MPa	2 bar
2	Torque	Torquemeter HBM T1	0.2	0–500 Nm	1.01 Nm
3	Rotational speed	Incremental encoder	–	0–60 Hz	0.017 Hz
4	Temperature	Thermocouple PT100	–	−50 °C–400 °C	0.5 °C @ 40 °C

4 Sample Results and Discussion

Using the methods and test stands presented earlier the following sample efficiency characteristics were obtained:

- volumetric, hydromechanical and overall efficiency of a pump presented in Fig. 6,
- overall efficiency characteristics of a hydraulic motor in Fig. 7,
- overall efficiency of a gearbox at IV gear presented in Fig. 8.

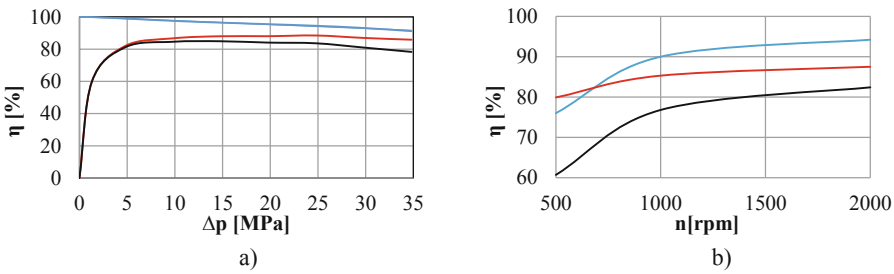


Fig. 6. Efficiency characteristics of a pump: a) as a function of pressure difference at n = 1,500 rpm; b) as a function of rotational speed at 30 MPa (blue – volumetric efficiency, red – hydromechanical efficiency, black – overall efficiency) (Color figure online).

Characteristics, of witch very small sample was provided in the article, proved useful and significant during product development process. First of all, they allowed to verify the correctness of design assumptions and confirmed that the gearbox is working properly, achieving satisfactory operating parameters. High efficiency will translate into lower fuel consumption and thus the product will be more economical and eco-friendly. Additionally thanks to a separate analysis of the efficiency of individual components of the gearbox, it was possible to quickly locate and solve problems. For instance at the early stage of product development the increased internal leakage occurred in a pump. If

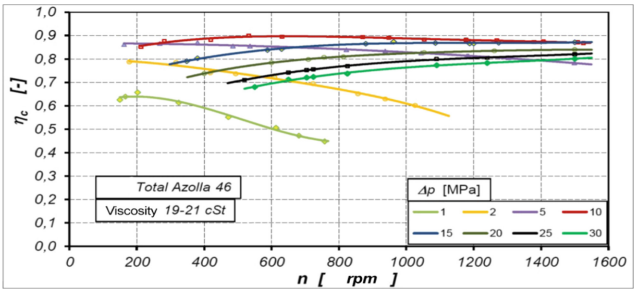


Fig. 7. Overall efficiency of a pump presented as a function of rotational speed at different pressures.

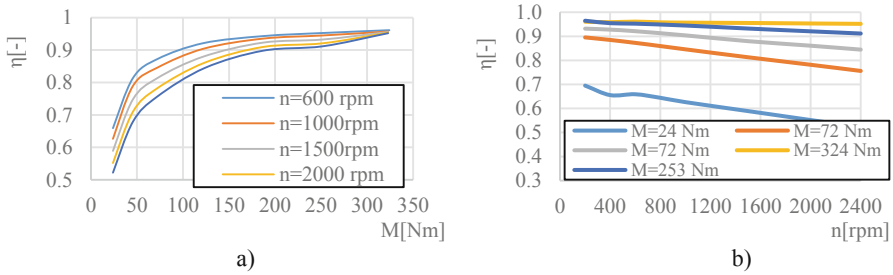


Fig. 8. Overall efficiency of the mechanical gearbox at IV gear: a) as a function of torque, b) as a function of rotational speed.

the research included only the test of full gearbox the problem would remain unresolved and may become very serious in the future.

The charts of efficiency were also used to prepare the model of a complete gearbox. Using the model and providing it with required input parameters it is possible to asses very accurately the output parameters such as power loss, maximal torque and rotational speed.

Funding. This research was funded by The National Centre for Research and Development within the framework of program LIDER, grant number LIDER/22/0130/L-8/16/NCBR/2017; Project title: Hydro-mechanical automatic gearbox for agricultural vehicles and heavy machinery; Funding value: 1,197,500.00 PLN.

References

1. Łopatka, M.J., Rubiec, A.: Concept and preliminary simulations of a driver-aid system for transport tasks of articulated vehicles with a hydrostatic steering system. Appl. Sci. **10**, 5747 (2020). https://doi.org/10.3390/app10175747
2. Kończalski, K., Łopatka, M.J., Przybysz, M., Rubiec, A.: Hydrostatic drivetrains efficiency of slow-moving terrain vehicles. AUTOBUSY – Tech. Eksploat. Syst. Transp. **19**, 876–880 (2018). https://doi.org/10.24136/atest.2018.194

3. Bury, P., Stosiak, M., Urbanowicz, K., Kodura, A., Kubrak, M., Malesińska, A.: A case study of open- and closed-loop control of hydrostatic transmission with proportional valve start-up process. Energies **15**, 1860 (2022). https://doi.org/10.3390/en15051860
4. Bąk, M.: Torque capacity of multidisc wet clutch with reference to friction occurrence on its spline connections. Sci. Rep. **11**, 21305 (2021). https://doi.org/10.1038/s41598-021-00786-6
5. Bąk, M., Patrosz, P., Śliwiński, P.: Torque transmitted by multi-plate wet clutches in relation to number of friction plates and their dimensions. In: Stryczek, J., Warzyńska, U. (eds.) NSHP 2020. LNME, pp. 367–376. Springer, Cham (2021). https://doi.org/10.1007/978-3-030-59509-8_33
6. Sliwinski, P.: Determination of the theoretical and actual working volume of a hydraulic motor. Energies **13**, 5933 (2020). https://doi.org/10.3390/en13225933
7. Sliwinski, P.: Determination of the theoretical and actual working volume of a hydraulic motor—part II (the method based on the characteristics of effective absorbency of the motor). Energies **14**, 1648 (2021). https://doi.org/10.3390/en14061648
8. Jasiński, R.: Volumetric and torque efficiency of pumps during start-up in low ambient temperatures. In: Stryczek, J., Warzyńska, U. (eds.) NSHP 2020. LNME, pp. 28–39. Springer, Cham (2021). https://doi.org/10.1007/978-3-030-59509-8_3
9. Osiński, P., Deptuła, A., Partyka, M.A.: Hydraulic tests of the PZ0 gear micropump and the importance rank of its design and operating parameters. Energies **15**, 3068 (2022). https://doi.org/10.3390/en15093068
10. Załuski, P.: Influence of the position of the swash plate rotation axis on the volumetric efficiency of the axial piston pumps. Mach. Technol. Mater. **8**(11), 12–15 (2014)
11. Załuski, P.: Influence of fluid compressibility and movements of the swash plate axis of rotation on the volumetric efficiency of axial piston pumps. Energies **15**, 298 (2022). https://doi.org/10.3390/en15010298
12. Załuski, P.: Experimental research of an axial piston pump with displaced swash plate axis of rotation. In: Stryczek, J., Warzyńska, U. (eds.) NSHP 2020. LNME, pp. 135–145. Springer, Cham (2021). https://doi.org/10.1007/978-3-030-59509-8_12
13. Bąk, M., Patrosz, P.: Metodologia Badania Skrzyni Biegów z Wykorzystaniem Układu Hydraulicznego Jako Hamowni. Napędy Sterow (2020)

The Use of Simulation Programs in the Traffic Accident Analysis

Ján Ondruš[1](✉), Eduard Kolla[2], Ľudmila Macurová[2], and Ján Podhorský[2]

[1] Faculty of Operation and Economics of Transport and Communications, Department of Road and Urban Transport, University of Žilina, Univerzitná 8215/1, 010 26 Žilina, Slovak Republic
jan.ondrus@fpedas.uniza.sk

[2] Institute of Forensic Research and Education, University of Žilina, 1. Mája 32, 010 26 Žilina, Slovak Republic
{eduard.kolla,ludmila.macurova,jan.podhorsky}@uzvv.uniza.sk

Abstract. In recent years, we have very often encountered increasing accident statistics where pedestrians are involved in traffic accidents. These collisions between pedestrians and vehicles are often associated with inattention on the part of the pedestrians and, from the drivers' point of view, the reason was insufficient attention to driving the vehicle. Pedestrians are among the most vulnerable road users. Compared to other types of traffic accidents, traffic accidents involving motor vehicles and pedestrians are specific in that, even at relatively low impact speeds, relatively serious injuries or even death can occur. The analysis of traffic accidents involving the most vulnerable road users is of particular social importance. The paper deals with the use of simulation programs in the analysis of an accident event. In the analysis of the accident event, a mathematical graphic analysis of the mutual positions of vehicles and pedestrian by means of 3D visualization, the driving technique of vehicle drivers and the possibilities of avoiding a traffic accident, are evaluated.

Keywords: Analysis · Road accident · Pedestrian · Vehicles · Simulation

1 Introduction

When considering traffic situations, car accidents with pedestrian participation include as a rule situations when the car in motion collides with the pedestrian [1]. Such traffic accidents result in various material damages, light or serious, to devastating consequences on the health of the people involved in such accident, but not rarely also in irrecoverable loss of human lives [1, 2]. Traffic accidents are caused by a complex of different factors, some of them being unpredictable events as well as inadequate reaction or behavior of the traffic participants [3]. Drivers are quite often inattentive, irresponsible, not enough foreseeing, they do not respect the traffic rules or they overestimate their abilities [4]. On the other hand, the pedestrians often step out on the road with no attention, not minding the traffic, they cross the pedestrian crossing absentminded, not rarely intoxicated, dressed in dark colours with no streak reflex [5, 6].

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 404–414, 2023.
https://doi.org/10.1007/978-3-031-25863-3_38

The origin, course and consequences of the traffic accident are largely affected by the general technical, physical and physiological properties of the subject and the object participating in the accident [7, 8]. With motor vehicles these are mainly the type and mode of the vehicle, their technical condition, type and condition of the tyres, the instantaneous load and the mediums used. With regard to the traffic participants these are physical parameters, age, actual health condition, practical experience, and the potential behaviour of the participants before and during the accident. The origin and course of different traffic accidents are investigated and examined by the traffic accident analysis [7, 9].

The analysis of the course of the accident event can be processed by means of different comp-simulating programmes; these can simulate e.g., the collision of the pedestrian with the vehicle by entering the respective parameters into the simulation process [10]. Also it is possible to specify the speed of the vehicles in the moment of collision as well as in the moment of the driver's reaction, to analyse the movements of the participants' bodies, to analyse different directions, capacities and configurations of the energies involved including energies effecting the participants of the traffic accident in separate phases of the event [10, 11]. The enter data are modified and entered in a manner to reach the situation when the calculated final position and the calculated trajectory during the course of the accident respond as closely as possible with the actual final position and actual trajectory of the respective vehicles and traffic participants [12].

2 Most Frequent Types of Mutual Vehicle - Pedestrian Contact

Traffic accidents with pedestrian participation may occur within different configurations, e.g., the pedestrian may fall down after stumbling with no further participant, to all kinds of collisions with bicycle, motorcycle, vehicle, fixed obstruction, etc. With regard to different types of contact between the pedestrian and the vehicles, described and classified can be the most frequent types of their mutual contact [7]:

Head-On Collision (Crash) - Complete Overlap. Considering this type of accident, pedestrian's entire body is located inside the vehicle. In the event of a collision pedestrian' body is accelerated to the speed of the vehicle.

When vehicle fully braking, pedestrian breaks away from it and after flying through the air he falls on the surface, where, after moving he stops completely. In this case of collision there are published precise results of research, from which it is possible to determine collision speed.

In collisions, when the vehicle does not brake at the time of collision, there may be the following cases:

- pedestrian remains on the vehicle up to the beginning of braking and then falls to the ground. According to the position of pedestrian on the vehicle and braking intensity, pedestrian can be carried on the vehicle up to time when the vehicle stops, when pedestrian falls to the ground,
- after collision pedestrian falls on the side and its final position is after final location of the vehicle,

- pedestrian flies over the vehicle (in most cases he leaves a damage to vehicle rear roof) [7, 13].

Head-On Collision (Crash) - Partial Overlap. Compared with a collision with complete overlap, in this case pedestrian's entire body is not inside the vehicle. However, such collision geometry does not always lead to pedestrian body slipping alongside the vehicle. It is necessary to distinguish two cases according to the direction of movement of pedestrian:

Pedestrian entering the corridor of movement of the vehicle comes into contact only with the front edge (most often only by foot just doing a step). After the initial contact there occurs rotating of body around the longitudinal axis. A large part of the energy of collision is changed for rotary energy of pedestrian body hitting the side of vehicle, where it leaves damage and the corresponding injuries to the pedestrian.

If pedestrian stands out from corridor of movement of the vehicle, there is also contact only with the front edge (often only by foot jut doing the step). After the initial contact there is a rotating body, because collision energy changes to rotary energy and pedestrian body rotates around the longitudinal axis. Pedestrian mostly does not hit on the side of vehicle [13, 14].

Side Collision. Regarding this type of collision, we divide accidents into:

Typical - if there comes into contact of body with side part of the vehicle. If pedestrian hits the side of the vehicle within his movement, he is thrown behind the imaginary line of the vehicle (toward the back).

Atypical - if pedestrian stands or moves in the direction of movement of the vehicle. The body is captured by protruding parts of the vehicle (e.g., rear-view mirror), it is immediately thrown away and does not leave any further traces on the vehicle (no secondary contact) [13, 15].

Run Over. While running over, the vehicle must go over the pedestrian body with at least one wheel. There are two types of running over:

Simple - without the prior contact with pedestrian (i.e., pedestrian already lay on the road from other reasons).

Complicated - pedestrian is first hit by vehicle and then run over. This case occurs frequently at tram-bus type of body and a small vehicle deceleration [13, 15].

3 Analysis of the Traffic Accident

The collision of the cars (Peugeot 2008 – year of production 2013 and Mercedes Benz – year of production 2007) was identified in daytime in the residential area of a village, on a geometrically complicated crossroad. During the crash, the car Peugeot 2008 was flung aside and while rotating its rear part hit the body of a pedestrian standing in that moment on the traffic island. The pedestrian's body after the collision hit the pole of the traffic sign. The pedestrian was fatally injured (brain crash, broken clavicle, forehead laceration, knee bruises).

The accident happened on the crossroad where the width of the road in the place of collision is 7.3 m. It is a four-arm crossroad with two traffic lanes where the right of way is signalled by vertical traffic signs. The surface of the road is made by asphalt, the quality of the surface was good. The accident has happened on the traffic lane with speed limit 40 km/h. In the near vicinity of the accident location are several pedestrian crossings. During the accident, the visibility was not limited or reduced by bad weather, the prospect was favourable.

3.1 Analysis of the Damage of Vehicles

The assessment of the correlation regarding the damage of vehicles has been done in order to define mutual position of vehicles in the moment of collision based on photo documentation and camera record. Mutual force action of vehicles in the collision moment has caused certain damages that have to correlate with respect to type, capacity and mutual position of vehicles in the collision moment (Fig. 1).

Fig. 1. All-over view on the damaged right part of Peugeot 2008 (on the left) and on the damaged front part of Mercedes Benz (on the right).

The progress of the car accident as recorded by camera with resolution 1920 × 1080, with frame rate 25 fps. The camera record proves the following:

- mutual position of the vehicles and the pedestrian in the moment just before Peugeot 2008 has entered the main road at c. 01:27,46 of the camera record (frame nr. 2187),
- the moment of the cars' collision and the position of the pedestrian at c. 01:28,19 of the camera record (frame nr. 2205) - see Fig. 2.
- the moment of the crash of Peugeot 2008 with the pedestrian at c. 01:28,79 of the camera record (frame nr. 2220),
- final position of vehicles after the collision at c. 01:32,39 of the camera record (frame nr. 2310).

According to the analysis of the camera record we could have calculated the approximate speed of the Mercedes Benz and Peugeot 2008 before the accident:

- the approximate position of the vehicle against the perspective grid at 01:27,59 of the camera record (frame no. 2190) and after elapsing the track of the respective wheelbase at 01:27,79 of the camera record (frame no. 2195) - see Fig. 3.

Fig. 2. The moment of the cars' collision and the position of the pedestrian.

Fig. 3. All The position of Mercedes Benz against the perspective grid during the first (on the left) and the second (on the right) focused positions.

Mercedes Benz has passed during the calculated time of the 5 frames (c. 0.2 s) the distance of its wheelbase c. 2.7 m + c. 0.1 m, which allows to calculate the approximate average speed on the said road section: v = s/t = 2.8/0.2 = 14 m/s = c. 50 km/h, under calculation tolerance ±10% this is the speed of the **Mercedes Benz c. 45 to 55 km/h.**

Similarly, we have carried out the analysis of the move of Peugeot 2008. Peugeot 2008 has passed the distance of its own wheelbase c. 2.5 m + 0.1 m during the calculated time of 5 frames (c. 0.20 s), which allows us to calculate the approximate average speed on the said road section: v = s/t = 2.6/0.2 = 13 m/s = c. 47 km/h, under the calculation tolerance ±10% this is the speed of the **Peugeot 2008 c. 42 to 52 km/h.**

To qualify the origin and course of this accident it was necessary to produce an analysis of the vehicles' movement and of the pedestrian move prior to the accident and during the accident, to assess the driving techniques of the drivers, as well as to consider if there were ways of avoiding the accident by the participants. The mathematical and graphic analysis of the vehicles' movement was processed by means of application programme PC-Crash (version 13.0) designed for simulation of mutual impact of vehicles and bodies [16].

3.2 Mathematical Graphic Analysis

The following print depicts graphical course of the general situation before the collision (mutual position of the cars) by means of 3D display in the moments c. 1.50 s before the collision, in the moment of collision (mutual position of the cars and the pedestrian) and in the moment of the Peugeot hitting the pedestrian (mutual position of the car and the pedestrian) (Fig. 4).

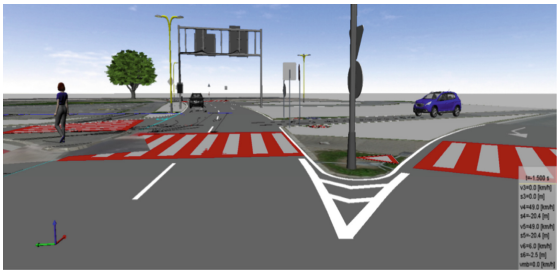


Fig. 4. Mutual position of the cars c. 1.50 s before the collision – 3D [authors].

C. 1.50 s before the collision the driver of Mercedes Benz was c. 20.4 m before the spot of collision driving with speed c. 49 km/h. The driver of Peugeot 2008 in the same moment was 20.4 m before the collision spot driving c. 49 km/h.

It is possible to conclude that Mercedes Benz must have been sufficiently visible. With regard to the distance and to the speed of the said vehicle the driver of Peugeot 2008 must have been aware of the fact that the Mercedes Benz driver could not have stopped the car before the collision spot and therefore could not have avoided the accident in any possible way (Fig. 5).

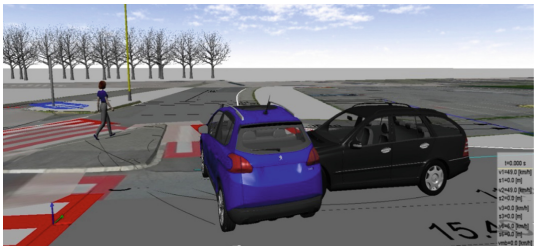


Fig. 5. Mutual position of the cars and the pedestrian in the moment of collision - 3D [authors].

The participating drivers of Mercedes Benz and of Peugeot 2008 did not react in any way to the developing traffic situation before the collision of their cars, i.e., the speed of both vehicles in the moment of collision was c. 49 km/h (Fig. 6).

Fig. 6. Mutual position of the cars and the pedestrian in the moment of Peugeot hitting the pedestrian – 3D [authors].

3.3 Assessment of the Driving Techniques of Drivers and of the Pedestrian's Movement

The driver of Peugeot 2008 was driving in the said location with the speed c. 47 to 51 km/h (with calculation tolerance ±5%), while the speed limit at that place was 50 km/h. He entered the crossroad from the byroad and he did not stop before entering the main road; moreover, he could have seen the Mercedes Benz on the right having no vision prevention. It is therefore possible to conclude, that owing to the speed and distance of Mercedes Benz the Peugeot driver must have been aware before entering the main road that the MB driver after recognising the situation could not have avoided the collision.

The Peugeot driver reacted to the traffic situation only in the moment of collision which can be assessed technically as a late reaction due to the fact that in the moment of collision he was driving at the speed of 47 to 51 km/h/with calculation tolerance ±5%. Technically, the Peugeot driver did not give right of way to the MB driver, this both with regard to the speed limit in the said spot (40 km/h) and to the speed of his car (c. 49 km/h).

With regard to the technically acceptable analyses of the course of the accident it is possible to conclude with high probability that the driving technique of the Peugeot driver was incorrect from the technical point of view. The incorrect aspect of his driving technique was the fact that he was not fully concentrated on the driving process and did not sufficiently follow the developing situation, this resulting in his late reaction to such situation. This improper driving technique of the Peugeot driver has therefore induced the collision situation and, consequently, made it impossible to prevent the accident.

The Mercedes Benz driver at the collision spot was driving at the speed of 47 to 51 km/h (with calculation tolerance ±5%), while the speed limit of the place was 40 km/h. The Mercedes Benz driver has reacted to the developing situation only at the collision moment which reaction can technically be assessed as a late reaction, yet this reaction was not the reason of the collision and was not in a position of preventing the accident.

With regard to technically acceptable analyses of the course of the collision it is possible to conclude with highest probability that the MB driver's technique was technically incorrect. The reason of such conclusion being that in the place with speed limit 40 km/h the MB driver was driving at the speed 49 km/h. Moreover, technically, his reaction to the developing situation was late.

With regard to the technically acceptable analyses of the course of the accident it is possible to conclude with highest probability that the pedestrian's technique of movement was correct. It is also possible to conclude that the pedestrian could in no way whatsoever avoid the collision.

With regard to the safety of the traffic participants and to the safety and fluency of traffic, and after considering the results of the executed simulations of the course of the accident and the possible prevention of this accident it is possible to conclude that the Peugeot driver by his way of entering the crossroad created the technically defined sudden obstacle for the MB driver because the MB driver could not have stopped the car before the collision spot even if he had driven his car properly technically-wise.

3.4 Defining the Possibilities of Avoiding the Traffic Accident by the Simulation

With regard to the results of the assessments of the Peugeot driver technique, it is possible to conclude that the driver could have avoided the traffic accident in the following cases:

- if he had been driving in the correct manner in the said section of the road,
- if he had entered the main road giving the right of way to the vehicles driving on the main road,
- if he had stopped before entering the main road section letting the MB driver pass.

To technically assess the course of the accident it is necessary to calculate the adequate speed of the MB driver in the said section of the road to be able to stop his car before the Peugeot driver entered the crossroad, if he reacted in-time on the developing situation and after elapsing the reaction time he would have braked the car with the maximum breaking deceleration.

With regard to the results of the analysis of the course of the accident and to the executed simulations it is possible to conclude that the driver could have avoided the accident in the following cases:

- if he had been driving in the said section of the road respecting the speed limit 40 km/h and after elapsing the reaction time he would have braked the car with the maximum breaking deceleration (the accident would not have been avoided but the collision speed would have been 40 km/h),
- if he had been driving at the speed 33 km/h and have reacted in-time to the developing situation braking the car with the maximum breaking deceleration (the accident would have been avoided with cars very closely avoiding the contact) – see Fig. 7.
- if he had been driving at the maximum speed 16 km/h and had reacted intime on the developing situation braking his car with maximum breaking deceleration (the accident would have been avoided avoiding the track of Peugeot 2008).

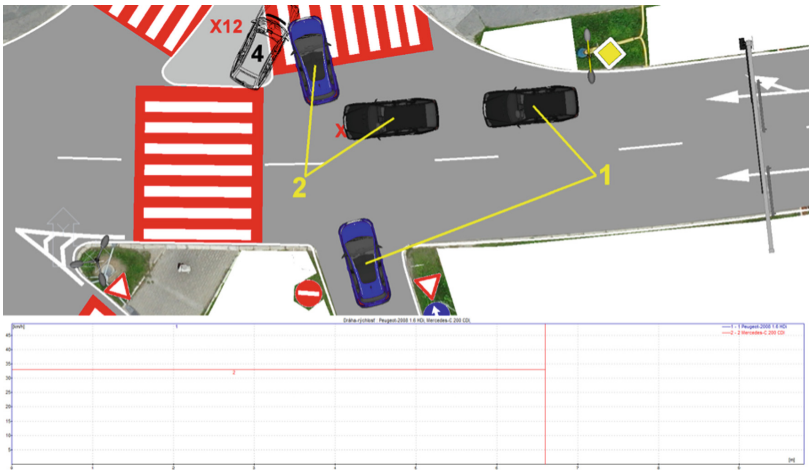


Fig. 7. Mutual position of the vehicles, prevention of the accident by the MB driver by slower drive – timewise (1 – mutual position of vehicles in the moment of the early reaction of the MB driver; 2 – mutual position of the vehicles in the moment of their closely avoided contact).

4 Discussion and Conclusion

Traffic accidents with mutual contact of vehicles and pedestrians occur practically every day, this resulting as a rule from disobedience and due to not respecting the law. The most frequent types of such collisions are head-on collision with complete overlap, head-on collision with partial overlap, side collision (typical, atypical) and run over (simple and complicated). The origin and course of different traffic accidents are examined by the analysis of traffic accidents being a part of forensic engineering of road traffic.

This article has analysed a particular traffic accident – a collision of two cars (Peugeot 2008 a Mercedes Benz). During the crash, the Peugeot has been flung aside, rotated and with its rear part hit the body of a pedestrian standing at that moment on the traffic island. The analysis of this accident included a mathematical graphic analysis of the mutual positions of the respective cars and the pedestrian by means of 3D featuring, it assessed the driving techniques of the involved drivers and also the possibilities of eventual avoiding the accident on the side of the individual participants of the accident.

Finally it can be concluded that the technical reason of this traffic accident was the incorrect driving mode of the Peugeot driver who did not give his full attention to the traffic situation, and did not follow sufficiently the developing traffic situation which altogether resulted in his late reaction and inability to avoid the accident. At the same time, it can be stated that the Peugeot driver created technically a sudden obstacle situation for the Mercedes Benz driver in the geometrically complicated crossroad. Therefore, the Mercedes Benz driver even with correct driving technique could not have stopped his car before the collision spot.

The analysed traffic accident was specific with regard to the fact that the pedestrian has entered the collision situation and with no infliction of her own has suffered fatal injuries after the collision of the said cars (Peugeot 2008 and Mercedes Benz) when

Peugeot under rotation hit her body. Technically significant is the fact that both the calculations and the camera record showed identical speeds of the vehicles before the collision, and because none of the drivers involved used the brakes, they showed also identical crash speed.

The results of the presented analysis of this specific traffic accident show that to minimise the rate of traffic accidents and their consequences it is inevitable to consider thoroughly the main aspects of the traffic situation such as the quality of the road, traffic means and for the most part, the traffic participants.

Acknowledgement. This work was supported by the Slovak Research and Development Agency under contract no. APVV-20-0626. This work was created within the project APVV-20-0626: Biofidelic human body surrogate to increase the objectivity within the forensic analysis of road traffic accidents.

References

1. Li, Z., Huang, H., Li, D., Li, P.: Analysis of influencing factors of pedestrian-vehicle accident reconstruction based on Pc-Crash. In: International Conference on Education, Management and Computing Technology (ICEMCT-15), pp. 1576–1580. Atlantis Press (2015)
2. Jie, W., Yutong, H.: Research on frontal collision reconstruction model based on coupling of PCCRASH and MADYMO. In: 2019 4th International Conference on Control and Robotics Engineering (ICCRE), pp. 54–59. IEEE (2019)
3. Zhang, X., Huang, F., Zheng, C.: Causes analysis of the serious road traffic accidents cases. In: 2016 5th International Conference on Energy and Environmental Protection (ICEEP 2016), pp. 817–822. Atlantis Press (2016)
4. Čulík, K., Harantová, V., Hájnik, A.: CAD software using for designing of traffic environment. Transp. Res. Procedia **44**, 248–254 (2020)
5. Jagelčák, J., Gnap, J., Kuba, O., Frnda, J., Kostrzewski, M.: Determination of turning radius and lateral acceleration of vehicle by GNSS/INS sensor. Sensors **22**, 2298 (2022)
6. Čulík, K., Kalašová, A.: Statistical evaluation of BIS-11 and DAQ tools in the field of traffic psychology. Mathematics **9**(4), 433 (2021)
7. Kohút, P., Kasanický, G.: Evalution of crash tests of the institute of forensic engineering. University of Žilina, aimed at ess. Commun. – Sci. Lett. Univ. Žilina **15**(2), 124–130 (2013)
8. Institute of Forensic Engineering ŽU in Žilina (ÚSI ŽU): Archive of expert opinions in the field of road transport
9. Synák, F., Jakubovičová, L., Klačko, M.: Impact of the choice of available brake discs and brake pads at different prices on selected vehicle features. Appl. Sci. **12**(14), 7325 (2022)
10. Zioła, A.: Verification of road accident simulation created with the use of PC-Crash software. Zeszyty Naukowe. Transport/Politechnika Śląska (2018)
11. Miao, Q., et al.: Analysis of pedestrian fractures in collisions between small cars and pedestrians based on surveillance videos. Am. J. Forensic Med. Pathol. **43**(1), 11–17 (2022)
12. Baikejuli, M., Shi, J., Hussain, M.: A study on the probabilistic quantification of heavy-truck crash risk under the influence of multi-factors. Accid. Anal. Prev. **174**, 106771 (2022)
13. Czech, P.: Underage pedestrian road users in terms of road accidents. In: Sierpiński, G. (ed.) Intelligent Transport Systems and Travel Behaviour. AISC, vol. 505, pp. 33–44. Springer, Cham (2017). https://doi.org/10.1007/978-3-319-43991-4_4

14. Xiao, D., Šarić, Ž., Xu, X., Yuan, Q.: Investigating injury severity of pedestrian–vehicle crashes by integrating latent class cluster analysis and unbalanced panel mixed ordered probit model. J. Transp. Saf. Secur. 1–20 (2022)
15. Penmetsa, P., Pulugurtha, S.S.: Modeling crash injury severity by road feature to improve safety. Traffic Inj. Prev. **19**(1), 102–109 (2018)
16. SW PC Crash (13.1.) SW XL Vision™

Expert Evidence in the Analysis of the Accident Event – Vehicle, Motorcycle and Pedestrian

Ľudmila Macurová[1](✉), Pavol Kohút[1], Gustáv Kasanický[1], and Michal Ballay[2]

[1] Institute of Forensic Research and Education, University of Žilina, Ul. 1. mája 32, 010 26 Žilina, Slovak Republic
{ludmila.macurova,pavol.kohut,gustav.kasanicky}@uzvv.uniza.sk
[2] Faculty of Security Engineering, Department of Fire Engineering, University of Žilina, Ul. 1. mája 32, 010 26 Žilina, Slovak Republic
michal.ballay@fbi.uniza.sk

Abstract. As part of expert evidence, in proceedings on traffic accidents, the basic basis for the analysis of the accident scene is the scene of the traffic accident, where vehicles and other participants in the traffic accident leave various traces. For example, according to the extent and nature of damage to vehicles and injuries to road users, it is possible to determine the nature of the collision and the approximate impact speed of the vehicle. Traffic accident analysts (forensic experts) perform accident scene analysis, where they assess the origin and causes of traffic accidents, evaluate driving techniques, determine the possibilities of avoiding a traffic accident, etc. For the calculation of various movement quantities of the accident event (calculation models), they use various application, mathematical simulation programs to determine the origin and course of the accident event. The paper deals with the analysis of an accident event in the configuration of vehicle - motorcycle - pedestrian, which occurred in the urban area of the village, on a road with a high frequency of pedestrians. In addition to the graphical analysis of the course of the accident in the PC-Crash simulation program (version 13.1), the driver's driving technique and pedestrian movement are evaluated. At the same time, the possibilities of averting traffic accidents on the part of individual road users are determined.

Keywords: Analysis · Accident event · Road traffic · Simulation · Pedestrian · Motorcycle · Vehicle · Expert evidence

1 Introduction

The traffic process consists of a large number of positive and negative phenomena adversely affecting society, including traffic accidents. These events are characterized mainly by extensive material and non-material damage, as well as various negative consequences for the health and lives of road users (light, serious and fatal injuries). In general, traffic accidents are mainly influenced by drivers and other road users (pedestrians, cyclists and motorcyclists) by their behavior and disregard for traffic rules, the

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 415–424, 2023.
https://doi.org/10.1007/978-3-031-25863-3_39

surrounding environment (road infrastructure and its traffic-engineering solutions, obstacles on the road, weather conditions) and technical condition of motor vehicles. These factors can affect the traffic accident rate either individually or in a mutual correlation [1, 2]. The analysis of road traffic accidents, which is the field of forensic engineering in the field of road transport, deals with the examination of the causes and events of various road traffic collision situations. When analysing of road accidents, one of the key parameters is the evaluation of the driver's ability to perceive different traffic situations, all associated stimuli, and density of optical information, accident, and pre-accident events according to different aspects [3, 10].

2 The Importance Analysis of the Accidents Event

In traffic accidents, there are often cases where in which the absence of cooperation of the traffic accident analyst (forensic expert) would not necessarily lead to a successful conclusion of the legal proceedings. Expert activity represents a specialized activity, which is carried out by experts in the relevant field for the client in accordance with applicable legal regulations, especially in criminal law, administrative and civil proceedings. Experts are called to the place of the transport agreement especially in cases of serious traffic accidents, if there are doubts about the course of the accident (after the initial inspection, questioning of the persons involved, other witnesses), if there was a technical malfunction, etc. [5, 11].

Traffic accident analysts perform an analysis of the accident scene based on the content of the file material, photo documentation, other opinions and expert statements, as well as statements of participants and witnesses. It is primarily about solving indirect causal problems (objective ascertainment of the facts), where, considering the consequences, structural and process characteristics, it is necessary to find out the course and causes of the traffic accident [4, 10]. Subsequently, they process the analysis of the accident scene using current calculation and simulation programs, such as Virtual Crash, PC Crash, PC Rect. These software programs provide the development of a detailed analysis of the accident scene, where it is possible to simulate any driving maneuvers of the vehicle (for example, braking, starting, passing a corner, vehicle rotation), as well as to simulate a collision with a pedestrian or other road user. The calculated final position and trajectory of movement during the accident scene must correspond as closely as possible to the actual final position and the actual trajectory of movement of vehicles and participants in the traffic accident. At the same time, the mutual force action of vehicles (interaction) and the physical properties of vehicles and participants in a traffic accident must be taken into account [3, 4, 6].

3 Analysis of the Accident Event – Vehicle, Motorcycle and Pedestrian

A traffic accident between a Škoda Octavia passenger car, a Yamaha motorcycle and a pedestrian occurred during the day in the inner city of the village. On a street with a high frequency of movement of people. Around the scene of the traffic accident, there is also a pharmacy in the populated area, restaurant, food, vegetable stall [11].

The traffic accident in question occurred as a result of the departure and lateral displacement of the Škoda vehicle, while the approaching motorcyclist reacted to this start with an evasive maneuver with a lateral displacement to the left, to the extent when the motorcycle entered the puddle area. A motorcyclist responded to a pedestrian crossing the road diagonally, by evasive maneuvers and also by intensive braking, as a result, the motorcycle lost its stability and fell onto the road. Subsequently, a skidding motorcycle collided with a pedestrian. The motorcycle skidded on the road on the right side, leaving scuff marks on the road caused by the right footpeg of the motorcycle rubbing against the road [8, 9].

The movement of individual participants in the accident scene was recorded by an industrial camera, until the moment just before the collision between the vehicle and the motorcycle. For the purposes of calculating the speed of individual participants in the accident scene, a spatial model of the traffic accident site was created using Agisoft Metashape software. Subsequently, with the help of the PC-Crash 13.1 program, the camera parameters were analyzed through the relevant reference points in such a way that it was possible (using the method of overlaying the corresponding video frame and the spatial model of the scene of the traffic accident) to establish the spatial position of the individual participants in the accident scene. The following images show the respective position of the Škoda vehicle and the motorcycle, on the one hand, on the image of the video recording and also in the spatial model of the traffic accident site at the relevant time before the collision [7, 13] (Figs. 1 and 2).

Fig. 1. The position of the participants in the accident scene in the time 2s before the moment of the collision [11, 12].

Fig. 2. The position of the participants in the accident scene in the time 1s before the moment of the collision [11, 12].

The video in question did not have the same amount of time between two consecutive frames. The number of frames taken in one second ranged from 25 to 39 frames. As a result of the above, it was necessary to make a correction in the calculation of the speed so that the mentioned effect was properly taken into account. The following table shows the time sequence of events displayed on the evaluated frames of the video recording (Table 1).

Table 1. The time sequence of events displayed [11].

Frame number	Event	Time of the original video recording evaluated from the time stamp [hours]	Image duration [s]	The time of the original video recording recalculated according to the duration of the frames[s]	Time sequence of the event [s]
348	start of the Škoda vehicle	14:05:28 + 9 images	1/25	28.36	**-6.0**
377	the start of the motorcyclist leaning to the left	14:05:29 + 13 images	1/37	29.35	**-5.0**
394	beginning of pedestrian crossing	14:05:29 + 30 images	1/37	29.81	**-4.6**
410	moment 4 s before the moment of collision	14:05:30 + 9 images	1/26	30.35	**-4.0**
436	moment 3 s before the moment of collision	14:05:31 + 9 images	1/25	31.36	**-3.0**
466	moment 2 s before the moment of collision	14:05:32 + 14 images	1/39	32.36	**-2.0**
500	moment 1 s before the moment of collision	14:05:33 + 9 images	1/25	33.36	**-1.0**
526	moment of collision	14:05.34 + 10 images	1/26	34.39	**0.0**
557	stopping the Škoda vehicle	14:05:35 + 15 images	1/37	35.41	**1.0**

The following picture shows the result of the analysis of the accident scene and the position of the individual participants in the traffic accident in question at the decisive moments of time (Fig. 3).

Position 1 – the position of the Škoda vehicle at the moment it stops, Position 2 – relative position of the Škoda vehicle, the pedestrian and the motorcycle at the time of the collision, Position 3 – mutual position of the Škoda vehicle and the motorcyclist in the moment 1 s before the moment of the collision, Position 4 – mutual position of the Škoda vehicle and the motorcyclist in the moment 2 s before the moment of the collision, Position 5 – mutual position of the Škoda vehicle and the motorcyclist in the moment 3 s before the moment of the collision, Position 6 – the position of the motorcyclist at the moment 4 s before the moment of the collision, Position 7 – the position of the pedestrian at the moment when he started to cross the road, Position 8 – the position of the motorcyclist and the Škoda vehicle at the moment when he started leaning his

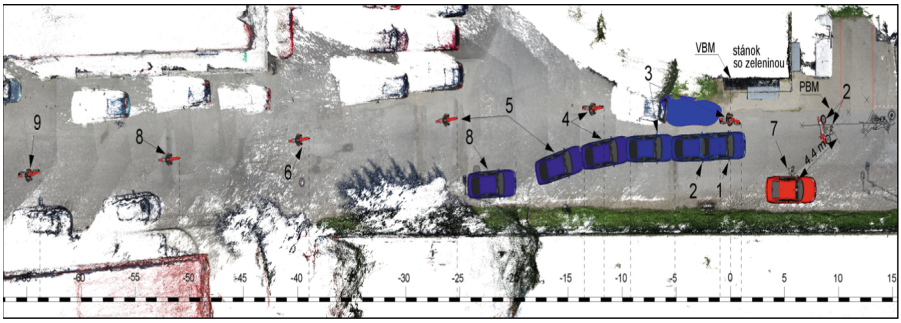


Fig. 3. The course of the accident [12].

motorcycle to the left, Position 9 – the position of the motorcyclist at the moment when the Škoda vehicle starts to drive off.

3.1 Evaluation of Drivers' Driving Technique and Pedestrian Movement

The driver of the vehicle was standing at the right edge of the road, from where she was making her start. When evaluating the traffic situation behind her (by looking in the rear-view mirror), at a moment about 0.8 s before the start of the vehicle's departure, the driver could not recognize the motorcyclist riding behind her vehicle (he was still in the area of obscured vision).

The evaluation of the traffic situation by the vehicle driver (approx. 0.8 s before the start of the start) can be considered correct. The driver of the vehicle had to evaluate the situation behind the vehicle and in front of the vehicle, while performing actions related to starting it (depressing the clutch pedal, engaging the speed, depressing the accelerator pedal, starting to release the clutch pedal), during which the vehicle does not move (Fig. 4).

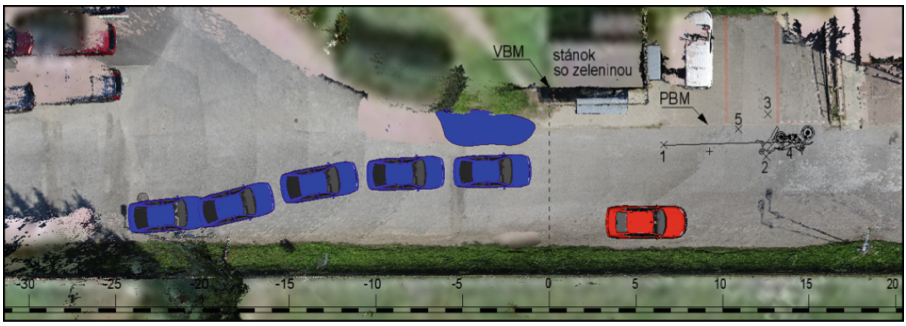


Fig. 4. The trajectory of the Škoda vehicle [12].

The driving technique of the driver of the vehicle from the point of view of the fact that she started to pull off from the right edge of the road in relation to the driving

technique of the motorcyclist can be described as wrong, as the driver endangered the driver of the motorcycle.

During the ride of the motorcyclist (who was moving at a speed of 47 km/h), the driver of the vehicle started to pull off with a lateral movement from the right edge of the road in front of the motorcycle, thereby narrowing the corridor of movement for the motorcyclist (approx. to the level of 2.3 m). After recognizing this fact, the motorcyclist could no longer safely slow down due to the driving speed. The motorcyclist was justified in starting to perform an evasive maneuver with a lateral displacement to the left (due to the lateral distance from the vehicle). At the moment of passing the vehicle, the motorcyclist also had to pass through the area of a pool of water.

The motorcyclist reacted to the movement of the pedestrian in about 2.34 s before the moment of the collision (about 26 m before the collision). During this reaction, the motorcyclist braked, while driving through a puddle of water, he lost directional stability and the motorcycle fell onto the road. Subsequently, the skidding motorcycle came into contact with a pedestrian crossing the road. The reaction of the motorcyclist by braking was correct, despite the fact that the motorcycle fell on the road, as it was not possible to safely pass the pedestrian and the motorcycle at that moment.

The reaction of the motorcyclist to the movement of the pedestrian may appear to be delayed, since the pedestrian has already covered a distance of approx. 1.9 m on the road in approx. 2.2 s. At the moment in question, however, the motorcycle and the vehicle had not yet met (the motorcycle was behind the rear of the vehicle). After this moment, the motorcyclist gave his attention to the vehicle as well as the roadway with the area of the pool of water (Fig. 5).

Fig. 5. The trajectory of the motorcyclist's movement [12].

However, the driving technique of the motorcycle driver cannot be considered correct in terms of the technical adequacy of his speed to the specific road traffic conditions in the given section. The motorcyclist entered the road where vehicles were parked on both sides and where there was a high number of pedestrians (7 pedestrians were present during the accident, including the pedestrian who was hit) (Fig. 6).

The pedestrian started to move from the parked VW Passat approximately 4.6 s before the collision. He was crossing the road at a speed of about 3.9 km/h, while moving in an oblique direction (Fig. 7).

Fig. 6. Occurrence of pedestrians at the scene of a traffic accident [11].

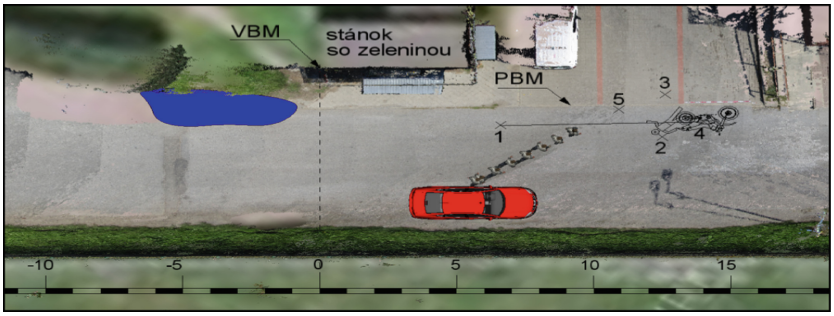


Fig. 7. The trajectory of the pedestrian's movement [12].

The fact that the pedestrian crossed the road in an oblique direction can be evaluated as an incorrect way of using the road on the part of the pedestrian. By moving in an oblique direction, the pedestrian did not have the opportunity to observe the situation from the left side, where the motorcyclist was coming from.

3.2 Possibilities to Prevent a Traffic Accident

From the point of view of the safety of road users, as well as the safety and smoothness of road traffic, it is possible to conclude that:

- if the pedestrian were to cross the road perpendicular to its longitudinal axis (in accordance with the relevant provision of the road traffic rules), he would be able to leave the movement corridor of the motorcyclist before the motorcyclist arrived at the collision site,
- the driver of the vehicle would have to start off and move the vehicle transversely only after the motorcyclist has passed on the right side of the road, which would create conditions in which a collision between a motorcycle and a pedestrian would not occur,
- the motorcyclist would have prevented the traffic accident in such a way if, at the time of his actual reaction to the movement of the pedestrian, he would have driven at a speed of up to approx. 39 km/h and would have reacted to the pedestrian with such

braking deceleration (approx. 4 m/s^2), in which there is no assumption that he would directional stability of the motorcycle has been lost. In that case, he would be able to stop the pedestrian in front of the corridor from a speed of 39 km/h by braking. The speed of 39 km/h can be considered as a speed appropriate to the width ratio at the point of collision between the motorcycle and the pedestrian.

3.3 Discussion and Results in the Analysis of the Accident Event

In the case in question, a traffic accident was analyzed in which the actions of three road users (driver, motorcyclist, pedestrian) were simultaneously influencing each other. Using video analysis (by projecting the 3D model of the traffic accident site onto a plane, in which the relevant frame of the video recording was made) it was possible to establish relatively precisely the relative movement of road users, then assess drivers' driving techniques and pedestrian movement, as well as to determine the possibilities of preventing a traffic accident.

The technical cause of the traffic accident in question was the combination of the pedestrian's incorrect movement across the road and the motorcycle driver's incorrect driving technique. A pedestrian was crossing the road in such a way that he would have passed safely in front of a motorcycle, but only under the condition that the Škoda vehicle does not start. He would have also passed safely in front of the Škoda vehicle, but only if there was no motorcycle moving on the road. However, during the accident, the movement corridor of the motorcyclist was affected by the departure of the Škoda vehicle, and with regard to the actual trajectory of the motorcyclist, the pedestrian did not cross the vehicle safely thereby creating a collision situation. As a result of incorrect movement (slanting across the road), the pedestrian made it impossible to prevent a traffic accident.

The driver of the motorcycle was moving on the road technically incorrectly, as he drove at a speed higher than the speed corresponding to the minimum lateral distance from the vehicles (approx. 18 km/h) when going around stationary vehicles. As a result of this incorrect driving technique, the ability of the driver of the Škoda vehicle to recognize that a motorcyclist was moving behind her (at the time just before it started) was significantly impaired.

At the time of the beginning of the motorcyclist's reaction to the movement of the Škoda vehicle, the motorcyclist was moving at a speed of approximately 47 km/h, while the speed was appropriate for the given traffic situation (increased number of pedestrians, vehicles parked on both sides of the road, a puddle on the road narrowing the movement corridor for the motorcyclist, etc.) is expected up to 40 km/h. As a result of the motorcyclist's driving above 40 km/h, the rate of a collision situation, which was created by the movement of a pedestrian on the road, was increasing. The driver also made it impossible to prevent the traffic accident at this speed.

Although the driver of the Škoda car drove off in a way that created a collision situation for the motorcyclist, the driver could recognize the motorcyclist in less than 0.8 s before she started to drive off. This is the usual value from the moment the driver evaluates the situation in the rear-view mirror until the start of the start. The brevity of the mentioned time interval was significantly influenced by the motorcyclist's incorrect

driving technique when overtaking stationary vehicles. With regard to the aforementioned departure of the Škoda vehicle, it is not an element of the accident that could reasonably be considered as an element of the technical cause of the traffic accident in question.

4 Conclusion

In the field of road traffic, the topic of safety and mutual consideration of individual road users on roads is very topical, prospective and necessary in view of the increasing intensity of road traffic and the development of other alternative modes of transport. Road traffic participants are persons who directly participate in road traffic (drivers, motorcyclists, cyclists and pedestrians), who are obliged comply with road traffic rules, behave in a disciplined and considerate manner, so as not to endanger the safety or flow of road traffic.

The origin and course of various traffic collisions and accident events are investigated by the analysis of traffic accidents. The certainty and reliability of the results of the accident scene analysis play an important role in expert practice. As part of the analysis of a traffic accident, forensic experts proceed systematically, while one of the key parameters for them is the evaluation of the ability of the driver and other road users to perceive the traffic situation, namely the accident event as well as the pre-accident event from different points of view (for different types traffic accidents).

The paper analyzed a traffic accident - vehicle, motorcycle and pedestrian. As part of the analysis of this accident event, the mathematical and graphic course of the accident event was processed, the driving technique of the driver of the vehicle and the motorcyclist was evaluated, as well as the way of using the road by the pedestrian. At the same time, the possibilities of preventing a traffic accident on the part of individual participants were determined. In conclusion, it can be concluded that the traffic accident in question confirms how the behavior of road users affects the occurrence of a traffic collision. Even a slight underestimation of road traffic rules can result in a traffic collision with serious or fatal consequences for the health and lives of road users.

Acknowledgements. This work was supported by the Slovak Research and Development Agency under contract no. APVV-20-0626. This work was created within the project APVV-20-0626: Biofidelic human body surrogate to increase the objectivity within the forensic analysis of road traffic accidents.

References

1. Čulík, K., Kalašová, A.: Statistical evaluation of BIS-11 and DAQ tools in the field of traffic psychology. Mathematics **9**(4), 433 (2021)
2. Čulík, K., Harantová, V., Hájnik, A.: CAD software using for designing of traffic environment. Transp. Res. Procedia **44**, 248–254 (2020)
3. Kasanický, G., Kohút, P.: Impact dynamics theory for the analysis and simulation of collisions. University of Žilina, Žilina, EDIS, 350 p. (2004). ISBN 80-8070-312-4

4. Kohút, P., Kasanický, G.: Evalution of crash tests of the institute of forensic engineering. University of Žilina, aimed at ess. Commun. – Sci. Lett. Univ. Žilina **15**(2), 124–130 (2013)
5. Kubica, M., et al.: Forensic science. Wolters Kluwer, s.r.o., 332 p. (2016). ISBN 978-80-7552-499-7
6. Li, Z., Huang, H., Li, D., Li, P.: Analysis of influencing factors of pedestrian-vehicle accident reconstruction based on Pc-Crash. In: International Conference on Education, Management and Computing Technology (ICEMCT-15), pp. 1576–1580. Atlantis Press. (2015)
7. Miao, Q., et al.: Analysis of pedestrian fractures in collisions between small cars and pedestrians based on surveillance videos. Am. J. Forensic Med. Pathol. **43**(1), 11–17 (2022)
8. Ondruš, J., Kolla, E.: The impact of ABS system on the braking characteristics of the specified motorcycle on the dry road surface. In: International Automotive Conference (KONMOT 2018). IOP Conference Series: Materials Science and Engineering, vol. 421, no. 2, p. 022024 (2018). ISSN 1757-8981
9. Ondrus, J., Hockicko, P.: Braking deceleration measurement using the video analysis of motions by Sw tracker. Transp. Telecommun. **16**(2), 127–137 (2015)
10. Rédl, M., Ondruš, J., Felcan, M.: Using measuring system Viewpointsystem® by perception of road accident. Paper presented at the Transport Means - Proceedings of the International Conference, 2021-October, pp. 812–817 (2021). ISSN 2351-7034
11. The case study - Analysis of the accident event vehicle-motorcycle-pedestrian (Archive ÚSI)
12. SW PC Crash (13.1.), SW XL Vision™
13. Zhang, X., Huang, F., Zheng, C.: Causes analysis of the serious road traffic accidents cases. In: 2016 5th International Conference on Energy and Environmental Protection (ICEEP 2016), pp. 817–822. Atlantis Press (2016)

Logistics and Transportation

Assessment of Trends in Improving the Performance of Transportation Companies

Algimantas Danilevičius[1](✉) and Irena Danilevičienė[2]

[1] Faculty of Transport Engineering, Department of Mobile Machinery and Railway Transport, Vilnius Tech, Plytines Str. 27, 10105 Vilnius, Lithuania
algimantas.danilevicius@vilniustech.lt

[2] Faculty of Business Management, Department of Financial Engineering, Vilnius Tech, Sauletekio av. 11, 10223 Vilnius, Lithuania
irena.danileviciene@vilniustech.lt

Abstract. Nowadays the principles of traditional business are obsolete and require new, more efficient ways of working. By integrating information technology into traditional business processes, the boundaries of the organization are constantly expanding, a wider range of target customers is brought together, and operational efficiency is improved. Every company needs to use information technology in its day-to-day operations to stay competitive. Companies offering transportation services expect more customers, a better quality of service, and shorter working hours. However, a problem arises when unsuitable the application of business principles hinders the activities of many transport companies and reduces development opportunities. The objective of this article is to evaluate the tendencies of improving the activity of transportation companies. To achieve this objective the main tasks are formed: to analyze the theoretical aspects of transportation activities to perform an analysis of the activities of Lithuanian transportation companies; to provide ways to improve transportation performance and to assess opportunities. The following research methods are used: analysis of scientific literature, analysis of statistical data, SWOT analysis, and forecasting method.

Keywords: Economic growth · Profit · SWOT · Transportation

1 Introduction

Nowadays the principles of traditional business are obsolete and require new, more efficient ways of working. By integrating information technology into traditional business processes, the boundaries of the organization are constantly expanding, a wider range of target customers is brought together, and operational efficiency is improved. With the growing importance of transportation in Lithuania and around the world in our daily lives, in the international trade activities of businesses and the state, it is understood that transportation is not limited to transportation from point A to point B.

Every company needs to use information technology in its day-to-day operations to stay competitive. Companies offering transportation services expect more customers, a

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 427–437, 2023.
https://doi.org/10.1007/978-3-031-25863-3_40

better quality of service, and shorter working hours. However, a problem arises when unsuitable the application of business principles hinders the activities of many transport companies and reduces development opportunities.

The objective of this article is to evaluate the tendencies of improving the activity of transportation companies. To achieve this objective the main tasks are formed: to analyze the theoretical aspects of transportation activities to perform an analysis of the activities of Lithuanian transportation companies; to provide ways to improve transportation performance and to assess opportunities. The following research methods are used: analysis of scientific literature, analysis of statistical data, SWOT analysis, and forecasting method.

1.1 Theoretical Aspects of Transport Activities

Special attention is paid to transportation activities and their improvement in modern research and practice. In a globalized world, companies that want to be competitive and attract as many customers as possible must meet their needs in a timely and high-quality manner. The importance of transport has increased particularly during the global pandemic when transport companies should be able to adapt to the changing needs to get the most out of their work. It follows that transportation activities should be improved.

Transportation is one of the most important logistics activities that help ensure the movement of products from production to consumption sites [10]. Transport costs are often the highest compared to others, so special attention must be paid to these activities. Transportation adds space and time to the production.

Transportation is the flow of material, information, and money between consumers and suppliers [4]. The transportation system is a system that defines the movement of goods from one point to another, ensuring that the process contributes to improving the economy and increasing the competitiveness of the company [12]. It is often difficult to plan how to deliver a product to the consumer quickly, efficiently and with minimal cost, so it must be a well-planned process that includes steps from delivery planning to product delivery to the end-user. When planning a transportation route, it is important to consider key criteria [6]: price, range, time, and availability.

Here 9 main transportation functions are highlighted:

- **economic growth** – transportation promotes economic growth when the most perishable products (fish, vegetables) are not discarded but sold because they reach end-users on time, even in distant markets;
- **increase in demand for goods** – due to faster transportation, the circle of new customers is expanding even in the regions furthest from the company's main headquarters;
- **the advantage of non-domestic goods** – raising living standards, which is a key factor in promoting marketing and economic development;
- **price stabilization** – due to the significant impact of transportation on the stabilization of the prices of several goods, when raw materials are moved from surplus to deficit areas, supply and demand are balanced;
- **time efficiency** – by improving the transport speed, products are distributed in the shortest possible time;

- **labour and capital mobility** – people are forced to migrate to find work, and at the same time capital, equipment and knowledge are "transported";
- **competitiveness –** the equipment offered for transport reduces the prices for large-scale production, which makes it worthwhile to buy in large quantities and foster large-scale production;
- **local utility** – closing the gap between production and consumption centers, as geographical and climatic factors force industry to move away from markets and in place where there may be no demand for products;
- **evenness of the flow of goods** – ensures an even flow of goods into the hands of consumers throughout the period of consumption.

Transportation is associated with many negative externalities, such as noise, air pollution, and events [3]. Transportation is becoming more important in industrialized countries, where it is becoming a major economic and social development activity that increases GDP.

These activities include the choice of mode of transport and means of transport, routing, and selection of a specific carrier. The most important transportation features that affect the customer service level [11]: reliability, delivery time, service area, product delivery flexibility, loss and damage to cargo, the ability of the transport company to provide not only transportation but also other service services.

When it comes to freight transport, here we can choose from many modes of transport – rail, road (car), air, water, pipeline, but each has its advantages and disadvantages. The choice of the appropriate mode of transportation depends on priority criteria for the cargo owner, which can vary widely. The most common include minimum transport costs, minimum delivery time, transport reliability, adequate vehicle capacity, "availability" of transport services in a given area, carrier's financial stability, additional services, service flexibility, transport regulation, qualification, or cargo tracking capability. The article pays special attention to the description of road transport.

1.2 Organization of Transport Activities and Opportunities for Improvement

An essential consequence of globalization is the constant increase in competition between companies. In the context of change in a company, it is important to constantly nurture the profitability of companies and look for new activities. It follows that traditional transport services need to be less standardized, more passive, but more focused on promoting flexibility.

Promoting positive transportation activity has 3 objectives: a positive impact on economic growth, the application of the latest technologies, the sharp rise in the trade agreement and the development of other innovation and logistics sectors. This can be achieved by optimizing the transportation process, minimizing costs and obtaining higher returns [1].

The transportation process includes the receipt and processing of orders, the provision of warehouses with the required volume of production, loading, transportation, unloading, document management and billing [5]. These processes generate corresponding costs, which are paid by logistics professionals. These professionals must coordinate all distribution activities, distribute them and thus reduce the costs incurred.

The main objective of transportation – to provide customers with services and goods, taking into account their needs and demand for services and goods [2]. This means that the transport process should guarantee the successful distribution of goods and the operation of the supply chain. Researchers in different countries now agree that the object of transportation activity is the material flow through the entire movement path, that is, from the primary source to the end-user, and the entity is cost optimization throughout the supply chain [8].

One of the most important elements of transportation processes is the choice of the optimal route. From the perspective of a transport company, a route is understood as a freight transportation route [13], which is influenced by many factors, the most important of which is the mode of transport. The road network depends on the mode of transport chosen. Transportation routes are created using appropriate applications, which are useful because it is easier to predict possible restrictions, mode of transportation, and route. The information technology used has a positive effect on the efficiency and competitiveness of transport companies, as it also meets the needs of customers (customers can get accurate information about the location of the load, monitor the speed of the driver, working hours and control the route).

Route selection is important to reduce cargo delivery time and thus use less fuel, pay fewer infrastructure charges, maintain cargo safety, and maintain proper vehicle condition [7, 9]. There are two main modes of transportation known:

- transportation in fully loaded vehicles (the vehicle is fully loaded at the consignor and transported to the customer, choosing the shortest possible route);
- transportation with partly loaded vehicles (loading of goods from different consignors and consignees into one vehicle (loading from similar locations and loading and unloading of goods on a circular basis)).

In summary, transportation activities should be organized very carefully: the right vehicle is chosen, the optimal route is chosen, and the available information is used properly.

2 Analysis of Lithuanian Transportation Companies' Activities

2.1 Research Methodology

To assess the current situation in Lithuanian transportation companies, a SWOT analysis is used. SWOT analysis is an analysis that summarizes and combines the results of the analysis of the external environment and the internal environment, classifying the factors determining the strategy into four groups: strengths, weaknesses, opportunities, and threats [14]. The objective of the SWOT analysis is to develop a strategy based on strengths and opportunities to address vulnerabilities and threats. Four types of strategies are formed according to this:

- strengths – opportunities;
- weaknesses – opportunities;
- strengths –threats;

- weaknesses – threats.

Strengths are those internal factors that give a firm a comparative advantage. Strengths show how a company stands out from other companies or what production, human, organizational factors give a company a competitive advantage.

Weaknesses are those internal factors that hinder the development of a company. Weaknesses indicate what factors hinder the development of the company in the relevant area, what are the most pressing and long-term problems to be solved in the first place.

Opportunities are those external factors that increase a company's comparative advantage. Opportunities show what international, national and sectoral trends could have a negative impact on the company's future development.

Threats are those external factors that jeopardize the development of the company or weaken the company's comparative advantage.

Strengths and weaknesses are internal circumstances that companies can control and opportunities and threats are external circumstances that they cannot control.

In order for the SWOT analysis to be carried out properly, the following key questions need to be answered:

- Which of the company's strengths can be adapted to take advantage of external opportunities?
- Which company strengths can help reduce threats?
- Which company vulnerabilities need to be addressed to reduce threats?
- What external opportunities can be used to address the company's weaknesses?

The company's SWOT matrix and analysis allow for appropriate tactical and strategic decisions.

2.2 Situation Assessment of Lithuanian Transportation Companies

In order to make accurate proposals for the improvement of transport activities, it is very important to assess the current situation in the transport sector.

Table 1 summarizes the results of the SWOT analysis of the activities of Lithuanian transportation companies – the main strengths, weaknesses, opportunities and threats.

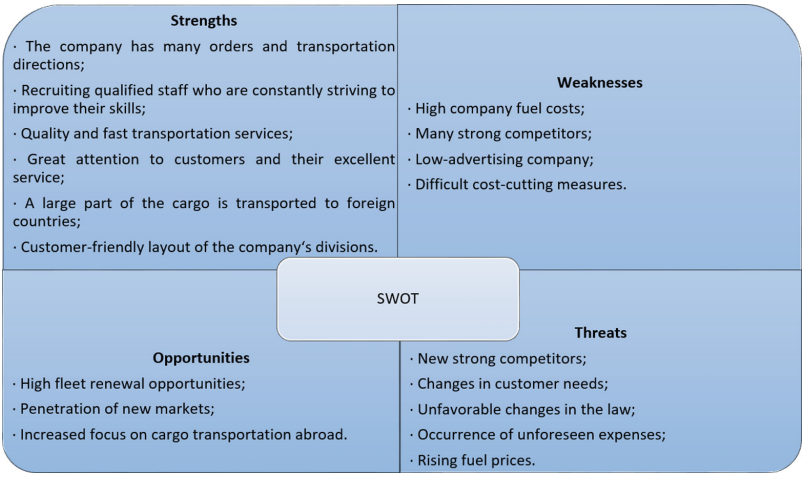
The results of the SWOT analysis show that the strengths fully offset the weaknesses, but the threats outweigh the opportunities. It follows that the company is quite strong and competitive, but internal and external negative factors should be avoided, as they can negatively affect the efficiency of transportation activities.

Particular attention should be paid to the fact that a just-in-time inventory management system is used for the transportation of goods, so goods are not stocked in a warehouse, but are transported with high quality and speed, but there are often various difficulties, the main ones being:

- Loading/unloading delays – delays are often due to equipment failures during the process, non-communication (which goods need to be loaded), loading of the wrong weight (when part of the load has to be unloaded due to the wrong weights), or large queues at unloading points.

- Human factor errors – difficulties arise due to inaccurate data entry or incorrect formatting of documents.
- Natural conditions – the process of transportation is often hampered (especially in winter) by natural conditions, which lead to road closures due to unfavorable weather, ferry delays, or slippery roads.
- Vehicle or technical accidents and breakdowns – unforeseen difficulties occur when a vehicle breaks down on the road and has to use roadside assistance services.

Table 1. SWOT analysis of Lithuanian transportation companies at 2011–2020 y. y. (compiled by the authors).



In order to protect against the negative consequences of transport difficulties, efforts are being made to improve the qualifications of drivers so that they can transport goods in various weather conditions, a lot of practical training takes place and drivers are trained to repair the vehicle themselves if the fault is very minor. Proper planning of transportation routes is also very important.

Another important aspect that needs to be mentioned is the cost of transportation. Transport companies incur very high transport costs, most of which are fuel costs, road charges, vehicle depreciation, wages and contingencies (bad roads, unprepared loading and unloading sites). The main costs associated with transport activities are fines for delays, expensive refueling, road tax costs, minor and more serious accidents. It follows that, in order to improve transport performance, it is necessary, first of all, to reduce the costs incurred and to look for other ways of improvement.

3 Ways to Improve the Activities of Lithuanian Transportation Companies' Activity

Statistics data are needed to assess the current situation in the transport sector and to assess possible trends for improvement. The data of the Department of Statistics of the Republic of Lithuania on freight turnover by road transport (expressed in billion km) were used to analyze the statistical data (Fig. 1).

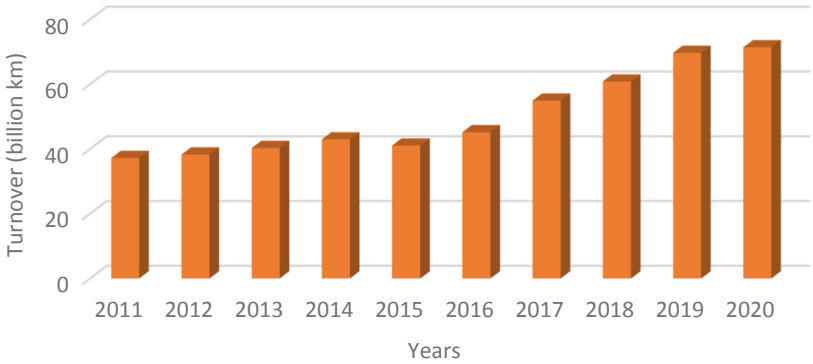


Fig. 1. Freight turnover by road at 2011–2020 y. y. (compiled by the authors based on Department of Statistics data).

A period of 10 years with validated data was selected for the study. Based on the data provided, a forecast for the next 6 years will be made later. It should be taken into min that the purchase of newer vehicles reduces the cost of repairing them and can be used more efficiently (more freight is transported and more revenue is generated).

Based on the analysis of the submitted data and applying the trend method, the corresponding changes in turnover for the next 6 years are forecasted (Fig. 2).

Figure 2 shows that the situation changes over the years. Due to the negative consequences of the pandemic, turnover may decrease (part of the existing assets must be sold because it is not being used efficiently at the moment), but the fleet should be expanded and more new vehicles purchased in the near future. In addition to fleet renewal, it is necessary to offer the Lithuanian transportation sectors:

- to distribute the responsibilities of the employees fairly and efficiently (concentrating the employees' attention on the operation assigned to them would help them to perform the work assigned to them quickly and efficiently and improve the company's financial results);
- improve information systems (to optimize routes, save fuel, etc.);
- to look for new qualified employees who would know additional foreign languages, thus expanding the transportation market and expanding the customer network.

The sale of existing but unused assets of transport companies is expected to lead to an increase in revenue (due to revenue from the sale of vehicles) and an increase in costs,

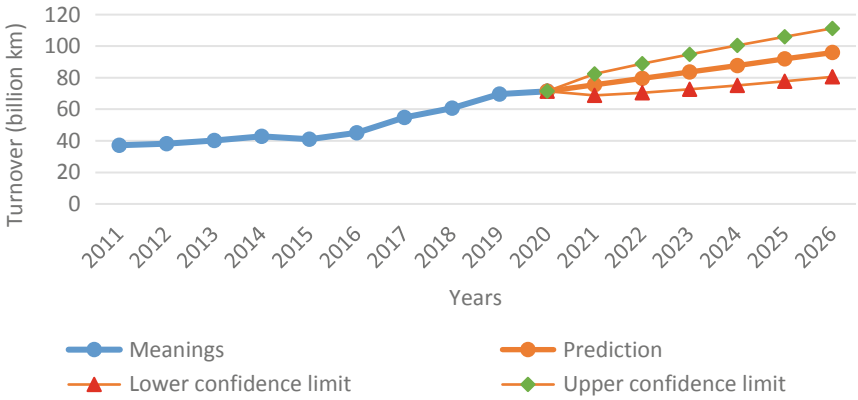


Fig. 2. Forecasting of the changes in turnover at 2011–2026 y. y. (compiled by the authors).

as the sale of vehicles and the partial restriction of freight traffic may lead to downtime and a relative increase in costs. However, the situation is expected to improve from next year when the increase in assets will lead to higher income and lower costs.

Summarizing the obtained results, it can be stated that the transportation sector in Lithuania has opportunities to prosper, only possible recessions should be noticed in time and responded to appropriately.

Based on the results of the SWOT analysis, it can be stated that the improvement of the company's transportation activities can be carried out in 3 directions (Fig. 3): renewal of the fleet, reduction of costs and increase in revenue. To achieve these objectives, certain measures are needed.

Renewal of the Company's Fleet. New vehicles are less likely to cause breakdowns and accidents. Newer vehicles are less perishable, so they lose time repairing or replacing them and they emit less CO2 and pay less in taxes. As a result, the company's fleet renewal will reduce costs and increase profits.

Cost Reduction. It is known that most of the financial resources are spent on wages, fuel, vehicle depreciation and the payment of taxes. The easiest way is to reduce fuel costs because it is known in which countries fuel is cheaper and it would be unnecessary to refuel in countries where fuel is more expensive. It is also important to calculate how much fuel is consumed. When checking, it is important for drivers to fill in the journey forms accurately (indicating initial and final condition, refueling, exact driving locations), as this makes it easier to calculate how much fuel has been used, what its price has been and what its average consumption has been.

Fuel costs can also be reduced by optimizing the driver's driving style (without unnecessarily accelerating or braking). It follows that drivers need to continuously improve their skills, improve their driving style, or be motivated by management to transport goods with minimal fuel consumption (by paying a supplement if the fuel consumption during transport was less than average).

It is also recommended to check the condition of the vehicles periodically, as only technically sound vehicles use less fuel and avoid accidents or unforeseen breakdowns

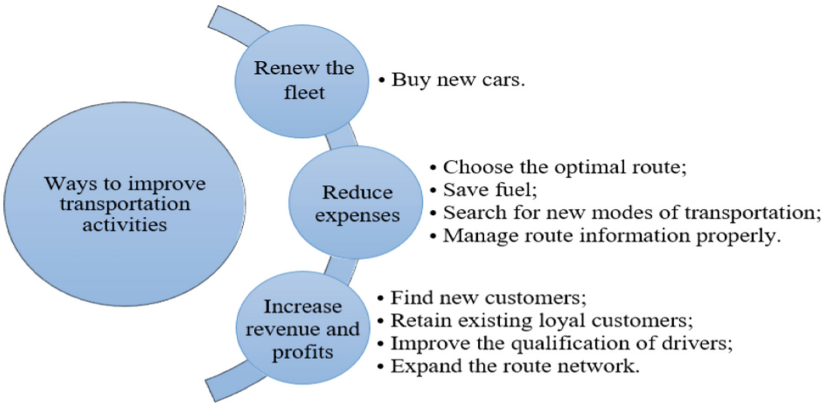


Fig. 3. Ways to improve transportation activities (compiled by the authors).

that lead to additional costs. This recommendation to check the condition of vehicles is closely linked to the fleet renewal proposals. If goods are transported in the latest vehicles, fuel consumption will be reduced, vehicles will be more economical, and the environment will be protected at the same time. In summary, fuel costs can be reduced by choosing the optimal (and most appropriate) route, saving fuel, or finding new modes of transport.

Increasing Profits. As already mentioned, there are different ways to increase profits. One of the main ones is to maintain good, sustainable and stable relationships with the company's existing customers and attract new ones. Customers will be loyal to the company only if their needs are met in a timely manner, with quality and at the lowest cost. It is very important to pay more attention to finding new customers (especially from abroad) and expanding the route network. This will increase the sales of the transportation company, attract more customers and make the company known abroad.

Customer testimonials also help to increase awareness and to increase their number, it is necessary to ensure that transportation services are provided quickly and with high quality. This can be achieved by improving the qualifications of drivers and focusing more on improving their driving skills. As drivers must travel a lot and in different weather conditions, it is necessary for them to organize training on how to transport goods safely and quickly on slippery, wet roads or in certain unforeseen weather conditions. It is also very important to ensure that in the event of minor breakdowns, drivers can repair the vehicle themselves and do not use expensive roadside assistance services.

4 Conclusions

1. In a world affected by globalization, transport services are evolving rapidly and are becoming increasingly important in fostering the productivity of sectors of economic activity. Transport activities should be organized very carefully, as the success of any transport company depends on the right vehicle and the optimal choice of route and the proper use of available information.

2. In Lithuania, the largest share of cargo in the warehouses of transportation companies consists of excise goods and the inventory management system is used just-in-time to manage inventories. There are many different difficulties in transporting goods (loading/unloading delays, human mistakes, adverse natural conditions, vehicle accidents and breakdowns). Cargo is transported mainly to foreign countries, therefore the company's employees mentioned route planning errors or incorrect loading/unloading numbers as the main difficulties. The inaccuracies listed affect transportation time and cause a lot of inconvenience at any time of the day.
3. Transport costs are high, most of which are fuel costs, road charges, vehicle depreciation, wages and contingencies. In order to reduce costs and increase profits, it is proposed to determine the optimal transportation route, save fuel and look for new transportation opportunities. The pandemic had a negative impact on the company's operations, freight volumes fell by a third and freight had to be transported at a lower cost to maintain a steady flow of transport and save driver jobs, managers. To improve transportation activities till 2026 year it is necessary to apply the following improvement methods: to renew the fleet (buy new cars), reduce costs (choose the optimal route), increase profit (find new customers).

References

1. Bashir, R., Vijayalakshmi, H., Bashir, N.: A comparative study on the prices of products in logistics companies and their impact on economic growth. In: 8th International Conference on Reliability, Infocom Technologies and Optimization (Trends and Future Directions), 4–5 June, 2020, pp. 934–939 (2020)
2. Beniušienė, I., Tijūnaitienė, R.: Marketingo logistika – laiko vertė aptarnaujant klientus. Socialiniai mokslai, ekonomika **1**(5), 111–114 (2016)
3. Faulin, J., Grasman, S. E., Juan, A.A., Hirsch, P.: Sustainable Transportation and Smart Logistics. Decision-Making Models and Solutions. Elsevier, United Kingdom (2019)
4. Frazelle, E.: Supply Chain Strategy: The Logistics of Supply Chain Management. McGraw-Hill Companies, New York (2002)
5. Gargasas, A., Kavaliauskienė, V.: Logistikos metodų naudojimo efektyvumas. Inžinerinė ekonomika **3**(18), 80–86 (2015)
6. Hidayatno, A., Destyanto, A.R., Fadhil, M.: Model conceptualization on e-commerce growth impact to emissions generated from urban logistics transportation: a case study of Jakarta. Energy Procedia **156**, 144–148 (2019)
7. Jaržemskis, A., Jaržemskis, V.: Krovininis transportas. Kaunas: Technika (2014)
8. Kalbarczyk-Guzek, E., Jóżwiak, A.: Decyzje taktyczne firm w zakresie ustalania warunków dystrybucji towarów. Systemy Logistyczne Wojsk **49**, 112–123 (2018)
9. Kopczewski, R., Nowacki, G.: Wykorzystanie inteligentnych systemów transportowych do monitorowania pojazdów przewożących towary niebezpieczne. Autobusy: technika, eksploatacja, systemy transportowe **20**(10–11), 64–73 (2019)
10. Lemtaoui, M., Rochdi, M.H., Eloueldrhiri, S.: Measuring the supply chain performance in Morocco: application of the Edward Frazelle's Model. In: International Colloquium on Logistics and Supply Chain Management, 27–28 April, 2017, Rabat, Morocco, pp. 188–192 (2017)

11. Nagulevičius, E., Jakubavičius, A.: Gamybos proceso modernizavimas, pramonės skaitmenizavimo iššūkių kontekste. 22-osios Lietuvos jaunųjų mokslininkų konferencija "Mokslas – Lietuvos ateitis", 2019 m. vasario 13 d. Vilnius, pp. 1–9 (2019)
12. Putra, A.A., et al.: Model of logistic transport distribution in the urban area. In: IOP Conference Series: Earth and Environmental Science, vol. 419, pp. 1–12 (2020)
13. Vasilis Vasiliauskas, A.: Krovinių vežimo technologijos. Vilnius: Socialinių mokslų kolegija (2013)
14. Vlados, C.: On a correlative and evolutionary SWOT analysis. J. Strateg. Manag. **12**(3), 347–363 (2019)

Ukrainian High-Speed Normal Gauge Railway: Factors of War and Peace

Viktor Myronenko, Valery Samsonkin, Oksana Yurchenko(✉), and Andrii Pozdniakov

State University of Infrastructure and Technologies, 9, Kyrylivska St., Kyiv 04071, Ukraine
yurchenko_og@gsuite.duit.edu.ua

Abstract. The expediency and problems of gradual transition of Ukrainian railways to the 1435 mm standard of normal track gauge are discussed, due to the experience of Russian aggression and war against Ukraine, the need to strengthen its defence capabilities in the future, closer integration of its transport system with TEN-T and the need to attract additional volumes of transit of goods by rail of partner countries on the Caspian-Black Sea intermodal route between China and the EU.

The first stage of the transition to the normal track width is the implementation of the Ukrainian high-speed railway project from the Black Sea ports to the western border of Ukraine with Poland and the connection of this HSR with the TEN-T network, including the Rail Baltica project.

The options of interaction between railway systems of 1435 mm and 1520 mm in Ukraine are discussed. A basic mathematical model is proposed for comparison of the options for technological solutions.

Keywords: High-speed railway · Transportation technology · The New Silk Road · Ukraine's transport system · Multimodal terminals · Gauge change · Wagon bogie · Variable gauge

1 Introduction

As the European integration processes intensified in Ukraine and the aggressiveness of its northeastern neighbor increased, specialists discussed the problems of transition of Ukrainian railways to the 1435 mm gauge standard. Finally, the concept of the same track width with most of the European and world railway network was also reflected in state program documents [1].

Among the arguments in favour of such a transition was the need for practical integration into the Trans-European transport network TEN-T, including the network for high-speed trains. Certain stages of the transition are envisaged, in particular, (a) in order to ensure the interoperability of the national transport system of Ukraine with the global multimodal transport network, including the railway network with a track width of 1435 mm; (b) creation of conditions for connecting regional centers with a network of speed railways (from 160 to 200 km per hour) by 2025 and high-speed railways (from 250 to 400 km per hour) by 2030 [1].

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 438–448, 2023.
https://doi.org/10.1007/978-3-031-25863-3_41

Previously, the authors expressed their principled position that the Ukrainian high-speed railway (HSR) should not be a purely domestic "passenger" railway, but should be part of transcontinental transport links, in particular, the New Silk Road [2], and it should also be used for the transportation of goods that require fast delivery (on share-use principle) [3].

Among the arguments in the discussions, the authors emphasized the great role of the new 1435 mm gauge railway to ensure the state's defence capability. Unfortunately, more arguments appeared the full-scale war launched by Russia against Ukraine on February 24, 2022. According to World Bank estimates, the Russian invasion will reduce Ukraine's economy by 45% this year! [4]. These losses could be less and how many lives could be saved if:

– the logistics of the aggressor's troops, which focuses mainly on railway transportation, would be significantly complicated by a different track width;
– Ukrainian troops could destroy large concentrations of enemy troops and weapons on our north-eastern border, in places of transhipment to another track;
– NATO countries could quickly and in large quantities provide us with any assistance, without delays on our western borders.

Therefore, when making state decisions regarding the restoration of the country's infrastructure after the war, a program for the transition of Ukrainian railways to the 1435 mm gauge standard must be provided.

This fully coincides with the tasks of the European integration of Ukraine facing it in the transport sector in accordance with the Association Agreement with the EU, in particular: "Cooperation shall also aim at improving the movement of passengers and goods, increasing fluidity of transport flows between Ukraine, the EU and third countries in the region, by removing administrative, technical, cross-border and other obstacles, improving transport networks and upgrading the infrastructure in particular on the main axes connecting the Parties. This cooperation shall include actions to facilitate border-crossings". [5, part 2 of Art. 368].

2 Problems Statement

The transition of the railway network of Ukraine to the 1435 mm gauge standard, starting with the introduction of high-speed transportation, creates problems of definition and scientific justification of:

- Routes and main parameters of the Ukrainian HSR network design and operation.
- Stages and options of the transition of Ukraine's railway network to the 1435 mm gauge standard, taking into account the interaction with the 1520 mm railway network.
- The operational and economic expediency of using alternative cargo delivery technologies in transport markets where railways of different track gauge and different transport modes interact.

3 Presenting Main Material

Already at the beginning of the Russian-Ukrainian war, changes began in the transport markets, affecting not only Ukraine, but also having a global dimension.

Thus, in March 2022, one of the Trans-Siberian railway transportation specialists noted that "Right now, the flow on the rail link is roughly 500,000 TEU. If this stopped it would add almost 10,000 TEU a week of demand onto Asia-Europe ocean services, where it would compete for space on vessels which are already full" [6].

Therefore, the use of alternative routes, including intermodal ones, has already begun. In particular, in April 2022 a Chinese rail operator launched a new freight train service from Xi'an in northwest China to Europe that traverses the Caspian Sea and the Black Sea via rail-sea combined transportation bypassing Russian territory. According to Chinese state media, the 11,300 km long route will pass through Kazakhstan, Azerbaijan, Georgia, Romania, Hungary, Slovakia and the Czech Republic and finally reach the city of Mannheim in Germany [7].

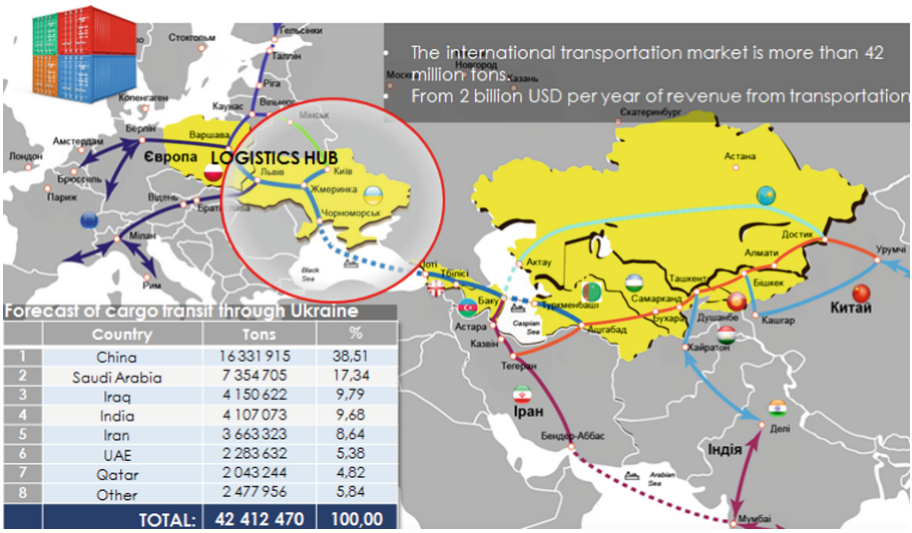
3.1 The Ukrainian HSR Route in the Transcontinental Context

Ukraine can offer its Caspian-Black Sea route which is not longer than the one mentioned above, but not through seven transit countries, which will reduce by two the number of delays at the borders. The authors have expressed this more than once (for example, [2]). Within Ukraine, it should be a new HSR which will be operated on the principle of shared use [8] by both passenger and freight trains, intended for the urgent delivery of goods with a high value added at commercially justifiable speeds. Having the experience of war, this railway must also be designed taking into account the rapid delivery of military personnel and dangerous goods of military purpose.

The route of the Ukrainian HSR, which will become part of the international Caspian-Black Sea intermodal route, is shown in Fig. 1. It has the advantage not only of a smaller number of transit countries, but also provides an opportunity to connect through Poland with the future 1435-mm track HSR of Rail Baltica [8].

In our opinion, the new Ukrainian HSR should be a dedicated high-speed line. Despite the fact that there are discussions about their expediency and the possibility of construction in Europe [9], in post-war Ukraine it is necessary to build such a line. It should become an integrating link in the system of both European HSR, which includes Rail Baltica [8, 10], and similar Asian transport projects within the Belt-and-Road Initiative (BRI) [11], in particular the Urumqi-Tehran HSR project [12]. The possibility of creating such international transport links is evidenced by Fig. 1.

This will restore at a higher technological level the Black Sea-Baltic route (which until recently passed through Belarus) – this historical route "from the Varangians to the Greeks", and will also connect it with another ancient trade route of mankind – the Silk Road, which and in ancient times passed through the current Ukrainian lands.



	Country	Tons	%
1	China	16 331 915	38,51
2	Saudi Arabia	7 354 705	17,34
3	Iraq	4 150 622	9,79
4	India	4 107 073	9,68
5	Iran	3 663 323	8,64
6	UAE	2 283 632	5,38
7	Qatar	2 043 244	4,82
8	Other	2 477 956	5,84
	TOTAL:	42 412 470	100,00

Fig. 1. New Ukrainian high-speed railway 1435 mm in the system of global transport links.

This will also be a significant contribution of Ukraine and its closest partners during the devastating war – the Baltic States and Poland – to the development of the "Three Seas - Trimarium" concept. For Ukraine and its partner countries, the new Ukrainian 1435-mm gauge railway will become a full-fledged integration into the TEN-T network and the pan-European space and a source of huge transit flows between China (and later India) and the countries of the European Union.

3.2 Stages and Alternatives

In our opinion, it will be possible to proceed to the implementation of such ambitious projects not sometime in the future, after the complete restoration of the country's railway infrastructure, which was destroyed by more than one-third in the first 100 days of the war, but already during the development of restoration programs. Because there is no point in restoring it to the way it was before the war.

This should be done taking into account both high-speed transportation based on the shared-use principle and the gradual transition of our railways to the normal track width of 1435 mm. But the stages and geography of such a transition must be (a) theoretically sound and (b) realistic for their practical implementation.

We will formulate the possible options and stages of the transition of our railway network from the current "zero" state (state 0) to other possible states, of which the "ideal" or most desirable is a complete transition – the so-called "re-stitching" of our network from the 1520 mm track on a track of 1435 mm, as in most countries of the European Union and the world. They are listed in the Table 1, which can only be considered as a guide, and not an exhaustive list.

Table 1. Options and stages of the transition of Ukraine's railway network to the 1435 mm gauge standard and alternative transportation technologies.

State/options/stages	Description	Costs	Benefits	Risks
0	Leave everything as it is - "zero state". The entire network of railways has a gauge of 1520 mm	CAPEX is minimal compared to other options	No changes, but also no growth prospects	A great military threat from the east and north
1	Extension or new construction of 1435 mm track lines from the western border into the interior of Ukraine to certain stations with terminal equipment for transhipment/replacement of bogies	CAPEX is increasing compared to the 0 state	Greater volumes of transportation and income due to better connections with the EU	Reducing the transit capacity of our railways. A significant threat from the east and north
2	Transition to operation of rolling stock with variable track width – Automatic Transfer Gauge System (ATGS)	CAPEX increases significantly compared to the 0 and 1 state	Acceleration of border crossing at track gauge change stations	A significant threat from the east and north
3	A combination of options 1 and 2	CAPEX can be the highest for conventional railways	Acceleration of border crossing	A significant threat from the east and north
4	Construction of new transit high-speed rail mainlines (HSM) of 1435 mm gauge in the specified directions of passenger and cargo flows with multi-modal terminals for interaction with the 1520 mm gauge and other transport modes, full integration with TEN-T network	CAPEX is not less than 30 billion euros during 5–7 years, on the basis of public-private partnership	"New" massive cargo transit between China and the EU	The risks of a military invasion are minimal due to large foreign investments in the new HSM

(*continued*)

Table 1. (*continued*)

State/options/stages	Description	Costs	Benefits	Risks
5	The railway network was completely "changed" from the 1520 mm gauge to the 1435 mm gauge	CAPEX is not less than 200 billion euros for 5–7 years, with the main load on the state budget	Full interoperability with the TEN-T network	Minimal threat of invasion from the east and north

In our opinion, considering the balance of benefits and risks, option 4 is the most desirable and quite realistic.

When considering alternatives, it should be taken into account that, in addition to almost 20,000 km of public railway tracks of 1520 mm gauge, in Ukraine there are almost the same length of industrial sidings tracks, with at least 90% of loading and unloading. It is likely that the operators of these (mainly private-owned) tracks will generally have neither the need nor the resources to switch to 1435 mm gauge.

Therefore, specialists are considering an alternative technology, namely the use of wagons on bogies that can change the width to fit the track gauge. The gauge is altered by driving the train through a gauge changer or gauge changing facility. We will not delve into the technical details of this technology, which are sufficiently covered in the literature, e.g., [13].

3.3 Economic Evaluations of Alternatives and Stages of Transition to the 1435 mm Track

How can these alternatives be evaluated economically in order to make an informed decision about the scope of use of (1) variable gauge freight trains and (2) terminal service system for rail customers at junctions of different gauges? To do this, it is necessary to compare two options for the organization of transportation service by railways of different tracks:

I – delivery of cargo to/from the terminal closest to the Ukrainian importer/exporter facilities, where railway systems of different track widths interact, with rolling stock of 1435 mm track and reloading it on rolling stock of 1520 mm (or other track width);

II – delivery from the foreign shipper to the consignee using wagons on bogies with variable track gauge.

These options are the basis for building an economic-mathematical model.

With regard to option I, it can be noted that it will require the construction of an appropriate number of terminals, and therefore, the preliminary determination of their throughput and other parameters, which will depend on the amount of capital and operating costs, and the processing of rolling stock and cargo at the terminals may slow down their delivery.

Regarding option II, we note that it accelerates the process of transition to a different track width compared to cargo overloading at terminals, but it has its disadvantages. In particular, the following is noted: "In contrast to passenger services, freight trains may be a challenge that the gauge-change train cannot solve. The rail links under the BRI are mainly freight services, particularly those between Asian and European cities. The intermittent rail networks of the Russian gauge require transferring cargo between trains twice from end to end. Technically, the Chinese rail industry could develop gauge-change locomotives and wagons based on the high-speed rail train, but the orders for cargo carriages and passenger ones are distinct in capacity and quantity.

Most rail cargo is heavy, and putting a greater load on bogies. With more moving parts, gauge-changing bogies would be more expensive to manufacture, compared to single-gauge ones, with greater maintenance demands and shorter lifespans. Furthermore, the diversity of cargo types for freight transport is much broader than on passenger trains, because the time of loading and unloading cargo is much longer than the boarding and alighting of passengers. As a result, rail operators have to prepare many more freight carriages than passenger ones, and thus to add a gauge-changing function on wagons would be expensive in both procurement and modification of existing fleets, as well as their maintenance. In other words, gauge-changing freight trains are unlikely to be economical" [14].

In order to take this into account when evaluating the proposed two options, we will build an economic-mathematical model for further analysis based on the graphic model of the transportation organization shown in Fig. 2, where transportation by 1435 mm rail is designated in solid, by 1520 mm in dashed and track gauge change transportation

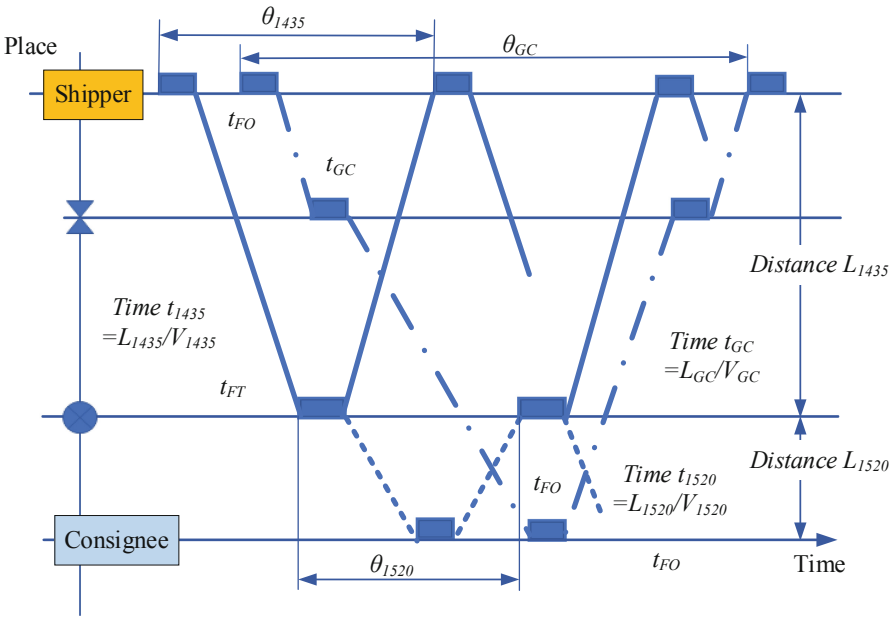


Fig. 2. Graphic model for the organization of rail transportation options by different gauge.

in dash-dotted lines respectively; θ_{1435}, θ_{1520} and θ_{GC} designations mean round-trip time for respective types of wagons that depend on distance L, speed V and time t with corresponding subscripts.

Currently, it is not known what the required number of terminals is, needed for interaction with the 1435 mm gauge railway and alternative transport modes and where they will be located on the transport network of Ukraine.

Using such terminals, we have the problem of the "last" or "first mile" performed by a railway of 1520 mm gauge to deliver cargo to a consignee from a terminal, or to deliver cargo from a sender to such a terminal. The distance of such transportation, conditionally the "last" or "first mile" of transportation on a track of 1520 mm (L_{1520}) is determined, theoretically, based on the following logical considerations.

This distance is greater, the greater the total transportation distance L and cannot be greater than the one remaining after the transportation to the terminal with a track of 1435 mm, i.e. greater than $L - L_{1435}$ (based on the condition that $L = L_{1435} + L_{1520}$). On the other hand, the distance L_{1520} will be smaller, the greater the number of freight terminals (N_{FT}) in the transport network, where railways of different track widths and alternative modes of transport interact, and the greater the transportation distance that can be provided by the alternative transport mode (L_{AT}):

$$L_{1520} = k_{TR} \frac{L - L_{1435}}{1 + \frac{L_{AT}}{L - L_{1435}} N_{FT}}, \tag{1}$$

where k_{TR} is an empirical coefficient that will refine the original mathematical model.

It is clear that in formula (1) the condition $L - L_{1435} > 0$ must be fulfilled, and at the beginning of the theoretical analysis we assume $k_{TR} = 1$.

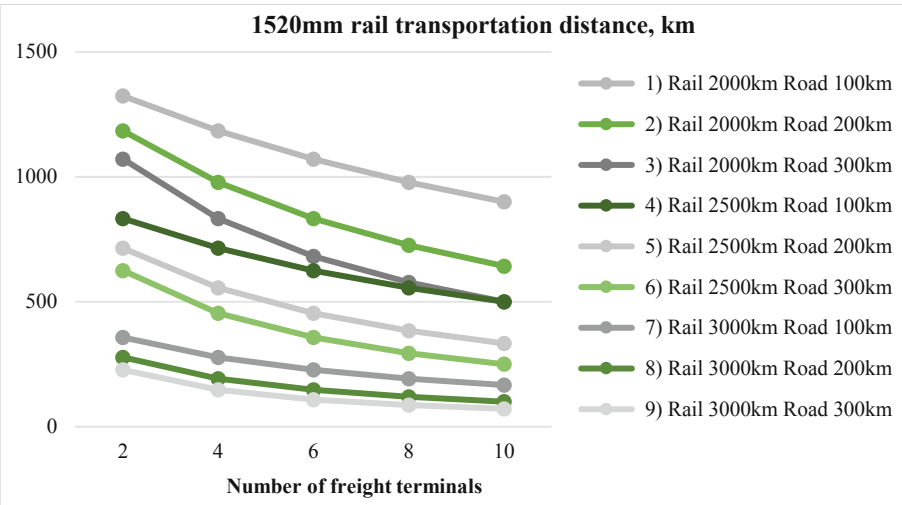


Fig. 3. The predicted distance of transportation by 1520 mm track from/to the terminal of interaction with 1435 mm track at different distances of transportation.

Formula (1) is the first "brick" of the future mathematical model of transport service processes using various technologies. Let's check its reliability and validity, without which the model cannot be adequate. In Fig. 3 shows the results of calculations according to formula (1).

Each of the curves in Fig. 3 corresponds to a pair of values, for example, for the upper curve, this pair is 1) Rail (1435 mm) 2,000 km Road (alternative mode) 100 km.

These curves show that with an increase in the number of terminals on the network (e.g., from 2 to 10), the projected distances of transportation on 1520 mm track from/to them, in the presence of a competing transport mode, become smaller and smaller. The nature and location of other curves in Fig. 3 indicate that with an increase in the distance of transportation on 1435 mm track (when it goes deeper and deeper into the territory of Ukraine), an increase in the number of terminals of interaction with the 1520 mm track and the distances at which competing (road or river) transport can operate, the predicted distance of transportation by 1520 mm track from/to the shipper/consignee decreases.

Thus, this block of the mathematical model, represented by formula (1), adequately reflects the processes and phenomena that occur in the real transport market, where various transport systems and technologies interact and compete.

The total transportation distance L and its part L_{1435}, which falls on railways with a gauge of 1435 mm, depend on the specific route. The possible distance of transportation by an alternative mode of transport (road, river) L_{AT} is determined from the statistics of these transportations.

Other variables of the model shown in Fig. 2 are:

t_{FO} is the average cargo operation time (loading or unloading a wagon), hours; t_{GC} is the average time of changing the track width of the carriages, h on a wagon; t_{FT} is the average time the cargo is in the process of moving to another track, hours (it is possible to take $t_{FT} = 2t_{FO}$).

These variables are used to determine the wagon round-trip time in various variants of transportation: θ_{1435} – on 1435 mm gauge track; θ_{1520} – on 1520 mm and θ_{GC} – in wagon on variable gauge bogies. Depending on this time, the need for wagon fleet, investments and operation costs necessary for the organization of transportation according to various options are determined.

4 Conclusions and Suggestions

Russia's war against Ukraine has led to the destruction of more than 1/3 of the railway infrastructure and may cause the country's GDP to fall by 45% this year.

The severe consequences of the war proved the correctness of the course for the real integration of Ukraine with the Trans-European transport network TEN-T, including the transition to the 1435 mm gauge standard and the introduction of high-speed rail transport. Among arguments in favour of these goals are increasing the country's defence capability, minimizing losses in the event of future military conflicts, closer integration with EU and NATO countries in the economic and military spheres.

The development of Ukraine's high-speed railways network of 1435 mm gauge should be carried out according to the principle of shared use both for the transportation of passengers and for certain categories of goods with high value added that require fast

delivery. Such railways must necessarily be part of large transit international routes and projects, such as the Silk Road, the Trimarium, the extension of Rail Baltica to the Black Sea, etc.

A rational approach to the post-war recovery and modernization of the railway infrastructure is the gradual expansion of the 1435 mm gauge railway network in Ukraine. The balance of risks and benefits shows that construction of new transit high-speed 1435 mm rail mainlines (HSM) with multi-modal terminals for interaction with the 1520 mm rail and other transport modes, integration with TEN-T is the optimal strategy for Ukraine and its partner countries. At the same time, the Automatic Transfer Gauge System (ATGS) should be used where it will allow better interaction with the railway networks of the EU and NATO countries.

Options and stages of reconstruction and modernization of Ukraine's railway network should be justified on the basis of adequate economic and mathematical models; the main parameters and controlled variables of the basic model are determined in this paper and will be brought to practical implementation in subsequent studies.

References

1. National Transport Strategy of Ukraine until 2030. https://zakon.rada.gov.ua/laws/show/430-2018-%D1%80#Text. Accessed 07 July 2022
2. Myronenko, V., Samsonkin, V., et al.: Ukraine in system of transport links. Int. J. Eng. Res. Dev. (IJERD) **13**(9), 1–6 (2017)
3. Myronenko, V., Hrushevska, T.: Problems of passenger and freight trains combined traffic on high-speed railway lines. Transp. Econ. Logist. **76**, 101–106 (2018). https://doi.org/10.26881/etil.2018.76.08. ISSN: 2657-6104
4. Russian Invasion to Shrink Ukraine Economy by 45 Percent this Year. https://www.worldbank.org/en/news/press-release/2022/04/10/russian-invasion-to-shrink-ukraine-economy-by-45-percent-this-year. Accessed 07 July 2022
5. ASSOCIATION AGREEMENT between Ukraine, of the one part, and the European Union, the European Atomic Energy Community and their Member States, of the other part. https://zakon.rada.gov.ua/laws/show/984_011#Text. Accessed 07 July 2022
6. Shippers with an eye on tougher sanctions cancel China-Europe rail bookings. https://theloadstar.com/shippers-with-an-eye-on-tougher-sanctions-cancel-china-europe-rail-bookings/. Accessed 07 July 2022
7. New Chinese train to Europe bypasses Russia despite close ties. https://economictimes.indiatimes.com/news/international/world-news/new-chinese-train-to-europe-bypasses-russia-despite-close-ties/articleshow/90969296.cms?utm_source=contentofinterest&utm_medium=text&utm_campaign=cppst. Accessed 07 July 2022
8. Best Practices in Shared-Use High-Speed Rail Systems. https://transweb.sjsu.edu/sites/default/files/02-02.pdf. Accessed 07 July 2022
9. Why are there no dedicated high-speed lines in Europe and the US?. https://www.railtech.com/infrastructure/2021/08/25/why-are-there-no-dedicated-high-speed-lines-in-europe-and-the-us/?gdpr=accept. Accessed 07 July 2022
10. Rail Baltica Final Report. Volume I. https://www.railbaltica.org/wp-content/uploads/2017/05/AECOM_Final_Report_Volume_I.pdf. Accessed 07 July 2022
11. The Silk Road economic belt policy in supporting Chinese geopolitic projections in the region. https://doi.org/10.33172/jpbh.v10i2.895

12. China wants to build a high-speed rail link to a newly open Iran. https://qz.com/557009/chinas-next-big-idea-is-a-high-speed-railway-to-iran/. Accessed 07 July 2022
13. Usamah, R., Kang, D., Ha, Y.D., Koo, B.: Structural evaluation of variable gauge railway. Infrastructures, 5, 80 (2020). https://doi.org/10.3390/infrastructures5100080, https://www.researchgate.net/publication/346019590_Structural_Evaluation_of_Variable_Gauge_Railway. Accessed 07 July 2022
14. Wu, S-S.: Gauge-changing train is no game changer for China. https://www.lowyinstitute.org/the-interpreter/gauge-changing-train-no-game-changer-china. Accessed 07 July 2022

Formation of Organizational Principles of Service of Export Cargo Flows in Transport Units

Oleksandr Gryshchuk[1](✉), Anatoliy Petryk[2], Yaroslav Yerko[2], and Litus Tetiana[2]

[1] Faculty of Management, Logistics and Tourism, National Transport University, Kyiv, Ukraine
gryshchuk@ntu.edu.ua

[2] Faculty of Transport and Information Technologies, National Transport University, Kyiv, Ukraine
tatianalitus@ukr.net

Abstract. The work examines the methodology of forming organizational principles for the maintenance of foreign trade cargo flows in international transport and logistics systems, characterizes the features of creating consolidated consignments of cargo in infrastructure nodes, simulates the transport maintenance of cargo flows using the main theoretical provisions of mass service systems, proposes mathematical models for determining system indicators under the conditions random demand for transport and commercial services. The peculiarities of the functioning of production structures in systems with batch receipt of service requirements are analyzed, the possibility of implementing the developed provisions for the coordination of management decisions regarding the maintenance of foreign trade cargo flows is substantiated.

Keywords: International communication · Foreign trade cargo flows · Transport service · Infrastructure support · Cargo consolidation · Batch receipt of requirements · Optimization of operational indicators

1 Introduction

As a result of the development of integration processes in the system of commodity-monetary relations, improvement of cooperation between individual countries and the introduction of new methods of logistics management of material flows in modern systems of international direction, new complex organizational structures are emerging. At the same time, trends in the development of world economic processes indicate an increase in the volume of production and sale of goods both in the domestic and foreign world markets. The specified trend requires special attention to the organization of deliveries of the specified goods, including the use of specialized terminals and improvement of infrastructural service at transport hubs. Under such a formulation of the question, the quality of transport service to consumers consists in the fact that in the process of transportation, the products are delivered in the required volume to the specified place at the specified time. And one of the main tasks of production structures of international

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 449–458, 2023.
https://doi.org/10.1007/978-3-031-25863-3_42

orientation is the organization of transportation of foreign trade goods with minimal costs. The results of the functioning of individual infrastructure elements in transport and logistics systems, as independent economic structures, play a decisive role in the process of processing and pre-accumulation of the export consignment of goods. Therefore, subject to clear compliance with the rules of trade organization and coordinated work of transport organizations, the service of foreign trade cargo flows in integrated structures becomes competitive on the world market.

2 Features of Transport and Logistics Service for Foreign Trade Freight Flows

Established trends to increase exports and transit of products through the territory of the state have outlined scientific prospects for the development of technological and structural foundations for improving the transport support of foreign trade cargo flows [1]. With the increase in the volume of accumulation for the delivery of goods in consolidated batches, and accordingly, the complexity of the tasks of transport service, on the example of the export of grain products, the issue of the rational use of road transport becomes relevant [2]. Therefore, for transport nodes, as elements of the territorial location of specialized terminals, an important characteristic is compliance with the terms of accumulation and processing of large volumes of export consignments of goods and optimization of total costs [3]. Taking into account the random nature of product arrivals and the impossibility of significantly increasing the daily volume of work on processing cargo flows, transport hubs in everyday production practice should count on the necessary capacities of the terminal and warehouse economy, or the possibility of accumulating the necessary volume of cargo in nearby rented premises [4]. The specified method of creating stocks has the disadvantage that storage of goods in warehouses requires additional overloading, and the accumulation of grain at a small distance from the transport hub requires, in addition, the additional use of railway cars [5]. Therefore, in order to comply with the deadlines for the processing of grain cargoes, the practice of servicing the specified cargo flows includes the construction of near-port elevators and specialized high-capacity grain processing complexes on the territory of the port [6].

Features of transport services for exporters (traders) are closely related to the production activities of these economic structures [7]. Based on the specific features of the deliveries of the mentioned cargoes, in order to comply with the terms of formation and dispatch of export batches, traders independently choose the methods of accumulation of the combined grain batch, the types and number of rolling stock [8]. Among the limiting factors, the possibility of attracting the necessary number of both own and leased road vehicles should be highlighted [9]. And taking into account the specified circumstances requires the development of a system of measures to optimize costs in international transport and logistics systems [10]. Therefore, the creation and rational use of organizational principles for the maintenance of export cargo flows in transport hubs, subject to the use of own and hired vehicles, will contribute to maximizing the profit of production systems.

3 Simulation of the Stochastic Process of Load Consolidation in Integrated Production Structures

A scientific study of the reliability and cost-effectiveness of transport services for foreign trade cargo flows requires a differentiated approach to the creation of mathematical models. The detailed development of such models will necessarily be associated with the need to take into account a large set of random factors that affect the current and final results of the operation of transport and logistics systems [11].

In general, a stochastic process is defined as some ordered collection of random variables. However, for the purpose of practical use of the obtained results, most of the stochastic processes characteristic of transport systems are presented in the form of appropriate mathematical models created using the methods of mass service theory [12]. Quite widespread systems include those characterized by a Poisson distribution of the duration of time intervals between successive requests and an exponential distribution of the service duration [13]. Technological processes of international direction, which can be described by the specified models, include the maintenance of rolling stock by a stationary mechanism at the final point of the route, or the terminal creation of a consolidated batch of cargo [14]. With the help of such mathematical dependencies in transport and logistics systems, the arrival of homogeneous requirements with a slight deviation of numerical characteristics is simulated.

In general, a stochastic process is defined as some ordered collection of random variables. However, for the purpose of practical use of the obtained results, most of the stochastic processes characteristic of transport systems are presented in the form of appropriate mathematical models created using the methods of mass service theory [12]. Quite widespread systems include those characterized by a Poisson distribution of the duration of time intervals between successive requests and an exponential distribution of the service duration [13]. Technological processes of international direction, which can be described by the specified models, include the maintenance of rolling stock by a stationary mechanism at the final point of the route, or the terminal creation of a consolidated batch of cargo [14]. With the help of such mathematical dependencies in transport and logistics systems, the arrival of homogeneous requirements with a slight deviation of numerical characteristics is simulated.

The creation of a consolidated batch of grain cargoes in a transport node for transportation in international traffic is considered on the example of the functioning of a multi-channel dynamic system with a finite number of degrees of freedom. The input flow λ of requirements is the arrival for unloading of cars with grain loads at the terminal to service mechanisms. The intensity μ of servicing the demand flow by each channel is determined by the average number of unloaded cars per unit of time.

Considering the organization of car service in terminals, the functioning of transport and logistics systems provides for the use of flow technology for unloading operations. Transition intensity diagrams of closed (closed) mass service systems with flow technology differ significantly from open systems in that the source of requirements is a limited, pre-known number of cars with goods arriving for service. In this case, the states of the closed system S_k $(k = 0, 1,\ldots, m,\ldots, n)$ will be associated with the number k of vehicles arriving for unloading. Then, if $k > m$, then the state S_k means that m cars are unloaded, and $k - m$ cars are in the queue (Fig. 1).

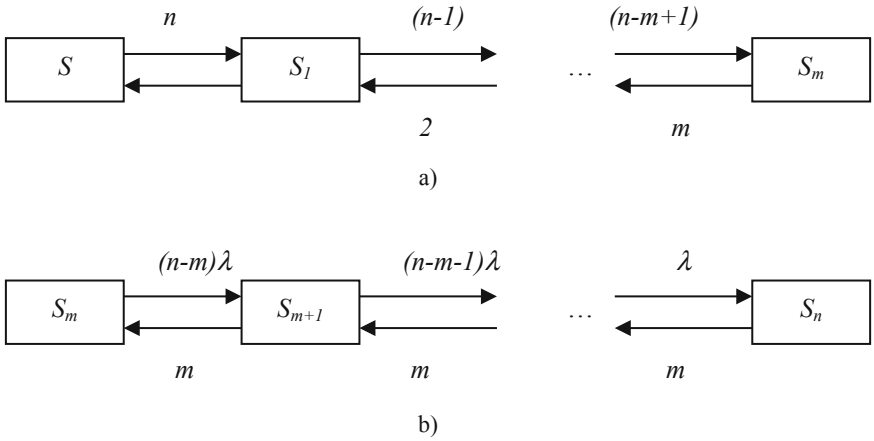


Fig. 1. Diagrams of the intensity of transitions of a closed queuing system: a) in the absence of a queue of cars for loading; b) with the presence of a queue around the loading means.

Diagrams of the intensity of transitions of a closed mass service system differ significantly when there is no queue of cars for unloading (Fig. 1a) and when it is present near the unloading means (Fig. 1b). Transition from S_k to S_{k+1} based on the FCFS (First Come First Served) non-priority service discipline principle – «first arrived – first served» is caused by the arrival of one car at the service station, and the transition from S_k to S_{k-1} occurs when the unloaded car starts moving in the return direction to the loading point. Then the process with parameters is observed

$$\lambda_k = (n-k)\lambda \ \ provided \ \ 0 \le k \le m$$
$$\mu_k = \begin{cases} k\mu, \ provided \ 0 \le k \le m; \\ m\mu, \ provided \ m+1 \le k \le m. \end{cases} \tag{1}$$

where n – the total number of cars in the system; m – number of service mechanisms.

The main task of studying the behaviour of queuing systems in production processes is to determine the probabilities of states p_k that at time t the system will be in state k. In the steady state to determine the value of p_k there are relations

$$[(n-k)\lambda + k\mu]p_k = (n-k+1)\lambda p_{k-1} + (k+1)\mu p_{k+1} \ provided \ 1 \le k \le m, \tag{2}$$

$$[(n-k)\lambda + m\mu]p_k = (n-k+1)\lambda p_{k-1} + m\mu p_{k+1} \ provided \ m+1 \le k \le n, \tag{3}$$

And the marginal probabilities of the system being in the k-th state are determined depending on the probability p_0 of the zero situations (absence of applications).

As you know, the operational characteristics of the system depend not only on the intensity of the demand flow, but also on its statistical fluctuations. The study of the behavior of the system during the transient process was carried out using the law of conservation of flow. It consists in the fact that the intensity of requests to the system is determined by the difference in intensity of input and output flows. With the use of the

diagram of the intensity of transitions, it became possible to determine the operational characteristics of the mass service system of the flow technology of unloading operations during transitional processes. And with the use of known mathematical dependencies, the results were obtained in the form of a matrix of solutions. The function of determining the variable p on the time interval $[t_1, t_2]$, which contains s solutions implemented in the *MathCAD* environment, has the form $Z := rkfixed\ (p, t_1, t_2, s, D)$ (Fig. 2).

Matrix of solutions:

Z =

	0	1	2	3	4	5
0	0	1	0	0	0	0
1	0.01	0.941	0.057	$1.753 \cdot 10^{-3}$	$3.555 \cdot 10^{-5}$	$5.874 \cdot 10^{-7}$
2	0.02	0.885	0.108	$6.548 \cdot 10^{-3}$	$2.652 \cdot 10^{-4}$	$8.326 \cdot 10^{-6}$
3	0.03	0.834	0.152	0.014	$8.336 \cdot 10^{-4}$	$3.935 \cdot 10^{-5}$
4	0.04	0.786	0.19	0.023	$1.841 \cdot 10^{-3}$	$1.166 \cdot 10^{-4}$
5	0.05	0.74	0.223	0.033	$3.35 \cdot 10^{-3}$	$2.673 \cdot 10^{-4}$
6	0.06	0.698	0.251	0.045	$5.397 \cdot 10^{-3}$	$5.206 \cdot 10^{-4}$
7	0.07	0.659	0.275	0.057	$7.993 \cdot 10^{-3}$	$9.063 \cdot 10^{-4}$
8	0.08	0.622	0.296	0.07	0.011	$1.454 \cdot 10^{-3}$
9	0.09	0.587	0.313	0.083	0.015	...

Fig. 2. The matrix of solutions of the system of differential equations with respect to the variable p for the time interval $[0, t2]$ for the queuing system with $m = 4$: $Z^{(0)}$ – the value of time steps; $Z^{(1)}$ – probability $p0$; $Z^{(2)}$ – probability $p1$; $Z^{(3)}$ – probability $p2$; $Z^{(4)}$ – probability $p3$; $Z^{(5)}$ is the probability $p4$.

With the use of the obtained solution matrices, it became possible to analyze the nature of the change in system parameters. The nature of the change in the probabilities of the states of individual elements of the transport system indicates the need to use modern computer technologies to obtain results in the form of a solution matrix, a time schedule and phase characteristics of a dynamic system. The obtained results once again emphasize the possibility of applying the basic provisions of the theory of mass service systems for the analysis of the internal structure of production formations.

4 Optimization of the Structural Indicators of the Transport System Under the Conditions of Packet Requirement

Possible variants of the structure of mass service systems can be a situation with group receipt of requirements. Characteristic production situations with the specified features of the functioning of transport systems are the formation of a combined (consolidated) batch of grain cargoes for transportation in international traffic or maintenance of the specified cargo flows during transshipment from one mode of transport to another. In a number of cases, the technology of the operation of transport systems involves the application of such requirements service discipline as the dependence of the incoming flow on the

state of the service channels, the presence of priorities, or the possibility of failure, etc. However, the mathematical models created based on the specified features of the structure of transport systems are, to a certain extent, varieties of the mass service systems considered above. At the same time, the performance of centralized transportation by road means the receipt of significantly larger volumes of cargo from suppliers. Then, each farm already has an increased fleet of rolling stock. In such a problem, it is assumed that the total number of service requests will consist of a random flow of requests and a random number of requests in each request. A similar situation occurs in the case when a shunting locomotive simultaneously serves several railway cars for unloading. Then several service channels are necessary to satisfy one requirement. Under such circumstances, the existing demand flow is an extraordinary random process. Therefore, the demand X_t for vehicles during the time period t is random and is described by a non-ordinary random process, that is, a process with group (batch) receipt of applications. And the total number of requests that enter the system during time t takes into account random variables of the number of groups of requests and requests for service in each group.

The use of known mathematical dependencies makes it possible to determine the average value of the required number of working vehicles, provided that service requests are received in batches. The practical application of the obtained mathematical dependencies is considered on the example of the use of road transport for the creation of a consolidated batch of international grain cargo. In the functionality of the task of obtaining the maximum profit from the operation of such a transport system, the following values are characterized as revenues and costs associated with the operation of motor vehicles:

- A – income from the performance of transport services by one car;
- B – operational costs for the operation of one car for the specified period;
- C – costs associated with downtime of motor vehicles due to lack of work;
- D – operating costs of an additional vehicle;
- E – possible loss of profit due to non-fulfillment of an order by one car.

Numerical values of A, B, C, D are calculated according to known mathematical relationships, taking into account the impact of changes in tariffs and costs. The magnitude of the possible loss of profit E is interpreted as the consequences of late delivery of transport services. The distribution function of the ratio of the quantities of available and engaged motor vehicles, taking into account the corresponding costs, is described by a mathematical relationship:

$$f(n, X_t, y) = \begin{cases} (A-B)X_t - C(n - X_t), & X_t \le n; \\ (A-B)X_t - D(X_t - n), & n+1 \le X_t \le n+y; \\ (A-B)(X_t + y) - Dy - E(X_t - n - y), & X_t \ge n+y+1. \end{cases} \tag{4}$$

with the use of mathematical dependence (4), it becomes possible to determine the numerical value of the quantity:

- own working cars $P_1(n)$;
- idle own motor vehicles $P_2(n)$;
- attracted from the available reserve $P_3(n)$;
- missing cars $P_4(n)$.

The average profit per unit of time taking into account the random value of the values X_t and y and the value of the function $f(n, X_t, y)$ on the example of a transport company was determined as the difference between revenues from the sale of services and costs, taking into account the possible loss of profit due to the lack of cars:

$$G(n) = Mf(n, X_t, y) = AP_1(n)\sum_{i=0}^{n} ip_i + n\sum_{i=n+1}^{y} p_i - Bn - CP_2(n) - (A - D)P_3(n) - EP_4(n). \quad (5)$$

with the use of mathematical dependence (5) as a function of expectation in a random process, it becomes possible to make organizational decisions aimed at achieving maximum profit, but it cannot be guaranteed due to the random nature and uncertainty of the economic situation. Taking into account the mentioned prerequisites, with the corresponding demand for transport services, mathematical models were created to determine the total profit under the condition of using own, hired and rented cars and road trains. With such a formulation of the question, the problem of rational use of available material resources in transport systems arises (Table 1).

Table 1. Dependence of the hourly profit of the transport company $G(n)$ when creating a consolidated batch of grain cargo.

Carrying capacity of the car, tons	The average length of a car ride l_m with cargo, kilometers					
	40	60	80	100	120	140
$q = 12$	6.23	6.46	6.67	6.86	7.03	7.18
$q = 14$	6.80	7.05	7.27	7.46	7.62	7.75
$q = 16$	7.38	7.65	7.89	8.10	8.28	8.43
$q = 18$	7.96	8.25	8.50	8.71	8.88	9.01
$q = 20$	8.54	8.85	9.12	9.35	9.54	9.69
$q = 22$	9.12	9.43	9.69	9.91	10.06	10.17

It is well known that with an increase in the carrying capacity of vehicles, the profitability $G(n)$ of one car increases. The same trend of changes in the indicated indicator $G(n)$ is observed under the condition of maintaining a certain number g of reserve cars. Limiting the influence of each of the two specified parameters on the numerical value of profit is determined by the financial capabilities of production formation. The main difference between typical productions formations is that the main volume of cargo transportation is carried out by own vehicles. In the absence of the required number or the corresponding specialization of motor vehicles, such enterprises use an additional

number of reserve rolling stock. The process of accumulation of a combined batch of goods was modeled on the example of deliveries by a transport company from fifteen $\sigma = 15$ senders, when the specified goods from each of them are transported by five ($\nu = 5$) cars.

According to the calculations, an increase in the transportation distance for cars with a carrying capacity of $q = 12$ tons per 80 km leads to an increase in the *G(n)* indicator by 15.2% (from 6.23 €/h for $l_m = 40$ km to 7.18 €/h $l_m = 120$ km). An increase in the numerical value of the indicator *G(n)* with an increase in the distance of transportation is explained by a decrease in the specific weight of the idle time of cars under service at the end points of the route, respectively, and an increase in income from the performance of transport services by one car. In this case, it becomes expedient to increase the numerical value of the number of the company's own *n* vehicles. An increase in the transportation distance for cars with a carrying capacity of $q = 22$ tons within the specified limits increases the *G(n)* indicator by 11.2% (from 9.12 €/h for $l_m = 40$ km to 10.17 €/h for $l_m = 120$ km). The decrease in the rate of growth of the indicator *G(n)* in the function $G(n) = f(l_m)$ with the increase in the carrying capacity of cars is explained by the increase in comparison with vehicles with a lower carrying capacity by the higher profitability of their use. Therefore, the trend of the change in the indicator *G(n)*, as the difference between income and expenses, indicates an increase in the stability of the transport enterprise.

An increase in the carrying capacity *q* of vehicles also has a positive effect on the change in the *G(n)* indicator. For example, an increase in the indicator *q* within $\Delta q = 10$ tons leads to an increase in the indicator *G(n)* within: 46.4% under the condition $l_m = 40$ km (from 6.23 €/h for $q = 12$ tons to 9.12 €/h for $q = 22$ tons) up to 41.6% under the condition $l_m = 120$ km (from 7.18 €/h for $q = 12$ tons to 10.17 €/h for $q = 22$ tons). This trend is explained by the fact that the rate of growth of incomes significantly exceeds the rate of increase in total expenses. In this case, the difference between these indicators increases as the carrying capacity *q* also increases, which has a positive effect on the numerical value of *G(n)* of the total profit. Thus, when performing centralized transportation for the formation of a consolidated batch of export goods, it is important to create temporary transport formations with appropriate transportation capabilities.

According to the proposed mathematical models, the optimal number of cars for the production process of creating a batch of consolidated cargo was calculated using the example of the operation of a transport enterprise. With the use of the specified theoretical provisions, it became possible to determine the influence of the transportation distance. Grains on the numerical value of the profitability *G(n)* of motor vehicles. At the same time, the transport company, taking into account the random nature of the demand for services, uses the opportunity to additionally rent up to thirty cars *g* with an average carrying capacity of $q = 20$ tons (Fig. 3).

Conducting multivariate calculations to determine indicators of reliability and cost-effectiveness of transport services confirm the theoretical assumptions that the specified characteristics are closely related. And the obtained results for the function $G(n) = f(g)$ take into account the structure of income and expenses in the methodology of determining the hourly profit *G(n)* in the system. For the case of $\lambda = 2$ cars/h, the indicator *G(n)* within a change of *q* up to 40 units of rolling stock varies in a rather wide range (from

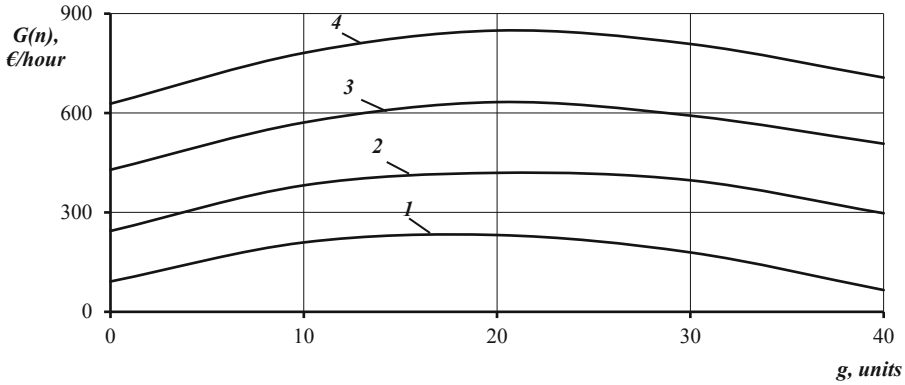


Fig. 3. Dependence of the average profit of the transport enterprise on the available number of reserve cars, subject to the intensity of requests, cars/hour: 1 – λ = 2; 2 – λ = 3; 3 – λ = 4; 4 – λ = 5

231.7 €/h for $g = 20$ units to 65.6 €/h for $g = 40$ units). The change in the *G(n)* indicator by 3.52 times is explained by a significant increase in excessive costs for maintaining reserve rolling stock. For the case of $\lambda = 5$ cars/h, the indicator *G(n)* has a more stable character (848.9 €/h for $g = 20$ units to 706.8 €/h for $g = 40$ units). The specified results indicate a much more stable operation of the system of consolidation of the export batch of grain cargoes. And the general growth of the *G(n)* indicator with an increase in the service intensity λ is explained by a significant decrease in non-production downtime of cars, and accordingly, an increase in the productivity of the system as a whole.

5 Conclusions

According to the calculations, when consolidating an export batch of cargo using the example of simultaneous service of $\sigma = 15$ senders under conditions of intensity $\lambda = 2\ldots5$ cars/h, the optimal value of the reserve rolling stock g that can be involved by the enterprise is within the range of 15 to 22 cars. As the volume of potential transport services increases, the specific weight of reserve g cars decreases. The use of heavy vehicles and road trains has a positive effect on technical and economic indicators. Thus, the application of the outlined theoretical provisions allows for a differentiated analysis of the nature of the change in the numerical value of the proposed indicators in the existing economic structures.

References

1. Prokudin, G., Chupaylenko, O., Dudnik, O., Dudnik, A., Omarov, D.: Improvement of the methods for determining optimal characteristics of transportation networks. Eastern-Euro. J. Enterp. Technol. **6**(3(84)), 54–61 (2016). https://doi.org/10.15587/1729-4061.2016.85211
2. Sharai, S., Oliskevych, M., Roi, M.: Development of the procedure for simulation modeling of interrelated transport processes on the main road network. Eastern-Euro. J. Enterp. Technol. **5/3**(101), 70–83 (2019). https://doi.org/10.15587/1729-4061.2019.179042

3. Sharai, S., Oliskevych, M., Roi, M.: Development of the procedure for simulation modeling of interrelated transport processes on the main road network. Eastern-Euro. J. Enterp. Technol. **5/3**(101). 70–83 (2019). https://doi.org/10.15587/1729-4061.2019.179042
4. Prokudin, G., Chupaylenko, O., Dudnik, O., Prokudin, O., Dudnik, A., Svatko, V.: Application of information technologies for the optimization of itinerary when delivering cargo by automobile transport, Eastern-Euro. J. Enterp. Technol. **2**(3(92)), 51–59 (2018). https://doi.org/ DOI:https://doi.org/10.15587/1729-4061.2018.128907
5. Apfelstädt, A., Dashkovskiy, S., Nieberding, B.: Modeling, optimization and solving strategies for matching problems in cooperative full truckload networks. IFAC-PapersOnLine **49**(2), 18–23 (2016). https://doi.org/10.1016/j.ifacol.2016.03.004
6. Harris, I., Wang, Y., Wang, H.: ICT in multimodal transport and technological trends: unleashing potential for the future. Int. J. Prod. Econ. **159**, 88–103 (2015). https://doi.org/10.1016/j.ijpe.2014.09.005
7. Shin, S., Roh, H.-S., Hur, S.: Characteristics analysis of freight mode choice model according to the introduction of a new freight transport system. Sustain. **11**(4), 1209 (2019). https://doi.org/10.3390/su11041209
8. Ritzinger, U., Puchinger, J., Hartl, R.F.: A survey on dynamic and stochastic vehicle routing problems. Int. J. Prod. Res. **54**(1), 215–231 (2015). https://doi.org/10.1080/00207543.2015.1043403
9. Danchuk, V., Bakulich, O., Svatko, V.: Identifying optimal location and necessary quantity of warehouses in logistic system using a radiation therapy method. Transport **34**(2), 175–186 (2019). https://doi.org/10.3846/transport.2019.8546
10. Lebid, I., Medvediev, I., Eliseyev, P., Sakno, O.: A modelling approach to the transport support for the harvesting and transportation complex under uncertain conditions. In: 26th Technical and scientific conference. Transport, ecology – sustainable development, EKO, IOP Publishing (2020). https://doi.org/10.1088/1757-899X/977/1/012003
11. Vorkut, T., Volynets, L., Bilonog, O., Sopotsko, O., Levchenko, I.: The model to optimize deliveries of perishable food products in supply chains. Eastern-Euro. J. Enterp. Technol. **5**(3–101), 43–50 (2019). https://doi.org/10.15587/1729-4061.2019.177903
12. Gryshchuk, O., Petryk, A., Yerko, Y.: Development of methods for formation of infrastructure of transport units for maintenance of transit and export freight flows. Technol. Audit Product. Res. **1**(2(63)), 26–30 (2022). https://doi.org/10.15587/2706-5448.2022.251505
13. Crainic, T.G., Perboli, G., Rosano, M.: Simulation of intermodal freight transportation systems: a taxonomy. Eur. J. Oper. Res. **270**(2), 401–418 (2018). https://doi.org/10.1016/j.ejor.2017.11.061
14. Silantieva, I., Katrushenko, N., Kushym, B.: Ensuring effectiveness in handling the movement of goods and passengers by enhancing information and communication technologies. In: Current Problems of Transport: Proceedings of the 1st International Scientific Conference, pp. 75–83 (2019). https://doi.org/10.5281/zenodo.3387287

An Application of Driver Behavior Questionnaire: Case Study of Amman

Khair Jadaan, Duha Alsarayreh(✉), Qasem Alqasem, and Zaid Alnusairat

University of Jordan, Amman, Jordan
k.Jadaan@ju.edu.jo, duha_wael@yahoo.com

Abstract. This research used the Manchester Driver Behaviour Questionnaire (DBQ) to analyze the driving behaviour of a group of a sample of drivers (N = 400) in Amman, the capital of Jordan. An Online Survey was distributed to respondents who accepted to take a part in this research. Out of 50 questions, 20 questions were selected according to the nature of the Jordanian drivers and the questionnaire consisted of two parts, general characteristics of driver and questions about driving behavior. The results of socio-demographic revealed that there were 242 males and 158 females, the largest age group was 19–34 years, and the majority of respondents reported (0–3) injuries in the last three years. The Principal Component Analysis (PCA) instrument analysis by Promax with Kaiser Normalization assessed four factors solution (lapses, (deliberately and ordinary) violation and errors). The largest number of items was observed to be correlated with errors in this current sample. Additional analysis showed the potential of certain elements (seven items) to predict injuries through a forecasting model, especially because most of these behaviors are unsafe and their actions lead to collisions. By comparing the average scores, Jordanian drivers were found to have received the lowest scores of Qatari and Emirati drivers, and a similarity was found in the traffic culture between Jordan and Qatar. The main findings of this paper showed the ability of DBQ to analyze the behavior of Jordanian drivers on the road.

Keywords: Accidents · Amman · Driver Behaviour Questionnaire (DBQ) · Jordan · Survey

1 Introduction

Driver Behavior (DB) is considered as the main factor that causes traffic accidents in Jordan. According to a local article which showed that Public Security said: 98% of traffic accidents in Jordan are caused by "the human factor". The cost of these accidents is estimated at 324 million dinars, which constitutes a great burden on the country's treasury, and has great social, material and moral impacts on society. It is imperative to address this problem, which has become troublesome to society and claim many lives of our children of all ages [1].

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 459–469, 2023.
https://doi.org/10.1007/978-3-031-25863-3_43

Another local article showed that a traffic accident results in human losses every 48.4 min, a run-over accident occurs every 2.4 h, and a person is injured every 30.9 min, while a traffic accident causes one death every 13.6 h. Collision accidents caused 332 deaths, run-over accidents at 207 deaths, and deterioration accidents caused 104 deaths. Note that the total number of injuries resulting from traffic accidents amounted to 17,656, including 10,159 minor injuries, 6,062 medium injuries, and 792 severe injuries, plus deaths. The estimated cost of accidents is 324 million Jordanian dinars, and Jordan loses more than 888 thousand dinars daily as a result of traffic accidents. The youth group (18–35 years) recorded the largest number of deaths (37.8%), the largest number of severe injuries (46.6%), the largest number of medium injuries (43.7%), and the largest number of minor injuries (52.3%) [2].

This study aims to investigate the DBQ under Jordanian conditions and analyzes the obtained results to know the most critical DBQ that may cause the traffic accidents in Jordan. After that, the study compares the obtained results with other obtained results from similar studies that have been performed in developing countries.

Subsequently, Amman, the capital of Jordan, was selected to be an understudy city because it has the largest number of populations in Jordan as 4,642,000 people for the end of year 2021 [3] and it has the largest number of traffic accidents in Jordan as a total of 4319 [4]. In order to make this study socially acceptable, public participation and community involvement were included by a survey which was based on a predesigned questionnaire. The Statistical Package for Social Sciences (SPSS) software was used for data analysis.

2 Methodology

The responses of the questionnaire were collected from 400 drivers in Amman city, the questionnaire couldn't be distributed the questionnaire to the drivers as face to face because of the COVID-19pandemic. So that, we made an online predesigned Manchester Driver Behaviour Questionnaire [5] and shared it by the social media, the online method of questionnaire distribution was faster and smoother to reach the drivers than the traditional method. The time needed to collect the responses was approximately a month, it was during September and October, 2020. According to the responses, most of the drivers were males with a percentage of 60.5% (242 responses), while the percentage of females was 39.5% (158 responses). During the analysis stage, we noticed from the responses that the highest number of responses was hit at the age group of 19–34 years. On the other hand, the lowest number was hit at the age group of under 19 (see Fig. 1).

3 Results

The responses of the question "number of accidents in the last three years" showed that 57% (288 drivers) were not subjected to accidents, 20.5% (82 drivers) exposed to one accident, 5.5% (22 drivers) exposed to three accidents (see Fig. 2). Ten drivers were involved in 4–6 accidents two respondents were affected by seven and ten accidents.

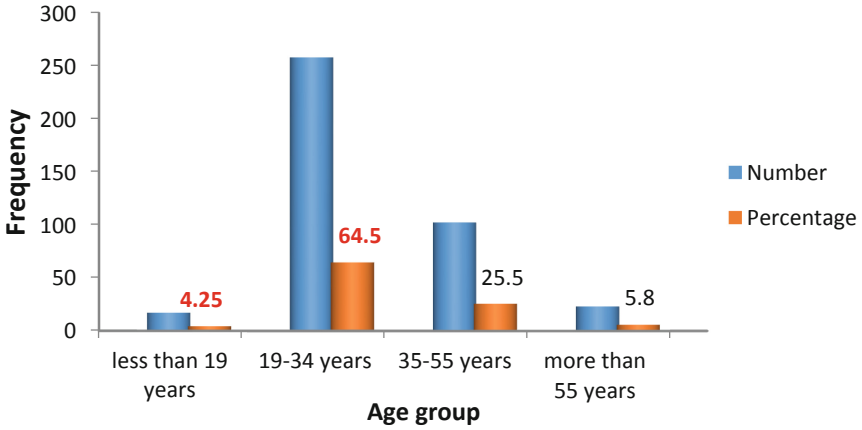


Fig. 1. Analysis of age groups.

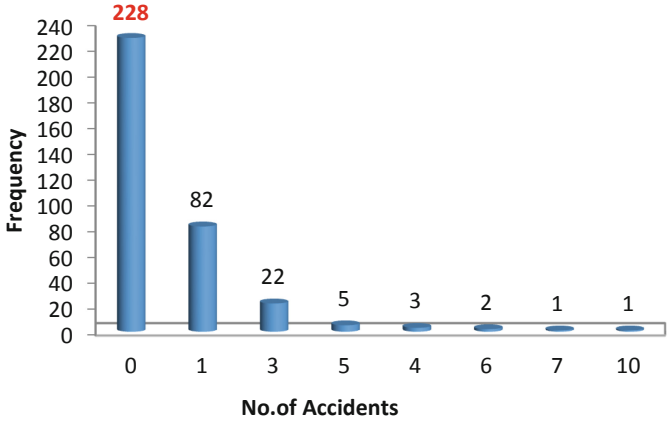


Fig. 2. Number of road accidents in the last three years.

The most of respondents were youth with relatively little driving experience. The minimum number of respondents (74 respondents) with a percentage of 18.5% had a driving experience as more than 15 years. This reflects that the majority of respondents had less than 2 years of driving experience (see Fig. 3).

Factor analysis was carried out with the setting of Eigen Value as one based on the rotation system of Promax with Kaiser Normalization (see Fig. 4) (The transparent red rectangle), four elements above one suggesting that there are four variables. There were four-factors explained in the results. These variables accounted for 52.740% of the overall variances. The first factor contained four items at 31.103% and described as "*lapses and slips*", the second factor contained five items at 10.425% and described as "*deliberately violations*", the third factor contained seven items at 6.001% and defined as "*ordinary violation*", and the fourth factor explained 5.211% and described as "*errors*". The factors values are presented in Table 1.The reliability of the PCA process has been

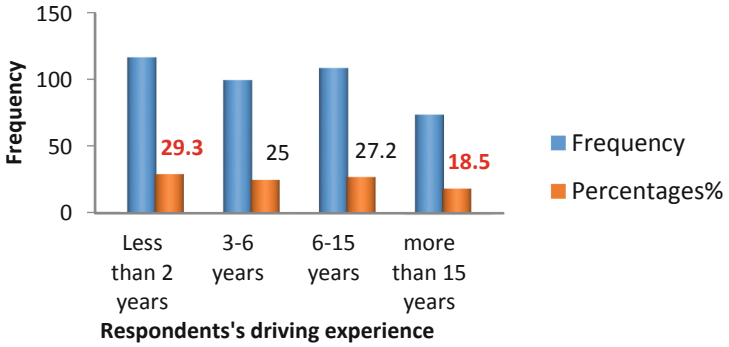


Fig. 3. The number and percentages of respondents according to the driving experience.

checked by Kaiser Meyer Olkin (KMO) where this instrument is an indication whether the measurement fits the data or not and considers it acceptable if the KMO value is greater than 0.5 [6] and the value for this measurement is 0.899 which is called Superb Vale.

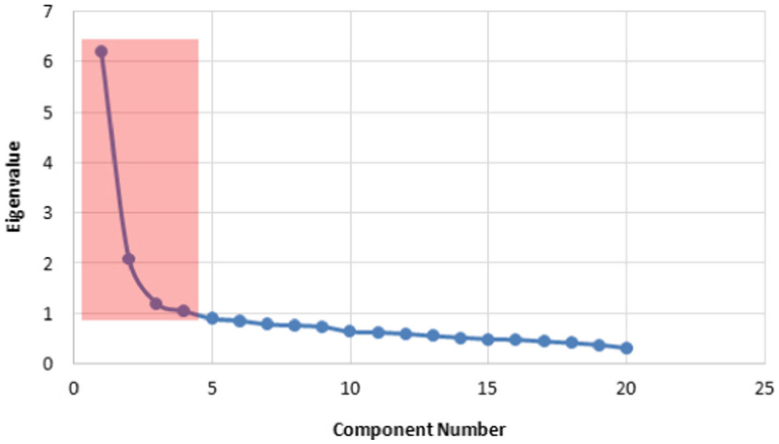


Fig. 4. Factor shape of DBQ items.

The descriptive results of the rearranged items are seen in Table 2. The findings estimated that the most frequent category (from occasionally "2" to frequently "4") occurred in "*deliberately violations*" followed by the "*ordinary violation*", "*lapses and slips*", and "*errors*".

A simple predictive model has been developed to inspect whether DBQ items can predict the number of accidents. The generated model results showed that 7 items only out of 20 can predict the accidents number. The residual random was significant (0.882 $>$ 0.05 at 18 df, Ljung-Box Q(18) = 11.293). The estimated significant parameters of (ARIMA) model are presented (see Table 3), all of variables included in the Table was Proved to be statistically significant.

Table 1. Factors structure of DBQ items.

Item*	F1	F2	F3	F4
How often do you Misjudge the available space where you parked your car and nearly (or actually) hit another vehicle	0.724			
How often do you Misjudge your crossing interval when turning right/left and narrowly miss colliding	0.709			
How often do you Brake too hard or quickly on a slippery road and/or steer the wrong way in a skid	0.687			
How often do you Turn left/right on to a main road into the path of an oncoming vehicle that you hadn't seen, or whose speed you had misjudged	0.598			
How often do you Become impatient with a slow driver in the outer lane and overtake on the inside		0.796		
How often do you Drive especially close to or 'flash' the car in front of you as a signal for that driver to go faster or get out of your way		0.776		
How often do you Deliberately disregard the speed limits at any time (morning, afternoon, evening, night)		0.620		
How often do you Stuck behind a slow-moving vehicle on a two-lane highway, you are driven by frustration and try to overtake in risky circumstances		0.516		
How often do you Take a chance and run the red light		0.483		
How often do you Forget where you left or parked your car			0.820	
How often do you Angered by another driver's signaling, you give chase with the intention of giving him/her a piece of your mind			0.604	
How often do you Realize you have no clear recollection of the road along which you have just been travelling			0.589	
How often do you Intending to drive to destination A, you suddenly realize that you are enroute to B, because that is your more usual destination			0.548	
How often do you Get into the wrong lane when approaching an intersection or a roundabout			0.511	
How often do you Lost in thought or distracted, you fail to notice someone waiting at a zebra crossing, or a pelican crossing light that has just turned red			0.501	
How often do you Get involved in unofficial 'races' with other drivers			0.483	

(*continued*)

Table 1. (*continued*)

Item*	F1	F2	F3	F4
How often do you Attempt to overtake a vehicle that you hadn't noticed was signaling its intention to turn right/left				0.666
How often do you Deliberately drive the wrong way down a deserted one-way street				0.595
How often do you Fail to check your mirrors before pulling out, changing lanes, turning etc				0.452
How often do you Fail to read the signs correctly, and exit from a roundabout on the wrong road				0.444

* Rotation Converged in 5 Iterations, (chi-square = 2477.964, 190 degree of freedom (df), 0.000 significant level(sig)).

Table 2. Mean and standard Deviation of DBQ Items.

No.	Description	Mean	Std. deviation
Lapses and slips		0.95	0.974
1.	How often do you Misjudge the available space where you parked your car and nearly (or actually) hit another vehicle	0.86	0.991
2	How often do you Misjudge your crossing interval when turning right/left and narrowly miss colliding	0.86	0.920
3.	How often do you Brake too hard or quickly on a slippery road and/or steer the wrong way in a skid	0.98	1.038
4.	How often do you Turn left/right on to a main road into the path of an oncoming vehicle that you hadn't seen, or whose speed you had misjudged	1.10	0.947
Deliberately violation		1.498	1.266
5.	How often do you Become impatient with a slow driver in the outer lane and overtake on the inside	1.93	1.398
6.	How often do you Drive especially close to or 'flash' the car in front of you as a signal for that driver to go faster or get out of your way	2.23	1.432

(*continued*)

Table 2. (*continued*)

No.	Description	Mean	Std. deviation
7.	How often do you Deliberately disregard the speed limits at any time (morning, afternoon, evening, night)	1.42	1.352
8.	How often do you Stuck behind a slow-moving vehicle on a two-lane highway, you are driven by frustration and try to overtake in risky circumstances	1.38	1.268
9.	How often do you Take a chance and run the red light	0.53	0.881
Errors		0.797	1.012
10.	How often do you Forget where you left or parked your car	1.07	1.241
11.	How often do you Angered by another driver's behaviour; you give chase with the intention of giving him/her a piece of your mind	0.63	1.012
12.	How often do you Realize you have no clear recollection of the road along which you have just been travelling	0.83	1.016
13.	How often do you Intending to drive to destination A, you suddenly realize that you are enroute to B, because that is your more usual destination	1.48	1.115
14.	How often do you Get into the wrong lane when approaching an intersection or a roundabout	0.48	0.950
15.	How often do you Lost in thought or distracted, you fail to notice someone waiting at a zebra crossing, or a pelican crossing light that has just turned red	0.74	0.909
16.	How often do you Get involved in unofficial 'races' with other drivers	0.35	0.841
Ordinary violation		0.843	1.03
17	How often do you Attempt to overtake a vehicle that you hadn't noticed was signaling its intention to turn right/left	0.97	0.975

(*continued*)

Table 2. (*continued*)

No.	Description	Mean	Std. deviation
18	How often do you Deliberately drive the wrong way down a deserted one-way street	0.77	1.120
19	How often do you Fail to check your mirrors before pulling out, changing lanes, turning etc	0.99	1.094
20	How often do you Fail to read the signs correctly, and exit from a roundabout on the wrong road	0.64	0.931

Table 3. ARIMA* model parameters.

No.	Description	Estimate	Std. error (SE)	t	Sig.**
7	How often do you Deliberately disregard the speed limits at any time (morning, afternoon, evening, night)	−0.143	0.064	−2.233	0.026
11	How often do you Angered by another driver's behaviour; you give chase with the intention of giving him/her a piece of your mind	0.212	0.082	2.588	0.010
8	How often do you Stuck behind a slow-moving vehicle on a two-lane highway, you are driven by frustration and try to overtake in risky circumstances	0.335	0.062	5.402	0.000
15	How often do you Lost in thought or distracted, you fail to notice someone waiting at a zebra crossing, or a pelican crossing light that has just turned red	−0.201	0.090	−2.229	0.026
1	How often do you Misjudge the available space where you parked your car and nearly (or actually) hit another vehicle	−0.266	0.082	−3.222	0.001
18	How often do you Deliberately drive the wrong way down a deserted one-way street	−0.233	0.077	−3.012	0.003

(*continued*)

Table 3. (*continued*)

No.	Description	Estimate	Std. error (SE)	t	Sig.**
19	How often do you Fail to check your mirrors before pulling out, changing lanes, turning etc	0.215	0.078	2.774	0.006

* ARIMA = Autoregressive Integrated Moving Average.
**Sig values > 0.05.

4 Discussions

The four-factor Jordanian DBQ solutions showed a consistency in items with a Cronbach Alpha value of 0.873 that consider a reliable value if equal to or greater than 0.7 [7]. This indicated that the factors in these chosen items have a clear structure of lapses, violations (deliberately and ordinary), and errors. Various studies [8, 9] have demonstrated four-factor solutions in their analyzes. This finding is important because there it seems to be a little research concerning the DBQ application in Jordan. It is obvious that the age and driving experience are linearly associated; with the rise in age, driving experience is getting higher (F-value = 69.825, sig at 3 df). On the contrary, there are no distinctive associations between the number of injuries and the age.

The Manchester Driver Behaviour Questionnaire [10] was adopted in Arab countries like United Arab Emirates (UAE) and Qatar in Arab Gulf [11]. The DBQ scores between Jordanian and Qatari drivers correlated to the category of errors in items 14 and 15 (see Table 2), while Jordanian drivers scored higher than Qatari drivers in the event of error to notice pedestrians while the Emirates drivers scored the lowest. Traffic culture in Jordan and Qatar seems to be similar where other literature has noted that [12].

In deliberately violation, Qatari drivers scored higher mean (2.10) in "*Deliberately disregard the speed limits at any time (morning, afternoon, evening, night)*" than Jordanian drivers (1.42). The item "*How often do you get involved in unofficial 'races' with other drivers"* loaded in violation category and rated a higher mean (1.89) for Qatari drivers and a lower mean (1.29) for Jordanian drivers in the Bener et al. [12] analysis while in the present findings this item was loaded with errors and rated a lower mean (0.35). Traffic laws appear to be well enforced in Jordan, so Jordanian drivers scored low for this behavior in both studies. Item "*Forget where you left or parked your car*" scored approximately the same mean for both countries.

A recent statistical study employed two independent research tools, the BIS-11 (Barratt Impulsiveness Scale) and the DAQ (Driver Attitude Questionnaire), to examine the traffic accident rate of young and inexperienced drivers. They discovered statistically significant relationships between the driver's history (skills, traffic accidents, age, etc.) and psychological features [13]. Primary study pilot survey definitely required a comprehensive survey with greater sample size would produce better results and this is what authors are planned to do in the near future to reach more conclusive results. Seven of the 20 items, the model was able to predict accidents in this study. This illustrates that the DBQ can predict accidents, but it would require precise models such that all items

can predict accidents. The results of Winter and Dodou's study showed that the DBQ is a prominent indicator of driver's behavior [14].

5 Conclusions

The results indicated that the DBQ was effective in investigating driving behaviour in Jordan. Most of the studies reviewed ranged from three to four factors extracted from the PCA technique. Another research found that the number of factors depends on the population driving. In Amman, the capital of Jordan, 400 drivers were collected to analyze driving behavior through the Manchester DBQ questionnaire. The findings revealed that four factors (lapses and slips, deliberately violation, ordinary violation, and errors) were obtained using PCA and that the largest number of items were in the error group. The highest mean score was registered for the item in deliberately violation (drive particularly near to or "flash" the car as a warning to the driver to get out faster of the way). The findings have shown that there was a correlation between the cultures of Jordanian and Qatari drivers, unlike the Emirate drivers. Although Jordanian drivers scored the lowest mean scores in most items, particularly in errors. The prediction model, based on the number of injuries reported by the drivers, revealed that seven elements of the DBQ were expected out of 20 questions. This indicates that Jordanian drivers are aware of the importance of driving behavior and its contribution to collisions.

References

1. Roya News, Homepage. https://royanews.tv/news/223177. Accessed 12 June 2022
2. Roya News, Homepage. https://royanews.tv/news/222354. Accessed 12 June 2022
3. Department Of Statistics, Statistical Year Book Of Jordan (2021). http://dosweb.dos.gov.jo/DataBank/Population_Estimares/PopulationEstimates.pdf. Accessed 12 June 2022
4. Annual Traffic Accidents Report (2019). https://www.psd.gov.jo/media/irvg0unk/%D8%A7%D9%84%D8%AA%D9%82%D8%B1%D9%8A%D8%B1-%D8%A7%D9%84%D8%B3%D9%86%D9%88%D9%8A2021.pdf. Accessed 12 June 2022
5. Reason, J., Manstead, A., Stradling, S., Baxter, J., Campbell, K.: Errors and violations on the road: a real distinction? Ergonomics **33**, 1315–1332 (1990)
6. Field, A.: Discovering Statistics Using SPSS, 3rd edn. SAGE Publications Ltd, London (2009)
7. Spiliotopoulou, G.: Reliability reconsidered: cronbach's alpha and paediatric assessment in occupational therapy. Aust. Occup. Ther. J. **56**(3), 150–155 (2009)
8. Kashani, T.A., Ravasani, S.M., Ayazi, E.: Analysis of drivers' behavior using manchester driver behavior questionnaire based on roadside interview in Iran. Int. J. Transp. Eng. **4**(1) (2016)
9. Harrison, W.: Reliability of the Driver Behaviour Questionnaire in a sample of novice drivers. Australasian Road Safety Research, Policing and Education Conference, Eastern Professional Services Pty Ltd, Sydney, New South Wales (2009)
10. Lucidi, F., Giannini, A.M., Sgalla, R., Mallia, L., Devoto, A., Reichmann, S.: Young novice driver subtypes: relationship to driving violations, errors and lapses. Accid Anal Prev **42**, 1689–1696 (2010)
11. Bener, A., Ozkan, T., Lajunen, T.: The driver behaviour questionnaire in Arab Gulf countries: Qatar and United Arab Emirates. Accid. Anal. Prev. **40**(2008), 1411–1417 (2004)

12. Bener, A., et al.: A cross, "Ethnical" comparison of the Driver Behaviour Questionnaire (DBQ) in an economically fast developing country. Global J. Health Sci. **5**(4), 165–175 (2013)
13. Čulík, K., Kalašová, A.: Statistical evaluation of BIS-11 and DAQ tools in the field of traffic psychology. Mathematics **9**(4), 433 (2021)
14. de Winter, J.C., Dodou, D.: The Driver Behaviour Questionnaire as a predictor of accidents: a meta-analysis. J Safety Res **41**(6), 463–470 (2010)

Influence of the Bridge's Status on the Military Mobility in the Slovak Republic

Ján Jančo(✉) and Jaroslav Kompan

Armed Forces Academy of General M.R. Štefánik, Demänová 393, 03101 Liptovský Mikuláš, Slovakia
{jan.janco,jaroslav.kompan}@aos.sk

Abstract. Military operations in the land based operating environment are linked to land-based communications – roads. Roads are essential for the strategic and operational mobility of units. Bridges, in terms of military requirements, are an exposed part of the roads and significantly affect the use of existing transport infrastructure. For this reason, the research problem represents the impact of the condition of bridges with a military load capacity of at least 60 tons of the road network of the Slovak Republic on military mobility in the territory of the Slovak Republic. The aim of the research is to identify the impact of the technical condition of bridges on the military mobility of military forces in the territory of the Slovak Republic. The first part of the paper is focused on defining the extent of the necessary military mobility in the conditions of the Slovak Republic, with regard to the potential requirements for the implementation of transfers and transports to the eastern border of NATO. In the second part, the article is focused on the evaluation of the current technical condition of Slovak Republic road network bridges.

Keywords: Military mobility · Bridges · Slovak republic

1 Introduction

Conducting operations in the land environment is in essence, a constant struggle to gain a position of relative advantage over the adversary [1], which requires constructive and destructive shaping of the physical component of the land environment [2], and of course obtaining information about it [3]. These activities allow freedom of movement and maneuver of their own forces and prevent the freedom of maneuver of the adversary. This requires a high degree of integration and synchronization of combat force elements [4] in time and space in all domains of the operating environment [5], even by high level of units' mobility [6].

The operations are linked to land infrastructure in the land operating environment, especially in the deployment phase. Land infrastructure (roads) is essential for the strategic and operational mobility of units [7]. The land forces are transported by railroads (distances from 500 km, significantly less for heavy armored vehicles due to shorter maintenance-cycle and higher operational expenses) or they are performing movements

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 470–478, 2023.
https://doi.org/10.1007/978-3-031-25863-3_44

along their own axis. They use roads for fast movements, but roads could be relatively easily degraded by the adversary's activities, especially the hybrid adversary could take advantage. This will cause a significant delay and a negative impact on the time factor. The combination of disruption on major rail routes results in delays on days and on road routes in hours, leading to a loss of initiative.

Bridges, in terms of military requirements, are an exposed part of the roads and significantly affect the use of existing transport infrastructure. Their importance is also given by the limited possibilities of building replacement bridges, which also greatly affects the mobility of military units. For this reason, the research problem represents the impact of the condition of bridges with a military load capacity of at least 60 tons of the road network of the Slovak Republic on military mobility in the territory of the Slovak Republic. The aim of the research is to identify the impact of the technical condition of bridges on the military mobility of military forces in the territory of the Slovak Republic. The research was executed as part of research projects, namely "Hybrid Warfare" and "Optimization of the possibilities of employment of the military engineering mobility support in the land environment".

The first part of the paper is focused on defining the extent of the necessary military mobility in the conditions of the Slovak Republic, with regard to the potential requirements for the transfer and transportation of heavy military equipment to the eastern border of NATO [8]. This is addressed by a qualitative analysis also with regard to possible transfers and transports of logistics supplies, which are necessary as military or humanitarian aid in favor of Ukraine's support.

In the second part, the paper focuses on the outputs of quantitative analysis of data from the Road Bank of the Slovak Republic, especially on the basis of comparison of the current state of monitored parameters of bridge structures of the road network of the Slovak Republic with identified military requirements. The most important parameter of bridges in the paper is their load capacity. In terms of road infrastructure requirements, the load capacity was identified as the most fundamental parameter influencing the possibility of military use of the existing bridges of the road network of the Slovak Republic.

The paper is primarily based on open-source available statistical data kept by the Slovak Road Administration [9, 10] and the results of inspections by the Supreme Audit Office of the Slovak Republic [11], in terms of statistical data use for developing paper's conclusions.

2 Peculiarities of the Military Mobility in the Slovak Republic

Mobility is a parameter that allows forces to be concentrated, and at the same time it is a feature that allows military forces to move through the physical environment, even in the case of adversary destructive activities [12]. It follows from the above characteristics that mobility is not absolute, but should always be dynamically assessed in a specific situation, with regard to the physical environment, the action and mobility of the adversary and the mobility of other components of one's own forces. This means, especially for land forces, that the overall mobility of whole formation is equal to the lowest mobility of its subordinated unit and this directly exposes this weakness – lack of mobility to adversary action.

Thus, the low level of mobility of the units directly affects the planning of operations, as the principles of planning, namely concentration of forces, freedom of action, initiative and offensive approach, will be disrupted in principle. At the same time, the principle of surprise will not be easy to follow. Therefore, maintaining and supporting the mobility of troops can be considered a priority for the military forces [2].

Current and anticipated future operations take place in non-contiguous areas of operations. The non-contiguous area of operations is characterized by the fact that secured areas of limited size (controlled by own forces) are separated from each other by large unsecured areas [13]. This means that movement and maneuver will be performed mainly in those unprotected areas. Adversary will try to operate in such areas, as it could cause greater manpower and material losses, but also a reduction in morale or a shift in public opinion from support of operations [14].

NATO's joint operations involve contributions from individual NATO member states, but they should be able to cooperate to conduct joint operations effectively [15]. Therefore, we could claim that NATO military forces based on national contributions from member countries require that national military forces are able to conduct operations characterized by decentralized command, freedom of action, momentum, and initiative. However, this concept could not be implemented by the armed forces, which are not adequately mobile. From these characteristics, it is clear that the mobility of the units will be the key to operational success. At the same time, these characteristics make it possible to face multidimensional threats and a rapidly changing situation.

And it is the global threats and challenges, as well as the development of the security environment, that call for very close international cooperation between the members of the European Union (EU) and NATO. As a member of both the EU and NATO, the Slovak Republic should constantly increase its defense capability, i.e. its ability to respond to threats in the security environment, and thus contributes to increasing NATO and EU defense capabilities [15]. It is a part of the measures resulting from the international agreements on joint defense, by which the Slovak Republic is bound. The Slovak Republic is also bound to provide such assistance to another NATO ally or EU member state in the event of a military attack [16].

The physical environment of the Slovak Republic is represented by the terrain, general climatic conditions and specific weather. The input parameters of the specific physical operating environment of the Slovak Republic are geographical distance, terrain morphology and climatic conditions, which increase the requirements for the deployment of forces and affect the manpower and technology. Another parameter in the territory of the SR is the scope and qualitative parameters of the built infrastructure, because it directly affects the deployment of forces and further affects mobility and also affects sustainability, either negatively or positively (it is usable and thus improves it or its degradation or absence directly undermines the aid and thus worsens it). The transport infrastructure of the Slovak Republic will have a significant impact on the sustainability of its own and NATO forces, but also on the public opinion and support attitude of the population and may be a target of adversary actions. Due to shaping of the operating environment by adversary it could be degraded and thus becomes a major obstacle to achieving the required level of military mobility.

The timely and accurate deployment of adequate military forces, while maintaining their mobility, protection and sustainability, is essential for operational success [17]. This is due to the fact that the management of transports through the territory of the Slovak Republic, i.e. the projection of military mobility, is characterized by the following aspects:

- Variating "density" of deployed forces and resources - due to non-linear or morphologically varying terrain conditions, which also causes distraction and makes it difficult to focus and concentrate forces, while placing high demands on freedom of movement and maneuver.
- Conducting movements and transports in a man-formed environment - from a minimally formed (e.g. agricultural landscape) to an extremely changed (from larger cities to megapolis).
- Rapid change of the situation - caused by technical and technological developments [18], which places high demands on decisions about changing traffic flows [19] and continuous deployment of available sensors, because the response time is significantly reduced.
- Development of technologies and development of new weapon systems - these significantly limit maneuvering in the area of operations (very precise weapons, scatterable minefields, area defense weapons, Antiaccess – Area Denial concepts), which instead of limiting the maneuver, effect more precisely on critical infrastructure, which requires great effort for mobility support to ensure a hidden and dynamic maneuver. At the same time, the need for constant movement comes to the fore, because the development of new types of nuclear warheads (in kiloton units), could lead to the concept of their tactical use.

The easiest degradable part of the transport infrastructure of the Slovak Republic are mainly road structures, especially bridge structures, because they represent a natural narrowing of the traffic flow, which could not be quickly redirected during their degradation.

3 Bridges Status Influence on Military Mobility

3.1 Bridges in the Slovak Republic

The physical environment and time are specific variables that have a significant impact on the conduct of operations, especially in the land-based environment. Due to the concept of NATO operations, with the growing need for a large number of deployed forces, the physical component of the operational environment is also increasing, and thus the need for maneuver is growing. Therefore, while maintaining military mobility in NATO operations, the constant need to improve the ability to move, but also to maintain the resilience of their own systems to the adversary's destructive measures, will come to the fore.

Given the number of road structures and their nature, it could be stated that the mobility of military units will be most significantly affected by bridges, which are built to overcome various obstacles. Their significance, in addition to the above, stems from

the expression of the ratio of the number of bridges in relation to the total length of roads. The recalculation of this relationship will allow us to generalize that there is one bridge on the approximately 2.2 km long section of the road in the territory of the Slovak Republic. Thus, after crossing every 2,200 m of road, the military unit encounters a bridge which it must be able to cross, which must meet certain characteristics and which, in relation to its parameters, could significantly affect its mobility. From this point of view, it is therefore essential that the bridges reflect the identified military requirements [20].

If the bridges do not meet these parameters, the units are forced to use alternative routes and detours [21], or they could strengthen the existing bridge or set up an alternative bridge. However, the last two alternatives are tied to limited resources and the nature of the obstacle they want to overcome, while with the identified "density" of bridges within the road network of the Slovak Republic, the satisfactory condition and technical specifications of bridges are key to ensuring mobility [20].

All bridges on roads are kept in the records of the road database of the Slovak Road Administration where each bridge represents a separate registration unit with specific data description. From the perspective of military use, data on the length of the bridge, the nature of the bridged obstacle, the structure, but especially the width of the bridge and its load capacity are relevant. It is the load capacity which represents the most limiting factor though [20].

According to the findings of the Supreme Audit Office of the Slovak republic, this is particularly problematic in relation to military mobility, as bridge structures in the territory of the Slovak Republic do not meet the required load capacity parameters, especially in relation to the weight of vehicles of NATO units [22]. Insufficient load capacity of bridges and the resulting consequences may pose a major risk to the strategic importance of the existing road network in relation to achieving effective military mobility. The issue of load capacity of bridges is a subject that needs to be given increased attention.

3.2 Military Load Classification of Bridges in the Slovak Republic

In terms of the above definitions the military use of bridges is mainly dependent on the exclusive, resp. exceptional load capacity. The next part of the paper is based primarily on the minimum exclusive load capacity of 60 tons, which is necessary for military use to ensure the transport of heavy military equipment (armoured vehicles transports – e.g. main battle tanks), as well as it si required by the State Defense Development Plan with a view to 2024 [23]. This parameter could be considered as a minimum requirement for the load capacity of bridges, but in the available documents we also encounter the requirement for an exceptional load capacity of at least 140 tons, and there is a presumption that these requirements will increase in importance in the future, given the modernizations of military weapon systems [20].

All bridges on roads are kept in the records of the road database of the Slovak Road Administration. From the perspective of the usability of bridges by military units, the most important requirement is the minimum load capacity of the bridge, which represents a value of 60 t for the roads of various organizational levels (Fig. 1).

Within the roads of the Slovak Republic, specific roads are identified which, at the time of the crisis, resp. war, are to ensure the transport of military units. These roads are called designated vehicle roads and are intended for the rapid and effective transport of

the Armed Forces of the Slovak Republic, as well as Allied forces in its territory [23]. The need for such a deployment, or the use of the infrastructure of the Slovak Republic, is not a remote fiction, even given the current geopolitical situation and tense relations in connection with the security of Ukraine. At the same time, it is necessary to realize that currently the eastern border of the Slovak Republic is at the same time even the eastern border of NATO and the EU. Due to its geographical location and security interests, the Slovak Republic represents political-geographically important area and a potential transit corridor [20]. For this reason, military mobility is referred to as a priority interest, defining the required parameters that those roads should meet [23]:

- underpass clear height (free height) at least 4.2 m,
- lane width, including the paved part of the curb, at least 3.5 m,
- exclusive load capacity of bridges at least 60 tons.

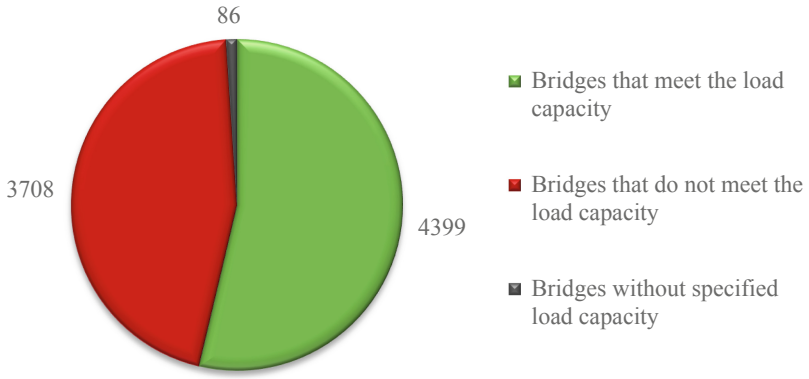


Fig. 1. The number of bridges in the Slovak road network meeting the exclusive load capacity 60 t (data retrieved from [9]).

In terms of the usability of bridge structures, it is, as with the existing road network, primarily determining the data on their exclusive load capacity. The report of the Analytical Department of the Ministry of Defense of the Slovak Republic from 2020 discusses that 20% of the total number of bridges at designated vehicle roads do not meet this requirement. It is based on data from the National Military Transport Center [24].

The usability of bridges in terms of their load capacity is directly affected by their construction and technical condition, the development of which in the territory of the Slovak Republic is characterized by considerable depravation (Fig. 2). The deterioration of the construction and technical condition is largely influenced by the long-term absence of investments in the modernization of bridges and the inefficient system of maintenance and repairs [11].

There is an obvious decrease in the number of bridges in the categories perfect, very good, and good, and on the contrary, the increase in the number of bridges in the categories sufficient, poor, very poor and unspecified. The number of bridges in a state of

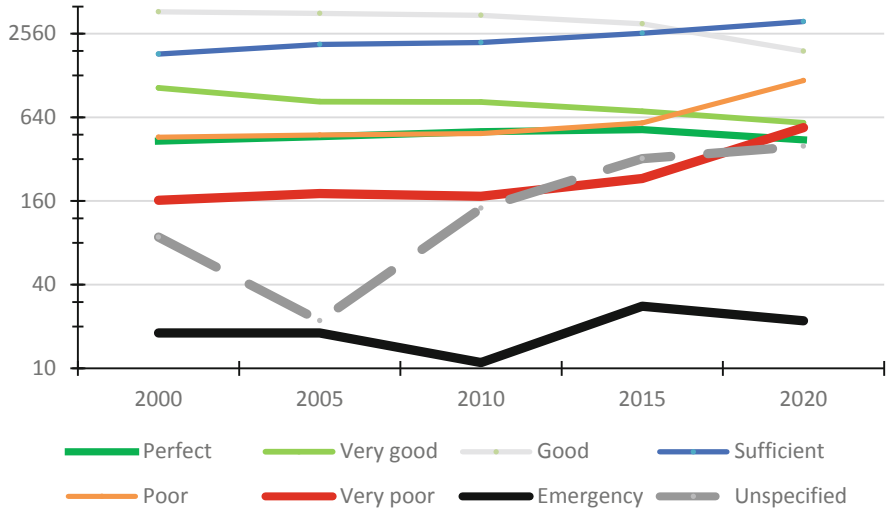


Fig. 2. Technical condition of bridges in the Slovak republic (data retrieved from [10]).

emergency is maintained in a relatively stable range. In order to maximize the usability of individual bridges, it is desirable from a military point of view that the state of the range of their construction and technical condition is formed by values from "good" to "perfect", while the evaluation is "acceptable". These levels do not immediately reduce the load capacity of bridges, which is already many times unsatisfactory [20].

4 Conclusion

Based on the above, it could be stated that the bridges of the road network of the Slovak Republic and their condition represent a significant variable in relation to military mobility. Whether at the state of peace, when bridges affect the possibilities of moving troops through the territory of the Slovak Republic, but also in relation to the collective defense of NATO and the EU during crisis response, when the ability to deploy forces quickly and effectively is required.

When assessing the usability of bridges in terms of their load capacity, their construction and technical condition are also important. This has a direct impact on the load capacity of bridges and the above analysis of its development over the last five years has outcomes which are not satisfactory because technical state of bridges is degrading. Poor construction and technical condition degrade load capacity, which in the context of military mobility means reducing the usability of existing road infrastructure. Thus, it could be stated that the degradation of bridges, as a part of the road network of the Slovak Republic, represents a security threat. This threat has the potential to negatively affect not only military mobility, but also the social and economic interests of the Slovak Republic as well as NATO security interests.

The quantitative impact of bridges on military mobility is also confirmed by their number with regard to the length of the Slovak road network - it follows that for every

approximately 2.2 km long section of the road, there is 1 bridge. The probability that this bridge meets the identified military requirements (based on the exclusive load capacity of at least 60 ton) is 54% [20].

From this it could be generalized that at a 500-km military movement via road network in the Slovak republic would be necessary to cross approx. 230 bridges. Of these only approx. 120 are compliant with military requirements. This means that on a route of 500 km up to 110 bridges do not meet the minimum military requirements in terms of load capacity.

It could be claimed that these values will be more favorable on designated vehicle roads, which are destined for military use, as they consist exclusively of motorways, expressways and Class I roads, where the load capacity of bridges is significantly better than the rest of the road network. But even on these roads, which should be unrestricted in terms of military requirements, there are a relatively high number of bridges which does not meet the minimal requirements [20].

The dilemma remains whether such a number of bridges in acceptable conditions during the crisis (war) would be sufficient to ensure military mobility in the Slovak republic.

References

1. Podhorec, M.: The Reality of operational environment in military operations. J. Def. Resource Manage. **3**(2(5)/2012), 41–50 (2012)
2. Rolenec, O., Šilinger, K., Žižka, P., Palasiewicz, T.: Supporting the decision-making process in the planning and controlling of engineer task teams to support mobility in a combat operation. Int. J. Educ. Inform. Technol. **13**, 33–40 (2019)
3. Majchút, I.: Deployability of armed forces in irregular warfare. In: The Knowledge-Based Organization - Management and Military Sciences, vol. XXIV, no. 1, pp. 130–136 (2018). https://doi.org/10.1515/kbo-2018-0019
4. Varecha, J.: Hodnotenie parametrov bojového potenciálu a bojovej sily ozbrojených síl. In: Národná a medzinárodná bezpečnosť 2020, Liptovský Mikuláš: Armed Forces Academy, p. 507–513 (2020)
5. Spilý, P.: Insight into contemporary operational environment. Secur. Dimen. Int. Natl. Stud. **11**(1/2014), 132–140 (2014)
6. Sedláček, M., Dohnal, F.: Possibilities of using geographic products in tasks of military engineering. Chall. Natl. Def. Contemp. Geopol. Situat. **2**, 145–155 (2020)
7. Spilý, P., Hrnčiar, M.: Vojenská taktika 1 [2nd edition]. Liptovský Mikuláš: Armed Forces Academy, 223 p. (2022). ISBN 978-80-8040-622-6, ISBN 978-80-8040-623-3
8. Andrassy, V.: Slovenská republika v operáciách NATO po summite vo Varšave. Politické vedy **22**(1), 80–107 (2019)
9. Slovenská správa ciest: Mosty. https://www.cdb.sk/files/documents/cestna-databanka/vystupy-cdb/2021/csv/sr_co_most_dc_2021-01-01.csv. Accessed 3 April 2022
10. Slovenská správa ciest: Cestné objekty – počty, štatistika. https://www.cdb.sk/sk/Vystupy-CDB/Statisticke-prehlady/Cestne-objekty-pocty-a-stav.alej. Accessed 4 April 2022
11. Najvyšší kontrolný úrad: Mosty sú kritickým miestom pre udržanie bezpečnej a dostupnej dopravnej infraštruktúry. https://www.nku.gov.sk/aktuality/-/asset_publisher/9A3u/content/mosty-su-kritickym-miestom-pre-udrzanie-bezpecnej-a-dostupnej-dopravnej-infrastruktury. Accessed 10 June 2022

12. Kompan, J.: Využitie distribučných úloh pri plánovaní ženijnej podpory mobility v stabilizačných aktivitách. In: *Vojenské reflexie:* Vojenský vedecký časopis. Akadémia ozbrojených síl generála Milana Rastislava Štefánika, Liptovský Mikuláš, vol. 13, no. 2/2018, 7–20 (2018)
13. Hrnčiar, M.: The counter insurgency operating environment. In: The Knowledge-Based Organization - Management and Military Science*s*, vol. XXIV, no. 1, pp. 87–92, (2018)
14. Hrnčiar, M.: Informačné aktivity v operáciách proti povstaniu. In: Národná a medzinárodná bezpečnosť 2016. Liptovský Mikuláš: Armed Forces Academy, pp. 153–158 (2016)
15. Kompan, J., Hrnčiar, M.: Security force assistance advisory team – inputs and outcomes. Vojenské rozhledy **30**(2), 055–069 (2021). https://doi.org/10.3849/2336-2995.30.2021.02.055-069
16. Mušinka, M.: The conflict in Ukraine and its impact on EU security. In: National and international security 2021, Liptovský Mikuláš: Armed Forces Academy, pp. 257–268 (2020). ISBN 978-80-8040-606-6
17. Kompan, J., Hrnčiar. M.: The security sector reform of the fragile state as a tool for conflict prevention. Politické Vedy **24**(2), 87–107 (2021). https://doi.org/10.24040/politickevedy.2021.24.2.87-107
18. Turaj, M.: Zhodnotenie aktuálneho stavu bojového použitia predsunutých leteckých navádzačov v podmienkach Ozbrojených síl Slovenskej republiky. In: *Vojenské reflexie:* Vojenský vedecký časopis. Akadémia ozbrojených síl generála Milana Rastislava Štefánika, Liptovský Mikuláš, vol. 13, no. 2, 164–174 (2018). ISSN 1336-9202
19. Ballay, M., Figuli, L., Zvaková, Z.: Using of intelligent transport systems to elimination of the negative effect on the transport security. In: Kravcov, A., Cherepetskaya, E.B., Pospichal, V. (eds.) Durability of Critical Infrastructure, Monitoring and Testing. LNME, pp. 249–260. Springer, Singapore (2017). https://doi.org/10.1007/978-981-10-3247-9_28
20. Jančo, J.: Mosty a ich vplyv na vojenskú mobilitu. In: Vojenské reflexie: Vojenský vedecký časopis. Akadémia ozbrojených síl generála Milana Rastislava Štefánika, Liptovský Mikuláš, vol. 17**,** No. 1, pp. 89–107. ISSN 1336-9202 (2022). https://doi.org/10.52651/vr.a.2022.1.89-107
21. Sedláček, M., Dohnal, F., Rolenec, O.: Proposal of an algorithm for evaluation of wet gap crossing using geoprocessing tool. In: Prentkovskis, O., Yatskiv (Jackiva), I., Skačkauskas, P., Junevičius, R., Maruschak, P. (eds.) TRANSBALTICA 2021. LNITI, pp. 542–551. Springer, Cham (2022). https://doi.org/10.1007/978-3-030-94774-3_53
22. Tonkovič Sudakovová, N.: Vojenský Schengen. https://www.mosr.sk/data/files/3914_2019-k-03-vojensky-schengen-vojenska-mobilita.pdf. Accessed 4 June 2022
23. Rozvojový plán podpory obrany štátu s výhľadom do roku 2024. https://rokovania.gov.sk/download.dat?id=AD09C77F07D848FC862A3A1374B36BAC-B229BA745F921B95FB0051B90F5A0344. Accessed 10 June 2022
24. Tonkovič Sudakovová, N.: Kam sa hýbe vojenská mobilita? https://www.mosr.sk/data/files/4285_2020-k-03-kam-sa-hybe-vojenska-mobilita.pdf. Accessed 2 June 2022

A Study for Identifying Fake News in the Information Society: The Case of the Logistics Sector

Kristina Čižiūnienė(✉), Artūras Petraška, and Gabrielė Žemaitytė

Vilnius Gediminas Technical University, Plytinės Street 27, 10105 Vilnius, Lithuania
{kristina.ciziuniene,arturas.petraska}@vilniustech.lt,
g.zemaityte@stud.vilniustech.lt

Abstract. In order to ensure the concept of green logistics, the aim is to automate all processes, to move them to the electronic space, etc., thus moving closer to e-logistics. However, today's current situation is a good reminder of the fact that online space is a place where fake news is widespread and can cause a significant damage not only to individuals, but also to companies. This article analyses the following at the theoretical level: the concept of fake news and the preconditions for its emergence, the types and characteristics of fake news, the purposes of its use and its possible sources. The practical part presents the results of quantitative studies carried out in 2020 and 2022 seeking to assess how people working in the logistics sector deal with fake news, whether they manage to spot it, etc. The study found that people working in this sector do not have sufficient skills to identify fake news and that companies should pay more attention to educating their employees on this issue.

Keywords: Logistics sector · Fake news · Information society · Identification · Employees of the logistics sector

1 Introduction

In today's rapidly changing world, knowledge about the current political, economic or social events is of interest and attracts attention of the majority of the public. They usually read news on official websites or portals, watch it live on TV or listen to it on the radio. It is brought to us by skilled journalists and other professionals, but unfortunately there are still people who want to profit from this activity. Taking advantage of short-term nature of daily news, news that have nothing to do with the reality, but is convincing enough for many people to believe it without even questioning it, often without realising or noticing that it's false, is disseminated. According to Johnson [1], more than two thirds of Europeans are exposed to fake news at least once a week, and a significant share (83%) of Europeans believe that fake news is a problem in democracy. Such news can damage the society, cause unnecessary panic, stress, tension, deception or mislead people. According to a survey conducted by the Pew Research Center, two-thirds of

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 479–490, 2023.
https://doi.org/10.1007/978-3-031-25863-3_45

Americans say they get at least some of their news from social media, and as many as 20% of them do that often [2]. These survey results show that fake news is pervasive and enshrined in the online space, and in social networks in particular. The logistics sector is no exception. Recently, in order to automate / accelerate certain processes in the supply chain, a lot of data have been moved to cyberspace, thus the provision of inaccurate information can have negative consequences not only for people working in this field, but also for companies themselves.

It is therefore very important to identify fake news, because it is misleading and, unfortunately, are becoming a part of life of the information society. Fake news can be spotted understanding the criteria for its identification.

The object of this article is fake news.

The aim of this article is to define the main criteria for identifying fake news in the logistics sector / field.

To achieve this goal, the following tasks have been set:

1. To carry out an analysis of issues relating to fake news at the theoretical level.
2. To research how people working in the logistics sector are exposed to fake news and how they are able to identify it.

2 Analysis of Issues Relating to Fake News at the Theoretical Level

The concept of news is common in the information society and is usually understood as news, various reports about certain events in various fields, including politics, economics, business world, sports achievements, etc. Everyone has probably noticed that news can be divided into two opposing groups. The first is true news that shows the reality, real events and facts, while the second group is false news, which is false, made-up, commonly known as fake news. Insights of the Forum for Social Studies state that fake news is generated information that imitates content in the form of media. Fake news, in turn, lacks editorial norms and assurance of the accuracy and reliability of information (see Table 1).

Table 1. Definitions of fake news.

No.	Source	Definition
1.	Lazer et al. 2018 [3]	Fake news is generated information that imitates content in the form of media. It is the same as misinformation (false or misleading information that is expected to be spread to deceive people)
2.	Tandoc et al. 2018 [4]	Propaganda, deception, manipulation, fable, news satire and news parody was called false news
3.	*Oxford Dictionaries* 2020 [5]	False reports of events written and read on different websites

(*continued*)

Table 1. (*continued*)

No.	Source	Definition
4.	Miller 2019 [2]	Fake news refers to news stories and social media that falsely publish it as real news and news stories, especially those that portray government representatives and celebrities in a negative light
5.	Hunt 2016 [6]	Fake news is classified as "yellow press" and propaganda news, the purpose of which is to deliberately misinform the public through the use of both traditional physical publications, online news sites, and social networks

Fake news, as defined by media representatives and experts, is classified as "yellow press" and propaganda news, which aims to deliberately misinform the public through traditional physical publications, online news sites, and social networks [6]. Fake news is written and published with the intention of deliberately causing damage to some agency, a race of companies, an individual, or to gain financial and political advantage. In many cases, this is done by using not only false facts, but also catchy headlines.

The analysis of the concept of fake news in different sources reveals its multifaceted nature and the use of different tools and features in pursuit of its purpose. It is therefore important to look at the preconditions that lead to the creation of fake news.

First of all, fake news came into the limelight in 2016 and was associated with several events, such as the US presidential election, when Donald Trump was elected US President, and the referendum, when the British people voted in favour of the United Kingdom's withdrawal from the European Union (Brexit), but the first signs of fake news were seen back in 2012 with the election of Barack Obama. According to the Lithuanian Culture Research Institute, year 2012 is the date that marks the emergence of two specific unprecedented "information disruptions" that have affected public opinion worldwide, namely, online radicalism and online disinformation [7]. Political elections are very important to a society, appointing future representatives of a country. Elections determine living conditions of the society in the years to come, national and foreign policy of the country, etc. Candidates seek to become elected because this may be a very important career step in their life and history, and the society seeks its own well-being. Some individuals try to mislead the public with fake news during the election period. Thus there are many persons pursuing different benefits during elections. Fake news is intended to mislead the public without them understanding it. After all, having fell for fake news, people would live in a world of illusions.

Moreover, when analysing the preconditions for the emergence of fake news, social networks can be named as one of them, because it is a medium where fake news could take root. According to Yuri Misnikov, a PhD: "One of the main purposes of social media is knowledge sharing, which also includes news creation. However, for a long time, social networks were not considered a part of the public communication ecosystem, because they often have too few links to journalism. Today, with the number and the volume of print media units declining significantly, getting news from alternative sources has

become common" [8]. Obviously, the emergence of information technology has enabled every user to have access to the internet and news production. Thus, if news did not exist in a virtual environment and was only disseminated by official editorial boards in printed newspapers or magazines, as was the case in the past, no outsider would have access to the production of news, and thus won't mislead the public. However, we can no longer change this, as the society is increasingly turning towards the convenience of smart technology, for example, they prefer reading books electronically, as it is easy, fast and convenient. So, although the society has been progressing in the information sphere and the use of social networks has grown rapidly, there is also a negative side to this.

To sum up, political elections and social networks can be considered to be preconditions for the emergence of fake news, because they are a medium where disseminating fake news is very easy. This is how fake news spreads rapidly in the business environment as well.

The analysis of fake news revealed that it can be grouped, distinguishing certain types of such news. The literature describes seven types of fake news and their characteristics [9] (Table 2):

Table 2. Types and characteristics of fake news.

Types	Characteristics
Satire and parody	Humour, irony, exaggeration, ridicule, mockery, scorn
Propaganda	Draws on emotions, can be helpful or harmful, used by governments or corporations to control attitudes, value and knowledge
Manipulation	Aims to create pressure and tension based on emotion and status
Fabricated content	Fake, gripping, intriguing stories or plots with no connection to reality, characterised by expressiveness
Alternative truth	Unsubstantiated facts with little evidence of their validity
False headline	Eye-catching, emotive headlines designed to distract; headlines are inconsistent with news content

According to Gaučaitė [10] experts have also divided fake news into 2 groups: 1) outright lies; 2) selective truth or interpretation of facts.

Therefore, fake news can be concluded to be spread because it can serve many different purposes determined by many factors, including the period of time, the benefit sought, and the type of fake news. According to literature, propaganda has been deliberately designed to control a particular field. Some sources state that there are many websites and online commentators who engage in propaganda fake news, but few would openly admit to being propagandists [11]. Fake news is spread by hiding the real authors, because it is still a lie and no one wants to reveal their identity, because spreading fake news is subject to penalties. However, the world easily believes in fake news, and it has a strong hold on the society.

In summary, fake news is often spread for financial or political gain. It is therefore important to identify the sources which can be expected to spread fake news.

On social networks, lies and fake news spread much faster and penetrate much further than real news, which was proven by a study conducted by the Massachusetts Institute of Technology. According to the researchers, people are more likely to share fake news because it contains an unexpected and new story [12]. This intrigues and persuades readers so that they believe it without looking deeper, understanding or thinking about its reality and veracity.

The article states that there is no longer a traditional hierarchy of information sources, and now anyone can publish what they think is important, with links to some websites that may have purposefully been created specifically for such a campaign: "All of this appears at the same level as reports from trusted news portals or other media sources. The other thing is that if people get hooked, they often share it, giving the impression that there must be some truth in the information" [13]. The presence of such an impression makes people believe fake news simply because it has many shares. It becomes like a mass deception that spreads among readers.

Fake news is thus a problem in the society, because members of the society themselves believe fake news and continue to spread and disseminate it to the detriment of themselves and others, and to the benefit of fraudsters whose aim is to spread lies.

Therefore, in order to avoid exposure to fake news and deception, it is necessary to learn how false news can be spotted. The detection of fake news is defined as the anticipation of the likelihood of deception for a given news article (news, report, editorial, publication, etc.) [14]. Fake news can only be spotted if certain criteria to be addressed are known. According to the document published by the European Parliament's Research Service in 2019, one of the ways to identify disinformation is to look at the author and his reputation: "If it is a journalist with a good reputation, you will definitely find his previous work. If the author's name is made up (or has not been published), the rest of information is also likely to be fake." [15]. Another important recommendation is to check images, as often an image is used for manipulation purposes, so it is best to do an image search to see if the image has not been used before in a different context. The next but equally important step is not to share information without giving a second thought, as all stories can be a distortion of real or old events, or a satire, and the headline is just a common tool to evoke strong emotions. If an event is real, credible media will report it. The latter aspect is combined with subjectivity and "cool head". In addition to these identification criteria, there are several aspects that require attention. The literature analysis allows distinguishing two important methods to identify false and fake news [16]:

1. Linguistic method – this method studies linguistics and vocabulary. It was observed that "liars" strategically use their language to avoid being identified and exposed.
2. Network method – the essence of this method is reliable sources, websites and portals. When credible sources and sites are cited and the official nature of the sites is guaranteed, the reader can be reassured that the site is reliable and safe to use.

In summary of the theoretical analysis of sources of literature, there are a number of criteria that can be used to identify fake news and thus avoid being misled. The different criteria allow for a multifaceted verification of a certain piece of news, checking both the text, the images used, the authors or the sources. It is very important not only to choose

websites carefully and pay attention to the language of the text, but also to take an interest in the author and his work. The authors of the analysed sources of literature distinguish the following main criteria for identifying fake news: reputation of the author of the published text; verification of visual information (images); credibility of the website address (or the source of information); and credibility of the facts presented.

3 Methodology

A questionnaire survey was chosen as the method of study. It is described in literature as a method widespread in social sciences due to its apparent simplicity, at the same time emphasizing that it is not as easy as it might first appear (Kardelis, 2002). In order to be effective in research, the survey method needs to follow its methodology, and the questionnaire needs to be developed responsibly and thoughtfully. A few questions can provide a lot of information quickly, but the data obtained must be reliable. While a questionnaire survey is often criticised for its incompleteness, its inability to reveal the phenomenon being studied and a lack of confidence in it, the criticism should not be directed at the method itself, but rather at the inadequate preparation for its application [17]. The survey method requires well-formulated questions, understanding the topic and delving in it, and a considerable time for data collection.

The aim of the survey is to determine the ability of people working in the logistics sector to identify fake news.

The survey was carried out twice on the website apklausa.lt:

1. in March – April 2020,
2. in March – April 2022.

First of all, a survey questionnaire consisting of 17 questions was created for conducting the survey.

All questions in the survey are closed-ended, providing respondents with several answers to each question. This makes the survey easier, as respondents do not have to formulate their answers, simply choosing the most appropriate one. The advantage of closed-ended questions is that it is easier for respondents to compare, contrast and quantify the data.

In order to be able to apply the survey results to the whole population, the survey must be representative, thus the sample size of respondents was calculated based on the formula [18]:

$$n = \frac{z^2 \times s^2}{\Delta^2}, \tag{1}$$

where n is the number of cases in the sample group.

Variables:
z is a coefficient found in the Student Distribution Tables. It is chosen on the basis of confidence level. When the confidence level is 95%, $z = 1.96$, and when the confidence is 99%, $z = 2.6$;

s is the root mean square deviation of the sample;

Δ (delta) is the margin of error, the difference between the mean of the sample group and the mean of the general population. It is freely chosen, taking into account the accuracy requirements of the data and data from previous surveys.

As this survey covers people who work in the logistics sector, the general population of the sample could be considered to be population of the entire country, but potential respondents selected in this survey are adults aged 18 years and over.

The sample size calculated according to the formula was 96 respondents. Based on recommendations, potential confidence of 95% and a margin of error of 10% was selected. The required sample size remained the same in 2022 after a corresponding recalculation.

4 Survey Results and Discussion

98 participants answered the questions of the survey in 2020 and 102 respondents – in 2022. Their distribution by gender and age was as follows (Table 3).

Table 3. Distribution of respondents by gender and age.

	Gender		Age			
	Female, %	Male, %	19–25, %	26–36%	37–47%	47 and older, %
2020	58.10	41.90	54.80	22.60	16.10	6.50
2022	51	49	49	21.60	21.60	7.80

In summary of the results, it can be concluded that both in 2020 and 2022, the majority of respondents were young people in the 19–25 age group, followed by other age categories in descending order: 26–36-year-olds, 37–47-year-olds and the fewest respondents in the 47 and older age group.

The majority of respondents have secondary, tertiary and vocational education, with secondary education dominating in 2020 (44.8%) and tertiary education – in 2022 (39.2%).

Both in 2020 and 2022, the majority of respondents (above 80%) said they knew what fake news was. It was therefore relevant to find out which sources of information respondents use the most.

In 2020, respondents identified the internet as the most frequent source of information (58.1%). Others said social networks (25.8%), television (12.9%) and the press (3.2%) were the most frequent sources of information. Having repeated the survey in 2022, the trend remained the same, with the internet still being the most popular source.

Although social networks were not the most frequent source of information for the majority of respondents, still more than 90% of respondents said they used social networks, with the majority of them (2020: 87.1% and 2022: 84.3%) spending their time on social networks every day.

The majority of respondents who used social networks said they often see fake news on social networks (2020: 61.3%, 2022: 56.9%), a third said they rarely spot it and the remainder said they never see it.

The analysis of respondents' opinions on whether they have been misled by fake news revealed that there was no significant change during the period analysed, with the majority saying that they have fallen for fake news believing lies (2020: 45.2%, 2022: 49%).

In 2020, a smaller share of 25.8% thought they had avoided it, while 29% were not sure and did not know if they had ever been misled. Meanwhile, in 2022, 21.6% said they have avoided being misled and 27.5% were not sure and did not know if they had been misled.

In order to find out the source of fake news, respondents were asked a question about it. Respondents who had been exposed to fake news were able to identify the source of information where they had encountered fake news. In 2020, 45.2% said they were misled by fake news on social networks, 19.4% – on the internet and 9.7% – on television, while in 2022, respondents also named social networks (39.2%) and the internet (29.4%) as the source of misleading news. The survey therefore aimed to identify the types of fake news that respondents know. Given the fact that in the logistics sector freight/means of transport are often searched online, investigating this issue is important.

Respondents indicated distortion of facts (24.8%) and propaganda (24.9%) as the most commonly known type of fake news in 2020 and 2022, respectively. The other predominant types also remained unchanged over the two years, and included deception (about 18%), manipulation (about 20%) and parody (about 7%). Therefore, the survey asked respondents to assess their ability to identify fake news. When analysing the results of the 2020 and 2022 surveys, there was no significant difference, and the distribution remained similar, with almost half of the respondents rating their ability to identify fake news as good, just over a third – as average and around 10% – as poor.

Respondents were asked to identify the criteria they used to assess the credibility of news.

In 2020, most respondents indicated that they most often relied on the credibility of the source (75%), the date of publication (62.1%), and the credibility of facts (71.4%). 50% of respondents said they rarely relied on the author's reputation, influence of celebrities, or on the opinion of family or friends (39.3%). In 2022, the most popular criteria remained the same (Fig. 1).

In the 2020 survey, 48.3% of respondents said that they are only interested in the credibility of a news source when the news seems unreliable, meanwhile in 2022, this figure increased to 54.9%. There has been a noticeable decrease in those who always check the credibility of sources, with a drop of 9%. It can be assumed that the public no longer views fake news with the same degree of caution and responsibility.

The majority of respondents (around 90%) believe that fake news about current affairs is a cause for concern.

Thus, the results of the survey suggest that there has been no significant change over the two years, however, as the public's skills have not changed over this period of time, it can be argued that the society still does not have enough skills to spot fake news.

The survey results can be illustrated in a "fishbone" diagram (Fig. 2).

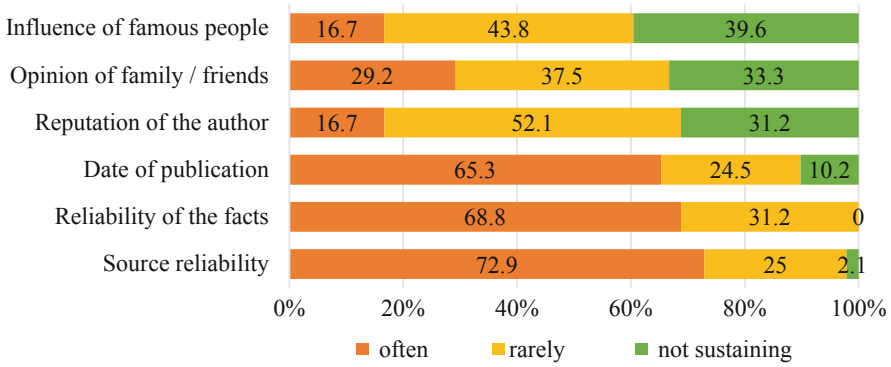


Fig. 1. Criteria for identifying fake news in 2022.

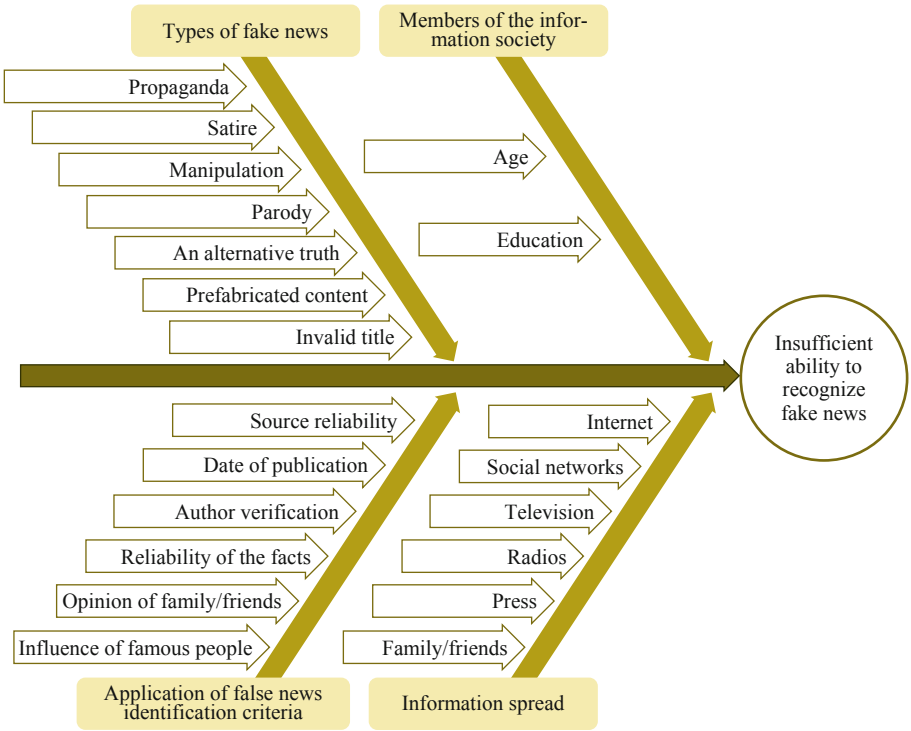


Fig. 2. Results of the assessment of identification of fake news.

There are many reasons for a shortage of skills to identify fake news. First of all, it depends on the member of the information society himself, his characteristics, intellectual abilities and knowledge, age and education. Another important aspect that affects the identification of fake news is the dissemination of information (Fig. 2). It can vary widely in nature and source. This can be audible information only, e.g. radio, or visible

information, e.g. the press. However, the most common sources of information are comprehensive, which provide the recipient with both audio and visual information. This is the most effective way of assimilating information. As the survey showed, information sources such as television, the internet and social networking platforms are the most visited sources and therefore have the greatest impact on the public.

Another important aspect that determines the ability to identify fake news is the types of fake news. There are many different types of fake news, differing in their nature, the type of information disseminated and its purpose. In order for a member of the information society to be able to recognise these types and spot fake news, he needs to be aware of the identification criteria and to rely on them. This is a key factor determining skills. When members of the information society understand the means which they can use to check the authenticity of news, the scale of deceit is expected to decrease. Education in the field is therefore very important, especially in logistics activities, which encounter extensive volume of information.

Therefore, in pursuit of the solution to the problem identified in the study, it can be stated that there are ways to achieve an increase in the ability to identify fake news. In order to develop fake news identification skills, the recommendation is to increasingly rely on such criteria as credibility of the source, verification of the author's reputation and credibility of facts. It is also very important to rely on official sources only. The knowledge and application of these criteria will reduce the spread of and belief in fake news and increase credibility.

5 Conclusions

1. The conducted literature analysis suggests that the concept of fake news is defined in sources of literature as generated information that imitates content in the form of media. It is the same as disinformation (false or misleading information that is disseminated to deceive people), and is characterised by its multifaceted nature and the use of different means and features in pursuit of some objective.
2. The conducted study found that people working in the logistics sector do not have sufficient skills to identify fake news. This may be due to a number of factors, such as the characteristics of the person himself, including age and education, or the dissemination of news and information, and the application of fake news types, and their identification criteria.
3. The proposed recommendations include the use and application of criteria for identifying fake news, reliance on official sources of information only, and continuous awareness-raising of employees on the issue.

References

1. Johnson, J.: Fake news in Europe - Statistics & Facts (2020). https://www.statista.com: https://www.statista.com/topics/5833/fake-news-in-europe/
2. Miller, M.: Fake News - Separating Truth from Fiction. Lerner Publishing, San Francisco (2019). https://books.google.lt/books?id=Njp_DwAAQBAJ&printsec=frontcover&dq=fake+news&hl=lt&sa=X&ved=0ahUKEwikj7LUodjoAhXxmIsKHa_FDWEQ6AEIJjAA#v=onepage&q=survey&f=false
3. Lazer, D.M.J., et al.: The science of fake news. Science **359**(6380), 1094–1096 (2018). https://doi.org/10.1126/science.aao2998
4. Tandoc, E.C., Lim, Z.W., Ling, R.: Defining "Fake News": a typology of scholarly definitions. Digit. J. **6**(2), 137–153 (2018). https://doi.org/10.1080/21670811.2017.1360143
5. Oxford Learner's Dictionaries. University Press, Oxford (2020). https://www.oxfordlearnersdictionaries.com/definition/english/fake-news?q=fake+news
6. Hunt, E.: What is fake news? How to spot it and what you can do to stop it. Retrieved from The Guardian. Social media (2016). https://www.theguardian.com/media/2016/dec/18/what-is-fake-news-pizzagate
7. Repšienė, R.: Medijų mitai ir mitai kaip medijos [Media myths and myths as media]. Vilnius: Lietuvos kultūros tyrimų institutas (2018)
8. Komunikacijos ekspertai: Naujienų gavimas iš alternatyvių šaltinių – norma [Communication experts: Getting news from alternative sources is the norm] (2017). https://www.15min.lt/naujiena/aktualu/lietuva/komunikacijos-ekspertai-naujienu-gavimas-is-alternatyviu-saltiniu-norma-56-860696
9. Ibrahim, Y.. Safieddine, F.: Fake News in an Era of Social Media – Tracking Viral Contagion. Rowman & Littlefield International, London, New York (2020). https://books.google.lt/books?id=C87LDwAAQBAJ&pg=PA6&dq=fake+news+types&hl=lt&sa=X&ved=0ahUKEwjT7dHGqZrpAhUkxKYKHfoOCr0Q6AEIRTAD#v=onepage&q=fakenewstypes&f=false
10. Gaučaitė, M.: Informacinis karas kaip išsipainioti iš netikrų naujienų tinklo [Information warfare as a break from the fake news network (2019). https://www.lrt.lt/naujienos/lietuvoje/2/705246/informacinis-karas-kaip-issipainioti-is-netikru-naujienu-tinklo
11. Barclay, D.: Fake news, Propaganda, and Plain Old Lies - How to Find trustworthy Information in the Digital Age. Rowman & Littlefield Lanham Boulder, New York, London (2018). https://books.google.lt/books?id=3UdODwAAQBAJ&pg=PA1&dq=fake+news+destination&hl=lt&sa=X&ved=0ahUKEwjmovXksqHpAhVYwsQBHWktBj8Q6AEIPTAC#v=onepage&q=purpose&f=false
12. Dizikes, P:. Study: On Twitter, False News Travels Faster Than True Stories. Institute of Technology Massachusetts (2018). http://news.mit.edu/2018/study-twitter-false-news-travels-faster-true-stories-0308
13. Trapikaitė, G.: Perspėjo kokiais būdais Rusija kitąmet kišis į rinkimus Lietuvoje [Russia warned of the ways in which Russia would interfere in the elections in Lithuania next year] (2018). https://www.lrt.lt/naujienos/lietuvoje/2/207780/perspejo-kokiais-budais-rusija-kitamet-kisis-i-rinkimus-lietuvoje. Accessed 20 March 2018
14. Rubin, V.L., Chen, Y., Conroy, N.J.: Deception detection for news: Three types of fakes. In: Proceedings of the Association for Information Science and Technology, vol. **52**, issue 1, pp. 1–4. Association for Information Science and Technology (2015). https://doi.org/10.1002/pra2.2015.145052010083
15. Bentzen, N., Chahri, S.: How to spot when news is fake (europa.eu). (Members' Research Service) Retrieved from European Parliamentary Research Service EPRS (2019)

16. Conroy, N.J.. Rubin, V.L.. Chen, Y.: Automatic deception detection: methods for finding fake news. In: Proceedings of the Association for Information Science and Technology, vol. 52, issue 1, pp. 1–4. Association for Information Science and Technology, Leesburg, USA (2015). https://doi.org/10.1002/pra2.2015.145052010
17. Tidikis, R.: Methodology of Social Sciences Research. Publishing Centre of the Law University of Lithuania, Vilnius (2003). https://repository.mruni.eu/handle/007/15459MRU
18. Kardelis, K.: Mokslinių tyrimų metodologija ir metodai [Research methodology and methods]. Vilnius: Mokslo ir enciklopedijų leidybos centras [Science and Encyclopedia Publishing Center] (2016)

Engineer Mobility Support on the Territory of the Czech Republic as One of the Host Nation Support Tasks

Jindřich Dologa(✉), Ota Rolenec, and Natálie Hanáková

University of Defence, Kounicova 65, 60200 Brno, Czech Republic
J.Dologa98@seznam.cz, {ota.rolenec,natalie.hanakova}@unob.cz

Abstract. With NATO's increasing requirements for greater mobility of all ground forces the importance of engineer support to troops is also growing. One of the most debated issues in military operations is the provision of military movements, not only of national but especially of coalition forces in support of the host nation. Infrastructure inadequate to technical parameters of military means is one of the main identified problems in the area of mobility support and redeployment. The article focuses on a partial part of the Host Nations Support issue in relation to the movement ensuring of military vehicles on the territory of the Czech Republic. The paper analyses the possibilities of mobility support by the engineer troops of the Army of the Czech Republic and the paper also deals with the road network and road infrastructure on the territory of the Czech Republic. The proposal section of paper is divided into two parts. The first one suggests a unit that would be predestined to support the movement in our territory. In the second part, sections of the road network suitable for use in the movement of troops through the Czech Republic are proposed.

Keywords: Host Nation Support · Mobility support · Road network

1 Introduction

Ensuring the mobility of forces is one of the most discussed issues in military operations [1]. Nowadays, it is no longer just about providing the mobility of own troops, but also about ensuring the mobility of coalition forces and foreign armies [2]. Engineer support has an indispensable role in this context, as engineer units are predestined to perform mobility support tasks within military engineering (MILENG). Historically, however, engineer troops of the Czech Armed Forces (CAF) have been far more numerous and better equipped than today's engineer force. There were also road units that played a significant role in the execution of support tasks on the roads [3].

Performing the Host Nation Support (HNS) tasks is still quite new at CAF and the army is adapting to new challenges. HNS is engaged mainly by logistic support units, which have extensive experience with the movement of foreign armies through our territory. There are no concept materials in the CAF dealing with the contribution of engineer corps to the HNS. With the ever-worsening security situation in the European

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 491–501, 2023.
https://doi.org/10.1007/978-3-031-25863-3_46

region, it is reasonable to believe that an allied operation in Europe requires strong rear support such as the allocation of road and rail tracks for troop movements, the construction of forward air bases, the procurement of fuel, as well as the provision of everyday life for deployed troops.

The aim of the paper is to analyse the possibilities of supporting movement on the road network and infrastructure on the territory of the Czech Republic within Host Nation Support by the engineer troops of the CAF. To achieve the aim of the article, the following tasks must be fulfilled. The first one is, based on capabilities of engineer troops' manpower and equipment, to propose a unit that would be predestined to support mobility on our territory, focusing on the construction, maintenance and reparation of roads and paths. The second task is to propose sections of the road network suitable for use in troop movements through the Czech Republic and locations of proposed unit for each section ensuring effective support response.

2 Methodology

The method of analysis was used mainly in the first part of the article, for the study of the literature and in the examination of the current situation of the problem. The literature research together with the knowledge gained from the internships in the engineer corps were the basis for the article elaboration. The method of synthesis was used especially in Sects. 4 and 5. Based on the analysis, the synthesis enabled the development of proposals.

Interviews were conducted with officers of the engineer corps in order to identify the level of experience of the engineers and the possibilities of the currently used and implemented equipment in the engineer units within the CAF. The interviews were conducted in person during the internships and some by correspondence. For the completion of this paper, methods of deduction and induction were used mainly to create conclusions from the findings obtained in the analytical part and the experiences from the officers of the engineer profession.

3 Road Communications in the Czech Republic

The road network in the Czech Republic is very well developed with almost 56,000 kms of roads in service by 1st January 2021. The highway network measures 1,298 kms and is still under construction [4]. Fact, that highways do not cover the entire territory in such a proper way, implies that intended roads network for troop movements will have to include Class I roads with lower possible vehicle capacity.

Figure 1 shows possible transportation problem in Prague area, where the D0 ring highway surrounds the city partially. There is also a problematic section southward from Prague to Austria, which fulfils the characteristics of highway just partly – the rest are mainly class 1 roads. A similar problem could arise in the area from Hradec Kralove to the Polish border.

On all these sections, the traffic intensity is over 10,000 cars per day and in some places this number reaches over 20,000. This fact, together with the absence of a completed highways on these sections, means that a large number of military transports could cause a traffic collapse on the roads in named sectors [5].

Fig. 1. Map of the highway network of the Czech Republic by 1.1.2021 with perspective sections (grey) [5].

4 Engineer Troops' Manpower and Equipment in Support of HNS

4.1 Mobility Support Capabilities of the 15th Engineer Regiment Units

Combat Engineer Support Companies includes engineer platoons, engineer machine platoons and barricading platoons. The *engineer platoon* consists of engineer squads equipped with assets identical to the units it provides support to. In the case of the 4th Rapid Deployment Brigade, these would be wheeled armoured personnel carriers in the engineer configuration and in the case of the 7th Mechanized Brigade, BMP-2 vehicles. Following tasks are mainly performed: engineer reconnaissance; lane establishment in engineer obstacles and cave-ins; participation in road maintenance and construction of protective structures. *Engineer machine platoon* consist of squads of excavators, dump trucks, loaders, bridge trucks, and an engineer demining squad. The engineer machine platoons perform especially: engineer reconnaissance; road improvement and maintenance; bridging water and dry obstacles up to 40 m; terrain demining and establishing passages in obstacles; using of earth moving machines across the full spectrum of operations. The excavator squad is equipped with UDS-114 and 214 hydraulic shovel excavators and JCB-4CX multi-purpose excavators. With them, it is capable to carry out terrain modification, especially rock acquisition and stockpiling. The loader squad is equipped with KN-251 wheeled carriers and JCB robot hydraulic loaders, so it can carry out terrain modification. The dump track squad is equipped with T-815 heavy off-road trucks and it is able to transport heterogeneous materials. The bridge truck squad is equipped with AM-50 bridge trucks and automotive cranes [6].

General Engineer Support Companies consists of engineer construction and engineer machine platoons are in the structure of these companies. The engineer construction platoon consists of an engineer squad and an engineer technical squad. The *engineer construction platoon* particularly performs: construction works (e.g. building of firing

and observation posts) and participation in road improvement and maintenance and construction of protective structures. *The engineer machine platoon* differs from the unit of the same designation of the combat engineer support company in replacement of demining and bridge truck squad by dozer and road machine squad. It is assigned to conduct earthworks using earthmovers. The dozer squad is equipped with CAT 5N (6K) bulldozers. The road machine team is equipped with CAT 120M graders and road rollers [6].

Engineer Special Companies are predetermined to perform engineer support tasks, with emphasis on combat engineer support. They consists of EOD teams, path clearance teams and engineer special platoons. The *road clearance team* consists of road clearance and technical groups. In particular, it performs: road reconnaissance; implementation of road clearance tasks; detection, confirmation and neutralisation of explosive devices and signs of their use. The *Engineer Special Platoon* consists of earthmovers squads, floating transporter squads, climbing squads, and firefighting squads. In particular, the Engineer Special Platoon shall perform these tasks: extinguishing small to medium fires; oil spill response; recovery of stranded and crashed vehicles; earthmoving and demolition works; ensuring the transport of personnel and material during evacuation. The firefighting squads have special firefighting equipment such as a forklift, a tanker and a truck sprayer. The earthmoving machinery squad has automobile excavators, JCB 4CX excavators and CAT D4 bulldozers. The floating transporter squad has PTS-10 amphibious tracked transporters with which it is able to conduct transport over water obstacles and vehicles for their transport [6, 7].

Based on an analysis of the capabilities mentioned above, might be assumed that the Engineer Corps are currently capable of supporting three following tasks within the HNS: (1) troop deployment (help with the construction of bases and facilities); (2) movement and transport (provision of trucks and partial road improvement and maintenance); (3) food, material and fuel supply.

4.2 Evaluation of Interviews with the Officers of the Engineer Corps

Semi-structured interviews were conducted with commissioned officers of the engineering corps. The aim was to find out the engineers' experiences and capabilities in mobility support of foreign armies located on the Czech territory. The interviews ascertained the MILENG corps' performance capability of mobility support within the HNS, proper equipment and required structure. Based on interview analysis, there are not enough commissioned officers in the engineering corps specialised in HNS area directly.

The engineers' experiences in HNS support are reflected in military logistics support entirely. The engineering corps helped within the fuel and drinking water supply as well and provided recovery in case of military vehicles got stuck. The incorporation of recovery vehicles into the convoy formation is a common occurrence. When it comes to a transfer of heavy equipment on roads, engineers have lots of experiences. A large number of engineering vehicles cannot be transferred over long distances separately and must be carried on trailers.

The engineering corps would probably not be conducting road repair and maintenance if they were intended to perform this mobility support task. The reason is the lack of equipment. Mentioned task would still come under the Directorate of Roads and

Motorways of the Czech Republic. MILENG units are able to fulfil tasks such as route clearance, removing roadblocks or clearing off-road routes, i.e. areas designated for troop assembly and maintenance of passing vehicles. Military engineers would support the construction of foreign troops' main command posts and military bases.

CAF military engineers are not capable of repairing and constructing roads or rapidly modifying terrain with inadequate load capacity. The unit suitable for the HNS task is primarily the General Engineer Support Company. Nevertheless, this unit is not capable of performing mobility support tasks independently due to lack of required equipment (e.g. bridge vehicles or MRAP and recovery vehicles). Mobility task groups would most likely be formed from multiple engineer units, therefore.

Czech engineer corps, based on interviews, have an appropriate equipment, but in limited quantity. The engineer units have no experience with HNS support and are not trained in road construction or road maintenance with the equipment at their disposal. The available equipment is not capable of building new roads or their effective repairing and maintaining. In terms of road improvement, maintenance and construction, the Czech engineer troops are capable of filling and compacting potholes or creating auxiliary roads from improvised materials (hats, wooden mats) at the most. On the other hand, these roads are not sufficient for the rapid movement of troops in our territory and should be used only in the most extreme cases.

The mobility support on the roads in the Czech Republic is not considered from the MILENG's point of view. To fulfil the task of mobility support on roads within the HNS, the purchase of modern road construction equipment and training of operators would be necessary.

4.3 Proposal of HNS Mobility Support Unit

The proposed unit should include a reconnaissance group and an earthworks and bridge groups. The size of the unit will be based on the size of the area to be tasked and/or the size of the unit it supports. The unit's predetermination will be to perform reconnaissance, repair, maintain, and construct roads on paths designated for troop movement. Also, establishing detours, reinforcing low-bearing terrain, and removing road obstacles. In peacetime, in addition to routine training, this unit will also perform road maintenance within the military units of the CAF. The proposed unit is equipped with not available assets of the engineer troops' equipment or other units of the CAF.

An HNS mobility support unit of company strength (Road Company - rocmp) should have the following structure (see Fig. 2). It should have Command squad (comsq); Engineer reconnaissance platoon (engrecpl) with 2 × reconnaissance squads (recsq); Engineer construction platoon (engconpl) with1 × loader squad (loasq), 1 × excavator squad (exsq), 1 × engineer squadron (engsq) and 1 × dozer squadron (dozsq); Engineer road platoon (engropl) with 2 × road machinery squads (romachsq) and 2 x dump track squads (dumtrsq) and Engineer special platoon (engsppl) with 1 × recovery squad (recosq) and 1 × bridge truck squad (brtrsq).

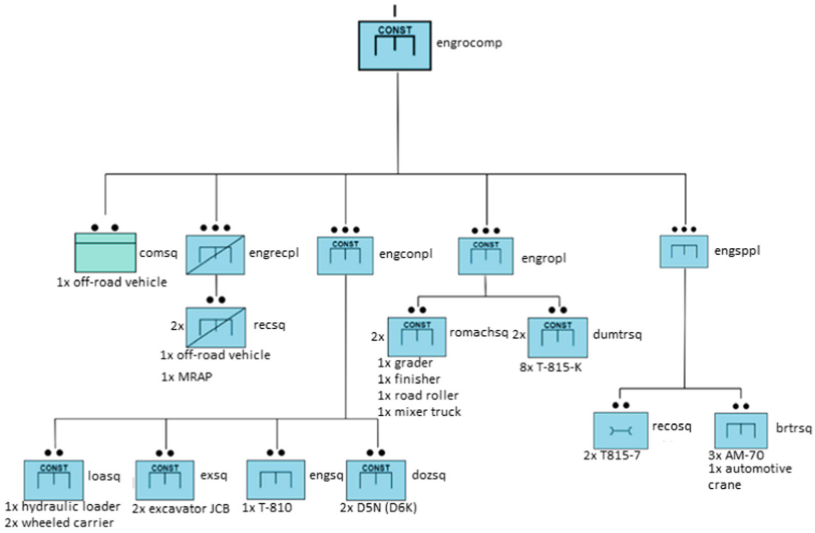


Fig. 2. Organisational structure of the proposed company [8].

The company's command squad should be equipped with a personal off-road vehicle and communications equipment for contact with higher echelons of command. The **reconnaissance platoon** should be equipped with an all-terrain personal vehicle and an MRAP vehicle. It should have engineer reconnaissance equipment such as rangefinder, crawler, telescopic and cone penetrometer. The **construction platoon** should be equipped with earthmoving equipment such as the JCB 4CX and a modern replacement for the KN-251, which is becoming obsolete. The **engineer road platoon** should be equipped with machines like the road squad of the engineer platoon of the general engineer support company. In addition, it should have road construction machines such as finisher, mixer truck or pneumatic rollers. The **engineer special platoon** should then be equipped with AM-70 bridge cars, the direct successor to the AM-50, a T-815-7 or T-815 AV15 recovery Tatra, or other wheeled recovery vehicle to provide the capability to extricate equipment being moved through our territory if it is not within the strength of the units that are part of the convoy. In addition, it should have an automotive crane and material for construction of auxiliary roads of the MOBI-MAT type and similar materials.

5 Proposal of Road Network Sections for Military Transport

The most suitable part of the Czech road network for military transport (therefore for movements within the HNS) are motorways and class I roads. Class I roads should be used mainly as diversionary routes for troop movements through our territory, rather than as directly designated routes for the movement of large numbers of troops. They are more easily blocked, leading to the prevention of traffic [9]. In the construction of the road network, the most important thing is to complete the motorway network according to the vision of the Directorate of Roads and Motorways. In that way it connects all

neighbouring countries by the shortest possible routes. The proposed corridors run along the route of the motorway network.

For the needs of military transport, the Czech motorway network would be divided into four sections (Fig. 3). The individual sections would be allocated and managed by a road unit. The sections are divided to Pilsen – Ceske Budejovice (350 km, red), Usti nad Labem – Hradec Kralove (300 km, blue), Prague – Breclav (300 km, green) and Brno – Ostrava – Pardubice (330 km, black).

Fig. 3. Proposed sections of the road network for military transport [8].

The Pilsen – Ceske Budejovice section (Fig. 4) consists of the D5 motorway (black; approx. 160 km), the D0 Prague ring road (green; approx. 30 km) and, depending on the speed of construction, would consist of the D4 motorway (blue; approx. 195 km) or the D3 motorway (red; approx. 160 km). If the D3 motorway is used for this section, the units passing through here would also have to use approximately 10 km of the D1 motorway (yellow; from the D0 exit to the exit at km 21). Approximately 95 km of motorway remain to be completed on the D3 section (shown in red in Fig. 4), while approximately 130 km of motorway remain to be completed on the section with D4. It should be noted, that the completion of the D3 motorway beyond Pisek to Ceske Budejovice is not part of the Directorate of Roads and Motorways' vision yet and therefore this option seems less likely. The unit tasked with managing this section would be located in Bechyne. If necessary, it would be advisable to locate the unit south of Prague, from where it would be able to react more quickly to situations arising in both directions of the corridor.

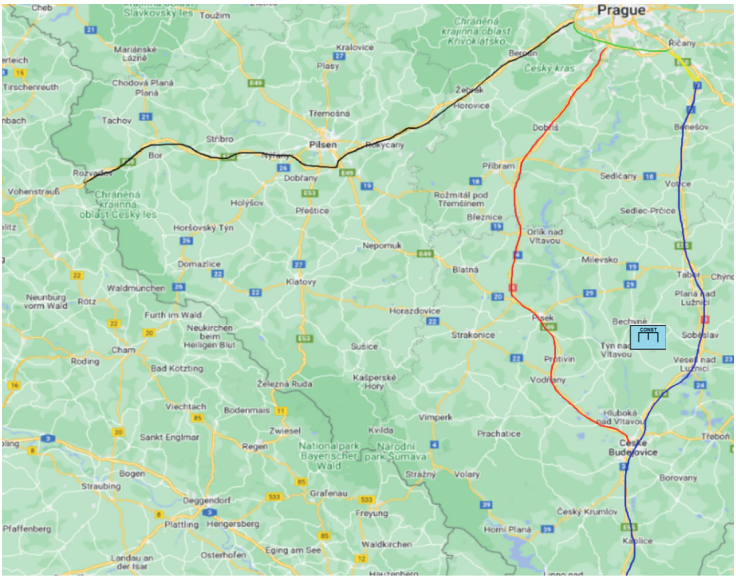


Fig. 4. Proposed section Pilsen – Ceske Budejovice [8].

The Usti nad Labem - Hradec Kralove section (Fig. 5) consists of the D8 motorway (black; approx. 100 km), a section of the D0 ring road (red), which is not completed at this location and would measure approx. 8 km, and the D11 motorway (blue; approx. 160 km). Approximately 45 km remain to be completed on the D11 motorway from Jaromer to the Polish border. The location of the company, if this segment is maintained, is best suited in the Podebrady area due to the ease of access to both directions of the corridor.

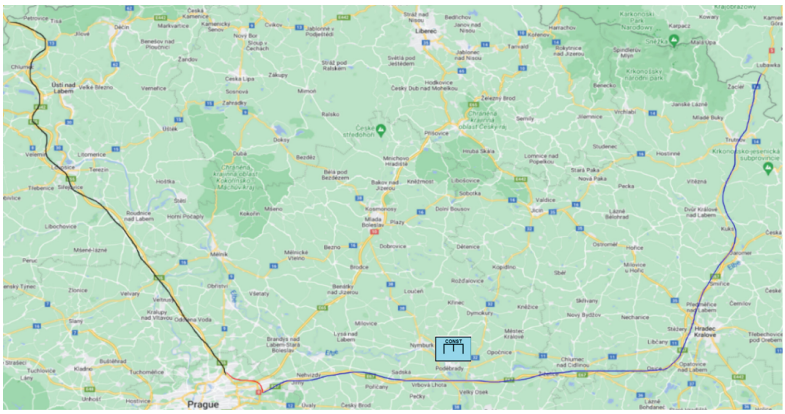


Fig. 5. Proposed section: Usti nad Labem – Hradec Kralove [8].

The Prague - Breclav section (Fig. 6) consists of the D1 motorway (black; approximately 190 km) and the D2 motorway (blue; approximately 60 km). The motorways are built in their entire length in this section and no further widening is needed. The location of the company in the area from Jihlava to Velke Mezirici is due to its location approximately in the middle of the section.

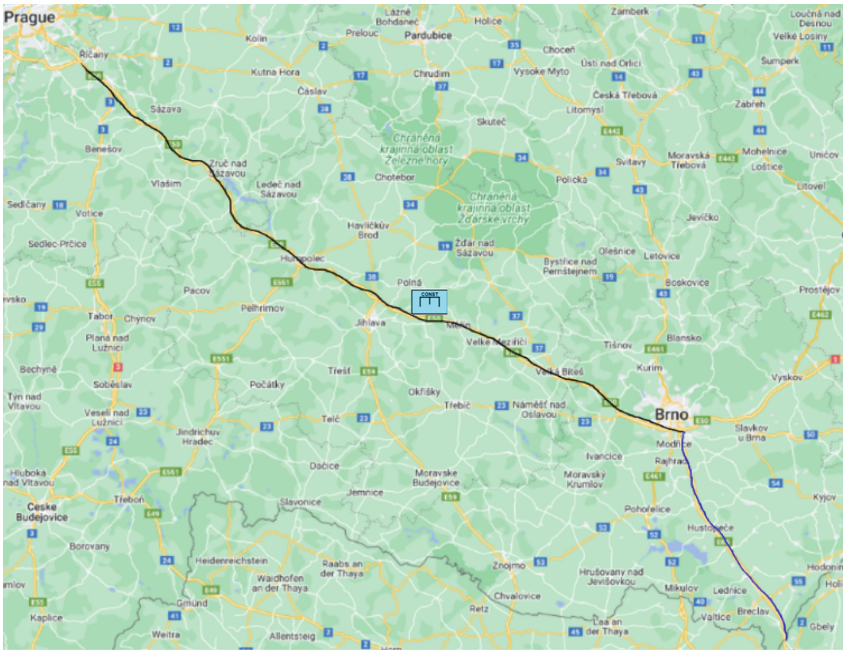


Fig. 6. Proposed section: Praha – Breclav [8].

The section Brno – Ostrava – Pardubice (Fig. 7) consists of the D1 motorway (blue; approx. 110 km), the D46 motorway (green; approx. 40 km) and the D35 motorway (black; approx. 175 km). Approximately 95 km of the D35 motorway still needs to be completed. If the section of the D1 motorway (approx. 10 km) near Prerov is completed, only this motorway could be used for access to Poland in some cases instead of the D46 motorway. This would mean extending the D1 section within this corridor by approximately 70 km (shown in red in Fig. 7). D1 would then be used instead of the D46 motorway section. The location of the company in case of maintaining this corridor is assumed to be directly in Olomouc.

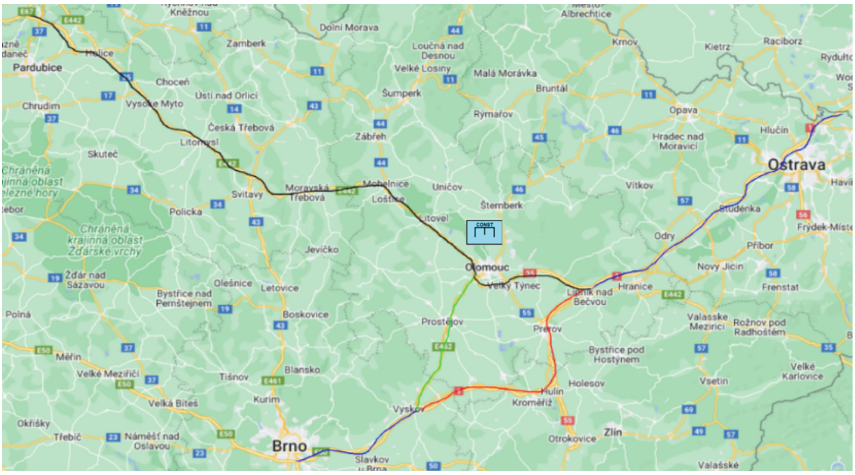


Fig. 7. Proposed section: Brno – Ostrava – Pardubice [8].

6 Conclusion

State security and the usage of tools to prevent or respond to crises mean an important approach to maintaining stability in region [10]. Joint military exercises can serve as an instrument of potential adversaries' deterrence. Speaking about international exercises, HNS plays an important role in movement and concentration of a larger number of forces in an area, which involves the maintenance and protection of critical infrastructure [11, 12].

In current state of the CAF, the engineer corps is equipped and ready to perform mobility support tasks, but its capabilities and options are outdated and its equipment in some cases does not meet the allies' requirements. This state is generally caused by military expenditures in most of the NATO countries which are lower the commitment to spend 2% of gross domestic product on defense [13, 14]. Engineer machine platoons of the combat engineer support company, the general engineer support company and engineer construction platoons of the general engineer support company are the most capable of supporting mobility on roads. They are equipped with construction assets.

According to the knowledge obtained from the officers of the engineer forces during the interviews, a unit that would perform the task of mobility support on the roads and would be suitable for both use within the HNS and for the units of the Czech Armed Forces was proposed. In the optimal case, four of these units would be predetermined on the four proposed sections of the road network intended for the transit of troops through the territory of the Czech Republic. The proposed road network sections have a total length of 1,300 km approximately. However, ca.320 km of highways remains to be completed on these sections.

By completing the above tasks, the aim of the paper was fulfilled. The unit proposal for mobility support within HNS and proposed sections of the road together with the locations of proposed unit could be used by engineer corps commanders as a guidance during the planning process. In the next research phase of the engineer support within

the HNS, other engineer roles should be assessed, namely survivability and counter mobility.

References

1. Cibulová, K.: Instruments used for terrain evaluation in the army of the Czech Republic. In: Kravcov, A., Cherepetskaya, E.B., Pospichal, V. (eds.) 21st INTERNATIONAL SCIENTIFIC CONFERENCE ON TRANSPORT MEANS, pp. 840–844. Kaunas University of Technology, Juodkrante, Lithuania (2017)
2. Foltin, P., Vlkovsky, M., Mazal, J., Husak, J., Brunclik, M.: Discrete event simulation in future military logistics applications and aspects. In: Mazal, J. (eds.) 4th International Conference on Modelling and Simulation for Autonomous Systems (MESAS), LNCS, vol. 10756, pp. 410–421. Springer, Cham (2018). https://doi.org/10.1007/978-3-319-76072-8_30
3. Kroupa, L., Doležel, L.: Ženijní vojsko: Historie a současnost. 1st edn. Ministerstvo obrany ČR - Agentura vojenských informací a služeb, Prague (2003)
4. Ročenka dopravy České republiky 2020. https://www.sydos.cz/cs/rocenka-2020/rocenka/htm_cz/index.html. Accessed 16 Dec 2021
5. Mapové podklady ředitelství silnic a dálnic. https://www.rsd.cz/web/guest/mapova-aplikace##/stavby?filters[]=StavbyRealizace
6. Zeleny, J., Porocak, L.: Organizace a použití jednotek ženijního vojska AČR, 1st edn. Univerzita obrany, Brno (2020)
7. Sedlacek, M., Zeleny, J.: Requirements for engineer information in water crossing. Vojenské Rozhledy-Czech Military Rev. **28**(4), 44–62 (2019)
8. Dologa, J.: Engineer Mobility Support of Troops in the Czech Republic as One of the Tasks of the Host Nation Support. University of Defence, Brno (2022)
9. Vlkovsky, M., Neubauer, J., Malisek, J., Michalek, J.: Improvement of road safety through appropriate cargo securing using outliers. Sustainability **13**(5), 2688 (2021)
10. Kompan, J., Hrnciar, M.: The security sector reform of the fragile state as a tool for conflict prevention. Politicke Vedy **24**(2), 87–107 (2021)
11. Manas, P.: The protection of critical infrastructure objects - technical principles. In: Kravcov, A., Cherepetskaya, E.B., Pospichal, V. (eds.) International Conference on Durability of Critical Infrastructure, Monitoring and Testing, LNME, pp. 1–13. Satov, Czech Republic, Springer, Singapore (2017). https://doi.org/10.1007/978-981-10-3247-9_27
12. Záleský, J., Palasiewicz, T.: Modelling of the force protection process automation in military engineering. In: Mazal, J. (ed.) MESAS 2018. LNCS, vol. 11472, pp. 599–613. Springer, Cham (2019). https://doi.org/10.1007/978-3-030-14984-0_45
13. Odehnal, J., Neubauer, J., Olejnicek, A., Boulaouad, J., Brizgalova, L.: Empirical analysis of military expenditures in NATO nations. Economies **9**(3), 107 (2021)
14. Odehnal, J., Neubauer, J.: Economic, security, and political determinants of military spending in NATO countries. Def. Peace Econ. **31**(5), 517–531 (2020)

Identification of Problem Areas of Traffic Flow Management and Solutions in Vilnius

Aldona Jarašūnienė and Gabrielė Žemaitytė(✉)

Vilnius Gediminas Technical University, Plytinės Str. 27, 10105 Vilnius, Lithuania
aldona.jarasuniene@vilniustech.lt, gabriezemaityte@gmail.com

Abstract. Nowadays, transportation is a globally powerful and significant and beneficial process for the whole world. Transport plays an important role in today's economy and society and has a large impact on growth and employment in Lithuania. With logistics industry the transport sector accounted for about 15% of GDP in 2019. At the beginning of 2021 this industry has been employing around 139 thousand persons or 15% of the total employment. 8.479 enterprises were active in the industry at the beginning of 2021 and 99% of them were small and medium-sized enterprises (SMEs) with 1–249 persons employed [1].

The article presents the analysis of the scientific literature on traffic flow management, identifies problem areas, analyzes the traffic flow management in Vil-nius city, presents the research, which identifies the problem areas of traffic flow management and suggests possible solutions.

Keywords: Transport · Vehicles · Traffic flow · Traffic management · ITS · Congestion · Environment · Air pollution

1 Introduction

Each of us uses transport to go about our daily activities – to work, to home, to supermarkets, to medical facilities, and so on. We have possibility to travel by private transport, such as a car, bicycle, scooter or public transport. Appropriate regulation of transport movements is also necessary for the proper functioning and smooth operation of the transport system. Traffic must run smoothly and safely and must not pollute the environment. The focus needs to be on the regulation of urban transport, as there is a high density of people here. Understandably, traffic flows are extremely high, which can make traffic regulation tight and a daily challenge. It is important to emphasize the need for analysis and research into problem areas in traffic management. Improving road traffic management is crucial for the well-being of the population. It is essential to maximize both traffic flow and safety and environmental friendliness, which is a global goal.

Investigation problem. What are the problem areas of traffic flow management and what are the possible ways to solve them in the city of Vilnius.

The object of the study is the problem areas of traffic flow management.

The purpose of the study is to identify problematic areas of traffic flow management, analyze them and propose appropriate solutions.

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 502–509, 2023.
https://doi.org/10.1007/978-3-031-25863-3_47

Tasks set to achieve the goal:

1. Carry out a literary analysis of the concept of traffic flows, parameters describing traffic flows, flow management and problem areas and their solution methods.
2. To carry out a study aimed at identifying problem areas of traffic flows and ways of solving them in the city of Vilnius.
3. To propose a project aimed at solving the identified problem areas of traffic management in the city of Vilnius.

Because of the ITS importance to traffic management at Vilnius city, it is possible to make a hypothesis, that improvement of traffic flow management measures will help to reduce congestion and the time spent there.

2 Literature Analysis

The concept of traffic flow can be defined as the number of vehicles moving in one direction. Traffic intensity, traffic density, speed, traffic flow structure, dynamic gauge, roadway conductivity, single-lane conductivity, pedestrian traffic speed, pedestrian traffic intensity, pedestrian traffic density are the parameters that characterize traffic flow on streets and intersections, and throughout the city. In order to carry out organizational projects, it is very important to rely on their meanings [2].

Traffic management is essential to ensure the smoothness and safety of transport traffic. Traffic management is carried out through ITS, which aims to prevent congestion and improve overall traffic efficiency. ITS (TMS – traffic management system) collects data related to traffic and its traffic and sends information to the traffic management center (TMC – traffic management center) [3]. ITS have been developed to reduce the negative economic, health and environmental impacts of congestion [4]. In fact, ITS can improve safety, traffic efficiency and environmental friendliness.

According to Li et al. [5] analysis, it is projected that by 2050. 70 percent population will live in cities, which increase the burden on infrastructure and transport systems. Traffic congestion is said to be among the growing problems that will be inevitable on an ongoing basis. In addition, congested traffic has been found to be approximately six times more likely to occur than free traffic [6].

According to a study conducted by INRIX Global Traffic Scorecard, a world leader in analytics, in 2019. Congestion cost the UK economy £ 6.9 bn. The busiest city in the UK was London, where drivers lost 149 h [7]. In order to get the most efficient traffic flow, it is necessary to understand and analyze the causes of congestion.

According to Afrin & Yodo [8], congestion can be divided into two types: typical and atypical. Typical congestion is repetitive and occurs at certain times, in certain places. Such congestion is due to an increase in the number of vehicles, for example, when everyone commutes to work in the morning. These congestions can be reduced by appropriate traffic management measures. Meanwhile, atypical – is formed randomly and unexpectedly. Such congestion is difficult to predict and assess their course.

According to de Souza et al. [3] and Nellore & Hancke [9], the main causes of congestion are traffic-related events such as traffic accidents (25%), road works (10%), adverse weather conditions (15%); traffic demand and transport infrastructure (40%). Congestion is also caused by interference with traffic management equipment or poor management of traffic flows (5%).

High traffic flows also harm the environment, increasing air pollution [10]. Air pollution has been around for quite some time, back in 2,000 transport has been reported to be recognized as a growing source of air pollution [11]. Air pollution causes damage to nature and climate change, as evidenced by the onset of global warming and various human illnesses. Long-term effects have been reported to be associated with air pollution, including chronic asthma, pulmonary insufficiency, cardiovascular disease, and increased mortality [12]. Every state must fight this problem in the interests of the population and nature, because air pollution is not a problem of one city or state – pollutants are in any case dispersed in the air and travel to the atmosphere, thus polluting the air quality of other parts of the world.

It is argued that air pollution from transport depends on the type of motor fuel, and the most popular fuels – diesel and its vehicles – cause the most air pollution [13]. The aim is to create the conditions for the abandonment of diesel cars. To achieve this, taxes are applied to the car's pollution. Diesel car pollution taxes are at least 2.5 times higher than those fueled with gasoline or gas [14]. Air pollution is also determined by the age of the vehicles involved in the traffic flow. The newer the vehicle, the more environmentally friendly and less likely it is to be harmful to the environment. Older cars are said to be a threat to both air pollution and the environment taken as a whole. Faults such as leakage of liquids or excessive emission of harmful gases are serious problems during the technical inspection [15].

The public's desire to use their own transport is proved by the fact that light vehicles provide an opportunity to be independent of the current level of service [16]. It can be argued that it is for this reason that cars have an advantage over other vehicles, as the person using them is independent of time, place and other aspects that are, for example, inevitable when using public transport [17].

According to R. Barusevičiūtė's [18] research aimed at finding out the possibilities of traffic congestion and their elimination, it has been noticed that the following ways to reduce congestion are distinguished: infrastructure improvement, traffic management systems, public transport improvement, ride-sharing system, traffic lane improving the use of high occupancy vehicles (HOVs) and cycling.

According to the Green Paper published by the European Commission, which sets out the main objectives for the development of urban transport systems and the possible means of achieving them, the following methods of reducing congestion can be identified [19]. Alternative transport methods increasing the attractiveness of public transport, bicycles, car-sharing, parking and driving systems; deployment of smart technologies; parking fees; improving the interoperability of different systems.

Nowadays, one of the alternatives to reduce air pollution is the use of electric cars. Over the past decade, global demand for electric cars has increased due to significant reductions in oil consumption, lower carbon emissions, reduction of air pollution, and economic benefits [20].

Thus, in order to avoid the problem of congestion, it is expedient to improve the infrastructure, traffic management systems, public transport, and to promote alternative transport methods. In order to reduce air pollution, it is recommended to choose electric cars and other modes of transport instead of conventional fuel cars.

3 Methodology, Research Results and Solutions

Detailed analysis of transport traffic flows and their management statistics, survey, SWOT analysis, forecasting method were performed.

In order to find out the problem areas of traffic management, their causes and solutions, an expert survey was conducted. According to Kardelis [21], the survey is a wide-spread research method in the social sciences, and according to R. Tidikis [22], the expert evaluation method is a specific type of survey of a specially selected group of people who know a certain field, and interview principles. Respondents must be competent persons with knowledge of the field of study and experience, as evidenced by their position, degree or seniority [22]. Based on the recommendations that the number of respondents usually consists of 5–7 people, seven respondents participated in the survey – experienced traffic flow management experts/specialists, i.e. managers and chief. Professionals with at least 5 years of experience in the field. The survey was compiled on the basis of the recommendations of the scientific literature, the method of the questionnaire survey was chosen to obtain information, and both closed and open-ended questions were formulated.

Summarizing the results of the SWOT analysis, it can be stated that various flow management measures are applied in Vilnius.

It has been clarified that traffic in Vilnius is characterized by high intensity, it is unevenly distributed and depends on the time of day or year. ITS is used to manage urban traffic flows, consisting of: traffic light, traffic monitoring, information board and fault recording device systems.

The aim of the proposal is the development of traffic flow management measures in order to reduce congestion in Vilnius. The measures chosen to achieve this goal are:

1. Improvement of traffic lights at uncoordinated management, as it was found that almost 32% (31.79%) Vilnius city intersections have uncoordinated management, therefore, with the installation of additional equipment and their becoming coordinated management, the traffic in the apartments would be regulated in real time;
2. Development of a traffic monitoring system, as the analysis showed that almost 40% (39.37%) Vilnius city traffic surveillance cameras are without a control function, in order to more efficient traffic monitoring, it was chosen to replace the existing cam-eras and install additional ones.

The tender activities are divided into 8 stages: preparation and submission of the tender to the Municipality of Vilnius City, approval, EU funding, public procurement, purchase of equipment, installation works, testing of the equipment, closure of the project. The main contractors are the customer, SĮ "Susisiekimo paslaugos", Vilnius City Municipality and a contractor company. The resources of the tender include human resources (20

employees: engineers, traffic flow analyst, chief operator, managers, lawyer, accountant, public procurement specialists, Municipality of Vilnius City and contractors), financial (EUR 786,877) and time resources (56 weeks). Risks such as lack of time and financial resources, managerial and technological. An economic evaluation has been carried out and forecasts have been made to save time and create added value over the year. It is taken into account that people in particular have purchasing power. They have their money at their disposal to buy certain goods for them, and time is of the essence. Thus, a minimum cost forecast is made to find out how much one person is affected by one minute in congestion and what would change if congestion were reduced by at least one minute (Table 1):

Table 1. Forecast of time congestion and lost value added per person.

	During the working day		During the year	
	Now	Forecast	Now	Forecast
Time in traffic jams	30 min	29 min	125 h	120.8 h
Added value	1 €	0.97 €	250 €	241.67 €

Source: Compiled by the authors.

As the problem of congestion mainly affects working people on weekdays, as they are most often exposed to the phenomenon of peak hours, the number of days chosen for the calculation of the forecast is equal to the approximate number of working days per year, i.e. 250 working days. Assuming that a person can create added value by spending € 1 in 30 min and does not do so because they spend that time in traffic jams, reducing the congestion time by at least 1 min would reduce the value added lost to € 0.97. This means that the value added generated in a forecast would be € 0.03 per minute. As a result, the time a person spends in congestion per year would be reduced by 4.2 h, potentially creating € 8.33 added value.

In 2021, 310 thousand people worked in Vilnius City Municipality population. The number of cars registered in Vilnius reached about 350 thousand. Assuming that only half of these cars (i.e. 175,000) were used for a daily commute to work and spend at least 30 min a day in traffic jams, we estimate that Vilnius may have lost almost 22 million hours a year (Table 2):

Table 2. Forecast of time congestion and lost value added.

	During the working day		During the year	
	Now	Forecast	Now	Forecast
Time in traffic jams	87,500 h	84,583 h	21,875,000 h	21,145,833 h
Added value	175,000 €	169,166,67 €	43,750,000 €	42,291,666 €

Source: Compiled by the authors.

Estimates show that 175 thousand the added value of employees spending 30 min every day in traffic jams in Vilnius is almost 44 million €. It is estimated that a reduction in congestion of at least 1 min would reduce lost value added to € 42,291,666 per year, resulting in an overall result of € 1,458,334 million € value added per year.

Thus, reducing congestion by at least 1 min would save 4.2 h per person per year. In total, at least 729,167 h would be saved in Vilnius and € 8.33 of added value would be created. In total, at least 1,458,334 € million added value would be created in per year.

Results of the project: 60 units installed new traffic surveillance cameras with control function, and 96 pcs. The intersections of uncoordinated control were transformed into coordinated control by installing sensors (384 units), which would result in lower time and financial costs for traffic participants. So the hypothesis, which was formulated, has been confirmed.

4 Conclusions

1. Based on the analysis of the scientific literature, it has been established that the flow of traffic depends on many aspects, which in turn leads to a corresponding increase in traffic density and congestion, which can be divided into two types: typical (repetitive) and atypical (unexpected) and depends on certain traffic incidents or infra-structure characteristics. Another global problem closely linked to congestion is air pollution. It affects both nature and humanity because air pollution causes various diseases. The amount of air pollution is also determined by the type of fuel, diesel is one of the most polluting.
2. The analysis of traffic management in Vilnius city revealed that traffic in the city is characterized by high intensity, which is unevenly distributed and depends on the time of day or even the time of year. The ITS used for the management of urban traffic flows consists of: traffic light system, traffic monitoring system, information boards, violation recording devices. These tools collect information that is provided to the Traffic Management Center.
3. The research – an expert survey – showed that the weak areas of traffic management in Vilnius are traffic lights and traffic monitoring systems.
4. A proposal for the development of traffic light control and traffic monitoring systems has been submitted for troubleshooting. The tender process consists of 8 stages, and the main executors of the project are three – the customer, SĮ "Susisiekimo paslaugos", Vilnius City Municipality and a contractor company. The total financial cost of the project will be € 786,877, of which equipment will cost € 584,000, installation work € 80,000, staff salaries € 112,877 and the remaining € 10,000 for unforeseen costs. 20 employees will work on the project – engineers, traffic flow analyst, operator, managers, lawyer, accountant, procurement specialists and contractors. A total of 56 weeks were spent on the project.
5. Based on the assumption that reducing congestion would allow more time for other activities, such as sports, leading to a 5% improvement in the health of the population and lower budget costs, potential savings of € 42 million could be achieved. €.

6. It is estimated that reducing the time spent in congestion by at least 1 min would create at least 1,458,334 million € value added per year, saving 729,167 h per year (take 175 thousand employed population). The proposed hypothesis was successfully confirmed.

References

1. Enterprise Lithuania Transport and logistics (NACE H49-H53). Overview, Vilnius, Lithuania (2021). https://www.enterpriselithuania.com/wp-content/uploads/2021/05/Overview-of-Lithuanian-Transport-and-Logistics-Industry.pdf
2. Paliulis, G.-M.: Traffic Engineering [Eismo inžinerija]. Technika, Vilnius (2007). (in Lithuanian). https://doi.org/10.3846/955-S
3. de Souza, A.M., Brennand, C.A.R.L., Yokoyama, R.S., Donato, E.A., Madeira, E.R.M., Villas, L.A.: Traffic management systems: a classification, review, challenges, and future perspectives. Int. J. Distrib. Sens. Netw. **13**(4), 1–14 (2017). https://doi.org/10.1177/1550147716683612
4. Bui, K.-H., Camacho, D., Jung, J.E.: Real-time traffic flow management based on inter-object communication: a case study at intersection. Mobile Netw. Appl. **22**(4), 613–624 (2017). https://doi.org/10.1007/s11036-016-0800-y
5. Li, G., et al.: Influence of traffic congestion on driver behavior in post-congestion driving. Accid. Anal. Prev. **141**, 105508 (2020). https://doi.org/10.1016/j.aap.2020.105508
6. Zheng, Z.: Empirical analysis on relationship between traffic conditions and crash occurrences. Procedia Soc. Behav. Sci. **43**, 302–312 (2012). https://doi.org/10.1016/j.sbspro.2012.04.103
7. INRIX Global Traffic Scorecard: Congestion cost UK economy £6.9 billion in 2019 (2020). INRIX: https://inrix.com/press-releases/2019-traffic-scorecard-uk/
8. Afrin, T., Yodo, N.: A survey of road traffic congestion measures towards a sustainable and resilient transportation system. Sustainability **12**(11), 4660 (2020). https://doi.org/10.3390/su12114660
9. Nellore, K., Hancke, G.P.: A survey on urban traffic management system using wireless sensor networks. MDPI AG. Sensors **16**(2), 157 (2016). https://doi.org/10.3390/s16020157
10. Bigazzi, A.Y., Figliozzi, M.A., Clifton, K.J.: Traffic congestion and air pollution exposure for motorists: comparing exposure duration and intensity. Int. J. Sustain. Transp. **9**(7), 443–456 (2015). https://doi.org/10.1080/15568318.2013.805345
11. Colvile, R.N., Hutchinson, E.J., Mindell, J.S., Warren, R.A.: The transport sector as a source of air pollution. Millennium review for submission to atmospheric environment. Atmos. Environ. **35**(9), 1537–1565 (2000). https://discovery.ucl.ac.uk/id/eprint/894/1/Millennium_rvw_final_october.pdf
12. Manisalidis, I., Stavropoulou, E., Stavropoulos, A., Bezirtzoglou, E.: Environmental and health impacts of air pollution: a review. Front. Public Health **8**, 14 (2020). https://doi.org/10.3389/fpubh.2020.00014
13. Uzuntonev, T., Penchev, B.: Impact of road transport on the pollution of ambient air with particulate matter. IOP Conf. Ser. Mater. Sci. Eng. **614**(1), 012016 (2019). https://doi.org/10.1088/1757-899X/614/1/012016
14. Gedgaudas, A., Jokubynienė, V.: Change of polluting cars in Lithuania [Taršių automobilių kaita Lietuvoje]. Klaipeda State College [Klaipėdos valstybinė kolegija], Klaipėda (2020). (in Lithuanian)

15. Glėbus, A.: Leaders of the Lithuanian car fleet through the eyes of technical inspectors [Lietuvos automobilių parko lyderiai techninės apžiūros kontrolierių akimis]. Lithuanian Association of Technical Inspection Companies "Transeksta" [Lietuvos techninės apžiūros įmonių asociacija „Transeksta"], Vilnius (2017). (in Lithuanian). https://www.vta.lt/lietuvos-automobiliu-parko-lyderiai-technines-apziuros-kontrolieriu-akimis/
16. Racevičė, D.: The influence of the southern and western fast-traffic street on vehicle flows in the city of Vilnius. Master thesis. [Pietinės ir vakarinės greitojo eismo gatvių įtaka transporto srautams Vilniaus mieste. Magistro baigiamasis darbas]. Vilnius (2008). (in Lithuanian)
17. Jarašūnienė, A., Česnulaitis, D.: Improving the efficiency of the Vilnius city transport system in the context of sustainable mobility and multimodality. Baltic J. Road Bridge Eng. **16**(3), 31–46 (2021). https://doi.org/10.7250/bjrbe.2021-16.531
18. Barusevičiūtė, R.: Research of traffic jams and their elimination possibilities in Vilnius. Master thesis [Transporto spūsčių ir jų pašalinimo galimybių Vilniaus mieste tyrimas. Magistro baigiamasis darbas]. Vilnius Gediminas Technical University, Vilnius (2010). http://vddb.laba.lt/obj/LT-eLABa-0001:E.02~2010~D_20100618_192545-12255
19. KOM (2007) 551: A new culture of urban mobility [Nauja mobilumo mieste kultūra]. Europos Komisija, EK, September 2007
20. Sharma, S., Panwar, A.K., Tripathi, M.M.: Storage technologies for electric vehicles. J. Traffic Transp. Eng. **7**(3), 340–361 (2020). https://doi.org/10.1016/j.jtte.2020.04.004
21. Kardelis, K.: Research Methodology and Methods [Mokslinių tyrimų metodologija ir metodai]. Science and Encyclopedia Publishing Center [Mokslo ir enciklopedijų leidybos centras], Vilnius (2016). (in Lithuanian)
22. Tidikis, R.: Methodology of Social Sciences Research. Publishing Centre of the Law University of Lithuania, Vilnius (2003). MRU.https://repository.mruni.eu/handle/007/15459

The Role of East Asia in Current Issues Focus on Value Chain Management of Logistics and Transport Market

Veslav Kuranovič(✉)

Vilnius Gediminas Technical University, 10223 Vilnius, Lithuania
veslav.kuranovic@vilniustech.lt

Abstract. Character of China modern supply chain circumstance accentuated, essential value logistics features outlined. Principally the main attention in research issues are focused on concept of empirical analysis of China logistics value, the criteria for evaluation the technological development supply chain management and economic impact assessment for a dynamic system, compilation of a survey questionnaire procurement processes specialists, identification respondents groups, monitoring SWOT and PESTL analysis production chain process, investigation analysis distribution systems documents, mathematical statistical study value chain MANOVA research and evaluation of logistics management strategic business trends. Findings and contribution of this article presented, outlined that East Asia value chain transportation management in the supply chain transportation system is very important topic for future research analysis. It is found that value chain transportation management is a flexible and in high level organized in their different logistics processes.

Keywords: Value chain · Supply chain · Logistics management · Logistics market · SWOT · PESTL · MANOVA research

1 Introduction

The logistics sector has a significant role in facilitating trade, reducing transport costs and stimulating economic growth [1]. Contemporary universe community is outlined by accelerated legislative, financial, communal and high-tech transformations, the East Asian transportation, logistics and supply chain wholesale is enhancing progressively pleasant to external shareholders, numerous essential then the global retail element. Regarding the specific channels of global value chain improvement, most scholars hold that international trade and international investment are the main ways to realize the integration of industries into global value chains and promote industrial upgrading [7]. After all, logistics organization in China transportation commerce besides closes a advanced, international universe-precept channel bounded by high tech, supply chain, trade and tradition. Therefore, to produce win-win solutions that facilitate both economic benefits and environmental sustainability simultaneously, firms have begun to place great emphasis

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 510–517, 2023.
https://doi.org/10.1007/978-3-031-25863-3_48

on innovation, especially environmental innovation capability [10]. Accepted to accordingly seize priority particulars China relocation and supply chain entity organization and the profitable instituting and advancement of assistance bounded by European countries and another localities with this wholesale place, it is urgently to handle a research of China recent logistics organization. Over time, scholars and business leaders have found that culture in an organization is a key competency that brings greater efficiency, differentiation between companies, and competitive advantage [13]. In this entryway, advanced vital elucidation of transportation merchandises application could be established, whatever associates the distinct of transportation organization in China supply chain retail with global trade, international business, technical, commercial and traditional relations. As a high proportion of today's world trade is characterized by the vertical specialization at different stages of production across countries, one country's export would require increased labor inputs at upstream and downstream along the global value chain process [4].

The scientific article projects to assess the current transportation and supply chain organization automation approaches, noticing logistics problems, grounded on leading analysis in the background of collaboration with the China logistics loads.

It is a part of adding value, which is included into strategic management and decisions through transport logistics [11]. The scientific article seeks for applied clarifications respecting to the individuals keys of transport organization in China logistics and supply chain to evaluate the negotiating capacity in worldwide trade debates, collective character, logistics organization procedures and considering the open background of global and regional trade advancement in China transportation and behind. Logistics is a basic activity in the context of value chain [9]. Explanation of the issue, transport corridors are very prominent segment of the country trade, logistics, supply chain and transportation-associated firms cause an extensive proportion of trade world place. Collaboration with the China economy is enhancing progressively prominent in the global background, with the China sale place and synergism with other countries performing progressively main task. This is vital for guiding transfer couloirs and transport loads, for the main countries of Europe. Contemporary global community is identified by quick trade, finance, business and high tech diversity, China transportation, logistics and supply chain is graceful with acceleration alluring to outside shareholders, critical then the global playing element. After all, transportation organization in China supply chain system as well as measures an advanced, international universe-imposed tie among technology, supply chain, country economy and tradition. By the way, modern mode of supply chain activity could be constructed, whichever merges the particulars of logistics organization in China supply chain transportation system with worldwide commercial loads negotiations. It addressed that logistics activities are subject to culturally influenced preferences prevalent across the globe, especially the general influences such as timeliness and responsiveness [8].

The scientific article proposes to assess the current supply chain and logistics tech science tactics, appreciating logistics value and its issues, grounded on set analysis with China logistics issues. Aim of the presentation, is to research the unequivocal of China supply chain organization to evaluate the impingement of the features of logistics mutual cooperation in loads system. Demonstration of the object is to present East Asia value

chain and supply chain main issues in transportation logistics market. Display of the tasks are to analyze theoretical aspects of global value and supply chains and logistics; to analyze concepts of global value and supply chain and logistics governance; to provide a methodology of empirical analysis for a logistics; to analyze activities of SWOT, PEST and MANOVA in global logistics and in transport system; to evaluate the efficiency of logistics issues solutions in global value and supply chain. Conferral of the issues to investigate the role of logistics in global value and supply chain based on a study case of SWOT, PEST and MANOVA analysis. In general, the qualitative and quantitative approach is used.

1.1 Transportation Loads Literature Analysis and the Essential Key Issue in Transport Market

East Asia corporate reputation and value chain management in logistics transport value Guanxi market 30 years or more also understood a transfiguration a Mao Ze Dong planning economy decentralized as a consequence Den Xiao Ping market economy, the priority accorded to industry stunted services development—particularly in productivity terms—while the emphasis on physical investment con-strained investment in human capital [2]. Commonly, supply chain and value chain management fuses worldwide loads transportation. Supply chain as the management of business processes or activities associated with coordination and there are linkages in the supply chain network [3]. Supply chain management formation affiliating essential problem of loads obligation for dealing unimportant and dominant transportation firms for composing elevated-condition logistics loads shipment standards. In area to promote this vast embodiment of firm, it is comprehendible demanded more guidance that pickled in the universal firms. The proper supply chain management is a process that reduces costs and increases the competitiveness of the company [6]. Three decades or more of fast extension and constructional change have reconsidered China's attitude in the international economy. The problem formulation is follow, the misunderstand in the global business and trade value chain and supply chain negotiations on international level by transportation loads from and to East Asia region.

1.2 Methodology of China Guanxi Aspects of Supply Chain and Value Chain Stands Conducive to Building Form of Companies on Logistics Market

China is an approaching economics that attempts many possibilities for contribution essentially in supply chain and value chain domain. Despite China has a enormous capability for trade expansion biding approach to a huge marketplace and prominent accumulations in employment outlays, discretion should be valued by cause of variations in the economical climate that generate danger and act ambiguity for stockholders (Tables 1 and 2).

Table 1. Guanxi SWOT analysis.

Guanxi strengths:	Authority heavy platform; Legitimate scheme pellucidity; Imposts duties translucent and effective; Country place position universe chic; Transoceanic and transpacific transactions chain acutely forceful; Tariff structure plain and inferior; Info tech/monetary reinforcement especial steady;
Guanxi weaknesses:	Performing expenses inferior; Bounded know-how for marketing advancement elsewhere; Non-fiscal peril organization potentialities in organization integrated accession; The inquiry for performance in transportation supply chains; Stash house and dissemination logistics terminals not recognized settlement; Shortage of achievement organization abilities;
Guanxi opportunities:	Bureaucratic balance actually substantial; Goods merger supply chains interest; Extended framework development on leading technological proposals; Local community transportability expanding; Dispersion of advanced e-maintenances;
Guanxi threats:	European-Sino interconnection foresight; Counteraction in distinction to alternative tournament axis no more prompt; Chinese national currency assessment plunging supply chain interest; Recent employment regulations no either important; Work source capturing strenuous;

Table 2. Guanxi PESTL analysis.

Guanxi politics:	Fluctuation and its supremacy customs criteria and regulations; Risky constitutional circumstances to remake extensive assets; Trade and authority inferior formation of project for country computerized marketing;
Guanxi law:	There no presented some customs promoting concealment, client freedoms and automated autograph; There no conferred obligatory juridical demand to open right trade;
Guanxi economics:	Up the anterior five periods, Chinese world biggest economics sophisticated impressive much expressive inflation and deflation range flowering quota then in previous decades; The marketplace has opened to consider that the fundamental fund could instantly promote dividends charges;

(*continued*)

Table 2. (*continued*)

Guanxi social:	The civil, artistic and historic is a essential issue sector of Chinese life is performing an main character in the process of the regionalization population permanently transformation; Clients purchasing conduct person to person cost communal intercommunication; Chinese rules basement is communalistic courtesy and Confucius familiar axioms;
Guanxi technological:	Recent merchandises alternating at rest in advanced approach and envelops the exhaustive course of collecting last artery to the marketplace; Top 10 technical articles manufacturing counting 3D and dissemination industrial pulpits;

In the fierce competition, the goal of the logistics service demand side is to obtain the most satisfactory logistics service at the lowest cost, and the goal of the logistics service supply side is to obtain the satisfaction of the logistics demand side while obtaining relatively high profits [12]. The problems areas are clearly identified after done SWOT and PEST analysis, it could be solved on the proposed methodology, stresses the importance of the integrity of the supply chain, is the how valuable marketing strategy in global value chain with study case on international logistics company is explained. As can be stated theoretically and found on empirical investigations on logistics companies.

1.3 Research and Results Based on China Customers Are Operated by Value Chain in Their Acquisition Outcomes

Investigation disserved the case society applying a primary survey that encompass locked concluded inquests and valuation ratio query to assemble facts. To schema outline in position are engaged in a trade intervention accord as delegate of present firm with outlander, in which way resolutely concur with the next issues. Sample present intervention modes, methods, and conduct of traders (Table 3).

Table 3. Between – subjects factors cities and respondents.

City	N
1.0	20
2.0	20
3.0	20
4.0	20
5.0	20

Different 5 cities and 100 respondents in total.

Table 4. Expressive data.

	City	Mean	Std. deviation	N
Q1	1.0	4.300	1.0809	20
	2.0	4.100	0.8522	20
	3.0	3.700	1.0809	20
	4.0	2.250	1.2513	20
	5.0	2.950	1.3169	20
	Total	3.460	1.3440	100
Q2	1.0	3.850	0.9881	20
	2.0	4.000	0.7255	20
	3.0	3.600	0.9947	20
	4.0	2.500	1.6059	20
	5.0	2.800	1.0563	20
	Total	3.350	1.2421	100
Q3	1.0	3.600	1.3917	20
	2.0	3.400	1.0463	20
	3.0	3.400	1.0954	20
	4.0	2.250	1.4464	20
	5.0	2.800	1.1050	20
	Total	3.090	1.3034	100
Q4	1.0	4.500	0.5130	20
	2.0	3.200	1.1050	20
	3.0	3.500	1.0513	20
	4.0	2.250	1.4824	20
	5.0	2.850	1.2258	20
	Total	3.260	1.3305	100
Q5	1.0	4.750	0.4443	20
	2.0	3.550	0.8256	20
	3.0	3.850	0.9333	20
	4.0	2.350	1.5313	20
	5.0	2.600	1.2312	20
	Total	3.420	1.3572	100

Main 5 questions for every city and every respondent (Table 4).

Table 5. Variables investigation.

Effect		Value	F	Hypothesis df	Error df	Sig
Intercept	Pillai's trace	0.998	460,515[b]	55,000	41,000	0.000
	Wilks' lambda	0.002	460,515[b]	55,000	41,000	0.000
	Hotelling's trace	617,764	460,515[b]	55,000	41,000	0.000
	Roy's largest root	617,764	460,515[b]	55,000	41,000	0.000
City	Pillai's trace	2,968	2,300	220,000	176,000	0.000
	Wilks' lambda	0,002	2,812	220,000	166,488	0.000
	Hotelling's trace	20,231	3,632	220,000	158,000	0.000
	Roy's largest root	12,859	10,287[c]	55,000	44,000	0.000

Relation between intercept and city (Table 5).

It is important to carry out this research, it is purpose which extends this analysis by taking into account multiple continuous dependent variables, and bundles them together into a weighted linear combination or composite variable and essentially tests whether or not the independent grouping variable simultaneously explains a statistically significant amount of variance in the dependent variable. The obtained result assumes that the observations are independent of one another, there is not any pattern for the selection of the sample, and that the sample is completely random, demonstrating that the problems value chain and supply chain are solved, the dependent variables cannot be too correlated to each other. It suggest that no correlation should be above $r = 0.90$.

2 Conclusions and Directions for Further Empirical Research Needs

The issue and purpose of scientific article is distinctly characterized to advance with empirical research section of scientific analysis source problem. It is displayed a certain the field of available analysis of China supply chain and value chain organization marketplace, scientific investigation of that category envelopes an ample spectrum of essential globules and essential orders. Present-day position in China value chain and supply chain organization along with loads transportation grounds of that position are presented in this scientific article. It is presented that China transportation marketplace decision taking philosophy based on guanxi approach, essential business traditional business cultural features for the global lifestyle flourishing and emerged meanwhile years. The empirical analysis reveals that East Asia value chain and logistics market management in the supply chain transportation system is very important topic for future research analysis. These value chains and goods transportation implement capital to a greater degree of conjectural convolution, beneficence and logistics market vitality. Scientific article analysis attempts perceptivities toward the beliefs to logistics and value chains among

another internal, independent logistics market transportation aspects. Scientific article theoretical and empirical results indicate that international logistics companies must emphasize the importance of business culture. Knowledge of the global value chain and keeps the supply chain's costs in transport market. This research is crucial for success in the value chain management, response the value of an international loads transportation and business relations negotiations. Methodology of research for a logistics transport market achieved study of value chain and supply chain to observe an international logistics market internally and externally for SWOT, PEST and MANOVA analysis. Based on these conclusions, practitioners should consider in this immense global value chain field to uncover all success variables in this study due to the fact that the value chain approach comprises several challenges. Further research is needed to determine the causes of effects on the value chain and supply chain of relationships between East Asia and other world countries.

References

1. Bugarčić, Z., Skvarciany, V., Stanišić, N.: Logistics performance index in international trade: case of central and Eastern European and Western Balkans countries. Bus. Theory Pract. **21**(2), 452–459 (2020). https://doi.org/10.3846/btp.2020.12802
2. Craig, R.C., Easton, P.L.: Sustainable supply chain management: evolution and future directions. Int. J. Phys. Distrib. Logist. Manag. **41**(1), 46–62 (2011)
3. Guijun, L., Wang, F., Pei, J.: Global value chain perspective of US–China trade and employment. World Econ. **41**(8), 1941–1964 (2018). https://doi.org/10.1111/twec.12545
4. Jain, J., Dangayach, G.S., Agarwal, G., Banerjee, S.: Supply chain management: literature review and some issues. J. Stud. Manuf. **1**(1), 11–25 (2011)
5. Kumar, V., Fantazy, K.A., Kumar, U., Boyle, T.A.: Implementation and management framework for supply chain flexibility. J. Enterp. Inf. Manag. **19**(3), 303–319 (2006)
6. Lambert, D.M., Cooper, M.C., Pagh, J.D.: Supply chain management: implementation and research opportunities. Int. J. Logistics Manage. **9**(2), 1–19 (1998)
7. Lichun, X., et al.: Advances in the global value chain of the shipping industry. J. Coast. Res. **106**, 468–472 (2020). https://doi.org/10.2112/SI106-105.1
8. Mentzer, J.T., Myers, M.B., Cheung, M.-S.: Global market segmentation for logistics services. Ind. Mark. Manage. **33**(1), 15–20 (2004). https://doi.org/10.1016/j.indmarman.2003.08.005
9. Porter, M.E.: Competitive Strategy. The Free Press, New York (1980)
10. Tang-Ting, W., Chin-Min, L.: The evolution of the supply chain management and the analysis of research trends. Int. J. Organ. Innov. **13**(3), 300–314 (2021)
11. Topolšek, D., Čižiūnienė, K., Ojsteršek, T.C.: Defining transport logistics: a literature review and practitioner opinion based approach. Transport (16484142) **33**(5), 1196–1203 (2018). https://doi.org/10.3846/transport.2018.6965
12. Wang, N., Yinzhen, L., Cunjie, D.: Decision-making approach of two-sided matching of supply and demand of logistics service based on the uncertain preference ordinal. Math. Probl. Eng. 1–12 (2020). https://doi.org/10.1155/2020/5480842
13. Zhang, X., Li, B.: Organizational culture and employee satisfaction: an exploratory study. Int. J. Trade Econ. Financ. **4**(1), 48–54 (2013)

Energy Consumption and Travel Time as Important Factors for Deciding on the Mode of Transport - Case Study from Slovakia

Juraj Grencik, Dalibor Barta(✉), Milos Brezani, and Denis Molnar

University of Žilina, Univerzitna 8215/1, 010 26 Žilina, Slovakia
{juraj.grencik,dalibor.barta,milos.brezani,
denis.molnar}@fstroj.uniza.sk

Abstract. Problems of energy consumption are of great importance in all sectors of our life, including transport. This is evident just in the current situation in Europe. Road and rail transport belongs to major consumers of oil products, which causes extensive pressure on the environment, in particular by emissions produced directly by vehicles with internal combustion engines or indirectly in case of electric traction vehicles. Various parameters of different transport modes were compared for passenger transport using diesel engines were compared in this article. Power consumption and travel time belong to the main factors influencing selection of transport mode. In the study, the comparison was performed by calculation of travel times, energy consumption and CO_2 emissions for road and rail vehicles used in selected regions in Slovakia. Inputs to the calculations were based on real data, although not all factors acting in real operation could have been considered.

Keywords: Rail and road transport · Transport mode comparison · GHG emissions · Fuel consumption · Travel times · Passenger vehicle capacity

1 Introduction

Mobility has been an essential need of humanity throughout its history. However, technological progress has caused it to grow at a much higher level than necessary. Slovakia is a typical example of how incorrect government decisions caused a significantly unbalanced state from a functional and balanced state. While in 1995 the ratio of public and non-public transport performance was almost the same, in 2014, after cuts in timetables, public transport already accounted for only a quarter of total transport performance. The logical consequence of this situation was a disproportionate increase in individual car traffic, which was and still represents a burden on road infrastructure and the environment [1]. With regard to pan-European activities, the Energy Policy of the Slovak Republic (EP SR), which defines main goals and priorities of the energy sector until 2035 with a view to 2050, seeks to reverse this situation. The EP SR is based on the basic goals of the "Europe 2020" strategy and is in line with the main goals of the Lisbon Treaty [2]. The

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 518–527, 2023.
https://doi.org/10.1007/978-3-031-25863-3_49

EP SR states how significantly transport contributes to air pollution and points out the problems that society will have to face in the growing trend of energy consumption in the future. The following are considered as partial solutions to the greening of transport: introduction, resp. Expanding the use of more environmentally friendly alternative fuels such as LPG, LNG, CNG or biofuels, promoting public transport and non-motorized transport (cycling), or achieving at least a 10% share of renewable energy sources in fuel consumption in transport, using the polluter pays principle [3]. Research into the use of biofuels has been significantly supported worldwide in recent years, with a number of major research institutions, e.g. [4, 5]. Within Europe, a significant amount of goods is transported by non-electrified railways and roads, as they are relatively short distances. However, this contributes significantly to overall emissions from transport. If only 5% of goods transported by road were diverted to electrified railways, one-sixth of the oil imported from the Middle East would be saved [6].

However, electrified railways are also not ideal, as in most countries of the world electricity is produced by burning oil or gas products or coal, which are non-renewable natural resources whose reserves are constantly declining [7, 8]. Some countries, including Slovakia, produce more than half of the electricity in nuclear power plants (Percent of the total electricity generation in Slovakia: Nuclear – 57.99%, Hydro – 17.32%, Solar – 2.38%, Wind – 0.02% and Fossil – 22.29% [3]) which places it among the "good countries" in terms of CO_2 production per MWh. However, the potential risk of nuclear power generation and long-term storage of nuclear waste is also a problem. As already described, the value of the efficiency of electricity generation is different for different sources. According to [3], the efficiency of fossil fuel combustion processes is in the range of 36–43%, for nuclear power plants it is about 31%, solar power plants about 15% and the most efficient hydropower plants 85%. These data are approximate, their actual value depends on the current weather and operating conditions, the age of the power plant technology used and the power of the power plant (usually, the larger and more powerful the power plant, the higher the production efficiency. According to sources [9, 10], only half of the railway network is electrified, so it is planned to increase this share in the future. However, on lines with low to medium utilization, electrification is not advantageous and thus part of the lines will remain operated with vehicles with internal combustion engines. Another solution is to replace internal combustion engines with hydrogen fuel cells [11]. According to Japanese and Chinese research institutes, these vehicles will use fuel cells with an output of around 130 kW [12, 13]. In Europe, the use of hydrogen fuel cells is being addressed by researchers in Italy [14] who have designed a drive of similar power to the Japanese. However, in 2016 Alstom introduced the Coradia iLint train with 2×200 kW fuel cells and 110 kWh lithium-ion batteries and began sales in 2018 [15]. A competitor from Siemens Germany together with Ballard, prepared a hydrogen version of its Mireo vehicle for 2021 [16].

Energy consumption is closely linked to air pollution (CO_2 emissions). Vehicles with new propulsion and traffic management technologies will be the basis for reducing emissions from transport worldwide. For example, a research carried out by Schnell et al. [17] studied the impact of electric passenger cars on the air quality in the USA. Team of researchers from China [18] concluded that it is not possible to assess the economic and environmental benefits of rail or road transport according to global rules.

Air quality in urban centers affected by transport has particular importance, which is presented in the research done by Soria-Lara et al. [19] in the context of transport policy. The environmental impacts of different types of regional passenger transport vehicles using diesel as a fuel are compared in the present article. The main factors in choosing the mode of transport on specific routes are, in addition to driving time, also energy consumption. Time of transport is closely related to energy consumption. These factors are therefore decisive in the choice of transport mode (vehicle), especially over long distances. As the article is dealing with regional transport in Slovakia and its influence on the environment in Slovakia, the actual situation of emissions in Slovak regions is shown in Fig. 1 [20].

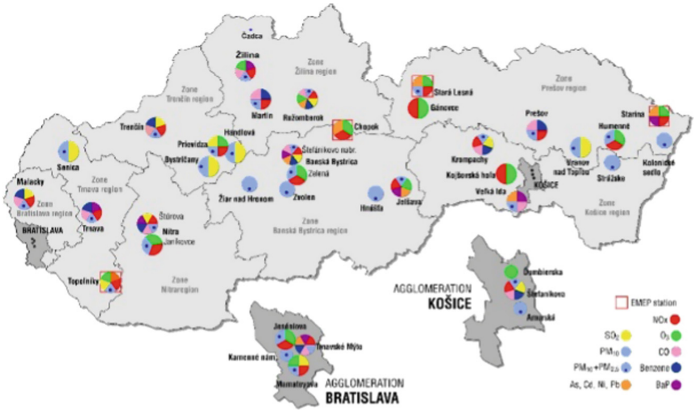


Fig. 1. Actual situation of emissions in Slovak regions in 2018 [20].

The monitored regional line is located in the border region of northern Slovakia with the Czech Republic in the Žilina region (Čadca - Makov).

2 Materials and Methods

To compare the environmental impact of the different means of transport used in a given region for passenger transport, a calculation according to EN 16258 standard is used [21]. This standard specifies a general methodology for calculating energy consumption and greenhouse gas (GHG) emissions for any type of service (passenger, freight, or both). It sets out and defines calculation methods while respecting general principles and system boundaries and rules on energy consumption and GHG emissions.

This methodology is often used in numerous research works dealing with GHG emissions production from transport, as for example in [22].

The standard considers both the secondary emissions produced and energy consumed during combustion of the fuel (energy conversion from fuel to mechanical energy), as well as primary, incurred in the extraction, production and distribution:

1. EW – Well-to-Wheels energetic factor for defined fuel;

2. GW – Well-to-Wheels emissions factor for defined fuel;
3. ET – Tank-to-Wheels energetic factor for defined fuel;
4. GT – Tank-to-Wheels emissions factor for defined fuel.

Well-to-wheels means "well on wheels". Primary and secondary emissions and consumption are covered in this factor, which is also included in LCA (life-cycle-analysis).

Tank-to-Wheels factor is considering only secondary emission and consumption.

This standard specifies general methodology for calculation. The declared value for the energetic factor and factor in GHG emissions must be selected in accordance with Annex A [21].

The different modes of transport (train, bus, car) used in the Kysuce region on one selected transport route from the town of Čadca to the village of Makov in northern Slovakia with a typical mountain range and long valleys where people live in scattered settlements are compared in this case study.

2.1 Methodology of Calculation for Regional Route

Calculation of total energy consumption of diesel multiple unit is according to formula (1). The fuel consumption has to be multiplied by an energetic factor for diesel fuel defined by Appendix A of the standard EN 16258:

$$E_{TT} = FC_V \cdot e_W = \left[\frac{E_{ME} \cdot BSFC}{\rho_F}\right] \cdot e_W, \tag{1}$$

where E_{TT} – total energy consumed by diesel multiple unit, MJ; F_{CV} – fuel con-sumption of vehicle, l or dm^3; E_{ME} – mechanical energy consumed by the movement of the train (train dynamics software result), kWh; ρ_F – fuel (diesel) specific weight (density) [kg/m^3]; e_W – energetic factor"WTW" for defined fuel, MJ/dm^3; BSFC – break specific fuel consumption of the vehicle engine, g/kWh.

Fuel consumption for the bus was provided by the bus carrier, which regularly monitors consumption on the lines and vehicles in operation. Thus, the actual value of the average fuel consumption in real operation on the line was known for the calculation.

$$E_{TB} = FC_V \cdot e_W = \left[\frac{F_{CA} \cdot L}{100}\right] \cdot e_W, \tag{2}$$

where E_{TB} – total energy consumed by bus, MJ; F_{CA} – average fuel consumption, l/100 km; L – distance travelled, km.

In calculation of emission production, the resulting energy consumed by diesel multiple unit is computed by dividing mechanical work with efficiency of the vehicle [23]. For diesel multiple unit:

$$G_{TT} = FC_V \cdot g_W = \left[\frac{E_{ME} \cdot BSFC}{\rho_F}\right] \cdot g_W, \tag{3}$$

where G_{TT} – the total amount of emissions produced by train, gCO_2eq; g_W – emission factor for defined fuel, tCO_2eq/MWh.

And for road vehicle (bus, car):

$$G_{TB} = FC_V \cdot g_W = \left[\frac{F_{CA} \cdot L}{100}\right] \cdot g_W, \tag{4}$$

where G_{TB} – the total amount of emissions produced by bus, gCO_2eq.

3 Results

It follows from the above facts that there are large number of influencing factors for deciding on the use of a particular type of means of transport on a given route and region and the concentration of the population in the vicinity of the transport route (track, road).

3.1 Results for Regional Route

The considered railway line between Čadca and Makov runs parallel to the road. The railroad has an east-west orientation with a distance of 25.9 km and an average gradient of 7.5‰. In the short section, the highest gradient reaches 17.2‰. The maximum speed on the given line is 50 km/h, while several sections are limited to even lower speeds. The road has a very similar elevation profile to the railroad, and due to the fact that it leads mostly through the villages, there is a minimum of short sections with a speed higher than 50 km/h. The actual length of the bus route is 4.1 km longer compared to the train route, which represents 15%, as the bus diverges to several stops in the villages or to the bus stations. The route leads through the valley of the river Kysuca, while the adjacent villages significantly extend into the mountainous region.

The basic technical parameters of the used means of transport are listed in Table 1. The 813 series multiple diesel units (Fig. 2a), which were modernized in 2006, operate on the Čadca - Makov line. The engine unit is powered by a MAN diesel engine that meets the EURO 3 emission standard. Power transmission is hydromechanical. The most commonly used type of bus on this route is the 10 m long version of the Iveco Crossway with an Iveco Euro 4 engine (Fig. 2b). Hyundai iX20 car (Fig. 2c), year of manufacture 2016, with a diesel engine meeting the Euro 6 emission standard was used as a representative of individual passenger transport. Vehicles of this class are the most used category in Slovakia.

a) b) c)

Fig. 2. Multiple diesel unit 813–913 (a), Iveco Crossway bus (b); Hyundai iX20 (c).

Table 1. Basic technical parameters of compared vehicles.

Vehicle type	Bus	Train	Passenger car
Model	Iveco Crossway	813–913	Hyundai IX20
Fuel	diesel	diesel	diesel
Maximum speed, km/h	100	90	185
Combustion engine	Tector EURO IV	MAN D 2876 LUE 21	1.6 CRDi
Engine power, kW	220	257	94
Tare weight, t	10.5	39	1.355
Gross weight, t	16.2	54	1.490
Vehicle length, mm	10,757	28,820	4,100
Number of seats	35	83	5
Maximum number of standing passengers	41	111	0
Total passengers capacity	76	194	5

Calculations of energy consumptions and emissions for train, bus and car on this route were performed in both directions and were summarized. Vehicles occupancy in real operation was obtained by all-day monitoring of number of passengers during the month of March 2022. The results are shown in Table 2.

The data show the advantage of public transportation in terms of energy spent and emission produced per passenger. The Table 2 logically shows that the best values of energy consumption and GHG emissions are achieved at the maximum passenger capacity utilization of each of the considered vehicles, which in real traffic is most often only in a car (way to work, family trip, etc.). This reaches a value of 27.32 MJ / person and 2.08 kgCO_2eq/person when fully occupied on the considered route, which is almost 5 times higher compared to the train and almost 3 times higher compared to the bus.

In the case of a car, standing passengers cannot be considered, so a more realistic comparison is based on the number of seats, also with regard to passenger comfort [25–27]. In this case, the values of energy consumption and GHG emission production of the car are about 2.3 times higher compared to the train and about 1.7 times higher in the case of the bus. In the case of the average real occupancy of vehicles, these ratios are slightly worse; compared to the train it is about 3.6 and compared to the bus 2.9 times more, which is also due to low number of people transported in the car. Regarding travel times, bus and train have almost the same times (54 respectively 55 min). In spite of only 10 train stops comparing to 32 bus stops, the train stays longer time at stops and it has to wait in the station Turzovka (half distance) for train crossing 10 min due to the single track railway. Travel time of car is shorter, about 42 min, depending on traffic situation. From travel time point of view, car is the best solution. A comprehensive view of the consumption of vehicles in the entire range of occupancy is given by the graph in Fig. 3.

Table 2. Comparison of energy consumed by individual vehicles and its emissions.

Vehicle	Maximum capacity			All seats occupied			Occupied seats in real operation		
	Train	Bus	Car	Train	Bus	Car	Train	Bus	Car
Total fuel consumption, l	25.45	15.24	3.20	23.04	13.74	3.20	22.54	13.50	2.75
Total energy consumption, MJ	1086	650.7	136.6	983.8	586.7	136.6	962.5	576.4	117.4
Total emissions production, $kgCO_{2eq}$	82.4	49.4	10.4	74.6	44.5	10.4	73.0	43.7	8.9
Number of passengers	194	74	5	83	37	5	62	30	2.1
Energy per passenger, MJ/person	5.60	8.79	27.32	11.85	15.85	27.32	15.57	19.21	55.9
GHG emissions per passenger, $kgCO_{2eq}$/person	0.42	0.67	2.08	0.90	1.20	2.08	1.18	1.46	4.23

From the graph in Fig. 3 it is possible to read when public transport becomes more advantageous for the car in terms of energy consumption on the route. For example, the same value of specific fuel consumption in liters per passenger kilometer (l/pkm) that is achieved by a car with 5 passengers is achieved by a bus with 21 passengers and by a train with 40 passengers. If there is only 1 passenger in the car, the same specific consumption in the bus is for 5 passengers and 10 in the train. In other words, if there are less than 5 passengers on the bus and less than 10 on the train, then the car is always more advantageous in terms of energy consumption and emissions. The fuel consumption of the diesel train obtained by simulation calculations was compared to the real consumption

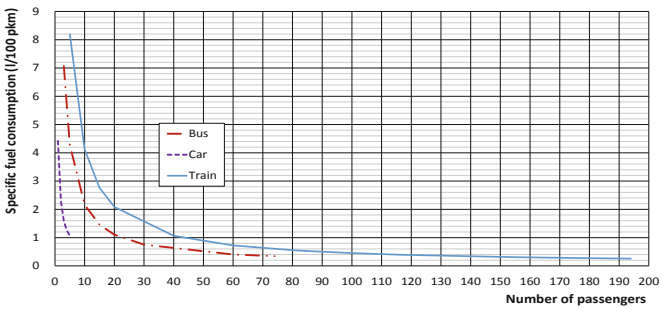


Fig. 3. Comparison of specific fuel consumption of 3 types of vehicles on Čadca - Makov - Čadca route.

of the trains operated on the given route. The results of calculations showed lower values compared to real consumption in operation by about 8%. So calculation results were increased by 8% to be closer to the reality.

Another possibility for GHG emission reduction in future could be in using of unconventional fuels and drives in road vehicles as many sources state [28–30].

4 Conclusion

The exploitation parameters of diesel multi-units, buses and cars on the regional route between Čadca and Makov are compared in this case study. The results showed that the transport times for rail and bus on this route are almost identical, i.e., 55 and 54 min respectively, with the number of bus stops approximately three times higher than for the train. Also, the length of the bus route is 4 km longer due to handling stops. The bus therefore provides better transport services than the train. In terms of energy consumption and thus emissions, the train achieved the best parameters, despite its advanced age. It is notecable, that the diesel multi-unit meets only the Euro 3 standard, while the Euro 4 the bus and the Euro 6 the car. In terms of driving time, the most advantageous is a passenger car, whose driving time is shorter by almost 25%. If driving comfort is considered and the need to get to the stop, then the car clearly outperforms public transport. It is in such a specific region, where the route leads through the valley and the dwellings are scattered over the adjacent valleys and hills, the advantage of the car is even greater. In terms of fuel consumption per passenger-kilometer (pkm), the calculation showed that with real numbers of people transported by public transport, train transport is slightly more advantageous than bus transport; train energy consumption per passenger represents 81% of bus consumption. However, the car consumes almost 3.6 times more fuel per passenger than the train. The use of vehicles with advanced drives and flexible passenger capacity of public transport vehicles could reduce energy consumption per passenger and by increasing number of connections improve availability of transport services in the region. For example, in the most common case of two-person use of a car, the results show that a bus carrying 9 passengers and a train of up to 18 passengers have the same energy consumption per person. For a fully occupied car with 5 people, this difference is even more pronounced – the bus must carry 21 and the train up to 40 passengers. The results of this study showed that energy efficiency and emissions do not only depend on the type of fuel or propulsion and energy sources. It is necessary to use diesel multi-units and buses with a reasonable number of passengers (appropriate choice of vehicles according to the traffic flow). Solution for future could be using of electric drives in road vehicles or using of alternative/ renewable fuels as many sources state. Because of low traffic intensity on the railway line, electrification will be uneconomic, so more feasible solution on railway would be using of e.g. battery or hydrogen drives. In addition to the technical aspects of energy consumption, logistics and transport planning play a major role in the choice of mode of transport and types of vehicles. The best technically functioning system cannot be efficient if empty vehicles are running (with-out passengers) and without "green" electricity, electric trains are not ecological. Depending on type of electric energy production the electric vehicles have indirect effect on the environment. Within EU, coal and oil burning power plants are pre-vailing and thus electric traction is also an

important GHG producer. As the Enviroportal [24] states, Slovakia belongs in this case to better countries of European union with 77.5% electric energy produced in nuclear, water and renewable sources power plants.

Acknowledgement. The paper was supported by the Scientific Grant Agency of the Ministry of Education of the Slovak Republic and the Slovak Academy of Sciences in project KEGA, no. KEGA 023ŽU-4/2020: Development of advanced virtual models for studying and investigation of transport means operation characteristics.

"This publication was realized with support of Operational Program Integrated Infrastructure 2014–2020 of the project: Innovative Solutions for Propulsion, Power and Safety Components of Transport Vehicles, code ITMS 313011V334, co-financed by the European Regional Development Fund".

References

1. Transport in European Union. https://ec.europa.eu/transport/sites/default/files/2019-transport-in-the-eu-current-trends-and-issues.pdf. Accessed 01 Jul 2021
2. Integrated National Energy and Climate Plan for 2021 to 2030. https://ec.europa.eu/energy/sites/ener/files/sk_final_necp_main_en.pdf. Accessed 01 Jul 2021
3. Ministry of Economy SR: Energetická politika Slovenskej republiky (Energy Policy of the Slovak Republic) (2014). http://www.economy.gov.sk/energetika/energeticka-politika/energeticka-politika-a-strategia-energetickej-bezpecnosti. Accessed 27 Jun 2021
4. Chang, W.R., Hwang, J.J., Wu, W.: Environmental impact and sustainability study on biofuels for transportation applications. Renew. Sustain. Energy Rev. **67**, 277–288 (2017)
5. Grahn, M., Azar, C., Lindgren, K.: The role of biofuels for transportation in CO_2 emission reduction scenarios with global versus regional carbon caps. Biomass Bioenerg. **33**(3), 360–371 (2009)
6. Brabec, D., Pilko, H., Starcevic, M.: Environmental aspects of comparing rail and road transport. In: Proceedings of the 6th International Conference on Ports and Waterways – POWA, Zagreb, Croatia, pp. 1–9 (2011)
7. Kendra, M., Skrucany, T., Gnap, J., Ponicky, J.: Energy consumption and GHG production in railway and road passenger regional transport. Int. J. Chem. Nucl. Metall. Mater. Eng. **9**(11), 1–4 (2015)
8. Skrucany, T., Ponicky, J., Kendra, M., Gnap, J.: Comparison of railway and road passenger transport in energy consumption and GHG production, In: Proceedings of the International Conference on Traffic and Transport Engineering ICTTE 2016, Belgrade, Serbia, pp. 744–749 (2016)
9. Peng, H., Li, J., Löwenstein, L., Hameyer, K.: A scalable, causal, adaptive energy management strategy based on optimal control theory for a fuel cell hybrid railway vehicle. Appl. Energy **267**(114987), 1–17 (2020)
10. Statista 2021. https://www.statista.com/statistics/451522/share-of-the-rail-network-which-is-electrified-in-europe/. Accessed 14 Apr 2021
11. Dacosta, C.F., Shen, L., Schakel, W., Ramirez, A., Kramer, G.J.: Potential and challenges of low-carbon energy options: comparative assessment of alternative fuels for the transport sector. Appl. Energy **236**, 590–606 (2019)
12. JREAST. https://www.jreast.co.jp/e/press/20060401/. Accessed 11 04 2021
13. Peng, F., Chen, W., Liu, Z., Li, Q., Dai, C.: System integration of China's first proton exchange membrane fuel cell locomotive. Int. J. Hydrogen Energy **39**(25), 13886–13893 (2014)

14. Mugnetti, P., Carbone, S., Pede, G.: A fuelcell switcher locomotive with an hybridised propulsion system. In: Proceedings of the Conference IEEE, pp. 1–6 (2006)
15. Jürgen, H.: Auf dem Weg zur Null-Emmision. Eisenbahn-Magazin **7**, 41 (2017)
16. Brennstoffzellen: Siemens beauftragt ballard power. https://www.iwr.de/news.php?id=34729. Accessed 25 Jan 2020
17. Schnell, J.L., et al.: Air quality impacts from the electrification of light-duty passenger vehicles in the United States. Atmos. Environ. **208**, 95–102 (2019)
18. Yang, Q., et al.: Comparison of the impact of China's railway investment and road investment on the economy and air pollution emissions. J. Cleaner Prod. **293**, 1–11 (2021). 126100
19. Soria-Lara, J.A., Tarrino-Ortiz, J., Bueno, P., Ortega, A., Vassallo, J.M.: A collaborative appraisal framework to evaluate transport policies for improving air quality in city centres. Cities **92**, 112–124 (2019)
20. Air pollution in the Slovak Republic - report of Slovak hydro-meteorological institute, Bratislava 2019. http://www.shmu.sk/File/oko/rocenky/SHMU_Air_Pollution_in_the_SR_v1.pdf. Accessed 14 Apr 2021
21. EN 16258:2013-04: Methodology for calculation and declaration of energy consumption and GHG emissions of transport services (freight and passengers)
22. Skrucany, T., Gnap, J.: Energy intensity and greenhouse gases production of the road and rail Cargo transport using a software in simulate the energy consumption of a train. In: Proceedings of the 14th International Conference on Transport Systems Telematics, TST 2014, Katowice/Kraków/Ustroń, Poland, pp. 263–272 (2014)
23. Skrucany, T., Kendra, M., Sarkan, B., Gnap, J.: Software simulation of an energy consumption and GHG production in transport. In: Mikulski, J. (ed.) TST 2015. CCIS, vol. 531, pp. 151–160. Springer, Cham (2015). https://doi.org/10.1007/978-3-319-24577-5_15
24. Enviroportal. https://www.enviroportal.sk/indicator/detail?id=762. Accessed 15 Apr 2021
25. Dizo, J., Blatnicky, M.: Investigation of ride properties of a three-wheeled electric vehicle in terms of driving safety. In: Proceedings of the 13th International Scientific Conference on Sustainable, Modern and Safe Transport (TRANSCOM 2019), Novy Smokovec, Slovakia, pp. 663–670 (2019)
26. Dizo, J., et al.: Evaluation of ride comfort in a railway passenger car depending on a change of suspension parameters. Sensors **21**(23), 1–16 (2021)
27. Dizo, J., Blatnicky, M., Steišūnas, S., Falendysh, A.: Investigation of ride properties of a rail vehicle with wheel defects. In: Proceedings of the 22nd International Scientific Conference on Transport Means (Transport Means 2018), Trakai, Lithuania, pp. 104–109 (2018)
28. Lebedevas, S., Pukalskas, S., Žaglinskis, J., Matijošius, J.: Comparative investigations into energetic and ecological parameters of Camelina-based biofuel used in the 1Z diesel engine. Transport **27**(2), 171–177 (2012)
29. Pukalskas, S., et al.: Comparison of conventional and hybrid cars exploitation costs. Adv. Sci. Technol. Res. J. **12**(1), 221–227 (2018)
30. Małek, A., Caban, J., Wojciechowski, L.: Charging electric cars as a way to increase the use of energy produced from RES. Open Eng. **10**(1), 98–104 (2020)

Optimization of Customs Processes for Improving Cooperation Between Third-Party Logistics Companies

Ieva Meidutė-Kavaliauskienė(✉) and Renata Činčikaitė

General Jonas Žemaitis Military Academy of Lithuania, Šilo Str. 5A, 10322 Vilnius, Lithuania
{ieva.meidute,renata.cincikaite}@lka.lt

Abstract. The growth of international trade and the development of business enterprises are inseparable processes of the development of the modern economy, promoting through their functioning more active integration of different countries, cooperation of various enterprises with each other, and optimization of common processes. There is a movement of products throughout the world taking place every day. Some goods arrive in the country, and other goods leave. The majority of the imported and exported goods are accompanied by customs procedures such as import, transit, and export declarations, which are beneficial to the states. This not only allows to increase the competitiveness of international companies in the global market but also, provides an opportunity to develop links of cooperation and raise the level of the country's economy. Given the importance of the development of international trade, it is also worth analyzing the simplification and integration of customs processes to facilitate existing operations and bring added value to the end-user. Along with simplifying customs procedures, it is necessary to analyse the importance of cooperation in the logistics sector. This article aims to present the impact of the logistics companies' cooperation with third-party logistics (3 PL) companies by analyzing the possibilities of improving customs processes. The study utilizes the analysis of scientific sources and qualitative and quantitative research methods.

Keywords: Logistical cooperation · Customs processes · Cooperation

1 Theoretical Aspects of Logistic Cooperation and Customs Processes

1.1 Analysis of Logistic Cooperation as a Phenomenon

Modern scientific literature defines logistics as a business sector, one of the main goals of which is the smooth and proper management of the supply chain and the movement of goods in it. To ensure smooth supply chain management, the most optimal options for solving supply chain management problems are being sought. According to Batarlienė and Jarašūnienė [1], the most effective scientific methods that are used in the entire

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 528–538, 2023.
https://doi.org/10.1007/978-3-031-25863-3_50

movement of goods - from the producer to the consumer - are analyzed to solve problems. The successful operation of the logistics sector guarantees not only the success of companies, but also the overall growth of the country's economic competitiveness and the development of logistics as a science. Cooperative relationships such as business-to-business are prevalent, where two or more businesses link their operations based on their transaction history. Such cooperation usually takes place through economic, functional, social, or even structural links [2]. According to Karazijienė and Černikovaitė [3], cooperation is often utilized on the basis of competitiveness - to use as few resources as possible, but in partnership with another company to create added value for the customer. Looking at the current trends in the development of logistics companies, it is necessary to mention Garcia-Alcazar et al. [4], who argue that, in general, the logistic approach should be focused on the core business of the company and only then should the focus shift to cooperation with other companies.

Further analysis of the concept and importance of cooperation in the logistics sector requires an understanding of the main reasons why companies choose to cooperate and work together with other companies. According to Aloui et al. [5], today's business world is strongly influenced by market globalization, rapidly changing customer expectations and desires, and certain sustainability requirements. In the context of cooperation, they distinguish horizontal cooperation, where companies share their available resources - warehouses, distribution centers, and vehicles between actors operating in different logistics networks. Cooperation in logistics is also analyzed by Tran and Le [6], who collectively perceive cooperation as a kind of cooperative activity between companies in the market of the same level, when they gain more benefits while working together. According to Tran and Le, combining processes can help optimize vehicle use, reduce costs for companies, and increase competitiveness in the market [6]. In a similar aspect, collaboration is studied by D. Yang et al. [7], who argue that the coexistence of companies is usually based on a common goal. They refer to cooperation as a coalition of certain two or more companies, where they exchange or share available resources to carry out activities that will be more beneficial than if acting individually. They also claim that cooperation in logistics, where information is exchanged, is seen as a means of reducing the impact of the Bullwhip effect on the supply chain. According to Diann [8], the Bullwhip effect is a kind of supply chain phenomenon that can be described as certain fluctuations in demand at the retail level, leading to gradually more significant fluctuations in demand at the wholesale level. The analysis of cooperation in logistics requires mentioning that this is usually widely related to a certain dependency. Authors Lehoux et al. [16] divide logistical cooperation into six main types that coexist with cooperation (combined interdependence; producer-consumer relationship; reciprocal relationship; intensive interdependence; interdependence of tasks / secondary tasks; simultaneous interdependence). Companies can be linked by a variety of connections and be dependent up to a level that suits them.

The functioning of the supply chain is also widely monitored and analyzed in international trade, where its management is crucial and necessary. Gruchmann et al. [9] analyses the importance of certain logistics partners in the supply chain and in the current economic system. The authors list such cooperation models as "3PL" and "4PL" as these partners. It is specifically 3PL – the operation of third-party logistics – is described

as the coordination of normal logistics processes to optimize the individual phases of the supply chain, strengthen the supervision of these phases, and improve mutual cooperation. Due to the complexity of this model and its straightforward, uncomplicated and efficient operation, it is noticeable that it is becoming probably the most popular model of cooperation between different companies.

The formation of a third-party logistics model is associated with the increasing demand to improve logistics processes. Globalization, competitive advantage pursuit, greater customer focus, and optimization of supply chain costs have led to an increasing focus on the development of logistics and third-party logistics. [10] As the volume of logistics flows expands and all systems improve, a certain tendency is observed in the modern business world to destroy the side activities of the company and transfer them to specialized companies. 3PL services do just that. In principle, companies abandon internal logistics departments and focus on improving financial and human resources to expand business activities [1]. Third-party actions may include processes such as warehousing, order processing, and shipping to customers. In addition, third-party logistics services allow you to focus on marketing, growth, and customer satisfaction. For these reasons, the 3PL business model can be said to be the most common type of outsourced logistics company. Although there are other types of cooperation in the market, such as "4PL", "5PL", but still the trends of more frequent choices of "3PL" are observed.

When examining the “3PL” operating model, some authors face the question of the effectiveness of this model in the supply chain. According to Alageel, in order to find out how to effectively use this model in the supply chain and fully exploit its potential, it is necessary to analyze the various conditions to achieve effectiveness. When analyzing the operating principles of 3PL, different authors present different operational goals [11]. The authors Batarlienė and Jarašiūnienė consider optimization of logistic processes as the main work of the “3PL” service, when operating costs depend on several process participants/companies [1].

Third-party logistics can be considered as an action in the market that not only creates added value for customers but at the same time optimizes all related processes and facilitates the overall operation of the supply chain. Of course, like every process, this collaboration model has its corresponding functions in the logistics sector. In general, 3PLs are used for traditional logistics functions, such as transportation and warehousing. However, as the market expanded and the demand for 3PL providers increased, more complex and diverse services were added to the already existing functions [12]. While it used to be common to think that such outsourcing companies could only coordinate precise and clear logistics processes, today companies often outsource almost all process functions and delegate authority to a 3PL provider. In turn, these suppliers can help the customer maintain and even strengthen the necessary competitive advantage in the market. Knowledge of experienced 3PL suppliers can essentially help ensure more efficient logistics operations, which in turn improves supply chain performance [11]. Another important point is that if an extremely experienced 3PL provider is chosen, he has a lot of skills in coordinating actions, so even in the event of unforeseen situations, such a provider will use reliable partners or subcontractors. This is a very important moment in the activity of a logistics company, as customers have become extremely sensitive and receptive over the years, so efficient supply chain and goods management is one

of the main goals of logistics. Also, "3PL" often performs business development functions when new customers and partners are sought for an existing company. If the 3PL provider has an extremely large informational advantage, then it is likely that the circle of the company's customers and partners will greatly increase, and in this way the main operating principle will be implemented, namely business and supply chain management will be efficient. The effectiveness of the 3PL model has many advantages and is highly appreciated among business enterprises. Below are Weerakkody et al. [13], Krasnov et al. [14], Angin and Gidener [15] highlight the main advantages of the third-party logistics model: Environmental care; Costs and financial risks are reduced; Increased competitiveness of companies in the market; Focus on the core activities; Great attention is paid to customers; Variety of services.

In summarizing the main functions and advantages of 3PL providers, it can be said that it is an excellent tool for all rapidly developing companies. It is an excellent support tool for companies that do not have enough resources to develop their activities individually. Indeed, it is an efficient and effective logistics process whose development and continued use will have a significant impact on the future logistics sector.

1.2 Analysis of the Relationship Between Logistical Cooperation and Customs Processes

The importance of cooperation is also observed in activities of the customs that work directly with third-party logistics companies. To gain a better understanding of the importance of cooperation and the need to develop this process, it is also worth examining customs procedures and the relationship with the cooperation process. Customs procedures, according to Rabetskaya A. I. [17], are perceived as a set of rules that underlines the customs requirements and conditions for the storage, use, and/or disposal of goods in a customs union or abroad. Mcdaniel and Norberg [18] describe the process of customs activity as the necessary requirements and conditions for transporting goods across the country. According to them, it is precisely because of the importance of customs procedures in the regulation of cross-border flows it is an integral part of any international trade transaction. They are supported by Benssasi et al. [19], who claim that customs procedures are typically considered a series of required authorizations for the transfer of products between countries or the conclusion of formalities for the entrance of goods into the EU. The ability of the merchant to deliver goods to the market promptly through an efficient customs clearance procedure is essential to maximize the benefits of international trade.

Meanwhile, Hoang Tien and Ba Hung Anh [20] argue that customs procedures, in general, are one of the most important indicators of international trade to assess whether international trade performs its functions and raises the level of the economy. A similar idea about the importance of customs procedures is supported by Loveimi et al. [21]. They argue that customs play an effective and important role in world trade, law enforcement, customs duty and tax collection. The authors are convinced that customs activities should not only facilitate customs processes, but also control the movement of goods, persons, and vehicles.

As mentioned by Pasichnyk et al. [22], for international relations to be smooth, various companies must understand not only the issues of transportation and distribution

of goods, but also the regulations on the import of goods, the tools to carry out the movement of goods and the possibilities to guarantee the proper further movement of goods. That is why understanding and improving customs procedures is an integral part of any company engaged in international trade.

In turn, international trade significantly contributes to the development and cooperation integration of logistics suppliers. In recent decades, the logistics market has become extremely complex; the pandemic has adjusted all the plans of business participants, and probably affected the activities of logistics suppliers the most. Their main goal is to satisfy the customers who utilize their services and provide added value [23].

According to Pasichnyk et al. [22], the development of a transport logistics and customs complex is designed to create a kind of partnership between producers and consumers through a flexible system of interoperability of different means of transportation. As the market expands and technologies improve, so does the need to optimize certain customs processes. The authors are convinced that one of the most effective mechanisms for optimizing customs procedures and reducing document processing time is the application of modern IT technologies in customs document processing.

Meanwhile, Shpak et al. [24] state that customs not only perform processes related to control, prevention of violations, customs duties and tax administration, but also play a certain functional role. Of course, customs are often confronted with certain provisions and requirements that they have to comply with. For example, Laurinavičius [25] states that the customs must not only fulfil the common goal, but also ensure the security of business and guarantee equal requirements for all economic entities.

The most significant problem faced by customs officials and businesses using customs services is the time required to carry out customs controls and inspections. Normally, regardless if the cargo is physically inspected or not, the processing of import documents can take from half a day to a few days. In general, with the expansion of the market and the growth of world trade, customs have become one of the essential institutions in foreign trade. According to Arasteh et al. the operation of customs directly impacts the economy. The authors agree that increased volumes of international trade are observed and highlight the growing development of IT, globalization, and liberalization as the main indicators [26]. It is said that these changes have turned customs into a multifunctional body responsible for various missions to ensure public security and support national production. Increased complexity and time costs make use of time-saving tools and methods crucial. Studies show that each additional day, spent on customs procedures, results in a loss of between 0.5% and 1.5% of the total value of the cargo. This is why the time element is often used to calculate a certain efficiency of customs processes. Arasteh et al. agree that automated customs systems are one of the most vital tools for facilitating trade procedures [26]. According to Widdowson [27], the automation of customs increases the transparency of customs duties and tax valuation. It significantly reduces the time and predictability of customs formalities, which improves the efficiency of the operation of all sectors.

In many cases, the efficiency of customs operations is assessed through the level of the logistics performance index. Kilibarda et al., while analyzing the efficiency of customs, named the logistics performance index created by the World Bank Organization [28]. Precisely the customs efficiency is one of the key elements of this indicator.

2 Methodology for the Optimisation of Customs Process

A qualitative and quantitative study was carried out to meet the objective of the study and to identify measures and opportunities for optimizing customs procedures that may have an impact on improving cooperation between the 3PL. The course of the study can be divided into several phases:

1. The method of secondary data analysis, According to Van den Akker et al. [29], involves the analysis of existing data to examine research questions, often in addition to the main ones for which data were originally collected. The data used in this study were based on the reports of the Customs of the Republic of Lithuania for 2010–2020, the data of the World Bank Organization, the data of the World Integrated Trade Solution and the reports of the Department of Statistics of Lithuania on international trade for 2010–2019.

2. Performance monitoring and evaluation, According to Song. et. al. [30], is a continuous and systematic process of data collection and analysis process measuring the performance effectiveness. During the monitoring method, the activities and evaluation of 5 customs agents of Terminality PJSC were used. From 15 March to 23 March, several key elements of the customs process were monitored: the number of transit, import, and export declarations filed per day by one intermediary. Attention was also paid to the time intervals of the processing of transit, import, and export declarations. These elements made it possible to understand the impact of the work of the agents on the operation of customs processes, what indicators prolong the preparation of declarations and how this process can be improved.

3. An expert survey Is considered to be a specific type of survey in which specialists in a specific field are interviewed. Expert surveys provide an opportunity to take a critical look at the questions raised, to obtain accurate and realistic answers, and to better understand the current situation in the aspect that is being researched [31]. A survey with 6 experts was conducted in March 2022 and in April 2022 in Vilnius. According to Mikalajūnaitė and Maskeliūnaitė [32], the generalized opinion of a group of respondents in studies involving specialists of the respective field is considered to be a certain result of the decision only when the opinions of all experts are similar and non-contradictory. To use the results of the expert survey and treat them as the result of a decision, it is necessary to determine the degree of concordance of opinions, which is indicated by the concordance coefficient W.

$$W = \frac{12S}{n^2 m(m^2 - 1)} = \frac{12S}{n^2(m^3 - m)}, \tag{1}$$

where W – Kendall's coefficient of concordance; S – the sum of the squares of the total mean of the ranks; n – number of criteria; m – number of experts.

This coefficient is perfectly applicable when the number of expert groups is greater than two. Specifically Kendall's coefficient of concordance that varies within the range of [0;1]. It is assumed that expert opinions are considered compatible when this coefficient is close to 1. As the coefficient approaches 0, it can be said that the specialists do not have a suitable, coordinated opinion for the study.

3 Results of the Study of Customs Processes

During the analysis of secondary data, the data were collected based on the reports of the Customs of the Republic of Lithuania for 2010–2020, the data of the World Bank Organization, the data of the World Integrated Trade Solution and the reports of the Department of Statistics of Lithuania on international trade for 2010–2018.

In the analysis of customs procedures, the import and export procedures were singled out as a dependent variable Y, as the size and optimization of these variables are significant and interesting in the study. The following were chosen as independent variables: Profitability, Number of import/export declarations, Number of goods in import/export declarations, Import/export volume index, Logistical level index, Logistical level index rating, Average import/export time in days/hours; GDP.

The minimum value of the profitability of the independent variable is 17653, while the maximum is 30943. According to the data provided, the average profitability is estimated at EUR 24 820.20 million per year. It is noticeable that this indicator has significantly increased from 2010 to 2018; therefore, it can be stated that this customs procedure is profitable and beneficial for the Lithuanian economy.

Based on the results obtained, it was found that the average import takes about 2 days, and the final submission of documents takes an average of 1 h and 10 min. These results suggest that the import declaration procedure is complex and places importance not only on the final submission of documents, but also on all previous processes – customs duties, collection of all necessary documents and agreements, and communication between different actors in the supply chain.

Finally, to assess the importance and significance of the data, it is necessary to analyse the size of GDP, as it is interesting to see whether the import procedure affects the change in its value. The resulting average GDP for the period presented is EUR 33,3511.60 million per year. It is noticeable that this indicator has been growing almost every year, but in 2018 there was a certain drop.

Overall, the analysis showed that the functioning of export declarations is mainly influenced by profitability, the export volume index, and the number of goods in export declarations. This means that changes in the procedures for export declaration filing would significantly affect the change in these variables.

During **the monitoring method**, the highest focus was on time factors. Terminality PJSC customs agents perform their work quite efficiently. Throughout the week, agents filed a total of 73 declarations, which is a welcome figure, given that the company's capacity is not distributed evenly, meaning that customs agents are often required to contact customers themselves and obtain all the necessary information about goods that are being imported. Summarizing the process of the filing of import declarations, it can be stated that the functioning of this process in Terminality PJSC can be considered sufficiently efficient, but it needs to be improved. One of the main means of improvement could be the aspect of the distribution of respective tasks. The study has shown that the procedure for filing an import declaration depends on the speed with which the customs system operates, the completeness of the documents, and the prompt payment of customs duties. If all these aspects are fulfilled, then the customs declaration can be filed in an average of a few hours.

Procedure for filing a transit declaration. As in the case of the import declaration procedure, speed was one of the main indicators during the monitoring of the filing of the transit declaration. The speed with which the relevant amount of cargo is cleared reflects the relevant principles of operation of the customs system and the efficiency of the work of the agents.

One of the most important things that was observed was the relationship between the amount of cargo and the time interval. It has become important to understand how the appropriate cargo amount can affect the clearance speed. It is necessary to mention that customers who utilize transit declaration processing services of Terminality PJSC have several options - to file T1 for each cargo separately (if there is more than one cargo and the place of delivery is different) or to create a joint transit declaration for all cargoes. Thus, if a joint transit declaration is created, it is considered a single procedure.

Given the time intervals for transit declarations and the frequent misunderstanding as to why the corresponding loaded vehicles take longer to process, despite the small volume of cargo, it is worth understanding certain moments that have an impact. One of the main aspects is the inspection of the relevant cargo by customs officers, otherwise known as the red channel. It is also necessary to mention that in the current situation with an ongoing war, customs agents are facing many difficulties due to sanctions on Belarus and Russia. Due to the rapidly changing circumstances and sanctions, there are cases when the goods are not released from Lithuania; therefore, it is necessary to change the cargo in the vehicle and to coordinate aspects with the customer of the customs service.

Another important aspect that affects the efficiency of the process is the uneven intensity of the days of the week. Typically, large cargo departures are organized at the beginning of the week and at the end of the week. This means that the time intervals that are in the middle of the week are not equal to the beginning and end of the week. One of the main options for improvement is to increase the workforce. Increasing the number of employees would increase productivity, faster processing of transit declarations and automatic meeting of the customer's needs. Also, to make the overall process even smoother, customers using customs services must provide legally correct and complete documents that equally facilitate the work of the customs agent. In general, the processing of a transit declaration is a highly complex process that requires diligence, sufficient information on the goods, accurate information on the place of destination of the goods, and some approval/authorization by the customs authorities.

For the study to be fair and reasonably valuable, it is necessary to calculate Kendall's coefficient of concordance discussed earlier. Based on the answers received during the survey, the weights of the selected criteria were determined and the ranking of the respective criteria was performed. The main and most important criterion was the customs process efficiency factor. According to the evaluation scale, the obtained concordance coefficient (0.57) is higher than 0.5; therefore, it can be stated that the expert opinions are concurring and suitable for further research.

4 Conclusion

An analysis of the scientific literature on the model of logistical cooperation, customs processes, and third part logistics has revealed that logistic cooperation is a crucial part of

the supply chain, affecting all its actors. Meanwhile, an analysis of customs procedures has shown that this is an important part of the development of both the logistics sector and international trade.

All the results of the methods applied in the study allowed us to identify the relevant problems of the customs processes and helped to form the appropriate options for improvement. Problems such as the lack of dissemination of information, frequent bottlenecks/failures of the customs system, and the complexity of customs procedures were emphasized. The following are suggested as possible solutions: increase the knowledge of logistics companies about the importance of customs, improve the technological side of the customs system, and reduce the participation of customs agents in separate phases of the declaration filing. Finally, as a result the reduction of time costs, increase of operational efficiency, and decrease of company costs would be observed.

References

1. Batarlienė, N., Jarašūnienė, A.: '3PL' service improvement opportunities in transport companies. Procedia Eng. **187**, 67–76 (2017). https://doi.org/10.1016/j.proeng.2017.04.351
2. Mojir, N., Anbil, S.: The value of professional ties in B2B markets. SSRN Electron. J. (2021). https://doi.org/10.2139/ssrn.3967275
3. Karazijienė, Ž., Černikovaitė, M.E.: Evaluation of logistic cooperation services in Lithuanian retail chains in the context of New Industralization (2019). https://doi.org/10.2991/sicni-18.2019.99
4. García-Alcaraz, J.L., Alor-Hernández, G., Maldonado-Macías, A.A., Sánchez-Ramírez, C. (eds.): New Perspectives on Applied Industrial Tools and Techniques. MIE, Springer, Cham (2018). https://doi.org/10.1007/978-3-319-56871-3
5. Aloui, A., Hamani, N., Derrouiche, R., Delahoche, L.: Systematic literature review on collaborative sustainable transportation: overview, analysis and perspectives. Transp. Res. Interdiscip. Perspect. **9**, 100291 (2021). https://doi.org/10.1016/j.trip.2020.100291
6. Tran, L.D.L., Le, K.: Horizontal cooperation in logistic : opportunities and impediments for logistic service providers in the central key, September 2019
7. Yang, D., Yin, W., Liu, S., Chan, F.T.S.: Understanding the effect of multi-agent collaboration on the performance of logistics park projects: evidence from China. Sustainability **14**(7), 4179 (2022). https://doi.org/10.3390/su14074179
8. Daniel, D.: "Bullwhip Effect (2019). https://www.techtarget.com/searcherp/definition/bullwhip-effect
9. Gruchmann, T., Pratt, N., Eiten, J., Melkonyan, A.: 4PL digital business models in sea freight logistics: the case of FreightHub. Logistics **4**(2), 10 (2020). https://doi.org/10.3390/logistics4020010
10. Wang, C.-N., Nguyen, N.-A.-T., Dang, T.-T., Lu, C.-M.: A compromised decision-making approach to third-party logistics selection in sustainable supply chain using fuzzy AHP and fuzzy VIKOR methods. Mathematics **9**(8), 886 (2021). https://doi.org/10.3390/math9080886
11. The mediating role of outsourcing in the relationship between speed, flexibility and performance in supply chain (A Saudi Arabian study). J. Arts, Lit. Humanit. Soc. Sci. **68**, June 2021. https://doi.org/10.33193/JALHSS.68.2021.518
12. Qureshi, M.N., Kumar, D., Kumar, P.: An integrated model to identify and classify the key criteria and their role in the assessment of 3PL services providers. Asia Pacific J. Mark. Logist. **20**(2), 227–249 (2008). https://doi.org/10.1108/13555850810864579

13. Weerakkody, H.D.W., Wijayanayake, A., Niwunhella, D.H.H.: Vehicle routing and shipment consolidation in a 3PL DC: a systematic literature review of the solution approaches. In: Proceedings of the International Conference on Industrial Engineering and Engineering Management, pp. 932–943 (2021)
14. Krasnov, S., Zotova, E., Sergeev, S., Krasnov, A., Draganov, M.: Stochastic algorithms in multimodal 3PL segment for the digital environment. IOP Conf. Ser. Mater. Sci. Eng. **618**(1), 012069 (2019). https://doi.org/10.1088/1757-899X/618/1/012069
15. Angin, C., Gidener, N.G.: The effects of relationship marketing on creating customer loyalty: a case study of 3Pl service providers in Izmir. J. Bus. Digit. Age **2**(1), 49–53 (2019)
16. Lehoux, N., Audy, J.-F., D'Amours, S., Rönnqvist, M.: Issues and Experiences in Logistics Collaboration. In: Camarinha-Matos, L.M., Paraskakis, I., Afsarmanesh, H. (eds.) PRO-VE 2009. IAICT, vol. 307, pp. 69–76. Springer, Heidelberg (2009). https://doi.org/10.1007/978-3-642-04568-4_8
17. Рабецкая, А.И.: "The system of customs procedures in the EU (2019). chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://rep.bntu.by/bitstream/handle/data/58306/THE_SYSTEM_OF_CUSTOMS_PROCEDURES_IN_THE_EU.pdf?sequence=1
18. McDaniel, C.A., Norberg, H.C.: Can blockchain technology facilitate international trade? SSRN Electron. J. (2019). https://doi.org/10.2139/ssrn.3377708
19. Bensassi, S., Jarreau, J., Mitaritonna, C.: Regional integration and informal trade in Africa: evidence from Benin's borders. J. Afr. Econ. **28**(1), 89–118 (2019). https://doi.org/10.1093/jae/ejy016
20. Hoang Tien, N., Ba Hung Anh, D.: The role of international trade policy in boosting economic growth in Vietnam Entrepreneurship. Int. J. Commer. Manag. Res. **5**, 107–112 (2019). https://www.researchgate.net/publication/338719463
21. Loveimi, M., Paseban, M., Fakhimiazar, S., Bohlooli, N.: Designing a risk management and customs data mining model. Indian J. Econ. Bus. **20**(1), 201–216, (2022). http://www.ashwinanokha.com/IJEB.php.
22. Pasichnyk, A., Mallnow, V., Kutyrev, V.: Customs restricted facilities within the logistics transport and customs complex. Customs Sci. J. CUSTOMS **40**, 42 (2017). http://zakon.rada.gov.ua
23. Tufano, A., Accorsi, R., Manzini, R.: Machine learning methods to improve the operations of 3PL logistics. Procedia Manuf. **42**, 62–69 (2020). https://doi.org/10.1016/j.promfg.2020.02.023
24. Shpak, N., Melnyk, O., Adamiv, M., Sroka, W.: Modern trends of customs administrations formation: best European practices and a unified structure. NISPAcee J. Public Adm. Policy **13**(1), 189–211 (2020). https://doi.org/10.2478/nispa-2020-0008
25. Laurinavičius, A.: Tarptautinės Prekybos Iššūkiai Ir Konceptualūs Muitinės Veiklos Pokyčiai. Mykolo Romerio Univ. **8011**(2), 25–35 (2007)
26. Arasteh et al., H.: ICCS: a novel optimized model for improving E-customs performance. Int. J. Acad. Res. **7**(4) (2015). https://doi.org/10.7813/2075-4124.2015/7-4/A.29
27. Widdowson, D.: International Network of Customs Universities. **2**(2) (2008)
28. Kilibarda, V., Andreji, M., Popovi, M.: Efficiency of logistics processes in customs procedures (2017). https://logic.sf.bg.ac.rs/wp-content/uploads/LOGIC_2017_ID_26.pdf
29. Van den Akker, O.R., et al.: Preregistration of secondary data analysis: a template and tutorial. Meta-Psychology **5** (2021). https://doi.org/10.15626/MP.2020.2625

30. Song, B., Zhou, X., Shi, H., Tao, Y.: Performance-indicator-oriented concurrent subspace process monitoring method. IEEE Trans. Ind. Electron. **66**(7), 5535–5545 (2019). https://doi.org/10.1109/TIE.2018.2868316
31. Ikart, E.M.: Survey questionnaire survey pretesting method: an evaluation of survey questionnaire via expert reviews technique. Asian J. Soc. Sci. Stud. **4**(2), 1 (2019). https://doi.org/10.20849/ajsss.v4i2.565
32. Mikalajūnaitė, Ž., Maskeliūnaitė, L.: Priežasčių, Nulemiančių Prekių Nesavalaikį Pristatymą Paslaugos Užsakovui, Svarbos Tyrimas, pp. 4–5, May 2018. http://jmk.transportas.vgtu.lt

Study of the Dynamics of Railway Passenger Traffic, Identification of Trends

Renata Činčikaitė and Ieva Meidute-Kavaliauskiene(✉)

General Jonas Žemaitis Military Academy of Lithuania, Šilo Str. 5A, 10322 Vilnius, Lithuania
{renata.cincikaite,ieva.meidute}@lka.lt

Abstract. Changes in passenger traffic and the choice of vehicle affect the country's environment, economic and social situation, as well as the operating costs of the transport infrastructure. Rail transport is more environmentally friendly (the CO_2 footprint of a train passenger per kilometre is about 14 g CO_2), more economical than road transport (the CO_2 footprint of a car passenger varies between 42 and 158 g/km, depending on the performance of the car and the number of passengers), but it is still inferior to it in terms of popularity (comparing them, in Lithuania only 10.41% cent (1st quarter of 2022) of passengers chose the railway, comparing the data of passenger traffic in 2019 with 2013, an increase of only about 13% is recorded). The aim of the article is to identify the dynamics of railway passenger traffic, the determining factors and make future forecasts. After carrying out a systematic and comparative analysis of the concepts published in the scientific literature, the factors determining the dynamics of railway passenger traffic have been identified. Forecasts for the year 2022 were made as a result of the empirical study. Secondary data analysis, statistical processing, correlation regression analysis, forecasting methods were used to achieve the aim.

Keywords: Passenger traffic · Railway · Forecast · Correlation regression analysis

1 Railway Passenger Traffic and Their Determining Factors

The significance of passenger transport for the economic and social life of the country is recognized by many scientists [1–4]. According to Tomasz Nowakowski, the main function of transportation is to realize the movement of people and goods from one place to another in a safe and efficient way with minimum negative impact on the environment [1]. G. Kos et al. in the study reviewed public passenger transport have been defined, all County transport lines of schoolchildren and other passengers have been analysed as well as actual deficiencies in the city, County and school transport needs. Road transport infrastructure, carriers, and transportation vehicles have been analysed. These have a large impact on the economy and social life in cities. A. Žvirblis et al. in the study described the impact of technological factors on the system of passenger transportation, the emphasis is placed on competitiveness as a criterion of evaluation the efficiency of its performance and provide a number of actions which improve passenger carriage

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 539–547, 2023.
https://doi.org/10.1007/978-3-031-25863-3_51

by railway is also described. The goal of the European Union's sustainable transport policy is to create transport systems that meet economic, social, and environmental needs [4]. It should be emphasized that globalization processes lead to the growth of the transport services market. Thus, to predict the future prospects of passenger flows by rail, it is necessary not only to observe changes in the number of transported passengers, but also to find the factors influencing the change. Railway passenger traffic is one of the most compliant with environmental requirements modes of transportation, which is characterised not only by low emissions, but also by high transport capacity. These characteristics of railway transport are one of the main reasons why the EU White Paper [5] emphasises its importance in medium-distance transport for an efficient multimodal network of transport between cities [6]. A large variety of railway rolling stock – trains, interconnected wagons [7] – helps to develop this, which can be divided into: intercity, suburban, urban, steep-hill trains [8]. Such a supply of passenger trains can adapt well to the needs of the user and provide the required service. Based on the detailed analysis of the technical characteristics of railway vehicles presented by C. N. Pyrgidis, it is possible to single out the most important aspects of each type. Intercity trains can offer one of the most modern ways to travel by rail – high-speed trains, thanks to which, the travel time is shortened and the level of comfort is increased accordingly. Suburban and urban trains offer traditional services – transportation of passengers on short, in-demand routes at normal speed; however, urban railways are also distinguished by their integrated infrastructure: tram tracks are laid on the streets, and the subway becomes part of the underground urban transport system. The unique steep-hill railway requires an appropriate geographical condition: mountainous areas. This means that it is not used in all countries; however, in Slovakia. it is a vehicle in demand both in the tourism and transportation sectors. In countries with plains as their main land surface, funiculars are mostly operated for tourism purposes – to go up to the visited object.

All these advantages of vehicles contribute to the main objectives of rail passenger transport, which are related to [9]:

- Increasing mobility;
- Shortening the travel time;
- Reduction of transportation costs;
- Increasing the number of passengers transported.

Scientists A. Jaržemskis and V. Jaržemskis also emphasise the importance of passenger transportation planning: correctly planned stopping places, planned routes, structured presentation of relevant information for passengers, and drawing up a schedule. After completing all these steps, traveling by rail transport becomes more attractive and efficient; therefore, users choose it more often, and the number of passengers transported by rail transport increases accordingly. In the scientific and legal literature, railway passenger traffic is described as a business, a social function and a service, the common main purpose of which is the transportation of passengers, ensuring their basic needs. This reveals a direct link between railway infrastructure and economic and social sectors. According to scientists V. Lingaitis and G. Sinkevičius, transport activity and the development of its infrastructure depend precisely on the development of these sectors [10]. Thus, economic and social factors have the greatest impact on rail transport, respectively.

According to the scientist S. Stoilova, it can be stated that the number of passengers per year describes the most accurate way of transporting passengers by railways; therefore, the influence of factors must be examined specifically for this indicator. The factors influencing passenger flows by rail are named differently by different researchers. J. Danis at all [11] separates the average wage. Other researchers [12] distinguish: GDP, the number of people who emigrated, the unemployment rate, the number of people and tourism. Scientist Stoilova supplemented the mentioned list with several more factors, i.e. length of railway and number of accidents [9]. The scientists Lingaitis and Sinkevičius [10] added the following factors to the list of influencing factors: the number of people of retirement age, the number of residents living in the countryside, the number of cars, and consumption costs.

GDP is usually mentioned in scientific articles and singled out as the most important factor that shows the level of economic development of the country. According to scientists V. Lingaitis and G. Sinkevičius, transport is one of the most important – the second or third – sectors that make up the GDP structure [10]. This can be justified based on statistics provided by the European Union, that on average 13.2% of each household's budget is spent on transportation services and goods related to this sector [13]. The direct relationship between the transport sector, more specifically, the number of passengers transported by railways, and the level of economic development of the country, is shown in the diagram below (Fig. 1).

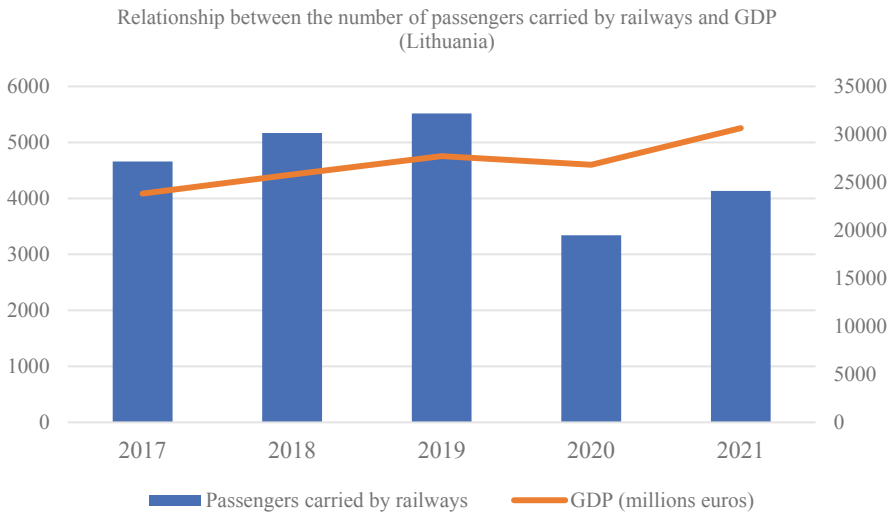


Fig. 1. Relationship between the number of passengers carried by railways and GDP.

Another factor often mentioned in scientific sources influencing railway passenger traffic is the number of accidents [9]. This factor is significant because it describes the safety and security of passenger rail transport. Although the infrastructure of passenger railway transport is constantly being improved, and the number of accidents is decreasing, one of their main causes is still suicide, the human factor, lack of caution on the

part of pedestrians and drivers, and train derailment [14]. This can be substantiated by the statistics of 2019, which show that 1,516 railway transport accidents occurred in the European Union, and the majority of them, 61%, were caused by an unidentified person on the tracks [15]. The length of railways is also a determining factor [9], which shows not only the level of infrastructure development, but also flexibility and adaptation to passenger needs: the better developed the railway network, the more attractive it becomes to existing and potential passengers. Scientists [12] distinguished tourism as an influencing factor. In the study, this factor is characterised by the hotel occupancy rate (the more intense the inbound tourism with overnight stays, the stronger it affects passenger transportation by rail). And, of course, changes in the population. Although we are not currently experiencing a demographic explosion, the population is gradually growing and requires a better public transport system, in this case railways, which is a more efficient means of public transportation and provides competitive services. Researchers [10, 12] singled out this factor because its changes directly react with the number of passengers transported by railways: the more the population in the state, the more traveling and potential passengers.

2 Methodology

In order to determine the influence of independent factors: GDP, average monthly salary, the number of cars per 1,000 inhabitants, the level of unemployment, and the number of inhabitants, on the dependent factor, the number of passengers transported by railways, a study will be conducted, which will consist of two steps. In the first step, a correlational regression analysis will be performed whose purpose is to determine causal relationships between factors. To achieve this goal, it is necessary to calculate:

1. Correlation coefficient, which shows whether there is a relationship between factors [16].

$$r = \frac{\left(\frac{1}{n-1}\right)\sum(x_i - \overline{x})(y_i - \overline{y})}{S_x S_y}, \tag{1}$$

   where n – amount of measured values; x_i – indicator values; y_i – indicator values; $\overline{x}$ – the arithmetic mean of the values of the indicators; $\overline{y}$ – the arithmetic mean of the values of the indicators; S_x – the variance of the value of the indicators; S_y - the variance of the value of the indicators.
2. Create a pairwise regression equation, the purpose of which is to determine the analytical expression of the dependence between the random variables X and Y [16].

$$y = a_0 + a_1 x, \tag{2}$$

   where a_0 and a_1 – linear coefficients.
3. Create the multivariate correlational regression equation, the purpose of which is to determine the relationship between the dependent factor Y and several independent factors $X_1, X_2, \ldots, X_n$ [16].

$$\hat{y} = a_0 + a_1 x_1 + \ldots + a_n x_n, \tag{3}$$

where $a_0, a_1 \ldots, a_n$ – linear coefficients.

In the second step, a forecast of passenger flows by railway will be prepared using several methods [16]:

1. Forecasting using the moving average method:

$$Moving\ average = \frac{the\ sum\ of\ the\ last\ n\ values}{n}, \tag{4}$$

where n – the duration of the selected period.

2. Forecasting by exponential smoothing method:

$$F_{t+1} = \alpha Y_t + (1 - \alpha) F_t, \tag{5}$$

where F_{t+1} – time series forecast for period t + 1; Y_t – relevant serial value in the period t; F_t – time series value in period t; α – smoothing constant ($0 < \alpha < 1$).

Forecast errors are calculated and the most accurate forecast of railway passenger traffic is determined. The research was carried out using two programs: MS Excel and SPSS.

3 Research Results

After analysing the scientific literature, it was found that the level of unemployment, GDP, the number of cars per 1,000 inhabitants, the number of inhabitants and the average monthly salary influence the transportation of passengers by railways (Y of this research). These factors will be denoted as X_1, X_2, X_3, X_4 and X_5 respectively below. Their significance, influence and connection with passenger traffic railways in Lithuania in the period 2015–2021.

In the first step, using the methods of correlational, paired regression and multivariate correlational regression analysis, we determine the existing relationships between passenger traffic on railways and the previously mentioned factors. The correlation coefficients obtained during it are presented in the table below (see Table 1).

Table 1. Correlation coefficients.

Correlation coefficients	r_1	r_2	r_3	r_4	r_5
Value of correlation coefficients	0.97	0.95	−0.92	0.84	0.92

Based on the data in Table 1, it can be said that there is a strong dependence between the listed factors (because all the values of the correlation coefficients are greater than 0.5). There is a direct relationship between rail passenger traffic and factors such as unemployment rate, GDP, population, and average monthly wages, while there is a

Table 2. Coefficients of the paired regression line.

Coefficients of the paired regression line	a0	a0	a0	a0	a0
Value of coefficients of the paired regression line	−4670808.40	−91767.60	115729.42	−27478589.71	−6399.62
Coefficients of the paired regression line	a1	a1	a1	a1	a1
Value of coefficients of the paired regression line	871853.67	1.70	−662.33	17357.07	0.01

strong inverse relationship between rail passenger traffic and the number of cars per 1,000 inhabitants. A paired regression analysis is performed to determine causality and possible prediction (see Table 2).

After compiling these equations, it became clear that the only factor that has a significant negative impact on passenger transportation by railways is the number of cars per 1,000 inhabitants. The graphical representation of the line $Y_3 = 115729.42 + (-662.33)*X_3$ in the diagram below demonstrates this well. The negative influence of the number of cars per 1,000 inhabitants is also proven by the inverse linear dependence equation, because when the independent variable increases by 10%, the value of Y decreases by 15.45%.

Multivariate correlational regression analysis is performed in order to establish a linear equation for determining causal relationships and possible prediction (see Table 3).

Table 3. Multivariate Linear model coefficients.

Multivariate linear model coefficients	a5	a4	a3	a2	a1	a0
Value of multivariate linear model coefficients	−0.0064	3512.50	−267.39	0.55	627190.89	−8907639.50

The value of the coefficient of determination is 0.997221348, therefore it can be stated that 99% of the behaviour of the dependent variable is explained by the behaviour of all X. After calculating the a0 and a1 coefficients, I made the expression of the linear model of multivariate correlation regression analysis: $Y_n = -8907639.50 + 627190.89 * X_1 + 0.55 * X_2 + (-267.39) * X_3 + 3512.50 * X_4 + (-0.0064) * X_5$.

However, this equation does not meet all the necessary characteristics confirming its usability in reality[17]:

- $R^2 \geq 0.20$.
- ANOVA $p < 0.05$.
- All t criteria $p < 0.05$.
- VIF ≤ 4.
- Meanings of the KUKO measure ≤ 1.
- The signs of the coefficients match the signs of the correlation coefficients.
- Judging from the histogram and the P-P graph, the residual errors are normal.
- Šapiro–Vilk criterion $p \geq 0.05$.
- Breuš–Pagan criterion $p \geq 0.05$.

Therefore, after performing a deeper analysis in the SPSS program, it was found that the multivariate regression model with independent variables number of cars per 1000 inhabitants and average monthly salary (X_3 and X_4) is suitable and can be used for analysing the influence of factors on railway passenger traffic: $Y = -10591957.26 + (-476.46)^* X_3 + 6738.82^* X_4$.

The second step of the research aims to use different forecasting methods to make a future forecast of passenger flows by train. For the first forecast, 2 years were chosen for the calculation of the last values, and for the second forecast 3 years. To determine which prediction is more accurate, the mean absolute relative errors of both were calculated. Data forecast using the moving average method). The error of the first prediction is equal to 0.126539, and the error of the second is 0.17771, which is larger and less accurate. Therefore, it can be said that the forecast is more accurate when two years were chosen for the calculation of the last values. A moving average chart (see Fig. 2) also illustrates this conclusion.

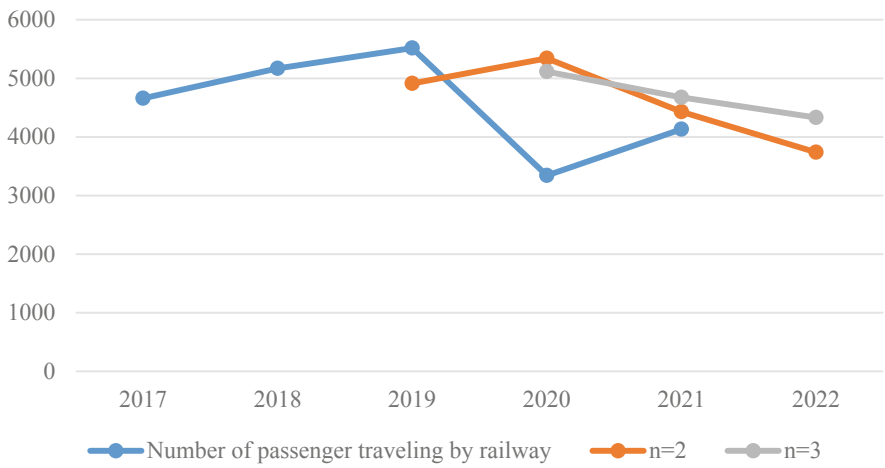


Fig. 2. Results of the Moving Average Method.

We forecast passenger flows by rail using the exponential smoothing method. To make a forecast, the smoothing constant values, 0.2 and 0.4, respectively, were chosen for the first and second forecasts. To determine which prediction is more accurate, mean

absolute relative errors were calculated with values of 0.2073 and 0.1541, respectively. Based on the results obtained, we claim that when calculating the forecast using this method, it is more accurate when alpha is equal to 0.4. This is also illustrated by the exponential smoothing graph (see Fig. 3).

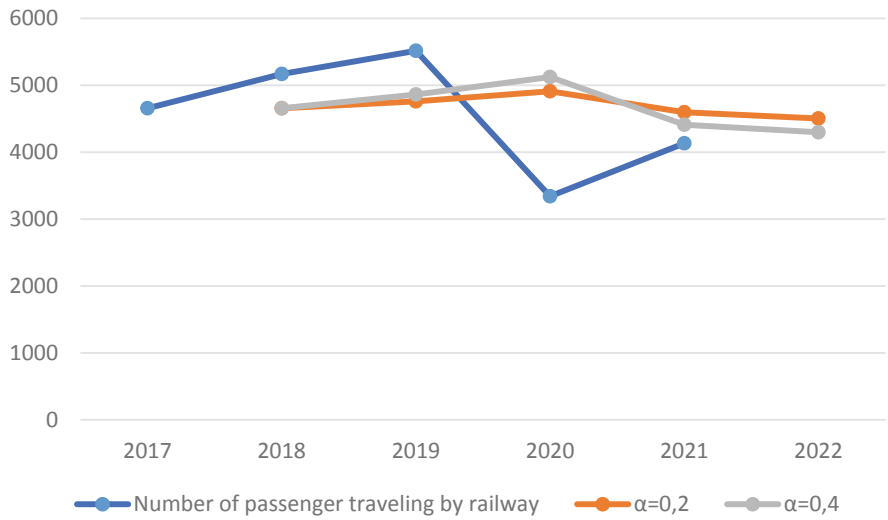


Fig. 3. Results of the Exponential Smoothing Method.

Thus, after forecasting passenger flows using the moving average and exponential smoothing methods, it was observed that passenger flows on the railway in 2022 must be higher than in 2021.

4 Conclusions

According to scientific sources, factors affecting passenger flows in rails have been identified. The most significant factor is GDP, unemployment rate, number of cars per 1,000 inhabitants, population average monthly salary. The results of the empirical study showed that 3 out of 5 factors (unemployment rate, GDP, and average monthly salary) were not appropriate, so the regression model needed to be improved. The inadequacy of the factors was determined based on the necessary criteria specified in the scientific sources (ANOVA $p < 0.05$; all t criteria $p < 0.05$; VIF ≤ 4; meanings of the KUKO measure ≤ 1), which resulted in a suitable regression model with the remaining two factors, the number of cars per 1,000 inhabitants, and the number of inhabitants. After these analyzes, I made a prediction of the change in the Y data, which determined the most accurate predictions with the smallest errors. After the forecast was made, it was found that the passenger flows by trains will increase.

References

1. Nowakowski, T.: Problems of transportation process reliability modelling (2012)

2. Kos, G., Brlek, P., Franolić, I.: Rationalization of public road passenger transport by merging bus lines on the example of zadar county. PROMET - Traffic Transp. **24**(4), 323–334 (1970). https://doi.org/10.7307/ptt.v24i4.439
3. Žvirblis, A., Butkevičius, J.: Evaluation of the competitiveness of the system of passenger transportation by railway. Transport **19**(4), 157–161 (2004). https://doi.org/10.1080/16484142.2004.9637969
4. Jarašūnienė, A.: Specialybės įvadas. Transporto inžinerinė ekonomika ir vadyba (2011)
5. Baltoji knyga. https://eur-lex.europa.eu/legal-content/LT/TXT/?uri=LEGISSUM:white_paper
6. Michniak, D.: Changes, problems, and challenges of passenger railway transport in Slovakia. Geogr. časopis - Geogr. J. **70**(3), September 2018. https://doi.org/10.31577/geogrcas.2018.70.3.12
7. Jaržemskis, A., Jaržemskis, V.: Keleivinis Transportas. Vilnius Gediminas Technical University, Vilnius (2017)
8. Pyrgidis, C.N.: Railway Transportation Systems. CRC Press, Boca Raton (2016)
9. Study of railway passenger transport in the European union. Teh. Vjesn. - Tech. Gaz. **25**(2), April 2018. https://doi.org/10.17559/TV-20160926152630
10. Lingaitis, V., Sinkevičius, G.: Passenger transport by railway: evaluation of economic and social phenomenon. Procedia - Soc. Behav. Sci. **110**, 549–559 (2014). https://doi.org/10.1016/j.sbspro.2013.12.899
11. Danis, J., Dolinayova, A., Cerna, L., Zitricky, V.: Impact of the economic situation in the slovak republic on performances of railway transport. Period. Polytech. Transp. Eng. **47**(2), 118–123 (2018). https://doi.org/10.3311/PPtr.11185
12. Döménya, ŠČI., Dolinayováa, A.: Methodology proposal of monitoring economic indicators in a railway passenger transport company using controlling tools. Transp. Res. Procedia **55**, 141–151 (2021). https://doi.org/10.1016/j.trpro.2021.06.015
13. Transport sector economic analysis. https://joint-research-centre.ec.europa.eu/scientific-activities-z/transport-sector-economic-analysis_en
14. Railroad accidents: common causes, statistics and prevention. https://www.sidgilreath.com/learn/railroad-accidents-causes.html
15. Railway safety statistics in the EU (2022). https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Railway_safety_statistics_in_the_EU
16. Pabedinskaitė, A., Činčikaitė, R.: Kiekybiniai modeliavimo metodai. Vilnius Gediminas Technical University, Vilnius (2016)
17. Čekanavičius, G., Murauskas, V.: Taikomoji regresinė analizė socialiniuose tyrimuose. Vilniiaus universiteto leidykla (2014)

Adapting Private Sector Warehousing Services to the Needs of the Lithuanian Armed Forces

Aidas Vasilis Vasiliauskas(✉), Ieva Meidutė-Kavaliauskienė, and Edgaras Čerškus

General Jonas Žemaitis Military Academy of Lithuania, Šilo 5A, Vilnius, Lithuania
{aidas.vasilisvasiliauskas,ieva.meidute}@lka.lt,
edgaras.cerskus@mil.lt

Abstract. The need for increase a military capability of the Lithuanian Armed Forces due to the increasing national threats (especially taking into consideration the latest events in Ukraine), calls for a growing number of military equipment and techniques (we do not consider explosives and ammunition). This, hypothetically, requires more storage spaces and warehousing operations, and encourage the Armed Forces to seek for a cooperation with the private sector, which, without any doubt, has more expertise and technical equipment. The potential of private sector warehousing services to meet the needs of the Lithuanian Armed Forces has not yet been fully assessed and exploited. For this reason, the main objective is to understand the nature of current relations between the Lithuanian Armed Forces and private sector providing logistics services. Using the method of systematic analysis of legal acts and documents led to the understanding of the theoretical aspects of public-private cooperation in the field of warehousing services, while application of qualitative research using a structured interview method allowed for the identification of current situation of cooperation between the Lithuanian Armed Forces and the private sector as well as identification of the reasons why private sector warehousing services have not been widely used in the Lithuanian Armed Forces. The article ends with counting the measures which would enable the use of private sector warehousing services to meet the Lithuanian Armed Forces' needs.

Keywords: Lithuanian Armed Forces · Private sector · Public-private partnership · Outsourcing · Warehousing services

1 Introduction

In today's world, logistics is an integral part of every developing and operating organisation. In the Lithuanian Armed Forces, logistics ensures the efficient supply for military units, keeping them in the required combat readiness, whether in peace, crisis, or war, for as long as required to fulfil the operational tasks. It is essential to develop an efficient and unified logistics system for the entire Lithuanian Armed Forces, which would ensure uninterrupted execution of the Army's tasks in both national and international operations. Private-public partnerships can be used to ensure a sustainable and efficient

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 548–555, 2023.
https://doi.org/10.1007/978-3-031-25863-3_52

logistics system for the Armed Forces and to ensure efficient use of resources and capabilities. The relationship between the private and public sectors creates a collaborative framework, which has become increasingly popular and widely used in recent years to enhance the capabilities of the military [9]. Private-public cooperation is widely used around the world for the provision of certain services, such as transport, storage, water and wastewater, energy, environment, public health, etc.

Like many other countries around the world, Lithuania is expanding the sectors of infrastructure investment and public services. Limited funding encourages both public and private sector actors to engage in cross-sectoral cooperation [1]. Public-private partnerships can be described as the provision of services by a private investor that are attributed to the public sector, with the development of the infrastructure necessary for the provision of these services. The Lithuanian Armed Forces is modernising and becoming a smart consumer, whose functionality requires a wide range of goods and services. The Lithuanian Armed Forces cannot sustain itself with its existing resources alone. Therefore, the need for cooperation with companies providing specific services in the civilian sector becomes relevant.

Public-private cooperation is widely covered in the academic literature. Some authors have explored the concept of public-private partnerships and the possibilities of partnerships between the two sectors [1, 3]. Others explore long-term relationships in the supply chain, discuss a model for managing human resource outsourcing in service companies [5, 8]. We even can find sources that analyse the field of expeditionary military cargo, where outsourcing is used to transport military equipment [2]. However, the use of warehousing services to meet the needs of the public sector has not been explored. This raises a legitimate question - what cooperation opportunities exist and what cooperation model would meet the needs of a modern, fast-growing Lithuanian army?

2 Concept of Private-Public Cooperation

Private sector involvement in the public sector is based on meeting the needs of the public sector. The structure of public-private cooperation is not a new phenomenon today. Public-private partnerships are becoming increasingly important to achieve the desired ever-changing organisational objectives and to reduce management problems in various specific areas. The concept of public-private partnership is defined as "a form of public-private contract that requires financial, technological, experience, knowledge and other investments from the private partner, in which the management of the main risks of the project is transferred to the private sector, and the public sector pays the private sector to provide the public with the services traditionally provided by the public sector itself". Scientists argue that the use of the private sector in the provision of public services can be supported in two ways: through outsourcing to the public sector and through public-private partnerships (PPPs) [7]. Public-private partnerships (PPPs) are a common process in modern society, both abroad and at home. When analysing the literature, it is noticeable that the term used by authors when referring to public-private partnerships (PPPs) is also cooperation.

Public-private partnerships can be described as "services provided by a private investor that fall within the competence of the public sector, and the development of

the infrastructure necessary for the provision of these services". Public-private partnerships can be defined as a collaboration between the public and private sectors over a certain period of time, which results in the creation of public goods and services, as well as the sharing of the risks, costs and resources associated with these activities.

Some scientists state that the key driver of public-private partnerships is mutual benefit [4]. There are also some sources that examines cooperation between the two sectors on the basis of a mutual agreement that allows private sector organisations to operate in the public sector [6].

PPPs are seen as an increasingly important factor in every country's economy. In Lithuania, as in many other Eastern and Central European countries, the management and implementation of public-private partnerships is still a novelty. Public-private collaboration is a well-known phenomenon in the modern world, which is increasingly relevant in order to keep up with the ever-changing goals and objectives of companies and the new financial, human resource management and strategic organizational direction issues that arise in organizations.

Summarising the concept of public-private partnerships, it can be argued that cooperation between different actors - public and private - is possible and increasingly popular in modern society. The private sector's pursuit of financial gain and the public sector's desire to improve public services encourage both parties to seek forms of cooperation with each other. It is very important to note that this form of cooperation, unlike simple public procurement, allows the partners to share and manage risks efficiently. The analysis of the scientific literature suggests that this form of cooperation improves and accelerates the implementation of projects, as well as providing better infrastructure solutions, and the possibility to reduce costs and fees. This form of cooperation allows public funds to be used in other public sectors. However, there is a risk that the private sector may not ensure the provision of quality public services to users to reap financial benefits.

3 Peculiarities of the Lithuanian Armed Forces Logistics System

In the Lithuanian Armed Forces, logistics is defined as activities related to the planning and execution of the movement and sustainment of forces (NATO Dictionary of Terms and Definitions, 2014). According to the Logistics Concept of the National Defence System (hereinafter referred to as the 'Logistics Concept of the NDS', 2021), it can be stated that through logistics, a military force is able to remain in a defined combat readiness for as long as necessary to achieve military objectives. The objective of logistic support is that the required assets, supplies, services and support will be provided at the right time, in the right place and in the right quantity.

To summarise the logistics system of the Lithuanian Armed Forces (hereinafter referred to as the LAF), the LAF logistics system performs the same logistics functions as the private sector. However, due to certain specific tasks, such as national defence, a distinction is made between peacetime logistics (institutional logistics) and wartime logistics (operational logistics). The LAF logistics system must ensure the proper functioning of the units in peacetime - military exercises, training, firing, day-to-day activities - and ensure the level of combat readiness of the army in relation to national defence

objectives and plans. In accordance to the regulations set in LAF strategic documents, to ensure that units are adequately prepared for battle, the LAF must stockpile adequate quantities of materiel in designated areas. To this end, and in accordance with the principles of *integrity, compatibility and interoperability and pre-positioning,* the private sector warehousing services could be used.

The Lithuanian Armed Forces, like any other public sector entity, relies on the services of the private sector (examples are waste utilization, food supply and etc.) to ensure the proper functioning of its daily operations. The army, its personnel and military units must be adequately equipped and maintained to be able to successfully carry out their assigned tasks. According to the Military Doctrine of Lithuania, the main functions of the Armed Forces are to respond to conventional-non-conventional threats, regional crises, information and cyber-attacks, activities of intelligence services of other states, crises, natural disasters, and possible terrorist attacks. As a result, the LAF carries out preparedness activities directly related to its tasks and functions in its day-to-day activities, while most of the administrative activities have been transferred to the private sector. The activities related to the procurement of services from the private sector are mainly: Administration and maintenance of military sites; maintenance and servicing of infrastructure (buildings); site security services; sewing-manufacturing services; transportation of military equipment and personnel; equipment repair and servicing; construction-engineering work, etc.

However, the use of third-party private sector warehousing services for LAF needs is not widespread. Document analysis showed that the first use of private sector warehousing services in the NDS started in 2017. As mentioned above, due to the increasing funding of the LAF and the increasing number of machinery and equipment, the Depot Service does not have sufficient capacity/infrastructure to cover the warehousing needs of the entire National Defence System. As a consequence, some LAF units already keep their assets in the warehouses of private sector companies located in different regions of Lithuania.

The growing number of defence and security procurements and the increasing needs for storage of equipment and machinery are forcing LAF to look for ways to provide adequate storage and warehousing services. According to the Strategic Operational Plan 2019–2021 of the National Defence System, new warehouses are to be built, existing engineering structures are to be reconstructed, and logistics infrastructure is to be expanded across the whole territory of Lithuania to achieve these goals.

Summarising the results of the analysis of the documents regulating the logistics and warehousing functions of the Lithuanian Armed Forces, it can be stated that the Lithuanian Armed Forces cannot survive on its own and therefore uses the private sector to implement some of its activities. Therefore, it can be assumed that the use of third-party private sector warehousing services for the needs of the LAF could ensure the implementation of the principles set out in the doctrines, meet the needs of the LAF's rapidly growing capabilities, ensure the security of the military logistic stocks, and address the lack of logistic warehousing infrastructure.

4 Research Methodology

The qualitative research method was chosen to determine the adaptation of private sector warehousing services to the needs of the Lithuanian Armed Forces. The qualitative research method chosen for the study was interviews, in order to obtain a diverse and informed opinion on the subject. A structured interview method was used. This method is carried out by preparing a plan of questions in advance which reflects the importance of the issue under study, but in the course of the questions, if the interview is oral, additional questions can be asked of the informant for the purposes of interpretation.

The aim is to investigate the peculiarities of cooperation between the Lithuanian Armed Forces and the private sector in the field of warehousing services.

Objectives:

- To analyse the current situation of cooperation between the Lithuanian Armed Forces and the private sector in the field of warehousing services.
- Identify the reasons why private sector warehousing services are not yet widely used in LAF.
- Identify measures to leverage private sector warehousing services to meet the needs of the LAF.
- Identify the potential benefits for the private and public sectors of cooperation between the LAF and the private sector in the field of warehousing services.

The informants for the structured interviews were selected based on a number of key criteria:

- more than 5 years' service in the Lithuanian Armed Forces;
- more than 5 years of experience in logistics in the Lithuanian Armed Forces;
- more than a year of experience in the warehousing sector of the Lithuanian Armed Forces.

A total of 27 informants (experts) were to be interviewed and a questionnaire was sent to all of them by email, but only 14 informants were able to provide information.

The interview questionnaire used consisted of four blocks of questions:

- *Block I*. It includes questions seeking expert views on the current logistics system in the LAF and the potential for using the private sector to provide warehousing services in the LAF.
- *Block II*. It covers questions to find out the reasons why private sector warehousing services have not been widely used in LAF so far.
- *Block III*. It covers questions aimed at identifying the means to leverage private sector warehousing services to meet the needs of the LAF.
- *Block IV*. It includes questions to identify the benefits that cooperation between the LAF and the private sector in the field of warehousing services would bring to the private and public sectors.

5 Main Findings

From the answers of the experts obtained during the interviews, we can determine the reasons why private sector warehousing services have not been widely used in the Lithuanian Armed Forces so far. Informants were asked to rate the reasons on a scale of 10 (most important, highest rating) to 1 (lowest rating). The most frequently cited reasons were legal regulations, lack of cooperation, material aspects and lack of experience. The most important reason given by the informants was legal regulations, with an average score of 6.7. The material aspects as a reason have an average score of 5.7 and are considered by the experts to be the second most important. The experts gave an average score of 3.6 to the lack of experience and an average score of 2 to the lack of cooperation between the LAF and the private sector.

To find out how to address the reasons for the lack of cooperation between the Lithuanian Armed Forces and the private sector, the interviews were aimed at finding out the ways to address the reasons. Summarising the responses of the informants, there was a wide range of opinions and several suggestions on how to address the reasons that make it difficult for LAF to use private sector storage services.

Except for the overlapping views of the informants on how to address the reasons that make it difficult for LAF to use private sector warehousing services, they were asked to rank the proposed measures/ways from easiest to implement/adapt (10 points) to most difficult to implement/adapt (1 point). The average score of the informants' responses to the three most frequently identified responses on the possible elimination of the problems that make it difficult for LAF to use private sector warehousing services was similarly distributed. The first most important and most likely to be implemented was 'familiarisation with the current situation' (7.5 points). The second most important was 'legal framework' (6.3 points) and the third was 'needs assessment' with 6 points. The following were also highlighted by the informants in the survey as the easiest to implement there should be a comprehensive solution to the situation/problem; optimal adaptation of the needs during peace and war; and optimal contracting and finance for peace years.

The analysis of the experts' responses to the survey highlighted two main aspects of the benefits of applying the tools in the LAF logistics system, namely the economic benefits and the facilitation of warehouse management control.

New tools to coordinate and manage the logistics system in the LAF and the warehousing services sector would create more opportunities.

The last interview question sought the experts' views on the benefits of the proposed measures for the private sector. The survey revealed that informants considered that the private sector would benefit from the assurance of financial inflows and the reliability, consistency, and cooperation of the supplier. Successful cooperation in the area under consideration would lead to improved economic benefits, which include many aspects such as operational savings in resources, less infrastructural capacity, freeing up existing LAF warehouses for strictly accountable material measures, etc. There are also views that it would improve the administrative work of warehousing: it would facilitate receipt, storage, distribution, issue, help to address weaknesses and gaps in the current system, and allow LAF assets to be stored in accordance with warehousing requirements.

6 Conclusions

After theoretical and empirical analysis of the cooperation between the Lithuanian Armed Forces and the private sector in the field of warehousing services, it can be stated that one form of outsourcing can be identified as *Military Outsourcing*. Military outsourcing is a specific outsourcing service provided to the national defence system with security requirements. The problem with such services is that private sector entities are subject to higher security requirements in order to provide the services.

Warehousing can be identified as one of the most important activities in the logistics process. Warehousing activities include the storage of stocks, products and raw materials, and the timely management of information on the status and quantities of stored items. Properly coordinated and organised warehousing activities ensure the smooth operation of the logistics process. The application of the latest innovative technologies in the private sector in the field of warehousing services ensures an efficient warehousing process. It can be assumed that the use of private sector warehousing services in the public sector would ensure modern, innovative warehousing activities.

The analysis of the documents regulating the logistics and warehousing functions of the Lithuanian Armed Forces has shown that the highest-level documents, the Lithuanian Military Doctrine (2016), emphasise the principles of logistics planning and organisation, such as: *pre-positioning, integrity and interoperability,* but in practice these principles are not applied. The Minister of National Defence's procedure for planning and storing stocks (2009) provides for the use of third-party warehousing services for the needs of the Lithuanian Armed Forces, but it is not centralised. It is assumed that the use of third-party private sector warehousing services for the needs of the Lithuanian Armed Forces could ensure the implementation of the principles set out in the doctrines, meet the needs of the rapidly growing capabilities of the Lithuanian Armed Forces, ensure the security of military logistic stocks, and solve the shortage of logistic storage infrastructure.

The survey revealed the reasons why private sector warehousing services are still not widely used in the Lithuanian Armed Forces. The main reasons are the lack of cooperation between the Lithuanian Armed Forces and the private sector, material aspects including lack of cost-benefit analysis, security requirements, finances, and lack of experience (training of specialists, lack of practice). The study also identified suggestions that would help to address the above-mentioned causes. The proposals include a flexible legal framework, a cost-benefit analysis of the current situation, simplification of the public procurement procedure, updating of the documents of the Lithuanian Armed Forces regulating the public procurement procedure, and the involvement of the private sector in the training of logistics specialists for the Lithuanian Armed Forces.

References

1. Chlivickas, E., Svogzlys, P.: Public-private partnership in Lithuania: areas for improvement. Pub. Adm. **1/2**(53/54), 34–42 (2017)
2. Erturgut, R., Alanur, H.: Freight forwarding and military logistics as a strategic outsourcing form: an empirical analysis on military freight forwarding firms in U.S. J. Multi. Eng. Sci. Technol. **2**(9), 2382–2390 (2015)

3. Hodge, G.A., Greve, C.: On public-private partnership performance: a contemporary review. Public Works Manag. Policy **22**(1), 55–78 (2017)
4. Hoppe, E.I., et al.: Public-private partnerships versus traditional procurement: an experimental investigation. CGS Working Paper **2**(2), 1–46 (2010)
5. Idris, S., Mohezar, S.: Logistics commitment: an evidence of long-term relationship on sustainable global supply chain. Int. J. Eng. Technol. **7**(4.28), 6–10 (2018)
6. Savas, E.S.: Privatization and Public-Private Partnerships, 2nd edn. Seven Bridges Press, New York (1999)
7. Tang, L.Y., et al.: A review of studies on public-private partnership projects in the construction industry. Int. J. Project Manage. **28**(7), 683–694 (2010)
8. Žitkienė, R., Blusytė, U.: The management model for human-resource outsourcing among service companies. Intelektinė ekonomika **9**(1), 80–89 (2015)
9. Wang, Y.: Evolution of public-private partnership models in American toll road development: learning based on public institutions' risk management. Int. J. Project Manage. **33**(3), 684–696 (2015)

Innovations Development in Intermodal Freight Transport: Polish Practitioners' Viewpoint

Ludmiła Filina-Dawidowicz[1](✉), Tatjana Paulauskiene[2], Alla Selivanova[3], Daria Możdrzeń[1], and Sara Stankiewicz[1]

[1] West Pomeranian University of Technology in Szczecin, 41 Piastów Avenue, 71-065 Szczecin, Poland
{ludmila.filina,daria.mozdrzen}@zut.edu.pl, sara-stankiewicz@wp.pl

[2] Klaipeda University, Herkaus Manto g. 84, 92-294 Klaipeda, Lithuania
tatjana.paulauskiene@ku.lt

[3] Odesa National Academy of Food Technologies, 112 Kanatna Street, Odesa, Ukraine

Abstract. Nowadays, the role of intermodal transport is increasing on the global market. This transport should be developed efficiently considering the customers' needs, as well as possibilities of services providers. Therefore, innovations are introduced in different areas of this transport to improve its operation, increase entrepreneurship of companies, and meet clients' expectations. The article aims to investigate the areas of intermodal freight transport development. The case study of Polish market dealing with intermodal transport operation was examined. The areas of innovations development in intermodal transport have been identified. The questionnaire was created, and survey was carried out among intermodal transport companies' representatives. The opinions of intermodal terminals representatives and forwarders were analyzed in detail. It was possible to create the ranking of areas considered by respondents as essential to introduce innovations in intermodal transport. The opinions of different groups of practitioners involved in intermodal transport were analyzed. Information and telematics technologies development and automation of handling processes were ranked as the most important for implementation of innovations in intermodal transport.

Keywords: Intermodal freight transport · Innovation · Transport efficiency · Intermodal terminal

1 Introduction

Intermodal freight transport plays a key role in global supply chains [1]. This transport is related to carriage of intermodal loading units (containers, semi-trailers, swap-bodies) using at least two transport modes [2]. Its dynamic development makes it susceptible to changes, including the implementation and operation of modern technical and technological solutions. The sustainable development of intermodal transport involves the development of activities, which bring higher economic and social results, as well as reduce the negative impact on the environment [3].

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 556–565, 2023.
https://doi.org/10.1007/978-3-031-25863-3_53

Innovations are crucial to improve company's competitiveness level [4]. On the one hand, intermodal transport has been already developed dynamically for last decades, on the other hand, the improvement of its operation is still needed. Different new, innovative solutions in intermodal transport are introduced [5, 6]. The challenges faced by companies involved in intermodal transport development are related to the selection of areas of innovations implementation.

Conducted literature analysis revealed that different areas of intermodal transport operation are improved by application of innovative solutions. However, current areas and needs for implementation of innovations were analyzed to the small extent. Therefore, the research question was set as follows: "In which areas of intermodal transport should innovative solutions be implemented?".

The article aims to investigate the areas of innovations development in intermodal transport, considering practitioners' viewpoint. The case study of Polish market was considered. The areas of innovative solutions implementation in intermodal transport were determined. The questionnaire survey was carried out among the practitioners dealing with intermodal transport operation and achieved opinions were analyzed in detail. It was possible to create the ranking of mentioned areas, considering practitioners viewpoint. Additionally, the opinions of different groups of practitioners involved in intermodal transport were analyzed and compared. The research results allowed to determine the areas of intermodal transport operation where innovations are needed.

2 Literature Review

Implementation of innovation is complicated decision-making process. Innovative activities of an enterprise depend on the variety of factors. These factors include, among others, structure of its links to get information, knowledge, technologies, practices, human and financial resources [7]. It should be noted that companies are also connected to other actors within the innovation system, e.g., government, universities, policy departments, competitors, suppliers, customers, etc. [6, 8]. Therefore, all these actors should cooperate to stive for synergetic effect of improved activity.

Different areas of intermodal transport operation are improved. Literature analysis revealed that these areas are related to innovations into technological solutions (handling operations, infrastructure, transport means), optimizing of intermodal transport and gateway concepts, environmental sustainability, digitalization of supply chains, organization, and management [9–11]. However, available studies put attention only to the selected possible areas of innovations implementation and do not cover the needs reported by practitioners.

One of the areas mentioned in the subject literature is related to technological innovations dealing with transport infrastructure development [11]. Due to the vast importance of infrastructure for local and global supply chains, its structure and quality should be improved to increase transport efficiency, level of safety, reliability and decrease the costs level and enhance economic development [6]. Intermodal transport involves infrastructure of different transport modes (road, rail, maritime, inland navigation, air) [12]. Each of modes should operate properly to enable performance of transport process. It is noted that innovations also concern port infrastructure, which integrates various modes

of transport [13]. Therefore, it may be stated that appropriate infrastructure network development influences the efficiency of intermodal transport [14, 15].

Next area of innovations implementation concerns transport means. The ways to improve the quality of water (maritime, inland), land (road, rail), and air transport means fleet were investigated [1, 16]. The attention is paid to fact that road transport impact negatively the natural environment, therefore, innovations in this area may also concern the implementation of ecological power sources for vehicles (e.g., the use of electric, hybrid, hydrogen fleet, etc.) [17, 18].

Among described activities improving of handling equipment and devices is noted, including emerging innovative technologies (e.g., automatic system for horizontal and parallel handling, container transhipment robots, automated gate for data exchange) used in ports and intermodal terminals [1]. These new devices aim to fulfil environment protection requirements and help the logistics sector to become safe, reliable and cost competitive [19].

Innovations may also deal with intermodal loading units (e.g., containers, semi-trailers, trailers) [20]. These units are transported under various modes of transport and enable safe cargo transport. Despite the introduced standardization of these units, innovations in this area are focusing on extending the possibilities of adapting the configuration of the load unit to individual requirements. Smart loading units, e.g., containers, are equipped with sensors that measure different parameters of cargo transport [21].

A lot of attention is drawn to information technologies and telematics development in intermodal transport. Innovative digital services are introduced in transport activity [9, 16, 22]. It is highlighted that digital transformation has become mainstream in Industry 4.0 to innovate many industries, including intermodal transport and supply chains. The use of digital technologies, such as the next generation of communication and networking (i.e., 5G), the Internet of Things, artificial intelligence, machine learning, big data analytics, and cloud computing is widely discussed [23]. These solutions allow to better integrate different modes involved in intermodal transport [5]. The role of digital solutions in seaports, as intermodal hubs, is discussed [22]. These nodes are the places where software is highly composite and tailored to a large number of users (from the so-called port communities). ICT services (Navigation Safety, e-Freight, and Logistics) are introduced, and their efficiency is examined [24, 25]. These solutions contribute to improve the performance indicators of seaports and decrease the risk level in relevant areas [13].

Organization of services and cargo handling processes are also mentioned in the literature as needed to increase the competitiveness of intermodal transport in a sustainable way [26]. Forwarders are planning the transport routes and face different challenged during decision-making process [27]. Distribution innovations that operate together as a system are also examined [28]. The introduced innovations focus on changes in the way the processes are implemented, which may be related to their automation, e.g., changes in the planning of the distribution of cargo on the means of transport (e.g., on a ship, train), the method of loading and unloading activities (increasing their safety, reliability, quality), reducing the risk associated with the implementation of processes, duration and costs.

The implementation of innovative solutions is in line with the idea of sustainable development, which aims to protect the natural environment. Environmental protection is one of the areas of transport development [29, 30]. Sustainable solutions are introduced to improve transport activity [31]. Transport is the world's significant source of pollution, so it is not surprising that many initiatives are being taken to reduce the level of pollutions. Therefore, renewable energy sources, energy-saving and zero-emission engines in transport means are introduced, transport infrastructure is modernized, etc. [32]. It is highlighted that the alternative solutions to integrate sustainable transportation modes into a coherent network should be provided [33].

Implemented innovations should ensure reliable communication and transmission of information in real time. This may deal with information sharing about the condition and location of the vehicle and/or cargo, enabling comprehensive service of systems supervising the functioning of transshipment processes, etc. [34]. Lack of proper contact with the transport operator or driver, as well as between companies cooperating in the implementation of the transport process may cause financial, material, reputational losses, etc. [35, 36].

Planning and organization of intermodal transport chains have to be performed by qualified staff [2]. People managing intermodal transport should possess appropriate education and professional experience. Lack of a sufficient level of competences and employees' insubordination often lead to losses, including financial and material one. It is important that intermodal transport operators keep improving their skills and draw conclusions from completed orders. They should constantly update their knowledge to be able to make the right decisions in the field of operation and development of enterprises, including implementation of innovative solutions.

Based on available literature review it was revealed that the issues of intermodal transport development prospects were analyzed to a small extent and there is a need to investigate the opinions of intermodal transport practitioners on the areas preferred for innovations.

3 Methodology

Based on conducted literature analysis the following areas of innovative solutions implementation in intermodal transport have been identified (Table 1).

The questionnaire was developed that contained both general and thematic questions. General questions aimed to set the respondents' profile, including gender, work experience and position occupied. In turn, thematic questions were formulated to get the opinion of practitioners on the needs to implement innovative solutions in intermodal transport.

The survey was carried out in September/October 2021 in Poland. The questionnaire in electronic form was sent to 53 company dealing with intermodal transport. There were: intermodal terminals located in seaports (container and ferry terminals) and in the hinterland (rail-road terminals), as well as forwarders. The questionary was filled by 21 representatives of intermodal transport companies. Then, the achieved data was analyzed and opinions of considered groups of practitioners were compared.

Table 1. Areas of innovative solutions implementation in intermodal transport.

Abbreviation	Area of innovative solution implementation
A1	Transport infrastructure (including seaports)
A2	Water transport means (maritime, inland)
A3	Land transport means (road, rail)
A4	Air transport means
A5	Handling equipment and devices (including automated solutions)
A6	Intermodal transport units
A7	Information and telematics technologies
A8	Organization of handling process
A9	Environmental protection
A10	Communication
A11	Staff qualifications

4 Results

The questionnaire was filled in mainly by men (86% of the respondents). Women constituted only 14% of practitioners. Respondents had different work experience (up to 25 years). The most of partitioners (48%) worked in companies that serviced more than 75% of orders related to intermodal transport.

76% of respondents dealt with innovations implemented in intermodal transport. Nevertheless, some employees were not familiar with new solutions application within the company's activity (or were not sure about it). Among the respondents (24%) who had not experienced innovations were 2 person who had no contact with innovations, while 3 people chosen the answer "Hard to answer".

According to the majority of respondents (90%), the implementation of innovative solutions in intermodal transport increases its efficiency. It should be noted that there were no opposite answers. On the basis of collected data it could be stated that the most of practitioners dealt with innovations and believe that their implementation allow to improve intermodal transport operation.

The main research question was formulated as follows: "In which areas of intermodal transport should innovative solutions be implemented?". The respondents were asked to express their opinion on that issue and rate earlier identified areas of innovative solutions implementation in Likert scale [37] from 1 to 5, where 1 - the least important area, 5 - the most important area of innovations implementation (Fig. 1).

Achieved answers analysis revealed that in opinion of practitioners the most needed areas in which innovative solutions in intermodal transport should be implemented are information and telematic technologies (area A7) and handling equipment and devices (including automated solutions) (A5). The calculated mean value was the same for mentioned options (4.57 points). In the survey, the respondents also gave high ratings to the need to improve organization of handling process (A8) and land transport means (A3).

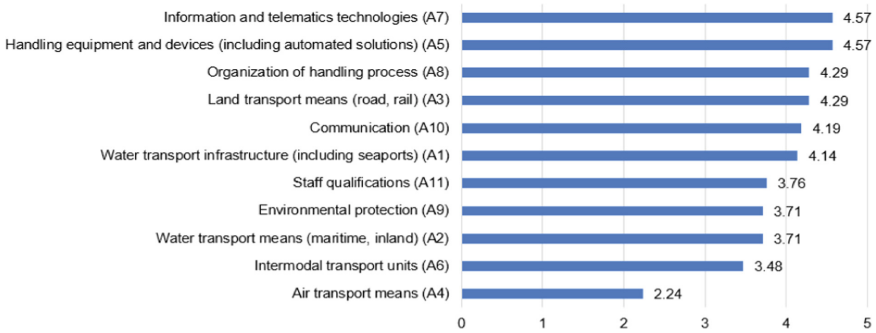


Fig. 1. The responses to the question "In which areas of intermodal transport should innovative solutions be implemented?" (mean value).

That lead to the conclusion that information flow and efficiency of handling operations in intermodal terminals affect the intermodal transport operation. Therefore, innovations in these areas are required.

In practitioners' viewpoint, the least important areas are related to improvement of air transport means (A4) and intermodal transport units (A6). That opinions may deal with the fact that air transport is rather advanced and well developed, as well as is relatively rare used to transport goods within intermodal transport chains, compared to other branched of transport.

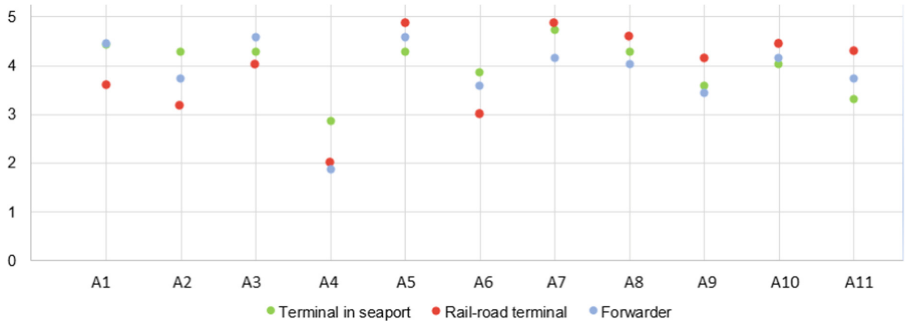


Fig. 2. Rates of areas for innovative solutions implementation in intermodal transport given by individual groups of respondents (mean values).

Moreover, selected areas of innovative solutions implementation in intermodal transport were analyzed in detail within the individual groups of respondents who represented (Fig. 2): (1) intermodal terminals located in seaports, (2) intermodal terminals located in the hinterland, (3) forwarders.

The mean values and standard deviation were calculated for selected areas considering assessments given by respondents. On that basis it was possible to set the ranking of areas within respondents' groups (Table 2).

Table 2. Ranking of areas for innovations implementation within respondents' groups.

Terminal in seaport			Rail-road terminal			Forwarder		
Area	Mean value	Standard deviation	Area	Mean value	Standard deviation	Area	Mean value	Standard deviation
A7	4.71	0.45	A7	4.86	0.35	A3	4.57	0.49
A1	4.43	0.49	A5	4.86	0.35	A5	4.57	0.73
A2	4.29	0.45	A8	4.57	0.49	A1	4.43	0.73
A3	4.29	0.45	A10	4.43	0.73	A7	4.14	0.35
A5	4.29	0.70	A11	4.29	0.45	A10	4.14	0.99
A8	4.29	1.03	A9	4.14	1.36	A8	4.00	0.93
A10	4.00	0.76	A3	4.00	0.53	A2	3.71	0.70
A6	3.86	0.83	A1	3.57	1.29	A11	3.71	1.28
A9	3.57	1.18	A2	3.14	1.12	A6	3.57	0.49
A11	3.29	1.28	A6	3.00	1.31	A9	3.43	1.29
A4	2.86	1.25	A4	2.00	1.07	A4	1.86	0.64

It should be noted that the opinions of different groups of respondents vary. Representatives of intermodal terminals located in seaports and hinterland consider information and telematics technologies (A7) as the most needed area for innovations implementation. In turn, this area was placed by forwarders on the fourth place after land transport means (road, rail) (A3), handling equipment and devices (including automated solutions) (A5) and transport infrastructure (including seaports) (A1). Nevertheless, all respondents had the same viewpoint on the need to introduce innovations in air transport means and gave the lowest rates to this area. It should be highlighted that the rankings of individual areas reflect the needs of analyzed groups.

Respondents were also asked to provide other areas (not mentioned in the questionnaire) which, in their opinion, may affect the efficiency of intermodal transport. The answers were given mainly by representatives of seaports and rail-road terminals. Among the proposals the following aspects were mentioned: implementation of automated reloading and autonomous vehicles, better work organization of railway carriers, better regulation of costs to access railway infrastructure, easy/equal access to infrastructure, improvement of railway infrastructure quality.

5 Conclusions

Intermodal transport development is conditioned by innovations implementation. The article investigated the areas where innovations may be implemented, considering practitioner's viewpoint. Effective execution of innovations within key areas of intermodal transport will allow to meet the needs of consumers of transport services, reduce operating costs and the level of risk, increase its efficiency and productivity.

In opinion of most of surveyed practitioners, implementation of innovative solutions has significant impact on the efficiency of intermodal transport. However, not all examined companies' representatives were familiar with innovations. Therefore, while introducing new solutions in enterprises the attention of intermodal transport companies should be paid to the need to take actions striving to increase both the efficiency of their operation and the knowledge of their employees on the possibilities to introduce new solutions.

Conducted research analysis revealed that representatives of examined intermodal transport companies consider the information and telematics technologies, as well as handling equipment and devices as the most important current areas for innovations implementation. The least important area deals improvement of air transport means.

The results of examination of opinions given within respondent's groups show that practitioners have different attitudes and needs for innovations implementation. Intermodal terminals' representatives mentioned the need to improve information and telematics technologies that deal with innovation in digitalization and artificial intelligence. Terminals located in seaports paid attention to the need to improve transport infrastructure. Rail-road terminals believe that innovations directed to handling equipment and devices will increase intermodal transport efficiency. Forwarders expressed the same opinion, and among the most important areas of innovations implementation also mentioned land transport means fleet improvement.

It should be noted that the research results demonstrate the viewpoint of representatives of intermodal transport companies located in Poland. Therefore, it could be reasonable to repeat the research and conduct the similar survey in other countries to collect data for comparative analysis.

The research results may be useful for managers of intermodal transport companies, as well as representatives of authorities' decision-makers who plan and execute the investments directed to improve intermodal transport efficiency. Our future research will cover the investigation of innovation development within selected areas of intermodal transport.

Acknowledgments. The authors would like to acknowledge intermodal transport companies' representatives who were willing to fill in the questionnaire survey.

References

1. Ricci, S., Capodilupo, L., Mueller, B., Karl, J., Schneberger, J.: Assessment methods for innovative operational measures and technologies for intermodal freight terminals. Transp. Res. Procedia **14**, 2840–2849 (2016)
2. Filina-Dawidowicz, L., Kostrzewski, M.: The complexity of logistics services at transshipment terminals. Energies **15**(4), 1435 (2022)
3. Pencheva, V., Asenov, A., Sladkowski, A., Ivanov, B., Georgiev, I.: Current issues of multimodal and intermodal cargo transportation. In: Sładkowski, A. (ed.) Modern Trends and Research in Intermodal Transportation. SSDC, vol. 400, pp. 51–124. Springer, Cham (2022). https://doi.org/10.1007/978-3-030-87120-8_2

4. Jacyna-Gołda, I.: Evaluation of operational reliability of the supply chain in terms of the control and management of logistics processes. In: Nowakowski, T. (eds.) Safety and Reliability: Methodology and Applications – Proceedings of the European Safety and Reliability Conference, ESRE 2014, 107147, pp. 549–558 (2014)
5. Altuntaş Vural, C., Roso, V., Halldórsson, Á., Ståhle, G., Yaruta, M.: Can digitalization mitigate barriers to intermodal transport? An exploratory study. Res. Transp. Bus. Manag. **37**, 100525 (2020)
6. Sénquiz-Díaz, C.: Transport infrastructure quality and logistics performance in exports. Economics **9**(1), 107–124 (2021)
7. Manual, O.: Guidelines for Collecting and Interpreting Innovation Data, OECD and Eurostat, 3rd edn. (2005). https://ec.europa.eu/eurostat/documents/3859598/5889925/OSLO-EN.PDF. Accessed 5 Oct 2021
8. Hasselwander, M., Bigotte, J.F.: Transport authorities and innovation: understanding barriers for MaaS implementation in the global south. Transp. Res. Procedia **62**, 475–482 (2022)
9. Pagano, P., Antonelli, S., Tardo, A.: C-ports: a proposal for a comprehensive standardization and implementation plan of digital services offered by the "port of the future." Comput. Ind. **134**, 103556 (2022)
10. Wagener, N., Aritua, B., Zhu, T.: The new silk road: opportunities for global supply chains and challenges for further development. Logforum **16**(2), 193–207 (2020)
11. Bell, D.: Intermodal mobility hubs and user needs. Soc. Sci. **8**(2), 65 (2019)
12. Agbo, A.A., Li, W., Zheng, L., Zhang, Y., Atombo, C.: Optimisation of intermodal freight transport network. Eur. Transp. Trasporti Europei (63) (2017)
13. Pagano, P., Falcitelli, M., Ferrini, S., Papucci, F., De Bari, F., Querci, A.: Complex infrastructures: the benefit of ITS services in seaports. In: Intelligent Transportation Systems: From Good Practices to Standards, pp. 172–192 (2016)
14. Kreutzberger, E., Konings, R.: The challenge of appropriate hub terminal and hub-and-spoke network development for seaports and intermodal rail transport in Europe. Res. Transp. Bus. Manag. **19**, 83–96 (2016)
15. Filina-Dawidowicz, L., Kostrzewski, M.: Impact of COVID-19 on shaping comprehensive services within intermodal terminals. In: Prentkovskis, O., Yatskiv (Jackiva), I., Skačkauskas, P., Junevičius, R., Maruschak, P. (eds.) TRANSBALTICA 2021. LNITI, pp. 648–657. Springer, Cham (2022). https://doi.org/10.1007/978-3-030-94774-3_63
16. Föhring, R., Zelewski, S.: ORFE to AFEX—a conceptual look into the future of online freight exchange. In: Clausen, U., Friedrich, H., Thaller, C., Geiger, C. (eds.) Commercial Transport. LNL, pp. 241–253. Springer, Cham (2016). https://doi.org/10.1007/978-3-319-21266-1_16
17. Vallera, A.M., Nunes, P.M., Brito, M.C.: Why we need battery swapping technology. Energy Policy **157**, 112481 (2021)
18. Stopka, O., Stopkova, M., Lizbetin, J., Soviar, J., Caban, J.: Development trends of electric vehicles in the context of road passenger and freight transport. In: 12th International Science-Technical Conference AUTOMOTIVE SAFETY 2020, pp.1–8, Kielce (2020)
19. Illés, B., Véha, A., Vida, L.: New ideas for inland intermodal transport. Transp. Probl. **15**(1), 117–130 (2020)
20. Mommens, K., Van Lier, T., Macharis, C.: Towards modal choice in agent-based freight transport model considering the used loading unit. IN: European Simulation and Modelling Conference 2016, ESM 2016, pp. 461–466 (2016)
21. Business Requirements Specyfication (BRS). https://unece.org/DAM/cefact/brs/BRS-SmartContainer_v1.0.pdf. Accessed 30 June 2022
22. Paulauskas, V., Filina-Dawidowicz, L., Paulauskas, D.: Ports digitalization level evaluation. Sensors **21**(18), 6134 (2021)
23. Tran-Dang, H., Kim, D.-S.: The physical internet in the era of digital transformation: perspectives and open issues. IEEE Access **9**, 164613–164631 (2021)

24. Barasti, D., Troscia, M., Lattuca, D., Tardo, A., Barsanti, I., Pagano, P.: An ICT prototyping framework for the "port of the future." Sensors **22**(1), 246 (2022)
25. Korpysa, J., Halicki, M., Uphaus, A.: New financing methods and ICT versus logistics startups. Procedia Comput. Sci. **192**, 4458–5446 (2020)
26. Arendt, T.: Flashlight on intermodal transport innovation in european seaport hinterland. In: Böse, J.W. (ed.) Handbook of Terminal Planning. ORSIS, pp. 517–530. Springer, Cham (2020). https://doi.org/10.1007/978-3-030-39990-0_23
27. Renna, A., Petrelli, M., Carrese, S., Bertocci, R.: An innovative simulation agent-based model for the combined sea-road transport as a DSS. Sustainability **13**(19), 10773 (2021)
28. He, Z., Haasis, H.-D.: Integration of urban freight innovations: sustainable inner-urban intermodal transportation in the retail/postal industry. Sustainability **11**(6), 1749 (2019)
29. Richardson, B.C.: Sustainable transport: analysis frameworks. J. Transp. Geogr. **13**, 23–39 (2005)
30. Jacyna, M., Wasiak, M., Lewczuk, K., Chamier-Gliszczyński, N., Dąbrowski, T.: Decision problems in developing proecological transport system. Rocznik Ochrona Środowiska **20**(2), 1007–1025 (2018)
31. Szymańska, E., Panfiluk, E., Kiryluk, H.: Innovative solutions for the development of sustainable transport and improvement of the tourist accessibility of peripheral areas: the case of the białowieża forest region. Sustainability **13**(4), 2381, 1–23 (2021)
32. Čižiūnienė, K., Bureika, G., Matijošius, J.: Challenges for intermodal transport in the twenty-first century: reduction of environmental impact due the integration of green transport modes. In: Sładkowski, A. (ed.) Modern Trends and Research in Intermodal Transportation. SSDC, vol. 400, pp. 307–354. Springer, Cham (2022). https://doi.org/10.1007/978-3-030-87120-8_6
33. Coenegrachts, E., Beckers, J., Vanelslander, T., Verhetsel, A.: Business model blueprints for the shared mobility hub network. Sustainability **13**(12), 6939 (2021)
34. Boschian, V., Fanti, M.P., Iacobellis, G., et al.: Using information and communication technologies in intermodal freight transportation: a case study. In: 2009 IEEE International Conference on Systems, Man and Cybernetics, 11004060. San Antonio, TX, USA (2009)
35. Filina-Dawidowicz, L., Cernova-Bickova, A., Możdrzeń, D., Semenov, I., Wiktorowska-Jasik, A., Bickovs, D.: Organization of cargo traffic using ferry connections. Period. Polytech. Transp. Eng. **50**(3), 279–284 (2022)
36. Shamsuzzoha, A., Ehrs, M., Addo-Tengkorang, R., et al.: Tracking and tracing of global supply chain network: case study from a Finnish company. In: Proceedings of the 23rd International Conference on Enterprise Information Systems (ICEIS 2021), vol. 1, pp. 118–125 (2021)
37. Joshi, A., Kale, S., Chandel, S., Pal, D.: Likert scale: explored and explained. Br. J. Appl. Sci. Technol. **7**(4), 396–403 (2015)

Investigation of the Possibilities of Optimization of Freight Road Traffic Flows in the Urban Logistics System

Šarūnas Šlajus and Nijolė Batarlienė(✉)

Vilnius Gediminas Technical University, Plytines 27, 10105 Vilnius, Lithuania
sarunas.slajus@stud.vilniustech.lt,
nijole.batarliene@vilniustech.lt

Abstract. This article presents the solutions proposed by various authors and already implemented for the optimization of freight car flows. The functions and tasks of urban logistics, the functions and characteristics of freight transport in the urban logistics system, the problems of using heavy transport in the first and last mile and applied solutions are reviewed. After conducting a survey of experts, the main problems and optimization possibilities of the optimization of cargo transport flows in urban logistics were clarified. The results of the feasibility study of the optimization of freight road transport flows in the urban logistics system are presented.

Keywords: Urban logistics · Road freight transport · Traffic flows · Terminals

1 Introduction

As cities grow, so does the need for transport services. The intensive growth of cities poses ever new challenges for mobility: 10–15% of the total mileage in cities is made up of freight transport mileage. Growing freight transport flows cause more and more problems in cities, such as restrictions on the free movement of cars, complicated planning of cargo loading and delivery at a specific time, increasing environmental pollution and noise. At the same time, other problems arise: the wear and tear of roads and the lack of heavy transport drivers.

Freight transport flows are unevenly distributed in the city's logistics system, especially during peak hours. Heavy freight transport reduces mobility in the city and is a frequent cause of traffic accidents. The quality of service provided by logistics companies decreases due to traffic jams and untimely pick-up or delivery of cargo.

Urban logistics, with the growing population, is gaining more and more importance in the life of mankind and is increasingly becoming the object of scientific research. Back in 2014 54% of the world's population lived in cities. The United Nations [1] predicted that by 2050 this number will reach 66%, and by 2100 we will have 85% of the population concentrated in cities [2]. The ever-increasing traffic flows are causing

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 566–575, 2023.
https://doi.org/10.1007/978-3-031-25863-3_54

more and more problems. Thus, many researchers study the problems of urban logistics, looking for various solutions [3].

The purpose of optimization of freight road transport flows is to predict how vehicle traffic will be distributed in the urban logistics system in the considered territory. Optimization of transport flows can be used to model the consequences of emergency situations and to search for optimal solutions for such a situation [4].

2 Theoretical Aspects of the Freight Road Traffic Flows in the Urban Logistics System

In nowadays urban logistics focuses on fast and reliable freight transport by choosing cost-effective routing and eco-friendly solutions. Urban logistics service providers have to pay attention to the dynamics in logistics processes, such as shorter delivery time, more frequent scheduling, reliability and flexibility of services [5]. In addition, urban logistics providers compete with other road users for limited space in cities and maximise the capacity of urban infrastructure.

Urban logistics is more than just transporting goods within urban areas. It can be seen as any service that helps to efficiently manage the movement of goods within an urban area and to provide innovative offers to meet customer needs [6].

Logistics, as it is understood today, involves the analysis, planning and integrated and coordinated physical management of information and decision-making across a network of multiple partners. The term logistics emerges from this approach, which shows the need for a systematic approach to freight transport issues and movement within urban areas. This system is characterized by the optimized consolidation of freight from a different shippers and carriers on the same vehicles and the coordination of freight transport activities in the city [7].

Urban logistics aim is to increase the efficiency of logistics processes and operations and to mitigate negative impacts, while supporting the sustainable development of urban areas [8].

Urban logistics is based on a systems approach, involving many processes, including modelling, information technology assessment and application [9, 10].

The sudden change of habits in modern society, the advancement of progress, the pursuit of wealth and prosperity, and the frenetic pace of life have led to the need to find new solutions for the development of freight distribution to achieve higher levels of efficiency [11]. This can be achieved through better use of currently available resources, smarter planning of the entire distribution process, intelligent network design and close cooperation between the carrier companies [10]. Researchers Anand & Duin, 2021 [12], based on the research of other colleagues, highlighted six areas of urban logistics development: information and communication technologies, urban logistics planning, stakeholder communication, public-private partnerships, subsidies and incentives, and regulation. Figure 1 shows the distribution of the identified measures across the six development areas.

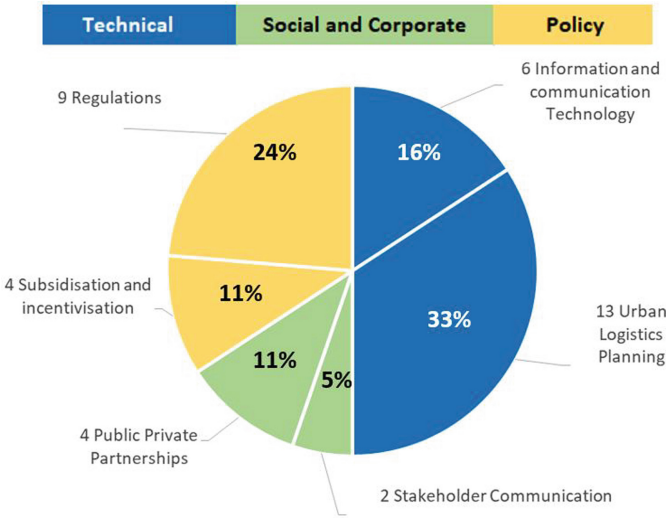


Fig. 1. Distribution of urban logistics development areas [12].

Heavy transport causes many problems and inconveniences in the cities. Some of them are traffic congestion, air and noise pollution, and safety problems such as traffic accidents [13]. However, in the cities are going intensive trading and various services are provided and freight transport is an inevitable part of urban life.

In their work, researchers Ploos van Amstel and Quack have identified a several options of a first and last mile based on the location of the terminals, depending on the size of the city and the distance of the terminal from the city boundary [14]. According to them, the last mile starts from the warehouse (distribution center) and ends with the delivery of the cargo to the destination, such as an office, a company building, a shop or a home [15].

Other researchers argue that several logistics solutions need to be combined to optimize last mile deliveries in the supply chain, such as warehousing of goods and the organization of new urban freight transport. For example, we cannot use electric trucks in the city without additional infrastructure such as a consolidation center in the city [16].

In 2015, researchers from The Netherlands estimated that the urban logistics greenhouse gas emissions dynamics reaches of 0.9 million tons per year nationwide [14, 15].

As complex and well-organized systems, modern cities are constantly moving and have difficult dynamics. Cities play a key role in social and economic development and have a major impact on the environment. Today's cities face technical (resource supply, transport, information), social (social and material inequalities, security) and environmental challenges [17].

3 Studies on the Evaluation of Freight Road Transport Flows

3.1 Research Methodology

A review of current research and proposed solutions for optimizing freight transport flows clearly shows that this issue is relevant today and will remain relevant in the future, due to the agglomeration of cities, environmental challenges, mobility constraints and the prospects for improving the overall quality of life in cities. Urban logistics problems are addressed from the strategic level to the cooperation between municipal administrations and economic operators.

The study on the feasibility of optimizing road freight flows included a survey of experts. There were selected experts with theoretical knowledge and practical skills in the field of urban logistics, and therefore with a direct relevance to the issue of optimizing road freight transport flows in urban areas. The data from the expert survey, expressed as numerical values, is distributed according to preference. The objective of the data processing is to obtain aggregated data for a study on the possibilities of optimizing freight transport flows in the urban logistics system.

The respondents of the survey are experts in the logistics sector, managers of a companies or departments of companies, with a university degree and at least 5 years of experience in the management of international and domestic transport, and in the organization of a logistics system for freight consolidation or distribution cities. The survey was sent to respondents electronically via www.apklausa.lt. The survey was based on the most used ranked scale of questions. The essence of this grouping is that all answers are in strict ascending or descending order [18]. The questions related to the problem under consideration are presented as statements or criteria and the extent to which the statement or criterion is agreed or disagreed with is determined by ranking. A several factors have influenced the choice of the written survey method:

- The method is suitable for scientific research.
- Allows easy and fast collection of expert data.
- Allows to achieve the aim and objectives of the study.

In order to answer the main problems, solutions and opportunities for optimizing road freight transport flows in the urban logistics system, the target audience has been identified as having sufficient expertise and experience in the urban logistics environment to be able to respond as objectively as possible to the questions asked.

In the survey were interviewed ten respondents, logistics experts with at least 5 years of experience in international freight transport and freight consolidation and distribution in urban logistics. All the experts that were interviewed have a university degree and a combined average experience in logistics is almost 14 years.

This study aims to identify trends in road freight transport optimization options and their implementation in practice. The questions aim to gain a deeper insight into the phenomenon under study and to obtain more detailed information on the nature of the behavior [18]. For the study on the optimization of road freight transport in the urban logistics system, the experts were asked questions related to urban logistics, the impact of freight transport on mobility, ecology, infrastructure, and a whole system. Questions

were also asked about possible measures to optimize road freight transport flows in the urban logistics system, the possibility of using small goods transport in the first or last mile, self-service terminals, investments in green transport and smart city technologies.

3.2 Results of the Survey of Experts

The study aimed to identify which freight vehicles in urban logistics are the most problematic for mobility and urban ecology in terms of vehicle carrying capacity. Respondents rated the impact of each vehicle on an 8-point scale (1 - least impact; 4 - medium impact; 8 - most impact (responses cannot be repeated)). Based on the answers received and the importance indicators calculated, it can be said that vehicles with a carrying capacity of up to 999 kg and 1,000–1,499 kg have the least impact on urban mobility and ecology (Importance indicator 0.047 and 0.078). It should be noted that these vehicles are the easiest to convert to environmentally friendly, electric vehicles. Meanwhile, vehicles with a carrying capacity of 15,000 kg or more are the most problematic for mobility and ecology in urban areas (importance indicator 0.206).

The study sought to identify which factors have the greatest impact on the urban logistics system. Respondents rated the influence of each factor on an 8-point scale (1 - least influence; 4 - medium influence; 8 - most influence (responses cannot be repeated)). Based on the responses received and the importance indicators calculated, it can be concluded that legal regulation, geographical location of operators, innovation and information technology, and cooperation between operators currently have a lesser impact on urban logistics (importance indicators of 0.083, 0.086, 0.078 and 0.086 respectively). In contrast, experts consider traffic regulation and urban road infrastructure to have the greatest impact on urban logistics (indicators are 0.181 and 0.2).

The survey asked experts to indicate how much companies are willing to invest in new information technologies to improve freight transport in urban logistics. The distribution of responses was quite clear. 50% of respondents were in favor of such an initiative and as many as 40% had already invested in such technologies. Only 10% of respondents would look for other alternatives to optimize freight transport flows in urban logistics. It can be said that companies are interested in optimizing freight transport flows by introducing information technology to organize transport in the first or last mile.

The experts were asked to indicate to what extent companies would be willing to pick up or deliver small loads to terminals on the periphery of the city. The distribution of responses was quite clear. 70% of respondents were in favor of such an initiative, while 20% of respondents were likely to support it (Fig. 2). It can be concluded that companies are ready to pick up or deliver small loads to terminals on the periphery of the city.

In the survey, experts were asked to indicate the extent to which companies are willing to cooperate in picking up or delivering freight to terminals on the periphery of the city. The distribution of responses was also quite clear. 50% of respondents were in favor of such an initiative, while the remaining 50% indicated that companies would be likely to cooperate. This reflects the general trend that cooperation is important for companies when consolidating freight or distributing freight from terminals on the periphery of the city.

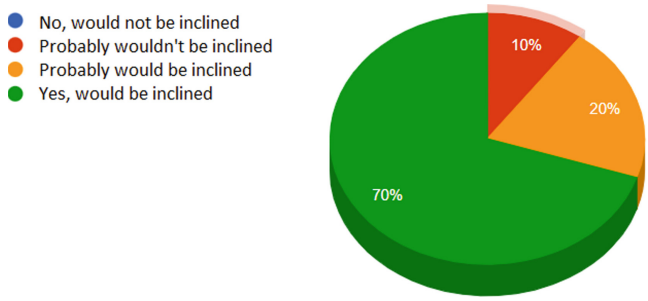


Fig. 2. Distribution of experts' opinions, according to whether companies would be inclined to independently pick up or deliver small loads to terminals on the outskirts of the city.

The experts were asked to indicate to what extent companies are interested in using electric cars to pick up or deliver goods to terminals on the periphery of the city. The majority of respondents (50%) indicated that this is a priority, 20% of respondents indicating that companies would also be likely to make use of this option. This distribution of experts' opinions shows the interest of economic operators to use environmentally friendly transport for transport operations in the urban logistics system (Fig. 3).

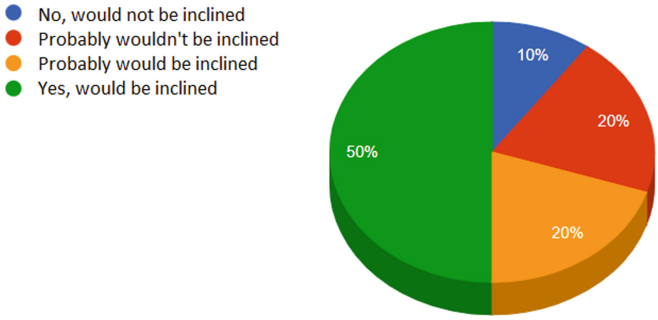


Fig. 3. Distribution of experts' opinion, according to whether companies would be inclined to use electric cars when bringing or delivering goods to terminals on the outskirts of the city.

The study sought to identify the factors that have the greatest impact on the optimization of the logistics system. Respondents rated the influence of each vehicle on an 8-point scale (1 - lowest influence; 4 - medium influence; 8 - highest influence). Based on the answers received from the respondents and the importance indicators calculated, it can be said that the most influential factors in optimizing the city's logistics system are the prohibition of access to the city center by urban transport (indicator 0.2) and the eco-tax on urban freight transport (indicator 0.172). Next in importance is the creation of a network of small self-service terminals in the urban periphery (indicator 0.147), the promotion by the State of the purchase of environmentally friendly vehicles (indicator 0.144), followed by the integration of logistics companies into a unified information

system for urban freight transport (indicator 0.097). These results show that the strategic role of the State is very welcome and important in the adoption and application of various regulatory and incentive measures to address the problems of optimizing road freight transport flows in the urban logistics system (Fig. 4).

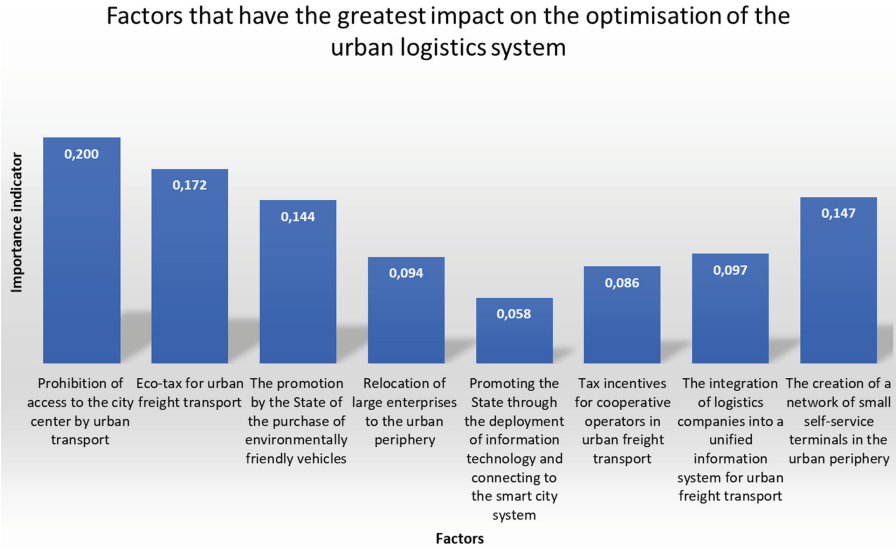


Fig. 4. Factors that have the greatest impact on the optimisation of the urban logistics system.

Respondents also indicated what additional measures they considered would help to address the challenges of optimising road freight flows in the urban logistics system. The responses can be structured into a number of key measures:

– restricting freight traffic to certain hours, weekends and public holidays.
– diverting transit traffic by detours;
– drone delivery of small cargo.

In the survey, the experts were asked to indicate to what extent companies would be interested in using self-service terminals in suburban logistics centres in the first and last mile. The vast majority of respondents (50%) answered that they were in favour of such a facility, but 40% of the experts doubted whether it would be attractive. Only 10% do not support such an idea. This divergence of opinions shows that the proposed measure is quite innovative and its attractiveness is still in doubt. Getting used to using the services of logistics companies is less of a problem for operators when organising transport and the loading and unloading of goods from terminals (Fig. 5).

In the survey, experts were asked to indicate to what extent operators would be willing to invest in environmentally friendly transport, for collection or distribution of small loads. The vast majority of respondents say that the company has already invested in green vehicles or would welcome such investments. Responses were split by 30%.

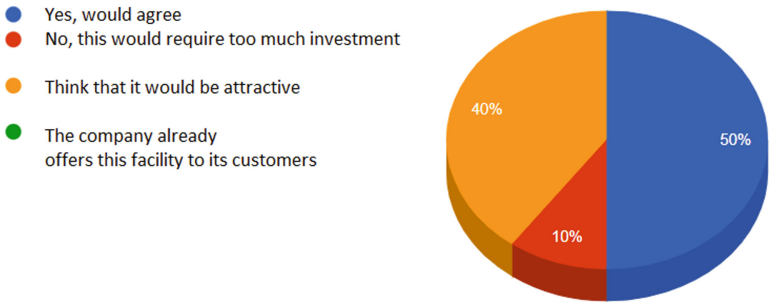


Fig. 5. Distribution of experts' opinions according to whether companies would use self-service terminals in out-of-town logistics centers in the first and last mile.

However, a significant proportion, 40%, indicated that State aid is needed for such a investments. To summarize the results, it can be said that farm operators are concerned about urban ecology and are ready to contribute to it themselves or with the help of the State.

4 Conclusions

1. The analysis of the scientific literature has highlighted a several solutions proposed by researchers to optimize freight transport flows:
- Management efficiency through innovation in both urban regulation and environmental solutions.
- The use and development of information technology to manage, coordinate and control information.
- Infrastructure development through innovative solutions and information technology.
- Location of large terminals in the countryside and small distribution centers, taking into account the location of shopping centers and industrial districts.
- Cooperation, collaboration, sharing, exchange of information and resources between actors in urban logistics.

1. A network of self-service terminals for the consolidation of small volumes of freight could be organized to address the problems of optimizing freight flows in urban logistics raised in the analysis. This would allow shippers or consignees in the central part of the city, or even in the wider urban area, to pick up or deliver their goods independently at their own convenience to self-service terminals. This would make it easier to plan the process and avoid having to deal with logistics companies and their mistakes due to delays. It would also create a niche for the targeted use of commercial electric vehicles in urban areas, which would help reduce pollution and noise.

- In urban logistics, optimizing freight transport flows and improving the ecological climate requires the use of low-capacity vehicles up to 999 kg, 1,000–1,499 kg and 1,500–2,999 kg. Electrically powered freight vehicles with this capacity are already available on the market from various manufacturers;

- The urban logistics system is most dependent on urban infrastructure and traffic regulation. Urban infrastructure must be continuously improved to optimize freight transport flows;
- Businesses are concerned with optimizing freight transport flows through the introduction of information technology to organize transport in the first or last mile;
- companies are prepared to pick up or deliver small loads on their own to terminals on the urban periphery;
- cooperation is important for companies to consolidate or distribute freight from terminals on the urban periphery;
- operators would use environmentally friendly transport for transport operations in the urban logistics system;
- the strategic role of the State is very welcome and important in the adoption and application of various incentive measures to address the problems of optimizing road freight transport flows in the urban logistics system.
- The idea of self-service terminals on the periphery of the city is quite attractive, but its innovative nature raises doubts as to whether it will attract enough users.
- Economic operators are concerned about the ecology of the city and are ready to contribute to it themselves, either through their own investments in environmentally friendly transport or with the help of the State.

References

1. United Nations: World Urbanization Prospects: The 2003 Revision. United Nations Publications, New York (2004)
2. OECD: Delivering the Goods: 21st Century Challenges to Urban Goods Transport. Paris, France: OECD Publications (2003). https://www.itf-oecd.org/delivering-goods-21st-century-challenges-urban-goods-transport
3. Absi, N., Cattaruzza, D., Gonzalez-Feliu, J.: Vehicle routing problems for city logistics. EURO J. Transp. Logistics **6**, 51–79 (2017)
4. Anand, N., Van den Band, N., Van Duin, J.H.R, Quak, H.J.: Designing sharing logistics as a disruptive innovation in city logistics. Rotterdam University of Applied Sciences, The Netherlands. Delft University of Technology, The Netherlands. Breda University of Applied Sciences, The Netherlands. TNO, The Netherlands (2020)
5. Hülsmann, M., Windt, K.: Understanding Autonomous Cooperation & Control - The Impact of Autonomy on Management, Information, Communication, and Material Flow. Springer, Berlin, (2007). https://doi.org/10.1007/978-3-540-47450-0
6. Dablanc, L.: City Logistics. University of Paris East/IFSTTAR, France (2019)
7. Crainic, T.G.: City Logistics. Université du Québec à Montréal, School of Management (2008)
8. Tadić, S.: City logistics performance. In: Conference: LOGIC, 2nd Logistics International Conference At: Belgrade, Serbia (2015)
9. Taniguchi, E., Thompson, R.: Modeling city logistics. Transp. Res. Rec. **1790**, 45–51 (2002)
10. Taniguchi, E.: Concepts of City Logistics for Sustainable and Liveable Cities. Procedia Soc. Behav. Sci. **151**, 310–317 (2014)
11. Mancini, S.: Multi-Echelon freight distribution systems: a smart and innovative tool for increasing logistic operations efficiency. Alpen-Adria-Universität Klagenfurt (2013)
12. Anand, N., Van Duin, Quak, H.: Development of City Logistics Maturity Model For Municipality Performance Measurement. Rotterdam (2021)

13. Carrillo, J., Cortes, P., Grosso, R., Muñuzuri, J.: City logistics: are sustainability policies really sustainable? Dpto. de Organización Industrial y Gestión de Empresas II. ETSI. Universidad de Sevilla. Camino de los Descubrimientos, s/n. Islade la Car tuja, 41092, Seville, Spain (2014)
14. Ploos van Amstel, W.: City Logistics. Amsterdam University of Applied Sciences (HvA), Faculty of Technology Urban Technology research program (2015)
15. Ploos van Amstel, W., Quak, H.: Annual Outlook City Logistics 2050. Amsterdam University of Applied Sciences/Centre for Applied Research on Education. Amsterdam (2017)
16. Özbekler, T.M., Akgül, A.K.: Last Mile Logistics in The Framework of Smart Cities: A Typology of City Logistics Schemes, Sinop University, Department of Logistics, Sinop, Turkey (2020)
17. Savin, G.: Smart city logistics. Ural State University of Economics, Ekaterinburg (2020)
18. Kardelis, K.: Mokslinių tyrimų metodologija ir metodai. Kaunas. Technologija (2007)

Streets and Urban Roads Surface Runoff Problems: A Case Study in the Poltava City, Ukraine

Iryna Tkachenko[1](✉), Tetyana Lytvynenko[1], Lina Hasenko[1], and Nataliia Sorochuk[2]

[1] National University «Yuri Kondratyuk Poltava Polytechnic», Poltava, Ukraine
ab.Tkachenko_IV@nupp.edu.ua
[2] Ukrainian State University of Railway Transport, Kharkiv, Ukraine

Abstract. Natural and climatic factors have a significant influence on mobility, which depends on the operational condition and durability of the street-road network and its elements, one of the main ones being surface water. As a result of the conducted research, were summarized the principles of drainage from the street and road network, which differ for open, closed and combined drainage systems. The main disadvantages of Ukraine cities surface drainage were revealed using Poltava city example. The most common are low longitudinal slope (0–5‰), an error in the intersection vertical planning execution, clogging of drainage elements (drainage well, tray, pipes), the adjacent sites slope is less than the minimum permissible, insufficient storm sewer capacity, subsidence of the pavement, drainage well above the pavement mark (subsidence of the pavement), destruction of the pavement (roadway, around the drainage well), subsidence of the pavement transverse profile, destruction of the pavement. Recommendations for improving surface water drainage from cities street and road network have been formulated: strictly adhere to surface drainage principles, and in particular, during construction, perform the designed slopes, and it is desirable to accept slopes greater than the minimum slopes of 5‰; when performing vertical design and construction, pay more attention to intersections and areas adjacent to the carriageway; apply a waterproof coating, from which water flows into the drainage system, from which it is possible to use water for irrigation; arrange water collection strips along the side stone, comply with the requirements for network elements operation, etc.

Keywords: Urban drainage · Surface runoff · Street and urban road · Urban floods

1 Introduction

Natural and climatic factors have a significant influence on mobility, which depends on the operational condition and durability of the street-road network and its elements, one of the main ones being surface water. Rainwater and stormwater, as well as water from melting snow are waters that form surface runoff. The formation of surface runoff

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 576–585, 2023.
https://doi.org/10.1007/978-3-031-25863-3_55

depends on the terrain conditions. Surface runoff, if the principles of drainage are not followed, leads to devastating consequences. One of the main means of organizing surface runoff is the carriageway of the street and road network. In Ukraine and abroad, there are many examples of surface water drainage principles violations, the consequences of which are: water stagnation on the carriageway of streets and highways; water stagnation on the sidewalks; flooding of territories; damage and destruction of the road surface and ground surface; damage and destruction of buildings and structures, damage to engineering networks; obstruction of traffic and pedestrians; injury to pedestrians; traffic events; damage to movable and immovable property, etc. (see Fig. 1).

a) b)

Fig. 1. Flooding of the carriageway of: a – street and sidewalk on the Shevchenko street, Poltava, Ukraine; b – highway in Hagen, Germany (foto by Sasha Steinbach/ERA).

2 Background and Related Work

Scientists from all over the world are interested in the problem of surface drainage from streets and roads. Researchers from China describes an integrated methodology, which initially makes use of high resolution 2D inundation modeling and flood depth-dependent measure to evaluate the potential impact and risk of pluvial flash flood on road network in the city center of Shanghai, China [1]. Reseachers from United Kingdom describes a detailed study based on a small (11 km^2) urban catchment in West Yorkshire, England. Radar and rain gauge data have been compared and used as the input to hydrodynamic sewer flow simulations, and the results of these simulations have been compared with measured flows in the sewer system [2]. An analytical probabilistic model was developed in Jun Wang's study that considers the differences between directly-connected and disconnected impervious areas of water runoff. The novel feature of this model is that it cannot only explicitly consider the effect of impervious area disconnection but also analytically calculate the runoff reduction effects contributed by impervious area disconnection. Model validity is demonstrated by comparing its outcomes with the results of a series of continuous simulations for cases with different types of soils and various land use parameters in Jackson, Mississippi and Billings, Montana, USA [3]. Cheng-Chun (Barry)Lee and Nasir G.Gharaibeh (USA) providing an automated process for the inspection and evaluation of roadside channel systems using data obtained from mobile lidar (Light Detection and Ranging) scanners [4]. Malaysia's researchers test has

significantly revealed that the pervious concrete has high potential in enhancing flow interception and able to reduce water ponding as a street curb [5]. Reseachers proposed to incorporate StormPav Green Pavement along the backstreet of Padungan and to investigate the effectiveness of the permeable road [6]. The effect of reducing surface runoff, which depends on trees, grass and green roofs, is revealed in some studies [7–9]. Calculation of the discharge capacity of street inlets for numerically modelling urban floods and managing flood resilience revealed in some research [10]. Influences of different street layouts and infrastructures on flood inundation processes are considered in studies [11, 12]. Modelling of urban flooding revealed in the many researches [13–15].

3 Case Study Area

Poltava (Ukraine), as the city in which the authors live, was explored in detail in the study. Places of street and road network flooding were chosen by surveying the city streets after the rain, photographing, determining the dimensions and displaying the location of the flooding on the map. Places with a flooded area of more than 10 m^2 were taken into account.

An original GIS-based road network dataset used in this study came from the Open Street Map. Terrain data came was taken from GMTED (Global Multi-resolution Terrain Elevation Data) from USGS Earth explorer.

4 Results

4.1 Road and Street Drainage Design Principles

The drainage system is an important part of the street and road network improvement [16]. They design drainage systems and structures of the street and road network, based on local natural, architectural, planning and sanitary and hygienic conditions in a complex interconnection with solutions for engineering preparation, improvement and infrastructure of the settlement and in Ukraine in accordance with the DBN V.2.5-75 «Sewerage. External networks and structures. Basic design provisions", DBN V.2.3-5 "Streets and roads of settlements». Engineering protection of territories against flooding and submergence is carried out in accordance with DBN B.1.1-25 "Engineering protection of territories and structures against flooding and submergence".

Surface water drainage is carried out by *open, combined and closed drainage systems* (see Fig. 2).

In each settlement, it is necessary to have a general scheme for the drainage network development, bases on the city master plan, which determines the path and sequence of collectors and network elements construction. On the basis of this scheme, the drainage network project of a particular drainage basin is being developed.

Are classified the elements of street and road system surface drainage in settlements (see Table 1).

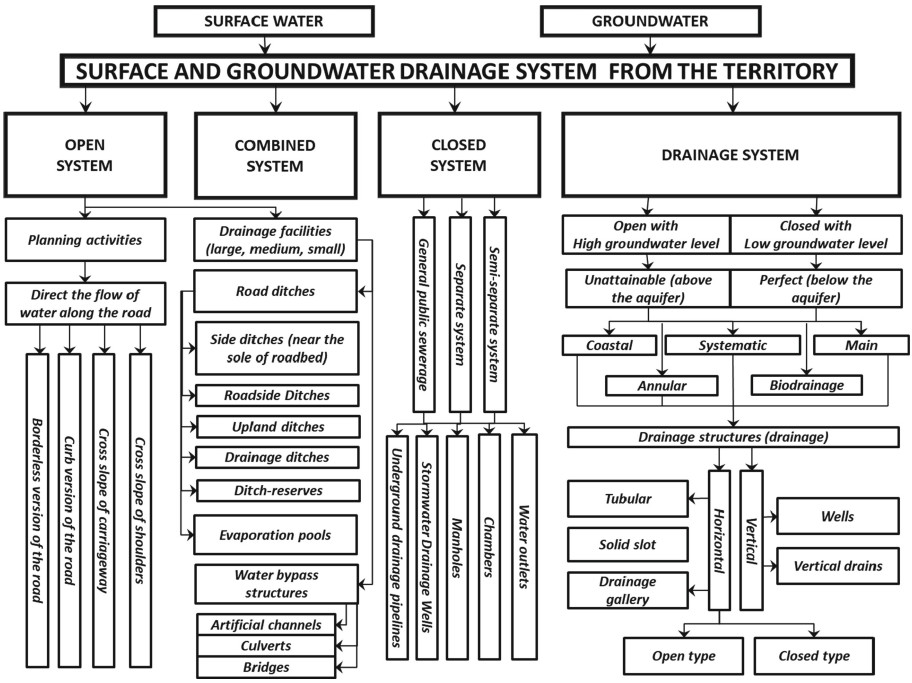


Fig. 2. Classification surface and groundwater drainage system from the territory.

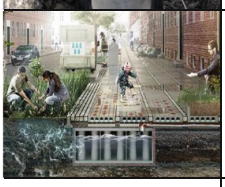
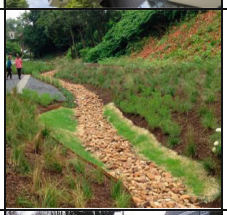
4.2 Study of Surface Water Drainage from Ukrainian Cities Streets Current State

During the study, the territories of periodic flooding in Poltava city, Ukraine with a size of more than 10 m^2 were surveyed and the main causes were identified. 100 places of water stagnation were discovered. The main problems of surface drainage are grouped and shown in Table 2.

On the scheme of Poltava city (see Fig. 3), we can see that many streets and roads are laid along horizontal lines, and therefore there is a problem with small slopes for water flow.

There is also a frequent problem of water stagnation at intersections or junctions, this place often coincides with pedestrian crossing, a mistake may have been made during construction (or design). Areas adjacent to the carriageway (stop, parking, utility areas) are also often constructed in violation of drainage principles. The following often encountered deficiencies are errors in street and road network operation: pavement destruction, road surface subsidence, rainwater receiving well clogging, rainwater receiving well above the surface mark (covering subsidence), deterioration of the asphalt

Table 1. Surface drainage elements of the street and urban road network.

Photo	Name	Photo	Name
	Water culverts, Artificial channels Bridges		Use of pervious concrete for curb
	Storm sewers and Treatment Facilities		Drainage of water from roofs through gutters not on the sidewalk, but immediately underground - in the collector
	The ditches are reinforced with granite slabs		Rainwater wells placement on the lawn. The water collected in the collectors will be using for irrigation
	Drainage from open trays		The sidewalk is always a little higher or flush with the curbstone, due to which the water drains quickly from it.
	Paving tiles that collect water for reuse		Shrubs, trees and lawns are planted on roofs, facades and in public places that absorb rainwater
	Rainwater wells in level with a pavement (round or rectangular). The slots are perpendicular to the direction of movement		Biodrainage systems (precipitation that falls on impermeable surfaces instead of rainwater colle ctors are intercepted in special streams
	Water collection strips (20-40 cm along the side stone 1-2 cm below the level of the pavement		The pavement is laid at a slight slope to the middle, so all the water flows into the drainage system from the permeable blocks

concrete coating around the rainwater receiving well, drainage elements (tray, pipes) clogging, pavement cross profile subsidence. Also, insufficient capacity of the storm sewer is a serious problem.

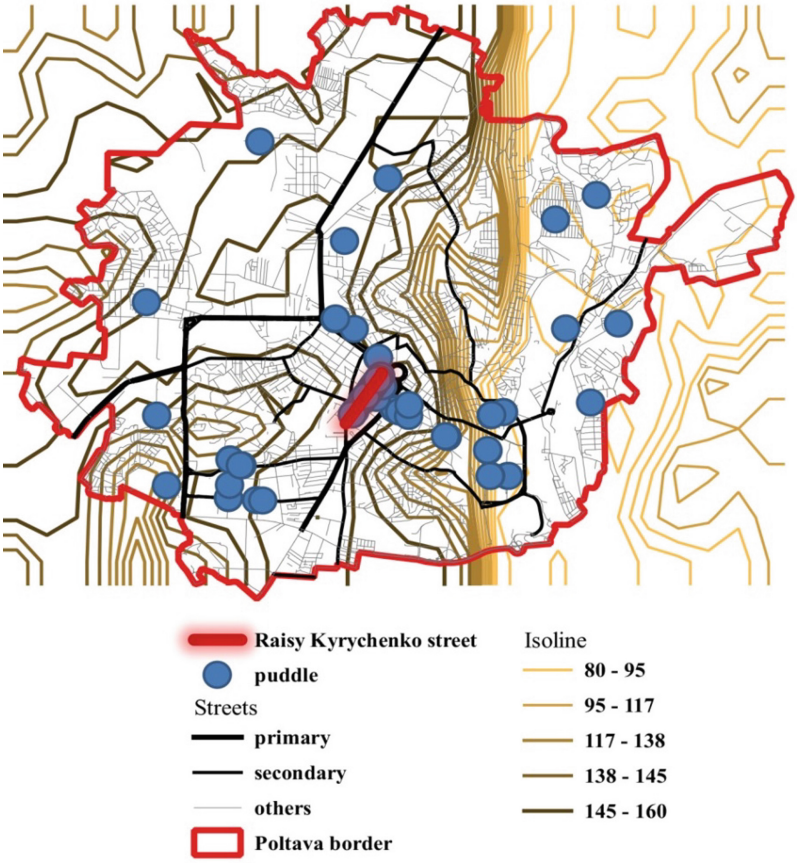
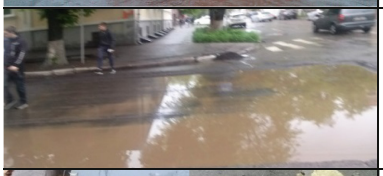
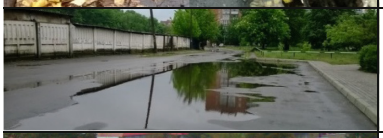
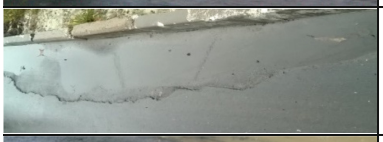
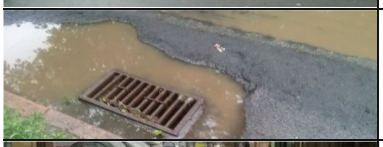


Fig. 3. The scheme of Poltava city streets with water stagnation places marking.

The frequency with which various types of surface drainage defects occur is analyzed (see Fig. 4). We see that the most frequent causes of water stagnation are insufficient longitudinal slope; an error in the intersection vertical design, as well as the drainage wells clogging.

Raisy Kyrychenko street has a beehive number of violated surface drainage principles. Taking into account the recently carried out road surface overhaul, there is significant water stagnation and the road subsidence, as well as all drainage wells clogging. Therefore, the authors performed a more detailed street survey and formulated project proposals to eliminate drainage deficiencies. The problem of a small longitudinal slope is proposed to be solved using the sawtooth profile technique.

Table 2. The main problems of surface drainage in Poltava.

Photo of the disadvantages	Type	Disadvantage name
	Type 1	Low longitudinal slope (0 - 5‰)
	Type 2	An error in the intersection vertical planning execution
	Type 3	Clogging of drainage elements (drainage well, tray, pipes)
	Type 4	The adjacent sites slope is less than the minimum permissible
	Type 5	Insufficient storm sewer capacity
	Type 6	Subsidence of the pavement
	Type 7	Destruction of the pavement (roadway, around the drainage well) and drainage well above the pavement mark (subsidence of the pavement)
	Type 8	Subsidence of the pavement transverse profile, destruction of the pavement

Also proposed: vertical planning with asphalt concrete layer covering the street in accordance with the developed profiles and vertical planning scheme, pavement covering overhaul with permissible slopes provision, change of the sites adjacent to the carriageway vertical design, cleaning of drainage elements (wells, tray, pipes).

Very often there is a problem of intersections drainage, which not only impairs the vehicles mobility, but is also a significant obstacle for pedestrians, it is in this place that a pedestrian crossing is usually located (see Fig. 5).

It is necessary to improve the surface water drainage from Poltava street and road network: strictly adhere to the designed slopes, and when designing, it is desirable to accept slopes greater than the minimum slopes of 5‰; when performing vertical design and construction, pay more attention to intersections and areas adjacent to the carriageway; apply a waterproof coating; comply with network elements operation requirements.

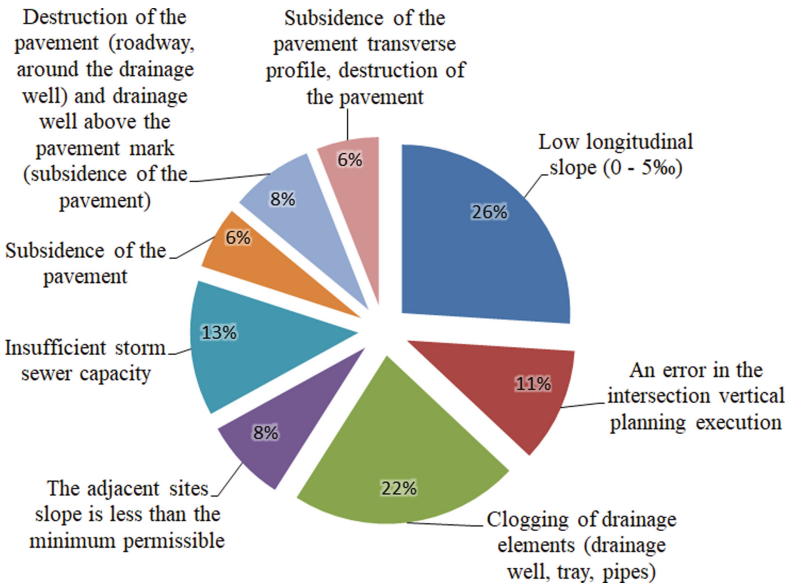
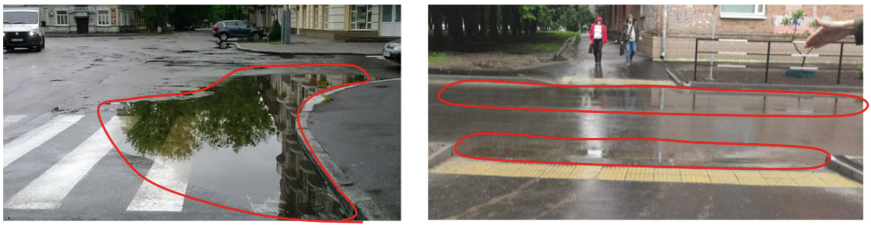


Fig. 4. Diagram of most common drainage deficiencies shares distribution in Poltava city, Ukraine.



a) b)

Fig. 5. Intersections drainage problem.

5 Conclusion

There is a need to improve the surface water drainage from settlements street and road network, because the result of territories flooding is the rapid destruction of streets road

surface, sidewalks and parking lots, so preventing and solving this problem as soon as possible is one of the priority tasks of design engineers.

As a result of the conducted research, were summarized the *principles* of drainage from the street and road network, which differ for open, closed and combined drainage systems. In particular, for the open drainage system planning measures are selected (water flow direction along the road by carriageway cross slopes, roadsides, possible curb and curbless road options); use of water drainage structures (road ditches: side ditches near the subgrade bottom, culverts, upland ditches, drainage ditches, culvert-reserves, evaporation basins; and spillway structures: artificial channel, pipes, bridges). The closed drainage system is divided into separate, semi-separate and all-alloy, which are provided by the following elements: water outlets, cameras, inspection wells, drainage wells, underground pipelines, etc. Drainage systems are also generalized.

The main *disadvantages* of Ukraine cities surface drainage were revealed. The most common are low longitudinal slope (0–5‰), an error in the intersection vertical planning execution and drainage elements (rainfall well, trays, pipes) clogging, as well as: the adjacent sites slope is less than the minimum permissible, the storm sewer insufficient capacity, the road surface subsidence, the stormwater well above the pavement mark (surface subsidence), destruction of the pavement (roadway, around the stormwater well), sidewalk transverse profile subsidence, sidewalk destruction.

Recommendations for improving surface water drainage from cities street and road network have been formulated: strictly adhere to surface drainage principles, and in particular, during construction, perform the designed slopes, and it is desirable to accept slopes greater than the minimum slopes of 5‰; when performing vertical design and construction, pay more attention to intersections and areas adjacent to the carriageway; apply a waterproof coating, from which water flows into the drainage system, from which it is possible to use water for irrigation; arrange water collection strips along the side stone, comply with the requirements for network elements operation.

References

1. Jie, Y., Dapeng, Y., Zhane, Y., Min, L., Qing, H.: Evaluating the impact and risk of pluvial flash flood on intra-urban road network: a case study in the city center of Shanghai, China. J. Hydrol. **537**, 138–145 (2016)
2. Schellart, A., Shepherd, W., Saul, A.: Influence of rainfall estimation error and spatial variability on sewer flow prediction at a small urban scale. Adv. Water Resour. **45**, 65–75 (2012)
3. Wang, J., Zhang, S., Guo, Y.: Analyzing the impact of impervious area disconnection on urban runoff control using an analytical probabilistic model. Water Resour. Manage **33**(5), 1753–1768 (2019). https://doi.org/10.1007/s11269-019-02211-0
4. Gharaibeh, N.G., Lee, C.-C.B.: Automating the evaluation of urban roadside drainage systems using mobile lidar data. Comput. Environ. Urban Syst. **82**, 101502 (2020)
5. Zaman, A. B. K., Mustaffa, Z., Giri, L. A.: Infiltration rate of pervious concrete on street curb application. J. Recent Technol. Eng. **8**(2S2), 86–90 (2019)
6. Darrien, Y., Darrien, M., Johnny, O., King, N., Vernon, L., Wan, W.: Augmenting drainage system in the old town of Kuching, Sarawak, Malaysia. Int. J. Eng. Technol. **7**(3.18), 36–39 (2018)

7. .Zölch, L., Hense, K. P., Pauleit, S.: Regulating urban surface runoff through nature-based solutions – an assessment at the micro-scale. Environ. Res. **157**, 135–144 (2017)
8. Armson, D., Stringer, P., Ennos, A.: The effect of street trees and amenity grass on urban surface water runoff in Manchester, UK. Urban For. Urban Greening **12**(3), 282–286 (2013)
9. Selbig, W.R., et al.: Quantifying the stormwater runoff volume reduction benefits of urban street tree canopy. Sci. Total Environ. **806**, 3, 151296 (2022)
10. Xia, J., et al.: A unified formula for discharge capacity of street inlets for urban flood management. J. Hydrol. **609**, 127667 (2022)
11. Dong, B., Xia, J., Zhou, M., Deng, S., Ahmadian, R., Falconer, R.A.: Experimental and numerical model studies on flash flood inundation processes over a typical urban street. Adv. Water Resour. **147**, 103824 (2021)
12. Li, X., Erpicum, S., Mignot, E., Archambeau, P., Pirotton, M., Dewals, B.: Influence of urban forms on long-duration urban flooding: laboratory experiments and computational analysis. J. Hydrol. **603**(C), 127034 (2021)
13. Kitsikoudis, V., et al.: Exchange between drainage systems and surface flows during urban flooding: Quasi-steady and dynamic modelling in unsteady flow conditions. J. Hydrol. **602**, 126628 (2021)
14. Mignot, E., Dewals, B.: Hydraulic modelling of inland urban flooding: recent advances. J. Hydrol. **609**, 127763 (2022)
15. Grimley, L.E., Quintero, F., Krajewski, W.F.: Streamflow predictions in a small urban–rural watershed: the effects of radar rainfall resolution and urban rainfall–runoff dynamics. Atmosphere **11**(774) (2020)
16. Lytvynenko, T., Tkachenko, I., Gasenko, L.: Principles of the road beautification elements placing. Period. Polytech. Transp. Eng. **45**(2), 94–100 (2017)

Transport Eurointegration of Ukraine (Ways to Revitalize Dnipro Reservoirs)

Grygoriy Shariy[1](✉), Svitlana Nesterenko[1], Vira Shchepak[1], and Evgeniya Ugnenko[2]

[1] National University «Yuri Kondratyuk Poltava Polytechnic», Poltava, Ukraine
shariy.grigoriy61@gmail.com
[2] Ukrainian State University of Railway Transport, Kharkiv, Ukraine

Abstract. Based on the monitoring of changes in the state of reservoirs over the past 50 years, the ways of their revitalization were analyzed and proposed in order to form a full-fledged waterway and return to the lands of transport part of the Dnipro reservoirs.

The Dnipro, on which a cascade of (six) reservoirs was built, forms the main element of the waterway from the Black Sea to the Baltic. But over the past 60 years, annual siltation and sedimentation of bottom sediments have significantly worsened the state of navigation on the Dnipro. Thus, depths of about three meters were formed on three sections, which makes it impossible for loaded cargo vessels to pass. The inland waterway on the Dnipro River is one of the main European integration elements of transport corridors and communications in Ukraine.

During the study, the condition of six reservoirs of the Dnipro cascade and hydraulic structures on the Dnipro, changes in shorelines and depths of the lake, shore protection works, coverage of the natural entropy of the aquatic environment were analyzed.

It is proposed to build alluvial and bulk peninsulas and islands, canals, which will allow, deepening the bottom of the Kamyanske, Kremenchuk and Kyiv reservoirs in the upper parts, to restore the full passage of cargo ships (barges) on silted areas. This will significantly improve the ecological condition of waters and return to economic use thousands of hectares of reclaimed land.

Keywords: Transport artery · Dnipro · Reservoir · Inland waterways · Revitalization · Remote sensing of the Earth

1 Introduction

The ecological condition of artificially formed territories, and especially reservoirs, is formed by technogenic catastrophes of local and regional levels. The threat of warming and climate change require emergency measures from states and governments. For Ukraine, the study of existing waterways and monitoring of the ecological condition, the rate of siltation of the waterway on the Dnipro, which is used for various needs of society and the economy, becomes especially important. There was a need to revitalize the reservoirs of the Dnipro in the economic, environmental sense, and especially as

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 586–597, 2023.
https://doi.org/10.1007/978-3-031-25863-3_56

a transport artery. This is one of the main parts of the European integration process of Ukraine, which requires study, scientific understanding and specific forecasts and engineering solutions for the reconstruction of reservoirs.

Comprehensive monitoring of the ecological condition of the Dnipro reservoirs confirms the need for urgent measures aimed at revitalization of reservoirs by deepening the bottom, shore protection, improving the ecological condition of reservoirs and will use water lands as a transport artery of Europe.

Annual subsidence of sand and silt and siltation of reservoirs by 1–2 cm per year for 60 years has changed the depth of the Dnipro waterways in many places in six reservoirs of the Dnipro cascade up to three meters: near the city of Kaniv (Cherkasy region), Svitlovodsk (Kirovohrad), Kamyanske (gorge Korchuvatyi, Dnipropetrovsk region). Only 60% of the waterway has guaranteed depths on the Dnipro. The national target program for the development of water management and ecological rehabilitation of the Dnipro River basin for the period up to 2021 was not implemented, as shore protection was not carried out, water protection zones and coastal protection strips have not been improved. In addition, this Program did not provide for the revitalization and reconstruction of reservoirs [1].

During the preparation of the article, open access publications and reports on the problems of monitoring the ecological condition of the Dnipro reservoirs and the waterway along the Dnipro were considered.

Studies of the history and consequences of hydraulic engineering on the Dnipro show a significant destruction of traditional settlement structures of the Ukrainian countryside and valuable historical monuments, as well as environmental damage to nature due to large-scale flooding [2]. Cartographic materials are important in the visualization of information about flooded areas, especially valuable are maps with the designation of individual flooded settlements [3].

Studies of the current state of use of reservoirs are mainly related to environmental monitoring, in particular, regarding the weediness of reservoirs, algae bloom and water pollution [4], as well as with the problems of operation of reservoirs and their management [5]. At the same time, technologies of geographic information systems and methods of remote sensing of the Earth are widely used [6].

Coastal areas are an integral part of water bodies as a connecting element between land and water. Therefore, solving the problems of reservoirs is closely linked to the issue of coastal use of space and its operation. In international practice, a comprehensive solution to these issues involves the concept of integrated coastal zone management (Integrated Coastal Zone Management), which aims to preserve coastal resources, their ecological functioning and their values through the use of proper land use planning in the social, institutional and economic context [7]. However, such management should be supported by the state, as it requires political priority, institutional cooperation, constant monitoring, quality expertise, and large investments.

Unfortunately, the work to improve the condition of reservoirs is carried out in small quantities in Ukraine. According to information sources [8] the Kremenchuk Reservoir annually attacks the shores on average from 2 to 8 m, due to the intensive collapse of the shores of the reservoir, new shallow waters are formed, where at high air temperatures occur man-made processes that cause water pollution. There is also a risk of flooding of

some settlements. Therefore, the situation around the Kremenchuk reservoir, as well as most other reservoirs of the Dnipro, requires a set of measures to restore the ecological condition of water bodies and the rational use of coastal areas. Often in practice the term 'revitalization' is used for this purpose, which in Latin means 'return of life' and is used in scientific and practical activities to characterize the processes of recovery, revitalization, reproduction. Revitalization involves, above all, the ecological restoration of water bodies in hydrology, that means the maximum preservation of natural factors of the aquatic ecosystem. For example, the revitalization of rivers involves abandoning the direction of the river, building coastal areas, concreting the shores, and aims to clear the riverbed, planting greenery, conservation of species biodiversity [9].

Another example is revitalization in urban planning is a way to socialize space and develop elements of infrastructure that regulate the development of industry, tourism, research, environmental protection and, consequently, promote investment. An interesting experience in this direction is the project of revitalization of the island of Khortytsia, which combines three components: culture and history; recreation and sports; nature. This project envisages a new transport infrastructure and a master plan of the island [10].

The problems of improving the ecological condition of Ukrainian reservoirs and preserving the waterway along the Dnipro require significant financial and material investments, as well as new approaches to the reconstruction and revitalization of reservoirs and protection from natural entropy, and the problems proposed by the authors are relevant.

The purpose of this work is to analyze the waterways of the Dnipro and its reservoirs, to suggest ways of revitalization and restoration of transport arteries of inland waterways.

2 Page Layout

Water resources are extremely important for human life and the functioning of ecosystems. The uneven distribution of these resources on the Ukrainian territory led to the creation of a network of reservoirs of artificial reservoirs to regulate the flow and accumulation of water and its further use for economic purposes. There are more than fifty reservoirs in Ukraine, the largest of which are cascading reservoirs on the Dnipro River. These are six reservoirs: Dnipro (water mirror area 410 km^2), Kamyanske (567 km^2), Kaniv (582 km^2), Kyiv (922 km^2), Kakhovka (2,155 km^2), Kremenchuk (2,250 km^2), which were created during 30 -70s of the XX century [11].

Despite the positive impact of reservoirs on economic activity (creation of cascades of hydroelectric power plants, creation of favorable conditions for river transport, irrigation of agricultural lands, etc.), in recent decades there have been a number of problems, including bank erosion, and so on. The causes of the problems are excessive anthropogenic load on reservoirs and adjacent territories, lack of investment in improving the infrastructure of reservoir operation, inconsistency of reservoir management with the principles of sustainable development, imperfection of land management in coastal areas. To solve the above problems in Ukraine, the issue of using the territories of reservoir ecosystems, taking into account their revitalization, is relevant.

The idea of forming an international waterway E40 allows the rivers Dnipro, Prypyat, Buh and Visla to unite the Black Sea and the Baltic, and most importantly, unloading transport corridors and railways, to form a new transport corridor from Ukraine to Europe (Fig. 1).

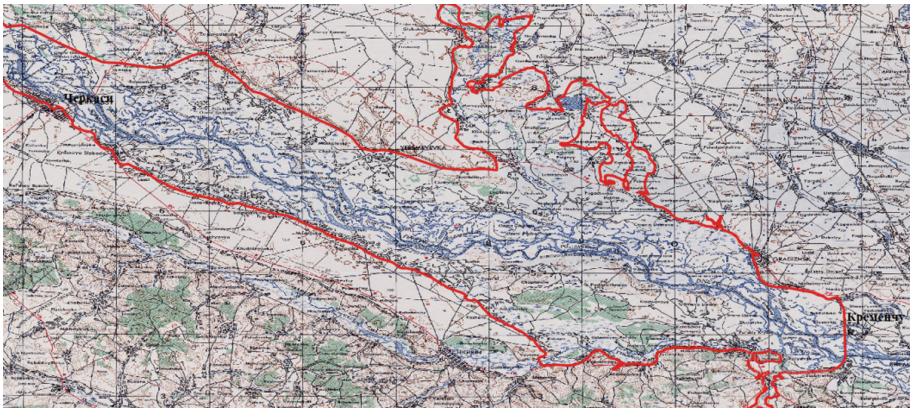


Fig. 1. The boundaries of the flooded areas of the Kremenchuk reservoir.

In modern conditions, the deterioration of the ecological state of reservoirs is influenced by the following factors: natural (global warming, rising average annual air temperature, decreasing average annual rainfall; soil erosion in the catchment area, destruction of shores, existence and expansion of shallow waters, including rocks by rivers flowing into reservoirs; anthropogenic (sewage pollution, inflow of pollutants to water bodies in the process of surface runoff of water from built-up areas and agricultural lands; use of water for agricultural purposes and production and technical purposes.

Since 1901, the temperature of the warm period of the year and the daytime temperature has been growing rapidly in the lands of Ukraine, the growth of which is more intensive than the growth of temperatures in the winter and night periods. Since the beginning of 1901, almost every subsequent decade was also warmer than the previous one: 1991–2000 yrs. – up to 0.5 ºC, 2001–2010 yrs. – up to 1.2 °C, 2011–2019 yrs. – up to 1.7 °C (Fig. 2).

Rivers flowing into reservoirs also carry solid particles of rock and form a kind of underwater deltas and island lands, which, along with the abrasion of the shores expands shallow water and silts up the reservoir to 2 cm or more annually.

Reservoirs are used not only for navigation, but also for electricity generation, irrigation, water supply of settlements, recreation. However, the navigable routes along the left banks of the reservoirs, which previously operated, are preserved now, only the piers of Irkliv, Adamivka, Lypove, Hradyzk, and Kremenchuk are partially used. Ecological problems increase every year: shores are destroyed, shallow waters are formed, excessive development of cyanobacteria (blue-green algae), waterlogging, self-afforestation and weediness of water mirror with swamp vegetation is observed. Leads to the degradation of the biotic complex of self-cleaning of the reservoir, mass slaughter of fish, makes it impossible to use reservoirs for shipping purposes. The development of bacteria is

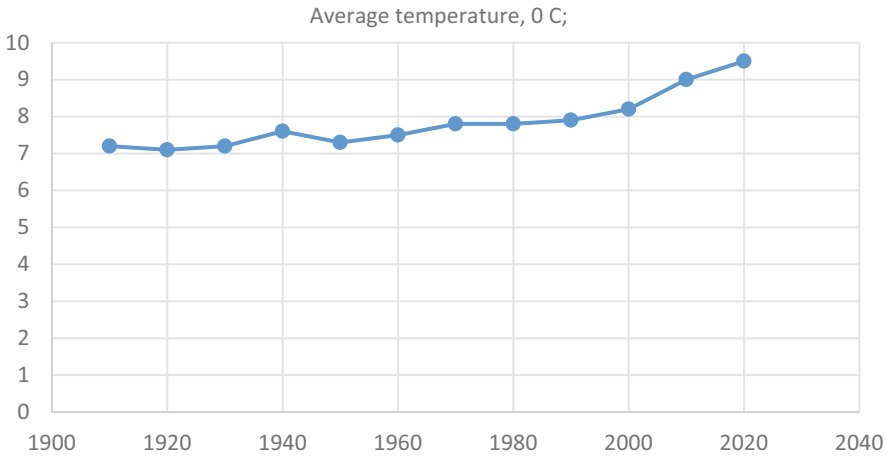


Fig. 2. Dynamics of change of average annual air temperature in Ukraine.

provoked by the discharge of phosphates and phosphonates into the Dnipro: through wastewater (up to 70%), car washes (20%), agricultural production (upto 5%) [12].

The above factors contributed to the expansion of shallow water, with a small depth (up to 2 m). Satellite surveys of reservoirs indicate the gradual weediness of shores with reeds and willows, as well as their shallowing. Therefore, degraded ecosystems of Dnipro reservoirs need to be reconstructed without waiting for their restoration due to chaotic natural entropy.

The analysis of the depths of the Kremenchuk Reservoir indicates a number of existing areas of shallow water that can be revitalized through drainage, reclamation, land construction by alluvium and backfilling and return to the lands of transport, conservation, recreation, forestry, housing and public buildings, energy. From 5 to 32% of shallow water is occupied by thickets of higher aquatic and terrestrial vegetation, these areas are characterized by slow currents, reduced turbulent mixing of water, greater warming.

This silts up not only shallow water, but also deep-water areas of the lake, especially in the upper part of reservoirs, which becomes unsuitable for navigation (Fig. 3).

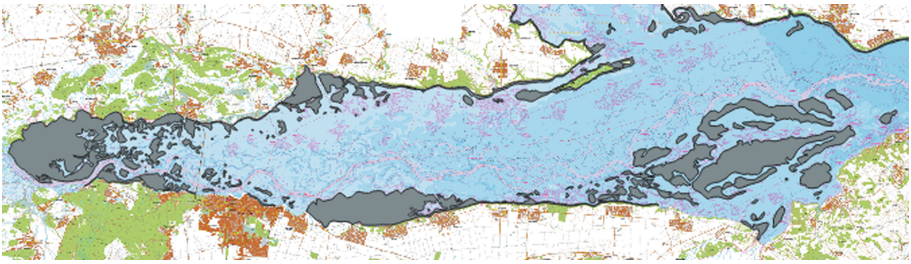


Fig. 3. Shallow water of Kremenchuk reservoir [analyzed on the basis of data http://fisher-club.com/news/karta_glubin_Kremenchukskogo_vodokhranilishha/2013-11-17-61].

The phenomenon of the algae bloom is widespread in shallow waters. Algae bloom is a phenomenon that manifests itself in the change of color of water due to the mass reproduction of microscopic blue-green algae (cyanobacteria), accompanied by a significant deterioration in water quality. Another process that affects the state of water bodies is overgrowing of water reservoir, that is a natural process of increasing the number of higher aquatic plants in the reservoir [13]. Algae bloom occupies about 70 percent of the reservoir, especially in the lower part and bays (Fig. 4). Excessive algae bloom deteriorates water quality and living conditions of organisms in water bodies. The main factors that lead to the algae bloom are: increasing water temperatures (depending on global climate change); slowing down the flow of water in the Dnipro (the first reservoirs were built on the river in the 20s of last century); wastewater from cities, industrial and agricultural enterprises contains compounds of nitrogen, phosphorus, iron, silicon and organic matter; pollution by phosphorus and its compounds. The layer of algae bloom can reach 10–15 cm thick. Identification of the algae bloom areas of the Kremenchuk reservoir was carried out on the basis of operational monitoring of large-scale clusters of planktonic algae according to remote sensing of the Earth. Methods of processing space images to detect areas of the algae bloom are usually based on the analysis of the difference in the spectral characteristics of the clean surface and subsurface layers of water and vegetation-covered reservoir. Sentinel − 2 satellite images were downloaded from the EO Browser service of the European Space Agency, and further processing of Earth's remote sensing data was performed in the QGIS geographic information system. The deciphering feature in identifying the algae bloom is the texture of the image. Areas of intense algae bloom are characterized by a specific filamentous texture. In the space image (Fig. 4) it is seen that the areas of intense algae bloom are extended along the currents of the right bank. When you adjust the combination of channels 11, 8, 4 (SWIR, NIR, Red) for pictures, deep water is displayed in the darkest color, and bright green spots appear in the algae bloom areas.

To control the algae bloom using the NDVI Index (Normalized Difference Vegetation Index) is a quantitative indicator of active (capable of photosynthesis) biomass. It is usually called simply the vegetation index. Today, NDVI is the most widely used index. Satellite or aerial photography makes it possible to observe changes in the state of the water surface to monitor the spread of algae that cause to the algae bloom.

The index is calculated by a formula that takes into account possible interfering factors: the reflectivity of water, the absorption of light by water vapor in the atmosphere. Numerous refinements have led to the fact that as a result of calculations accurate data are obtained.

The use of the NDVI index allows tracking the development of algae in the Kremenchuk Reservoir (Fig. 5). The NDVI value varies from -1.0 to 1.0. Vegetation is reflected in shades of green.

The shores of reservoirs are high (up to 30–40 m), steep, widespread erosion processes. The shore is sandy, mostly under cliffs separated by ravines. In Fig. 6 shows photos of the shores of the Kremenchuk reservoir.

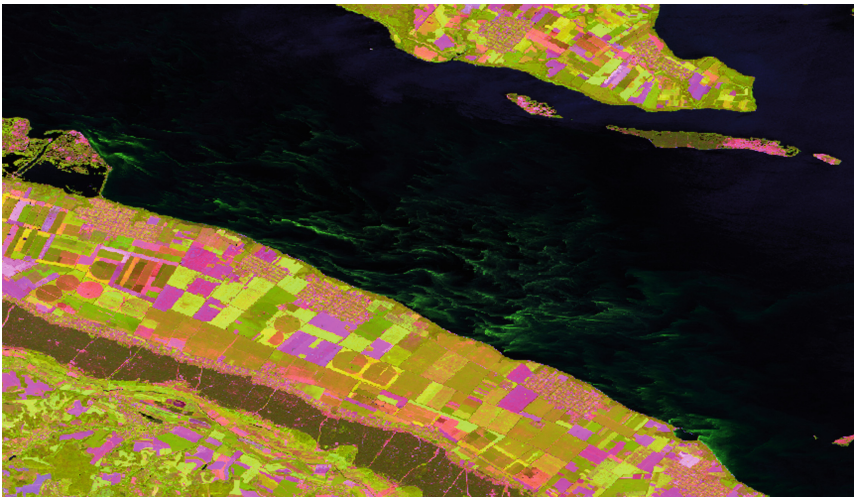


Fig. 4. Algae bloom of Kremenchuk reservoir.

The shores of reservoirs are under the constant influence of water and waves, which contributes to the development of landslides and abrasions of soil rocks. Abrasion is the process of destruction of shores (oceans, seas, lakes or large reservoirs) and the demolition of rocks in the coastal zone of reservoirs by waves and surf, abrasion of the shores of artificial reservoirs is called shore processing (Fig. 7).

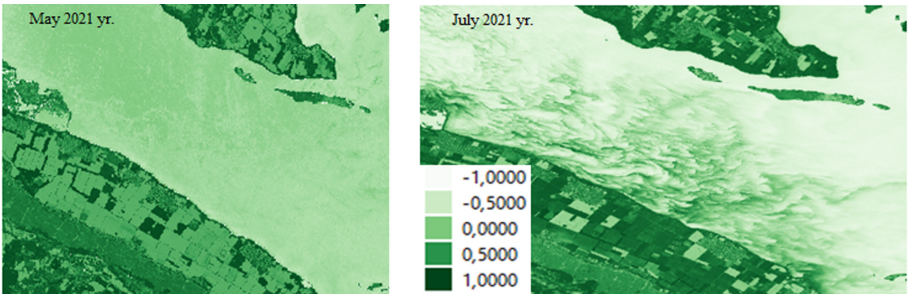
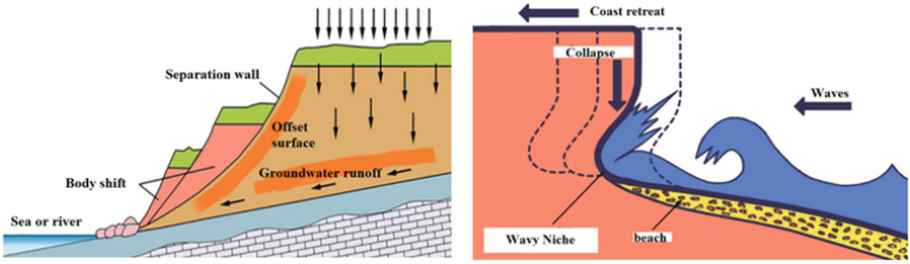


Fig. 5. Calculation of the vegetation index of the NDVI reservoir on the Sentinel − 2 satellite image [Resources for downloading images: EO Browser, USGS Earth Explorer].

To combat landslides and abrasions of the shores, various hydraulic methods of shore protection are used: artificial sandy beaches and estuaries, stone outlines, spurs, banquets and bogs, as well as their various combinations, for example, almost a third, 43.9 km, the shores of the Kremenchuk reservoir, because every year the water takes from 2 to 7 m of shore. The cost of shore protection of 1 km is about 30 million UAH - 1 million Euro.

a) b)

Fig. 6. Abrasion of the shores of the Kremenchuk reservoir: a) photo of the coast; b) on the Sentinel – 2 satellite image. Resource: https://poltava.to/news/57597/.



a) b)

Fig. 7. Phenomena of landslides and abrasions: a) rock shift; b) abrasion of the shores.

The most difficult ecological and hydrological situation has formed in the Kamyanskyi, Kremenchuk and Kyiv reservoirs. In addition to shore protection works, for example on the Kremenchuk reservoir, the authors propose to build alluvial and bulk peninsulas and islands, canals, which will deepen the bottom of the Kremenchuk reservoir, significantly improve the ecological condition of waters and return to economic use. Such methods are common in world practice and help to create new territories for various purposes.

The cities of Singapore, Rotterdam, Hong Kong, Mykolayiv, Cherkasy, Kherson, Monaco, Dubai and many others see prospects for development in alluvial areas.

Analysis of the depths of the Kremenchuk reservoir indicates a number of existing areas of shallow water, which can be revitalized by drainage, reclamation, land construction by alluvium and backfilling and return to the lands of transport.

The authors have developed and propose to build alluvial and bulk peninsulas, islands and canals, which will deepen the bottom of reservoirs, significantly not only improve the ecological status of waters, but also return to economic use thousands of hectares of reclaimed land (Fig. 8). The project achieves social, environmental and commercial goals, as part of the construction of embankments «Yaremiyevka Mounds» and «Veremiyivka water lilies» under the common name Veremiyivka Sich (on the site of flooded villages Veremiyivka (historical name before 1917 Yaremivka), with the allocation of built-up and a whole archipelago of alluvial islands for various purposes: port,

transport and sports facilities, yachts, fisheries, residential complexes and recreation centers.

The scientifically substantiated project of construction of the Yaremivka complex will provide ecological and technical stability of constructions, aesthetics, ecological friendliness, economic self-sufficiency, and safety of object as a whole. The territory proposed for development and development has a sandy bottom, on it and before flooding there were coniferous forests and sand mounds (hills).

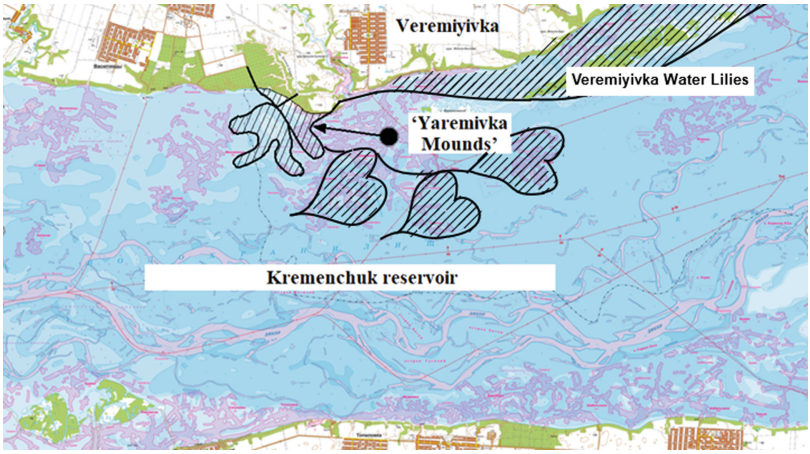


Fig. 8. Scheme-proposal for construction of bulk-alluvial complexes «Yaremivka Mounds» and «Veremiyivka Water Lilies» in the shallow water of the Kremenchuk reservoir.

Particularly strong social and ecological attraction, characteristics and method of development determine the place of construction of a complex of hydraulic structures on alluvial islands and in drained shallows near the present villages of Tymchenko and Veremiyivka on the site of the flooded villages of the same name. The area of drainage of the reconstructed water area and bulk areas and alluvium is expected to be up to 50 thousand hectares. Feasibility study of the project determines the expected required amount of about 5 billion. UAH annually for 10 years.

Technologically, it is considered expedient to pour stones along the contours of new massifs, create dams, drain development areas, conduct archaeological, geological and hydrological surveys, build drainages and canals, providing transport and waterways.

According to the general development plan, plots for buildings and structures should not be dumped, but frame foundations and pile belts should be built, basements should be created and only adjacent, recreational plots, common areas and afforestation plots, as well as industrial and transport development should be prepared for alluvium.

Sand alluvial soils 5–6 m thick, form a multilayer solid base (internal friction angle 28-36º, deformation modulus 28.0–35.0 MPa); namely: I layer - above the water surface level of 3–4 m, which will be dense and will not sag; The second layer - 1.5–2 m of sand - will remain water-saturated and loose for many years, it is necessary to sew with pile belts; III layer - the bottom of the reservoir, where peat, clay and other bases may lie,

which will sag for many years (1.5–4 m); The IV layer is alluvial sands, which ensure the stability of the territories.

Alluvial soil (sand) from the bottom of the reservoir should be removed from underwater quarries from remote areas of the navigable part, which will be determined according to a mathematically high-tech model. These models will be built taking into account promising waterways and the need to build wintering holes for fish (former old women of the Dnipro).

Alluvial soils with pile belts and reinforced concrete frames have a high predictable bearing capacity.

The use of brick-monolithic technologies with the supply of most building materials from the bottom of the reservoir 'floating vacuum cleaners' will form a transport-accessible water area and pave waterways, promote the formation of water currents.

At the state level, it is necessary to direct part of the budget funds and investments of international investors to these purposes for engineering, transport and social development.

It is necessary to envisage afforestation of the territory with windbreak protective plantings, especially on the north-western side, and construction of roads of state importance, bridges, berths, richports.

The problematic issue remains the unresolved legal issues regarding the reclamation of the shallow part of the reservoirs to restore the land and return the Dnipro valley to its previous state, the restoration of transport characteristics of the waterway.

In December 2020, the President of Ukraine signed the Law of Ukraine № 1054-IX 'On Inland Water Transport'. Even on the coastal slopes of inland waterways for the purpose of navigation safety, the use of forest areas is determined by this Law.

It is necessary to introduce into the Land and Water Codes legal norms on the conditions of termination of a water body and change the purpose of water fund lands on land for transport, housing and public buildings, recreation, forestry, energy, industry, agriculture and environmental protection.

As a result of capital construction and reclamation of water fund lands, it is possible to create attractive urban areas, reduce evaporation areas, lower temperatures, improve the ecological condition of reservoirs, and most importantly, create a modern transport European integration corridor.

It is necessary to act systematically. The authors elaborated some program elements that need to be finalized and the Verkhovna Rada adopts the Law of Ukraine 'Program for the Development of the Dnipro Basin until 2050' (hereinafter—Program), which provides for the stages of a set of works and specific measures, both, reservoirs, ponds and adjacent areas; implement the Program in 3 stages: the first by 2030, the second by 2040 and the third by 2050: to develop and adopt inland waterway projects, conducting public discussions and examinations of the reconstruction of the Dnipro reservoirs (by 2025); provide funding for the Program from the state, local budgets and investors, both domestic and international; adopt amendments to the Tax Code for the purpose of targeted use of payments for the use of natural resources (land, water, hydrocarbons) exclusively for reclamation, reclamation, afforestation, land conservation, revitalization of reservoirs, rivers, swamps, streams, industrial disturbed lands and contaminated areas; to carry out shore protection of reservoirs, but not along the existing shoreline, but along

the shoreline (up to 2 m depth) with subsequent drying and alluvium and revitalization (Kyiv, Kaniv, Kremenchuk, Dnipro and Kamyansk reservoirs).

3 Conclusion

1. Scientifically substantiated revitalization of Dnipro reservoirs through shore protection, shallow water drainage, deepening of the bottom will help to restore the internal waterway, eliminate stagnant areas, intensify water movement and reduce its temperature in summer by 5–6 °C, ensure the formation of constant currents and water circulation. Deepening of the bottom will help to restore internal waterways, alternate cooled and heated parts for water circulation, increase the number of wintering holes for fish, stop the excessive development of cyanobacteria in the summer.
2. It is necessary to develop a state program for the reconstruction of the Dnipro reservoirs at the state level, together with Polish partners to create a single inter-basin management of the waterway of the two seas.
3. Revitalization of the Dnipro involves the reconstruction of reservoirs by shore protection, drying shoals, reducing floodplains, deepening, restoration and reclamation of hundreds of thousands of hectares of shallow water to afforestation and urbanization, restoration of hundreds of kilometers of waterways and create European integration.
4. Socio-ecological attraction, determined the place of construction of the complex of hydraulic structures «Veremiyivka Sich» in drained shallow waters. The area of drainage and reconstruction of water area and embankments and alluvium is expected to be up to 50 thousand hectares, the feasibility study of the project provides for the amount of annual investment up to 5 billion UAH. The project should become one of the links of specific projects, initiated by the public, on the way to Ukraine's European integration.
5. It is necessary to revitalize the reservoirs of the Dnipro in the economic, environmental sense, and especially as a transport artery. Dnipro is one of the main links in the transport European integration process of Ukraine. This requires further study, scientific understanding and specific forecasts and engineering solutions for the reconstruction of reservoirs.

References

1. National target program for water management development and ecological rehabilitation of the Dnieper river basin for the period up to 2021: Law of Ukraine of 24 May 2012. https://zakon.rada.gov.ua/laws/show/4836-17#Text. Accessed 28 June 2022
2. Horlo, N.V.: Ecological consequences of hydraulic engineering on the Dnieper (50–70's of the XX century): history and current state of the problem. Zaporizhzhia Hist. Rev. **1**(21), 240–247 (2007)
3. Old Dnieper: Map of villages before and after the flood. https://olddnieper.org.ua/maps/item/84-karta-sil-do-i-pislia-zatoplennia. Accessed 28 June 2022
4. Vyshnevskyi, V.I.: Dnieper reservoirs and problems of their use. Hidroenerhetyka Ukrainy **3–4**, 18–23 (2018)

5. Petrashenko, V.O., Kozyuba, V.K.: Coast of Kaniv Reservoir (catalog of archeological monuments). NAS of Ukraine, Institute of Archeology, Institute of Monument Protection Research, Kyiv, 329 p. (1999)
6. Zahorodnia, S.A., Sheviakina, N.A., Novik, M.I., Radchuk, I.V.: Research of ecological condition of Kremenchug reservoir within Cherkasy region by remote sensing methods. Sci. Notes Tauride National University named after VI Vernadsky, Geography Ser. **23**(62), 2, 84–91 (2010)
7. Belenok, V., Derkach, D.I., Rul, N.V.: Use of aerospace methods and remote sensing data processing methods for ecological monitoring of Kakhovka reservoir. Visnyk Astronomichnoi shkoly **13**(1), 54–63 (2017)
8. Skourtos, M., Kontogianni, A., Georgiou, S., Turner, R.K.: Valuing coastal systems. In: Turner, R.K., Salomons, W., Vermaat, J. (eds.) Managing European Coasts: Past, pp. 119–136. Springer Verlag, Present and Future (2005)
9. Bashlyk, O.: The shores of the Kremenchug Reservoir need strengthening. Cherkasy regional online media «Procherk» (2017). https://procherk.info/news/7-cherkassy/56749-beregi-kremenchutskogo-vodoshovischa-potrebujut-ukriplennja. Accessed 28 June 2022
10. Khilchevskyi, V.: Hydroecological problems of rivers revitalization on the urban ares - international and Ukrainian experience. Hidrolohiia, hidrokhimiia i hidroekolohiia **2**(45), 6–12 (2017)
11. Khortytsia National Reserve: official site. About the project. https://hortica.zp.ua/ua/about. Accessed 28 June 2022
12. Vermenich, YV.: Dnieper rapids. Encyclopedia of the History of Ukraine: in 10 volumes. Vol. 2: G-D. Institute of History of Ukraine. Kyiv, pp. 408–410 (2004)
13. Sharyi, H.I., Nesterenko, S.V., Shchepak, V.V.: Ways to increase the sustainability of the agricultural sector of the economy. Sci. Ind. J. «Land management, cadastre and land monitoring» **1**, 4–19 (2021)
14. Tomiltseva, A.I., Jacik, A.V., Mokin, V.B., et al.: Ecological bases of water resources management. Institute of Environmental Management and Sustainable Nature Management, Kyiv, 200 p. (2017)
15. Dovhyi, S.O., Babiichuk, S.M., Kuchma, T.L., et al.: Remote sensing of the earth: analysis of space images in geoinformation systems, Kyiv, 268 p. (2020)
16. Hlotov, V.M., Tereshchuk, O.I., Movenko, V.I.: Analysis of the results of determining the volume of flushing of the shoreline of the Desna riverbed. Zbirnyk naukovykh prats Zakhidnoho heodezychnoho tovarystva UTHK «Suchasni dosiahnennia heodezychnoi nauky ta vyrobnytstva» **1**(19), 210–215 (2010)
17. Sharyi, H.I., Nesterenko, S.V., Stoiko, N.I.: Ways of revitalization of coastal territories of Kremenchug reservoir. In: V International Scientific and Technical Conference «Effective technologies and structures in construction and rural architecture», Lviv, pp. 71–72 (2022)

The Impact of Third-Party Logistics Intermediaries on Supply Chain Responsiveness

Aidas Vasilis Vasiliauskas(✉) and Olga Navickienė

General Jonas Žemaitis Military Academy of Lithuania, Šilo 5A, Vilnius, Lithuania
{aidas.vasilisvasiliauskas,olga.navickiene}@lka.lt

Abstract. To compete internationally, businesses organize global strategic networks (supply chains) to provide fast, efficient, and high-quality responses to demand anywhere in the world. To respond as quickly as possible to unforeseen demand, businesses choose to adopt a responsive supply chain strategy by engaging outsourcing companies. There is still a lack of empirical research on the impact of 3PLs on supply chain responsiveness. Therefore, the question does the provision of 3PL services have a significant impact on the responsiveness of the supply chain and does it allow for the generation of additional added value for the recipient companies still needs to be answered. The objective of given article is to assess the impact of third-party logistics intermediaries on supply chain responsiveness and to propose reasonable measures to manage this impact.

Keywords: Supply chain · Lithuanian manufacturing companies · Logistics service providers · 3PL · Outsourcing · Responsiveness

1 Introduction

Major economic changes and globalization is opening new markets and increasing competition between businesses. The challenge for companies is to stay ahead of the curve, not lose market share, and their customers' growing expectations. To compete internationally, businesses organize global strategic networks (supply chains) to provide fast, efficient, and high-quality responses to demand anywhere in the world. To respond as quickly as possible to unforeseen demand, businesses choose to adopt a responsive supply chain strategy by engaging outsourcing companies because they lack the expertise, capacity, information, and human resources or simply find it too costly to provide the desired level of responsiveness themselves.

It is, therefore, important to analyse the services, quality, and supply of third-party logistics intermediaries to determine the real impact on supply chain responsiveness.

There is a lack of empirical research on the impact of 3PLs on supply chain responsiveness, which shows not only the real benefits for the company but also the impact on supply chain responsiveness to identify possible areas for improvement of 3PL services. In this context, the question is: Does the provision of 3PL services have a significant impact on the responsiveness of the supply chain and does it allow for the generation of additional added value for the recipient companies?

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 598–605, 2023.
https://doi.org/10.1007/978-3-031-25863-3_57

The objective is to assess the impact of third-party logistics intermediaries on supply chain responsiveness and to propose reasonable measures to manage this impact. To do this, article starts with the analysis of various literature sources examining issues of supply chain efficiency and responsiveness. The next chapter discusses the role of 3 PL companies in the supply chain. Third section describes the research methodology applied to empirically assess the impact of 3PL service providers on the responsiveness of the supply chains of Lithuanian manufacturing companies, while the fourth one presents the main results of the research?

2 Issues of Supply Chain Efficiency and Responsiveness

Modern global market trends and the ever-growing needs of consumers are forcing organisations to cooperate and network to deliver the goods they need at the right time, in the right place, and at the right price so that in a competitive marketplace, business organisations do not lose their competitive edge. Such networks are called supply chains. Successful supply chain management adds value to all business organisations in the network, and the main objective is to satisfy the needs of the consumer, so it is in the interest of each actor in the network to perform its function well. Also, actors in the supply chain concentrate on performing their specific activities and engage in free and trusting mutually beneficial cooperation with suppliers and consumers.

The complexity of a supply chain depends on the number of actors in it [9].

It should be stressed that there are also several main types of supply chains. Some authors distinguish between efficient/lean and responsive/agile supply chain types [2, 5]. Some also state that supply chains differ in terms of whether they are highly responsive or highly efficient [7].

A review of the academic literature reveals different definitions of an efficient supply chain. Some describes supply chain efficiency as the ratio of the result achieved to the resources used, whereas a company can increase the efficiency of the supply process by reducing supply chain costs. Other argue that supply chain efficiency is the efficient use of resources when the desired objective is achieved at the lowest cost, or the maximum result is achieved by using all the resources in the chain. Efficiency in a supply chain is the ratio of the result achieved to the resources used to achieve that result, or, more simply, the maximisation of benefits with limited resources. In summary, the basic idea of an efficient supply chain is to create the greatest possible benefit for the consumer with the minimum of resources.

There is also a case for a responsive supply chain. Responsive supply chain is characterised by a rapid response to changes in consumer demand and rapid response to changes in supply. According to Fernie and Sparks (2012), a responsive supply chain is quick to react to changes in the market, as customer satisfaction is a key performance indicator [7]. According to Ariadi et al. (2021), in an agile supply chain, the actual demand for goods is identified and responded to quickly [2]. Supply chain responsiveness could be understood as adapting quickly and efficiently to ever-changing technological advances, increasing competition and geopolitical conditions.

An analysis of the characteristics of efficient and responsive supply chain types allows us to compare them (see Table 1).

Table 1. Comparing efficient and responsive supply chains.

Characteristics	Efficient supply chain	Responsive supply chain
Aim	Meeting demand with minimum resources	Responding to unforeseen demand as quickly as possible
Production objective	Reducing costs through better use of internal resources	Increasing capacity flexibility to protect against market volatility
Key indicators	Price and productivity	Focusing on meeting consumer needs
Logistics:	Stable, periodic	Rapid response (instantaneous)
Delivery time objective	Using internal resources to reduce delivery times and maintain a stable price	Using only the fastest delivery methods
Choice of suppliers	Based on value for money	Priority is given to speed, flexibility, quality
Pricing	Reduce profit margins, as the price is the main motivation for consumers	Increase profit margins, as the price is not the main motivation for consumers

Source: Christopher, 2011; Fernie and Sparks, 2014; Tarafad and Qrunfleh, 2017; Ariadi et al., 2021

3 The Role of Outsourcing Providers in the Supply Chain

Due to the ever-increasing demands of consumers, businesses tend to focus on their core functions and outsource their logistics processes.

In the current competitive environment, outsourcing is becoming one of the key drivers of business responsiveness and efficiency across the supply chain for businesses, irrespective of their activities [11]. Outsourcing means that businesses are prepared to outsource some of their business functions or processes to a third party (contractor).

Recently, there has been a rapid expansion of the business category of outsourced logistics service providers (logistics intermediaries), which have a significant impact on the logistics sector as a whole, generating more added value for the recipients of the services they provide and increasing the volume of trade and competitiveness [3]. One of the basic principles of outsourcing is: 'I reserve for myself only what I can do better than others, and I outsource to the logistics provider what they do better than me and competitors'.

Outsourcing service providers offer their customers support in supply chain management, integration of advanced information technologies, use of new equipment, logistics infrastructure that meets modern standards: modern warehouses, state-of-the-art transport, fast and efficient freight transport, planning of the fastest routes, freight document management, etc. [1].

According to Premkumar and Gopinath (2020), companies now find it difficult to operate without logistics service providers, as these collaborations reduce costs for the company and speed up the introduction of goods into the market [10].

As a manufacturer needs to produce products in response to consumers' demands, the supply chain needs to be responsive, i.e., quick to react to volatile demand and short product life cycles [12]. However, a responsive supply chain strategy can hardly do without the logistics services provided by a 3PL, as in today's world of globalisation and constant technological development, there is a huge amount of competition, and inappropriate use of costs (in the case of companies carrying out the logistics processes themselves) can lead to a loss of competitive edge and profits, and thus to the loss of loyal consumers.

Thus, the overarching objective of integrating supply chain actors with 3PLs is to maximize the speed of service to the consumer at a lower cost and to obtain a rapid flow of information regarding volume, services and products [8].

In summary, the various studies and analyses conducted in Lithuania on the topic of 3PL show that 3PL services, the growth potential of this market, the benefits of services and collaboration, efficiency, responsiveness, speed, competitive advantage in the supply chain, and service user satisfaction are mentioned in all studies conducted. It is important to note that there is significantly less research on 3PL in Lithuania compared to the foreign 3PL market. Also, comparing the Lithuanian 3PL market with the foreign market reveals differences and opportunities for improvement, as most of the authors highlight that the Lithuanian 3PL market is in its infancy or nascent stage. However, it can be stated that no openly available studies have been found on the impact of 3PL on supply chain responsiveness. This conclusion, therefore, implies the need for such a scientific problem and its assessment and justifies the relevance of the study.

4 Research Methodology

In the literature review, it was noted that the concepts of 3PL and supply chain responsiveness are not a new term. However, compared to the global academic literature, there is a lack of a greater number of contributions from Lithuanian authors, not only on 3PL and the supply chain but also on the impact of the services provided by a 3PL on the responsiveness of supply chains. In Lithuania, no openly available studies have been found on the impact of 3PL on supply chain responsiveness, at least so far. Therefore, the objective of this research is to empirically assess the impact of 3PL service providers on the responsiveness of the supply chains of Lithuanian manufacturing companies.

One of the most popular quantitative research methods, the questionnaire survey, is utilised to achieve this objective. The questionnaire survey method is often used in research as it is the most convenient way of collecting data to obtain the respondents' views and ensure their anonymity. It is, therefore, likely that the answers given by the respondents will reflect the actual situation, as the aim is to collect as much data as possible to be able to assess overall trends and identify problem areas. One of the biggest advantages of this chosen research method is the speed with which it can be conducted compared to observational or qualitative research methods.

The questionnaire uses closed-ended questions. Managers or employees of Lithuanian manufacturing companies that use 3PL services in their operations had to choose one answer option.

The questionnaire is based on purposive sampling, targeting a segment of manufacturing companies. Based on the Entrepreneurship Trends in Lithuania 2022, there are

107,362 business entities (excluding natural persons engaged in economic activity) in Lithuania in 2022, of which 9,941 are engaged in manufacturing [6]. With purposive sampling, the author of the questionnaire selects only those data, situations, or individuals whose use can inform the research. Main criteria for selecting manufacturing companies and their respondents:

1. Supply chain management processes must be implemented within the company;
2. Intra-company logistics processes must be implemented within the company;
3. The respondent must be involved in supply chain management or the company's logistics processes.

The questionnaires were sent by e-mail to manufacturing companies operating in Lithuania.

The sample is designed so that its characteristics reflect those of the general population. The questionnaire sample will be based on the Paniotto formula:

$$n = 1/\left(\Delta^2 + 1/N\right) \tag{1}$$

where n – sample size, Δ – the amount of sampling error (in social science research, a 5% error is acceptable, i.e., $\Delta = 0.05$, with a confidence level of 0.954), N – the size of the general population.

$$n = 1/(0.05^2 + 1/9941) = 1/(0.0025 + 0.00010059) = 1/0.00260059 = 384.52 = 385 \text{ (informants)}$$

Using the data available on the website of the Centre of Registers, and with a small margin of error, a sample of 450 informants was selected for the research, and the questionnaire was sent to them by e-mail [4]. The questionnaire survey of manufacturing companies returned 298 completed questionnaires out of 450.

5 Main Finsdings

The aim at the outset was to determine the size of the companies participating in the questionnaire. Most of the manufacturing enterprises surveyed are medium-sized enterprises (50 to 249 employees) – 42.4%, followed by small enterprises (10 to 49 employees) – 29.6%, micro-enterprises (up to 10 employees) – 16.9%, and lastly, large enterprises (more than 250 employees) – 11.1%.

The next question was to establish the annual turnover of manufacturing companies in the euro. Most of the companies surveyed reported an annual turnover of between €1–3 million (25.1%). The next category of enterprises is those with an annual turnover of up to €1 million (29.5%). Third, are companies with an annual turnover of €3–5 million (18.3%). Other companies report an annual turnover of €5–10 million (16.9%). The lowest percentage of respondents (10.2%) indicate that they have an annual turnover of over EUR 10 million.

From the results, we can see that a huge part of the surveyed companies (91.5%) sell their products in Lithuania and also export to foreign markets. The rest (8.5%) sell their products only in Lithuania.

The survey found that a higher proportion of companies (63.4%) have opted for an efficient supply chain strategy. Meanwhile, 36.6% of respondents have chosen to use a responsive supply chain strategy.

The questionnaire asked companies whether the success of a responsive supply chain strategy is due to the attraction of 3PL providers into their supply chains. A higher proportion (75.6%) of the informants in the study stated that the success of a responsive supply chain is due to the attraction of 3PL providers to supply chains.

Most respondents (82.4%) say that their company has used 3PL providers in their supply chains.

29.4% of respondents use only one 3PL provider, while the majority (70.6%) work with several 3PL providers.

20.6% of respondents say they have one-off cooperation agreements with 3PL providers. 26.9% of respondents indicated that they have short-term contracts with 3PL service providers. 23.9% of respondents to the questionnaire indicate that they have medium-term contracts with 3PL providers. The highest number of respondents (28.6%) said that their companies sign long-term cooperation agreements.

72.6% of informants say that they have achieved the desired level of supply chain responsiveness by using 3PL providers. The remainder (28.4%) say that they have achieved the desired level of responsiveness in their supply chains with 3PL.

59.5% of the informants say that they have mainly managed to reduce costs in assets (e.g., real estate, storage space, transport, etc.). The next highest proportion (25.2%) say that they have reduced costs related to information technology systems. A third of the informants (12.1%) indicated that they had mainly managed to reduce costs related to staff or training. The remainder (3.2%) say they have mainly reduced other costs.

The research was concerned with determining whether using 3PLs has helped to increase responsiveness to consumer needs while simultaneously increasing the value created for consumers. 71.9% of the informants in the study say that they have been able to increase responsiveness to the needs of consumers and increase the added value they create for consumers by using 3PL providers.

The most important considerations before choosing the right 3PL provider are reliability (71.5%) and the price of the service (69.7%). The level of customer service is also very important (57.3%), while recommendations from partners (41.1%) and awareness of 3PL providers (33.5%) are also important for informants.

Based on the data obtained, we observe that the very important motives for working with a 3PL in a sensitive supply chain are cited as the pursuit of higher profits (79.7%), the focus on meeting consumer needs (71.5%), companies' desire to respond to unforeseen demand as quickly as possible (65.3%), increasing capacity flexibility to protect against market fluctuations (67.4%) optimising logistics processes (61.1%), improving the company's competitive edge (60.4%), speed, quality, and value for money (58.9%). The motives mentioned above are driving this cooperation with 3PL in a responsive supply chain since it is aimed at creating more added value, which is made possible by the optimisation of the logistics processes, which will lead to a higher ratio of speed, quality, and price of service, flexibility, and a faster response to unforeseen demand, resulting in a higher degree of competitiveness.

The study was concerned with identifying which 3PL services have helped achieve the desired level of supply chain responsiveness. Based on the data obtained, the most important 3PL services that helped to achieve the desired responsiveness of supply chains are related to local transport (67.9%), international transport (54.1%), warehousing (61.1%), transport planning and management (49.1%), freight forwarding (48.8%) and customs brokerage (45.6%), transhipment (34.8%) and inventory management (24.2%).

At the end of the questionnaire survey, informants were asked how they had been affected using 3PL providers in responsive supply chains. The most significant impact on supply chain responsiveness through 3PL providers is related to higher levels of customer service (66.5%), increased flexibility of the company (63.5%), optimisation of the company's in-house logistics processes (63.1%), increased competitiveness of the company (62.4%), and the company's ability to quickly adapt to new supply chain challenges (61.3%). In addition, there is a high level of information retrieval (51.1%) and economies of scale and scope (51.2%). 3PLs are also seen to have a positive impact on the adaptability of businesses to the ever-changing needs of consumers (44.4%), provide better and more favourable conditions for creating more added value (43.1%), the increased logistical possibilities offered by 3PLs help companies to attract new customers (40.2%) and, in the event of a disruption in a sensitive supply chain, can provide additional resources to deal with such disruptions (37.4%).

6 Conclusions

The analysis of the research results showed that manufacturing companies (82.4%) use 3PL services in their operations. Attracting the right one or more 3PL providers can significantly reduce the cost of internal logistics, capital investment in assets or personnel related to warehousing or transport.

The success of a responsive supply chain strategy is based on collaboration with 3PL providers, as reported by 75.6% of informants. In sensitive supply chains, 3PL providers have been the most successful in reducing the cost of assets (manufacturing companies have been the most successful in getting rid of the cost of maintaining their own warehouse or transport). It has also significantly increased responsiveness to consumer needs while simultaneously increasing the value added for consumers. The 3PL services that have helped to achieve the highest responsiveness in the supply chain are mainly related to freight forwarding, transport planning and management, freight forwarding and customs brokerage.

Using a 3PL in a responsive supply chain provides an opportunity to increase your competitiveness, open up new markets and, most importantly, maximise the profits generated from the transfer of non-core activities. The majority of companies surveyed claim that they would not have the resources to achieve the desired level of responsiveness without 3PL intermediaries (75.6% of the informants in the survey say that the success of a sensitive supply chain is determined by cooperation with a 3PL).

The study found that 36.6% of the respondents have chosen to use a responsive supply chain strategy in their operations, so there is room for improvement in this area for 3PL providers to convince manufacturing companies to adopt a responsive supply chain strategy and to offer collaborative services, as 75.6% of the informants in the study

say that the success of responsive supply chains is determined by the attraction of 3PL providers to their supply chains. Therefore, it seems that manufacturing companies are not convinced by the expertise available in a 3PL, or the cost of providing such services is too high for them to change their strategy.

References

1. Alcazar-Garcia, J.L. et al.: New Perspectives on Applied Industrial Tools and Techniques. Management and Industrial Engineering. Springer, Cham (2018). https://doi.org/10.1007/978-3-319-56871-3
2. Ariadi, G., et al.: The effect of lean and agile supply chain strategy on financial performance with mediating of strategic supplier integration & strategic customer integration: Evidence from bottled drinking-water industry in Indonesia. Cogent Bus. Manag. **8**(1), 1930500 (2021)
3. Azimov, P.: The state of the world transport and logistics infrastructure and transport and logistic services market. J. Ural State Univ. Econ. **6**(74), 52–63 (2017)
4. Center of Registers Homepage, https://www.registrucentras.lt/jar, Accessed 24 Mar 2022
5. Molamohamadi, Z., Babaee Tirkolaee, E., Mirzazadeh, A., Weber, G.-W. (eds.): LSCM 2020. CCIS, vol. 1458. Springer, Cham (2021). https://doi.org/10.1007/978-3-030-89743-7
6. Entrepreneurship Trends in Lithuania Homepage. https://www.verslilietuva.lt/wp-content/uploads/2021/07/2021.06.30_verslumo_apzvalga.pdf. Accessed 20 Feb 2022
7. Fernie, J., Sparks, L.: Logistics and Retail Management. Kogan Page Ltd, London (2014)
8. 2022 Third-Party Logistics Study. The State of Logistics Outsourcing. Results and Findings of the 26st Annual Study. https://www.penskelogistics.com/i-nsights/industry-reports/3pl-study. Accessed 1 Apr 2014
9. McKeller, J.M.: Supply Chain Management Demystified. McGraw-Hill Education, Wisconsin (2014)
10. Premkumar, P., et al.: Trends in third-party logistics – the past, the present & the future. Int. J. Logist. Res. Appl. **24**(6), 551–580 (2021)
11. Sremac, S., et al.: Evaluation of a third-party logistics (3PL) provider using a rough SWARA–WASPAS model based on a new rough Dombi aggregator. Symmetry **10**(8), 305 (2018)
12. Tarafdar, M., Qrunfleh, S.: Agile supply chain strategy and supply chain performance: complementary roles of supply chain practices and information systems capability for agility. Int. J. Prod. Res. **55**(4), 1–14 (2016)

Method and Results of the Most Efficient Means of Transport Selection for Executing Orders of the Grain Crops Delivery

Viktoriia Kotenko(✉)

Vinnytsya National Technical University, Vinnytsya, Ukraine
mialkovska.viktoria@gmail.com

Abstract. The analysis of the state of development and use of intelligent decision-making support systems in road transport logistics systems has been carried out. The expediency of selecting the most efficient means of transport for executing orders of the grain crops delivery from agricultural enterprises to the grain elevator on the basis of technologies of computational intelligence has been substantiated. A method for selecting the most efficient means of transport executing orders of the grain crops delivery from agricultural enterprises to the grain elevator is proposed. It involves three stages with the use of machine-learning, in particular the grounded RF random forest model for predicting the specific fuel consumption by vehicles. The proposed method ensures that many factors of the production conditions are taken into account, allowing accurate results in the selection of efficient vehicles. On the basis of the developed method and computer model, the selection of the most efficient means of transport for executing orders of the grain crops delivery from agricultural enterprises to the elevator by the criterion of the minimum prime costs of executing the orders under given production conditions was elaborated. It has been determined that the prime costs of the execution of orders of the grain crops delivery from agricultural enterprises to the grain elevator varies in the range from 16.5 to 33.3 UAH/km. The obtained results of the researches are designed to be used by the managers of transport enterprises that organize the grain crops delivery from agricultural enterprises to the grain elevator.

Keywords: Transport processes · Grain crops · Computer model · The most efficient vehicles

1 Introduction

Year after year, intelligent decision-making support systems in road transport logistics systems are gaining more use [1, 2]. At the same time, the use of computational intelligence in logistics management is one of the most promising areas for increasing the efficiency of cargo delivery. This also applies to management in logistics systems for the delivery of agricultural products, including seeds of crops from agricultural enterprises to the grain elevators. In such logistics systems, individual tasks are solved intuitively based on the experience of managers. However, their efficiency is affected by a number

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 606–617, 2023.
https://doi.org/10.1007/978-3-031-25863-3_58

of factors which are interrelated and cannot be fully taken into account without the use of appropriate intelligent information systems. Furthermore, methods and models based on the use of computational intelligence should be developed to solve such scientific and applied problems [3, 4]. One of such unresolved problems that managers of trucking companies involved in the delivery of seeds of crops from agricultural enterprises to the grain elevator, is the most efficient means of transport selection to execute existing orders.

With regard to the most efficient means of transport selection to execute delivery orders, there has been a fair amount of scholarly attention. However, with regard to the development of intelligent systems for selecting most efficient means of transport for executing orders of the grain crops delivery from agricultural enterprises to the grain elevator using computational intelligence, there are no corresponding articles. In practice, such problems are solved intuitively by managers, which mainly leads to erroneous decisions on the selection of most efficient means of transport for executing orders of the grain crops delivery from agricultural enterprises to the grain elevator.

2 Literature Analysis and Problem Statement

Logistical problems of road transport enterprises concerning the most efficient means of transport selection for the orders execution of the different goods delivery have become quite widely used [6–10]. Also, scientists have paid sufficient attention to the issues of research and selection of most efficient vehicles for execution of orders for delivery of agricultural goods [5, 11–15]. The studies concerned both the development of general concepts and the development of methods and models of matching the parameters of vehicles for the delivery of perishable goods, which include agricultural raw materials and finished products. As for the selection of most efficient means of transport for executing orders of the grain crops delivery from agricultural enterprises to the grain elevator, there are several articles on this issue [11, 15], which reveal the peculiarities of these transport processes. However, they do not fully take into account many factors that reflect the specific production conditions of the delivery of grain crops from agricultural enterprises to the elevator.

Existing methods and models for selecting most efficient means of transport for the orders execution of the delivery of various goods types by road transport, do not take into account the changing nature of the behaviour of production conditions. This is characteristic of production conditions for delivery of grain crops from agricultural enterprises to the grain elevator. The efficiency of such transportation is largely influenced by the type of loading (combine harvesters, grain streams, grain storage sites, etc.), the state of road conditions, vehicle composition and state. These, together with weather conditions [5] and the volume of delivery of grain crops have a systematic influence both on fuel consumption and duration of the relevant transport processes, and on the prime costs of the transportation.

Regarding the use of computational intelligence in logistics systems, there have been a growing number of publications recently [15–18]. However, there are no publications on the use of computational intelligence for the selection of most efficient means of transport for executing orders of the grain crops delivery from agricultural enterprises

to the grain elevator. Therefore, there is a need to develop a method for selecting the most efficient vehicles for carrying out orders of grain crops delivery from agricultural enterprises to the grain elevator, based on machine learning algorithms to predict the fuel consumption of vehicles and taking into account the specific production conditions, which is an actual problem of both scientifical and practical point of view.

3 Aim and Objectives of the Study

The aim of the work is to develop the method of selecting most efficient means of transport for orders execution of grain crops delivery from agricultural enterprises to the grain elevator for required production conditions.

To achieve the goal there is a need to solve the following tasks in the work:

- to offer a method for selecting most efficient means of transport to execute orders of the grain crops delivery from agricultural enterprises to the grain elevator, which is based on machine learning algorithms for predicting fuel consumption by vehicles and takes into account the specific production conditions;
- to select most efficient means of transport to execute orders of the grain crops delivery from agricultural enterprises to the grain elevator on the basis of the proposed method.

4 A Method for Selecting Most Efficient Means of Transport to Execute Orders of the Grain Crops Delivery

One of the specific tasks solved by road transport enterprises engaged in the delivery of grain crops from agricultural enterprises to the grain elevator is the choice of most efficient means of transport to perform the existing orders. The solution of this problem has its own peculiarities in comparison with tasks relating to the delivery of other types of goods. Particularly, executing of orders on delivery of grain crops to the elevator is made by pendulum routes from one agricultural enterprise irrespective of the volume of cargo. That is, during transport processes several agricultural enterprises cannot be served by one route due to inadmissibility of mixing of grain crops, which have different quality and type. In this case, the routes are selected according to the minimum distance travelled and are the same regardless of the type and carrying capacity of the vehicles.

The delivery of grain crops during the harvesting season is carried out at weather intervals. At the same time, one of the main criteria that determines the prime costs of providing transport services for the delivery of grain crops to the elevator is the costs of resources. At the same time, r mark composition of vehicles and specific fuel consumption (SFC_{ri}) are determinative. This is also due to the fact that the satisfaction of users of transport services depends to a large extent on both the volume of the delivery fare and the quality and timeliness of delivery. At the same time, the quality of the choice of available means of transport and their coordination with orders depend on these indicators. Consequently, taking into account the above-mentioned, we propose a method of selecting most efficient means of transport from those available for executing orders of the grain crops delivery from agricultural enterprises to the grain elevator, taking into account the peculiarities of the mentioned transport processes.

The choice of available r means of transport (Ca_r^i) for the execution of i orders of the grain crops delivery from agricultural enterprises to the elevator depends on many factors. The choice of r means of transport (Ca_r^i) for the execution of i orders is made on the basis of functional $\left(\left\{\psi_f^i\right\}\right)$ and costs $\left(\left\{\psi_c^i\right\}\right)$ indicators of grain crops delivery from agricultural enterprises to the elevator:

$$Ca_r^i | V_j \Leftrightarrow \left(\left\{\psi_f^i\right\}, \left\{\psi_c^i\right\}\right). \tag{1}$$

where V_j – the vector of factors determining the efficiency of use of r means of transport (Ca_r^i) for the execution of i orders of the grain crops delivery from agricultural enterprises to the elevator; $\left\{\psi_f^i\right\}$, $\left\{\psi_c^i\right\}$ - the set of functional and costs indicators of performance of i orders of the grain crops delivery from agricultural enterprises to the elevator.

The proposed method of selecting most efficient means of transport for executing orders of the grain crops delivery from agricultural enterprises to the elevator is presented in 3 stages (Fig. 1).

Stage 1. The first stage is to collect and prepare the necessary data to select the most appropriate means of transport for executing orders of the grain crops delivery from agricultural enterprises to the elevator. In particular, information (I_{ni}) on the individual i orders of the grain crops delivery is analyzed on the basis of the data from the agricultural enterprises:

$$I_{ni} = \left\langle \begin{matrix} Cargo_volume, Type_cargo, \\ Territorial_location, Delivery_priority \end{matrix} \right\rangle, \tag{2}$$

where *Cargo_volume* – cargo delivery volume, tonnes; Type_ cargo – type of grain crops (wheat, rapeseed, corn, etc.); Territorial_ location – cargo location (village, granary, field, etc.); Delivery_ priority – cargo delivery priority (from combine harvester - 1, from granary - 2, from storage - 3, etc.).

Based on the information $I_{(\text{Territorial_location})}$. about the territorial location of the cargo (village, granary, field, etc.) using Internet services OpenStreetMap [19] or Google Maps [20], distance matrices (M_{Li}) and speeds (M_{Vi}) of vehicles from agricultural enterprises to the elevator during the execution of i orders of the grain crops delivery are generated:

$$M_{Li} = \{L_i\}, i = 1, n, \tag{3}$$

$$M_{Vi} = \{V_i\}, i = 1, n, \tag{4}$$

where M_{Li}, M_{Vi} – respectively, matrices of distances and speeds of vehicles from agricultural enterprises to the elevator during the execution of i order of the grain crops delivery; L_i – distance from the agricultural enterprise to the elevator in the i order, km; V_i – speed of the vehicle during the execution of i order, km/h; n – number of agricultural enterprises, units.

A matrix of cargo characteristics $\left(M_{\gamma c}\right)$ (grain crops) is then generated:

$$M_{\gamma c} = \begin{vmatrix} Q_1 & Q_2 & \dots & Q_n \\ \varphi_1 & \varphi_2 & \dots & \varphi_n \\ \rho_1 & \rho_2 & \dots & \rho_n \end{vmatrix}. \tag{5}$$

where Q_1, Q_2, ..., Q_n – respectively the volume of cargo in the first, second and n agricultural enterprise which made an order for the grain crops delivery, tons; $\varphi_1, \varphi_2, \ldots, \varphi_n$ – respectively the type of cargo in the first, second and n agricultural enterprise which made an order for the grain crops delivery; ρ_1, ρ_2, ..., ρ_n – respectively the priority of cargo delivery in the first, second and n agricultural enterprise.

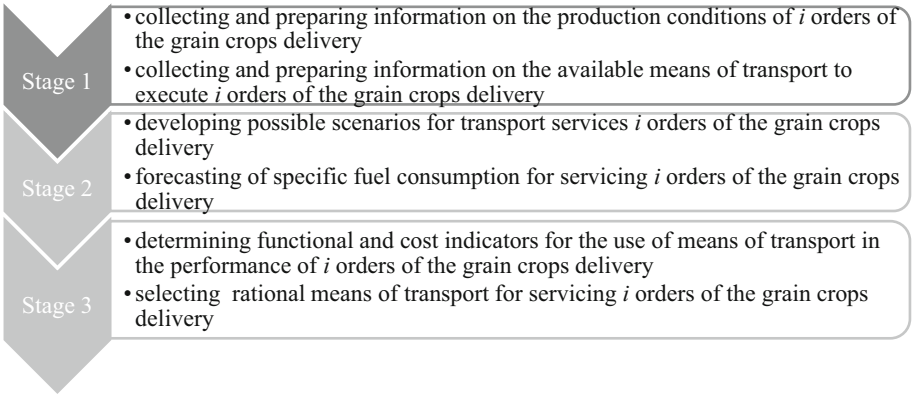


Fig. 1. Stages in the method of selecting most efficient means of transport for executing orders of the grain crops delivery from agricultural enterprises to the elevator.

The next step is to form a matrix of the characteristics $(M_{\text{¡}_r})$ of the vehicles available for grain crops delivery, based on the information from the transport company:

$$M_{\Upsilon_r} = \begin{vmatrix} \mu_{Ca1} & \mu_{Ca2} & \cdots & \mu_{Car} \\ q_{Ca1} & q_{Ca2} & \cdots & q_{Car} \end{vmatrix}, \tag{6}$$

where μ_{Ca1}, μ_{Ca2}, ..., μ_{Car} – accordingly mark and model of the first, second and r vehicle available in the motor transport enterprise for delivery of grain crops;

$q_{Ca1}, q_{Ca2}, \ldots, q_{Car}$ – accordingly load of the first, second and r vehicle available in the motor transport enterprise for delivery of grain crops, tons.

Stage 2. The second step of the proposed method is first to create possible scenarios for transport services and i orders of the grain crops delivery. This is done by first analyzing existing i orders of the grain crops delivery from the agricultural enterprises to the grain elevator (Fig. 2).

All available orders are doubly ranked by priority ρ_n of delivery (from combine harvester - 1, from grain store - 2, from storage - 3, etc.) and by volume of cargo ρ_n (grain crops) in i agricultural enterprise

$$\rho_3^1 < \rho_8^2 < \ldots < \rho_n^3, \tag{7}$$

$$Q_3^1 < Q_7^2 < \ldots < Q_n^3. \tag{8}$$

This is the basis for forming a vector with the order of transport services to agricultural enterprises. In addition, a vector of vehicles available in the road transport company

(Ca_r^i) for the delivery of grain crops from agricultural enterprises to the elevator is formed.

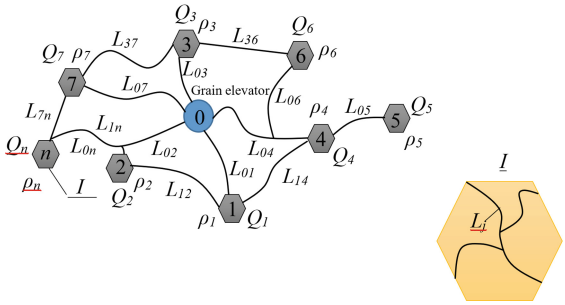


Fig. 2. Graph of location of agricultural enterprises in relation to the elevator with cargo characteristics (grain crops): 1, 2,…, n – agricultural enterprises; *L0i* – distance between the elevator and *i* agricultural enterprise; l_j^m – shortest branch of road network *i* agricultural enterprise.

The number of options for transport service scenarios for agricultural enterprises to deliver goods (grain crops) to the elevator depends on:

$$N_{Sc} = f\left(\{N_{oi}\}, \left\{Ca_r^i\right\}, \left\{R_{er}^i\right\}\right) \tag{9}$$

where $\{N_{oi}\}$ – the set of *i* orders of the grain crops delivery from agricultural enterprises to the grain elevator, units; $\left\{Ca_r^i\right\}$ – the set of available *r* vehicles for executing *i* orders of the grain crops delivery from agricultural enterprises to the grain elevator, units; $\left\{R_{er}^i\right\}$ – the set of regulations on the use of *r* vehicles for executing *i* orders of the grain crops delivery from agricultural enterprises to the grain elevator.

Further, for each of the scenarios of *r* vehicle use, specific fuel consumption forecasting (SFC_{ri}) is carried out during the execution of *i* orders of the grain crops delivery from agricultural enterprises to the grain elevator. For this purpose, the justified most efficient model of forecasting specific fuel consumption by vehicles during delivery of grain crops from agricultural enterprises to the elevator is used.

A reasonable RF random forest model consisting of 5 randomised base regression trees is assumed:

$$\left\{r_n\left(X_{11}, X_{12}, ..., X_{1j}, SFC_{ri}, D_n\right), m \geq 1\right\}. \tag{10}$$

where (SFC_{ri}) – predicted values of specific fuel consumption (SFC_{ri}) by *r* means of transport during the execution of *i* orders of the grain crops delivery from *n* agricultural enterprises to the grain elevator, liters/100 km.

All the resulting random trees are combined to form an aggregate regression estimate:

$$\overline{r}(X, D_n) = E(SFC_{ri})[r_n(X, SFC_{ri}, D_n)]. \tag{11}$$

The resulting quantitative prediction values for specific fuel consumption (SFC_{ri}) using the RF random forest model are represented as the average of the prediction values obtained by each of the 5 decision trees of the valid ensemble.

Stage 3. At the third stage of the proposed method of the selection of most efficient means of transport for executing order of the grain crops delivery from the agricultural enterprises to the grain elevator, determining of functional and costs parameters of vehicles use is made during the execution of i orders of the grain crops delivery.

A set of functional $\left\{\psi_f^i\right\}$ performance indicators for the delivery of grain crops from agricultural enterprises to the elevator include:

$$\left\{\psi_f^i\right\} :\Leftrightarrow (t_i, L_i, Q_i, W_i, g_{ni}, P_i), \tag{12}$$

where t_i – duration of the execution of i order of the grain crops delivery from the agricultural enterprises to the grain elevator, h; L_i – total mileage of vehicles the execution of i order of the grain crops delivery from the agricultural enterprises to the grain elevator, km; Q_i – total volume of the transported cargo of vehicles total mileage of vehicles the execution of i order of the grain crops delivery from the agricultural enterprises to the grain elevator, t; W_i – cargo turnover total volume of the transported cargo of vehicles total mileage of vehicles the execution of i order of the grain crops delivery from the agricultural enterprises to the grain elevator, t.km; g_{ni} – fuel consumption during the execution of i order of the grain crops delivery from the agricultural enterprises to the grain elevator, liters; p_i – productivity of vehicles during the execution of i order of the grain crops delivery from the agricultural enterprises to the grain elevator, t.km/shift (t/shift).

A set of costs $\left\{\psi_c^i\right\}$ indicators of the execution of i order of the grain crops delivery from the agricultural enterprises to the grain elevator include:

$$\left\{\psi_c^i\right\} :\Leftrightarrow \left(\left\{E^i\right\} \rightarrow C^i\right), \tag{13}$$

where $\left\{E^i\right\}$ – the set of operating costs for the execution of i order of the grain crops delivery from the agricultural enterprises to the grain elevator, UAH; C^i– prime costs of the execution of i order of the grain crops delivery from the agricultural enterprises to the grain elevator, UAH/t (UAH/t.km).

The prime costs C^i of the execution of i order of the grain crops delivery from the agricultural enterprises to the grain elevator is determined by:

$$C^i = \frac{\left\{E^i\right\}}{W^i VQ^i} = \frac{C_s^i + C_{fl}^i + C_a^i + C_v^i + C_t^i + C_o^i}{W^i VQ^i}, \tag{14}$$

where $\left(C_s^i\right)$ – drivers salary costs, UAH; C_{fl}^i – fuel and lubricants costs, UAH; C_a^i – depreciation costs, UAH; C_v^i – vehicle costs, UAH; C_t^i – tyre maintenance and repair costs, UAH; C_o^i – overheads, UAH.

The most efficient r means of transport $\left(Ca_r^i\right)$ available at the road transport company for the execution of i order of the grain crops delivery from the agricultural enterprises to the grain elevator are those that satisfy the condition:

$$Rational \;\; Ca_r|V_j = C^i \Rightarrow min. \tag{15}$$

5 Results of the Most Efficient Means of Transport Selection for Executing Orders of the Grain Crops Delivery

The most efficient i means of transport $\left(Ca_r\right)$ are determined at the stages of planning transport processes of the grain crops delivery from agricultural enterprises to the grain elevator. At the same time, for the qualitative planning of the mentioned processes, it is necessary to forecast the prime costs of the execution of i orders of the grain crops delivery from agricultural enterprises to the elevator, which is a rather labour-intensive process. The problem of the mentioned forecasting is obviously super-complicated, since it is influenced by quite a few factors and it is difficult to predict specific fuel consumption (SFC_{ri}), since transport processes take place under specific production conditions.

The qualitative selection of the most efficient means of transport for the execution of i orders of the grain crops delivery from the agricultural enterprises to the elevator requires development of the appropriate computer model. With the purpose of acceleration and improvement of the quality of selection of the most efficient means of transport for the execution of i orders of the grain crops delivery the corresponding computer model, which is based on the proposed method with the use of reasonable model RF of a random forest for forecasting of the specific fuel consumption (SFC_{ri}) by vehicle.

Based on the use of reasonable RF random forest model, forecasting of specific fuel consumption (SFC_{ri}) by r vehicles during the grain crops delivery from agricultural enterprises to the elevator was performed. We compared real (Volyn - Zerno-Product Ltd., Lutsk, Volyn region) and predicted specific fuel consumption (SFC_{ri}) by r vehicles during the grain crops delivery from agricultural enterprises to the elevator. It was found that the average absolute percentage error *(MAPE)* of forecasting specific fuel consumption (SFC_{ri}) by r vehicles during the grain crops delivery from agricultural enterprises to the elevator is:

$$MAPE = \frac{\sum_{i=1}^{n}\left(\frac{g_{pi}-g_{ni}}{g_{pi}}\right)}{n} \cdot 100\% = 4.6\%. \tag{16}$$

Consequently, the results obtained show sufficient accuracy of the grounded RF random forest model for predicting specific fuel consumption (SFC_{ri}) by r vehicles during the grain crops delivery from agricultural enterprises to the elevator.

The proposed computer model of choosing the most efficient means of transport for executing i orders of the grain crops delivery from agricultural enterprises to the elevator was tested for adequacy by the Mann-Whitney criterion. The deviation of the prime costs of the grain crops delivery didn't exceed 4.3% that testifies to the adequacy of the proposed computer model. With the help of the computer model the process of choosing the most efficient means of transport for executing orders of the grain crops delivery in the production conditions of Volyn-Zerno-Product Ltd (Lutsk, Volyn region) was carried out. DAF FT XF 105-2 units; DAF FT XF 105.460-1 unit; КАМАЗ 45143-012-15-2 units; DAF XF95.480-1 unit.

Five orders of the grain crops delivery from agricultural enterprises to the elevator with the following characteristics were taken:

1. delivery of wheat seeds from a combine harvester in the amount of 10 tons, distance from the field to the elevator 25 km, order priority – 1;

2. delivery of rape seeds from grain-storage farm in the volume of 22 tons, distance from grain-storage farm to the elevator 46 km, order priority – 2;
3. delivery of rye seeds from the storage of agricultural enterprise in the volume of 20 tons, distance from storage to the elevator 53 km, order priority – 3;
4. delivery of wheat seeds from the combine harvester in the volume of 12 tons, distance from the field to the elevator 32 km, order priority – 1;
5. delivery of wheat seeds from the combine harvester in the volume of 12 tons, distance from the field to the elevator 32 km, order priority – 2.

For each of the 20 possible scenarios of transport service of agricultural enterprises the functional and costs indicators of the use of vehicles of executing of *i* orders of the grain crops delivery determined (Table 1).

Table 1. Determining results of the functional and costs indicators of the use of vehicles of executing of *i* orders of the grain crops delivery.

Enterprise number	Mark of available vehicle	Delivery distance, km	Cargo volume, t	Cargo turnover, t.km	Specific fuel consumption, l/100 km	Total fuel consumption, l	Prime costs of *i* order execution, UAH/km
1	DAF-FT-XF-105	25.0	10.0	250.0	30.2	7.5	16.5
4	DAF-FT-XF-105	32.0	12.0	384.0	39.1	12.5	21.5
1	DAF-XF95-480	25.0	10.0	250.0	39.7	9.9	21.8
5	DAF-FT-XF-105	62.0	20.0	1240.0	39.9	24.8	22.0
1	КАМАЗ-45143-012-15	25.0	10.0	250.0	40.8	10.2	22.4
4	DAF-XF95-480	32.0	12.0	384.0	41.1	13.1	22.5
5	DAF-FT-XF-105-460	62.0	20.0	1240.0	41.2	25.5	22.6
3	DAF-FT-XF-105	53.0	20.0	1060.0	41.1	21.8	22.6
2	DAF-FT-XF-105	46.0	22.0	1012.0	41.2	19.0	22.7
3	DAF-FT-XF-105-460	53.0	20.0	1060.0	43.0	22.8	23.7
4	DAF-FT-XF-105-460	32.0	12.0	384.0	43.3	13.9	23.9
4	КАМАЗ-45143-012-15	32.0	12.0	384.0	44.4	14.2	24.4
2	DAF-FT-XF-105-460	46.0	22.0	1012.0	44.5	20.5	24.5
1	DAF-FT-XF-105-460	25.0	10.0	250.0	46.0	11.5	25.3
2	DAF-XF95-480	46.0	22.0	1012.0	53.1	24.4	29.2
3	DAF-XF95-480	53.0	20.0	1060.0	53.3	28.3	29.4
5	DAF-XF95-480	62.0	20.0	1240.0	54.0	33.5	29.7
2	КАМАЗ-45143-012-15	46.0	22.0	1012.0	56.3	25.9	31.0
5	КАМАЗ-45143-012-15	62.0	20.0	1240.0	58.0	36.0	31.9
3	КАМАЗ-45143-012-15	53.0	20.0	1060.0	60.6	32.1	33.3

As a result of the conducted researches it is established that functional and costs indicators of the use of means of transport during executing *i* orders of the grain crops

delivery fluctuate within a wide enough range. In particular, the prime costs C^i of the execution of i orders of the grain crops delivery from agricultural enterprises to elevator varies in the range from 16.5 to 33.3 UAH/km. It is the prime costs C^i of the execution of i orders that is the basis for the selection of the most efficient means of transport.

It has been established that four marks of available vehicles should be involved in the execution of the above orders for the delivery of grain crops from agricultural enterprises to the elevator, providing the minimum prime costs C^i of execution of actual i orders (Fig. 3).

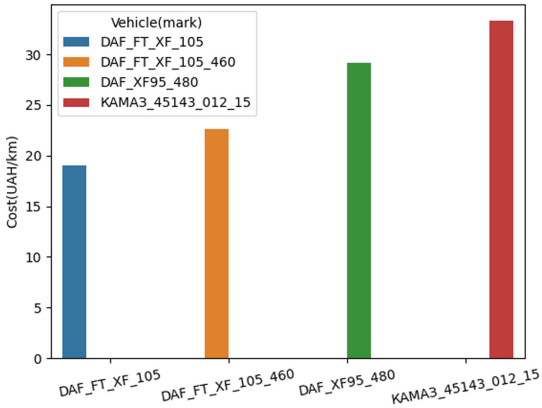


Fig. 3. Histogram of the change in the prime costs C^i of the execution of i orders by the selected most efficient means of transport.

On the basis of the analysis of the results obtained in relation to individual transport service scenarios for agricultural enterprises, the most efficient means of transport that ensure the minimum prime costs C^i of the execution of actual i orders under given production conditions are selected from the possible scenarios (Table 2).

Table 2. Determining results of the functional and costs indicators of the use of vehicles of executing of i orders of the grain crops delivery.

Enterprise number	Mark of available vehicle	Delivery distance, km	Cargo volume, t	Cargo turnover, t.km	Specific fuel consumption, l/100 km	Total fuel consumption, l	Prime costs of i order execution, UAH/km
1	DAF-FT-XF-105	25.0	10.0	250.0	30.2	7.5	16.5
4	DAF-FT-XF-105	32.0	12.0	384.0	39.1	12.5	21.5
5	DAF-FT-XF-105-460	62.0	20.0	1240.0	41.2	25.5	22.6
2	DAF-XF95-480	46.0	22.0	1012.0	53.1	24.4	29.2
3	КАМАЗ-45143-012-15	53.0	20.0	1060.0	60.6	32.1	33.3

It is defined that the most efficient scenarios of the grain crops delivery organization from the agricultural enterprises to the grain elevator under the condition of servicing by the available vehicles are following: agricultural enterprise №1 – vehicle DAF-FT-XF-105; agricultural enterprise №2 - vehicle DAF-XF95-480; agricultural enterprise №3 - vehicle KAMAZ-45143-012-15; agricultural enterprise №4 - vehicle DAF-FT-XF-105; agricultural enterprise №5 - vehicle DAF-FT-XF-105-460. The obtained results of the researches are designed to be used by the managers of transport enterprises that organize the grain crops delivery from agricultural enterprises to the grain elevator. The use of the developed method and the computer model will ensure acceleration and improvement of decision-making quality, as well as efficiency of the corresponding transport processes.

6 Conclusions

The proposed method of the most efficient means of transport selection for executing orders of the grain crops delivery from agricultural enterprises to the grain elevator involves three stages with the use of machine-learning, in particular the grounded RF random forest model for predicting the specific fuel consumption (SFC_{ri}) by vehicles, also ensures that many factors of the production conditions are taken into account, allowing accurate results in the selection of efficient vehicles based on possible transport service scenarios and the determination and comparison of the functional and costs performance of vehicles in a given production environment.

On the basis of the developed method and computer model, the selection of the most efficient means of transport for executing orders of the grain crops delivery from agricultural enterprises to the elevator by the criterion of the minimum prime costs C^i of executing the actual i orders under given production conditions was made. It has been determined that the prime costs C^i of the execution of i orders of the grain crops delivery from agricultural enterprises to the grain elevator varies in the range from 16.5 to 33.3 UAH/km. The obtained results of the researches are designed to be used by the managers of transport enterprises that organize the grain crops delivery from agricultural enterprises to the grain elevator.

References

1. Tryhuba, A., Tryhuba, I., Mushenyk, I., Pashchenko, O., Likhter, M.: Computer model of resource demand planning for dairy farms. Independ. J. Manag. Prod. (2nd Special Edition ISE, S&P). **11**(6), 658–672 (2020)
2. Hridin, O., Slavina, N., Mushenyk, I., Dobrovolska, E.: Managerial decisions in logistic systems of milk provision on variable production conditions. Independ. J. Manag. Prod. (Special Edition ISE) **11**(8), 783–800 (2020)
3. Tryhuba, A., Tryhuba, I., Mykhalchyshyna, L., Mushenyk, I., Koval, N., Haybura, Y.: Forecasting the time stock for chemical plant protection based on computer simulations. Independ. J. Manag. Prod. **12** (2021)
4. Tryhuba, A., Bashynskyi, O., Medvediev, Y., Slobodian, S., Skorobogatov, D.: Justification of models of changing project environment for harvesting grain, oilseed and legume crops. Independent J. Manag. Prod. **10**(7), 658–672 (2019)

5. Tryhuba, A., Ivanyshyn, V., Chaban, V., Mushenyk, I., Zharikova, O.: Influence of agrometeorological component of the project environment on the duration of works in chemical protection projects of agricultural crops. Independent J. Manag. Prod. (Special Edition ISE, S&P) **12**(3), 138–149 (2021)
6. Chan, F.T.S., et al.: Bi-objective optimization of three echelon supply chain involving truck selection and loading using NSGA-II with heuristics algorithm. Appl. Soft Comput. J. **38**, 978–987 (2015). https://doi.org/10.1016/j.asoc.2015.10.067
7. Malladi, K.T., Quirion-Blais, O., Sowlati, T.: Development of a decision support tool for optimizing the short-term logistics of forest-based biomass. Appl. Energy **216**, 662–677 (2018). https://doi.org/10.1016/j.apenergy.2018.02.027
8. Zhao, X., Dou, J.: Bi-objective integrated supply chain design with transportation choices: a multi-objective particle swarm optimization. J. Ind. Manag. Optim. **15**(3), 1263–1288 (2019)
9. Özdağoğlu, A., Öztaş, G.Z., Keleş, M.K., Genç, V.: An integrated PIPRECIA and COPRAS method under fuzzy environment: a case of truck tractor selection Alphanum. J. **9** (2), 269–298 (2021). https://doi.org/10.17093/alphanumeric.1005970
10. Isnafitri, M.F., et al: A Truck allocation optimization model in open pit mining to minimize investment and transportation costs. In: IOP Conference Series: Materials Science and Engineering, p; 1096 (2021)
11. Mogale, D.G., Kumar, K.S., Márquez, P.G.F., Tiwari, M.K.: Bulk wheat transportation and storage problem of public distribution system, Comput. Ind. Eng. **104**, 80–97(2016). https://doi.org/10.1016/j.cie.2016.12.027
12. Fikry, I., Gheith, M., Eltawil, A.: An integrated production-logistics-crop rotation planning model for sugar beet supply chains. Comput. Ind. Eng. **157** (2021). https://doi.org/10.1016/j.cie.2021.107300
13. Soysal, M., et al.: Modelling food logistics networks with emission considerations: The case of an international beef supply chain. Int. J. Prod. Econ. **152**, 57–70 (2013)
14. Soysal,M., Bloemhof-Ruwaard, J.M., Haijema, R., Van der Vorst, J.G.A.J.: Modeling a green inventory routing problem for perishable products with horizontal collaboration, Comput. Oper. Res. **89** (2016). https://doi.org/10.1016/j.cor.2016.02.003
15. Rykała, M., Rykała, Ł.: Economic analysis of a transport company in the aspect of car vehicle operation. Sustainability **13**, 427 (2021). https://doi.org/10.3390/su13010427
16. Samimi, A., et al: A comparison between different data mining algorithms in freight mode choice. Am. J. Appl. Sci. **14**(2), 204–216 (2017)
17. Singh, A., Das, A., Bera, U.K., Lee, G.M.: Prediction of transportation costs using trapezoidal neutrosophic fuzzy analytic hierarchy process and artificial neural networks. IEEE Access **9**, 103497–103512 (2021). https://doi.org/10.1109/ACCESS.2021.3098657
18. Якушенко, О.С., Шевчук, Д.О., Мединський, Д В.: Нейромережева модель для прогнозування часу на виконання транспортної задачі. Sci. Based Technol. **49**(1), 33–38 (2021). https://doi.org/10.18372/2310-5461.49.15289
19. OpenStreetMap. https://www.openstreetmap.org/#map=12/50.7421/25.3190. Aaccessed 16 July 2022
20. Google Maps. https://www.google.com.ua/maps. Aaccessed 16 July 2022

Green Logistics and Marketing Features: Literature Review

Margarita Išoraitė(✉)

Vilnius University of Applied Sciences, Didlaukio Street, 49, Vilnius, Lithuania
m.isoraite@vvf.viko.lt

Abstract. Green logistics include production transportation activities. Green logistics meets the needs of meeting the minimum costs, causing what less negative impact on the environment. The article examines the concept of green logistics, green logistics indicators and green logistics marketing and its significance in a theoretical aspect. Barysienė et al. [2] and Jefimovaitė, Vienažindienė [6] notice that green logistics factors that organizations could be useful are: rejection of suppliers who do not care about environmental issues; employee training/improvement of competence; cooperation with government institutions solving problematic issues; public reports declaring the efforts and achievements of companies in solving environmental problems; cooperation with foreign countries on environmental protection issues; promotion of employee social responsibility, determined by the product designer/designer; green logistics product design; green distribution; green warehouses; green packaging. Green marketing is the result of 21st century marketing, which created conditions for the formation of specific markets and the fight against environmental problems, green product development trends. Green marketing reflects an approach to the development of organic products and the creation of new organic ones, which are beneficial not only to the environment, consumers, but also to the company itself, as it brings more profit in the long term, as the interest in organic products increases every year.

Keywords: Green logistics · Marketing · Green logistics indicators · Logistics · Supply chain

1 Introduction

Green logistics involves supply chains dealing with carbon emissions from waste management and disposal, packaging, recycling, reducing energy consumption. Between different national and global entities promoting or establishing greater corporate sustainability and more consumers preferring green consumption, more and more transport companies are committing to net zero in order to be as green as possible. In all and any stage of logistics operations, the greener process is most easily achieved through digitization processes. Digitization can be used to eliminate paper footprints and reduce energy costs by using alternative fuels and increasing efficiency. [5, 21] and others scientists analyzed green logistics and green marketing development problem. Object of article

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 618–626, 2023.
https://doi.org/10.1007/978-3-031-25863-3_59

is to analyze green logistics and marketing features: The article uses scientific literature analyzes and comparison methods. The analysis of scientific literature helps to get acquainted with the works of predecessors, research methods, to find material that confirms or contradicts the research facts, and to plan the work. The literature review aims to describe the situation and achievements of the selected research area [7]. The literature review realizes several goals: it "shares" with the reader the results of other studies that are closely related to the specific study being conducted, it encourages a dialogue with already published material, it fills in the gaps, and it expands the conducted studies. The comparison method can be used to achieve various methods of solving methodological or methodical problems: descriptive (identification of similarity or difference) or analytical (explanation, prediction, practical recommendations). Comparison is understood as a thinking operation. Comparison only makes sense when comparing similar objects. Comparison is related to the operations of analysis and synthesis. When comparing, the object is divided into parts, their features are distinguished. Their juxtaposition means connecting the elements. The method of comparison reveals the relations of sameness, difference, identity and similarity of objects. The purpose of the article is to analyze the features of green logistics and green marketing. Tasks of the article: to analyze the concept of green logistics, to analyze the indicators of green logistics, to study green marketing. The problem is formulated as a problematic question: how green logistics and green marketing solve environmental problems.

2 Green Logistics Concept

Green logistics is a field of activity that includes various issues of goods, movement, and organizational processes of commercial activities, using environmentally friendly means of transport. Green logistics includes the organization of optimal cargo flow, management of transportation, storage and other tangible and intangible operations from the acquisition of raw materials and materials to delivery to the company. Green logistics includes activities related to the transportation of products and the integration of environmental protection. The main goal of green logistics is to take into account not only the company itself, but also the environment. Logistics is also responsible for climate change. In order to reduce CO_2 emissions and combat climate change, the logistics industry has developed green logistics. This is related to sustainable logistics processes that aim to reduce the CO_2 left by the company's activities. [21] mentioned that green logistics is defined as an effort to explore ways to reduce these externalities. Great attention is paid to green logistics. Green logistics helps to shape the perspectives of green transport development, which includes issues of environmental protection and sustainability. Transport is an area where green logistics is implemented. Recently, both in Lithuania and the world, great attention has been paid to green logistics, the transition to the use of environmentally friendly vehicles and education in this regard. Green logistics definition is presented in Table 1.

Table 1. Green logistics definition comparison.

Author	Definition	Highlight
Tüzün Rad, S., Gülmez, Y., S (2017)	Green logistics is a concept which combines product development strategies and environmentally sensitive methods for production and service	Combines product development strategies and environ-mentally sensitive methods
Popescu (married Bîzoi), A., C., Sipoș, C. A. (2015)	Green logistics or ecological is reducing the ecological footprint of logistics, reduction of energy consumption for logistics purposes related activities and substance use	Reducing the ecological foot-print of logistics
Jefimovaitė, L., Vienažindienė, M. (2021)	Green logistics are logistics processes that help organizations reduce costs and increase profitability as well as maintain a positive impact on the environment and improve the sustainability of the company's operations	Help organizations reduce costs and increase profitability as well as maintain a positive impact on the environment and improve the sustain-ability
Saroha, R. (2014)	Green logistics is a form of logistics that is calculated to protect the environment and often not only economically functional but also socially friendly. It describes all the tests measure and minimize the ecological impact of logistics activities	Protect the environment and often not only economically functional but also socially friendly
Pillay, K., Mbhele, T. B. (2015)	When it comes to green logistics challenges faced by logistics companies operating in the Durban region, it is essential to understand impact of logistics road freight operations and green supply chain management initiatives to overcome challenges green logistics. Transition to green supply chain management will help eliminate the harmful effects of environmental damage	It is essential to understand impact of logistics road freight operations and green supply chain management initiatives to overcome challenges green logistics

(*continued*)

Table 1. (*continued*)

Author	Definition	Highlight
Zowada, K. (2020)	One of the concepts that can be the answer to the related requirements environmental protection is the concept of "green logistics". The literature review shows that publications talking about the development of "green logistics" has so far focused mainly on processes implementation and development of "green logistics" in large companies. In other words, the reviewed studies did not take into account the specific nature of the SME sector, which is a a very important factor given its diversity and, above all, its great importance and size economy	Publications talking about the development of "green logistics" has so far focused mainly on processes implementation and development of "green logistics" in large companies
Vyacheslavovna Larina, Larin, A.N., Kiriliuk, O., Ingaldi, M. (2021)	Green logistics brings positive results not only for the company, but also for the state and society. Often green logistics is limited to environmental protection, however, it is worth noting that in a broad sense it should be of social concern	Green logistics is limited to environmental protection

Tüzün and Gülmez [24] stated green logistics combines product development strategies and environ-mentally sensitive methods, while [17] notice that green logistics reducing the ecological foot-print of logistics. [6] mentioned that green logistics help organizations reduce costs and increase profitability as well as maintain a positive impact on the environment and improve the sustainability, [20] notice that green logistics protect the environment and often not only economically functional but also socially friendly. [16] mentioned that green logistics is essential to understand impact of logistics road freight operations and green supply chain management initiatives to overcome challenges green logistics.

Mesjasz-Lech [10] notice that green logistics is important because it allows programming to be transformed into the way logistics work to protect the environment and contribute to economic sustainability. Green logistics cares for the environment while promoting efficient economic growth.

Herrmann et al. [5] discuss sustainability and environmental issues. Green supply chain management ensures societal and corporate efficiency policy, increasing its activities, increasing market share, improving the image of the company and reputation and increasing profits. Paužuolienė and Kaveckė [15] mentioned that this practice reveals

an increase in the volume of goods delivered on time, a better use of capacity, promotes the quality of products or services, increases product variety and reduces waste. Applying green logistics reduces financial costs, develops the concept of sustainable development, supports sustainable energy and urban logistics policies, supports sustainable urban logistics through the use of clean energy and the goals of improving traffic and cargo efficiency.

Kumar [8] mentioned that in highly competitive environment, green logistics issues are receiving a lot of attention.

Lew et al. [11] found that there are four intrinsic implementation factors and three external factors of green logistics implementation. According to the aforementioned authors, the four internal factors are cost effectiveness, human resource skills, knowledge and support, information technology and systems, and organizational/top management support.

Zowada [26] observes that the scientific literature on green logistics examines large companies, but the aforementioned author examines small companies and their specifics in the field of green logistics in his article.

Pazirandeh and Jafari [14] in their article examine the relationship between sustainable corporate strategy and logistics performance in improving transport performance. Companies that have developed sustainable strategies pursue sustainability and environmental goals, which are very relevant recently.

Based on the analysis of green logistics scientific literature [5, 11, 15] green logistics is characterized by reducing the external impact of transport, increasing market share, improving the image of the company, developing a sustainable strategy.

3 Green Logistics Indicators

Radavičiūtė and Jarašiūnienė [12] discussed general green logistics measures that could help solve the aforementioned problems: intermodal transport promotion, route optimization, use of cargo bikes, green carriers and greater public sector involvement. Barysienė et al. [2] distinguished green logistics factors that organizations could be useful:

- rejection of suppliers who do not care about environmental issues;
- employee training/improvement of competence;
- cooperation with government institutions solving problematic issues;
- public reports declaring the efforts and achievements of companies in solving environmental problems;
- cooperation with foreign countries on environmental protection issues;
- promotion of employee social responsibility.

Zhang and Zhao [25] observe that the goal of green logistics is to reduce environmental pollution and resource consumption, the use of advanced logistics technology, planning and implementation. Transportation, storage, packaging, handling, processing and distribution. Zhang and Zhao [25] mentioned that green logistics includes the

following aspects: green transportation, green warehousing and green packaging storage, loading and unloading system, green distribution, green information collection and management.

According to Paužuolienė and Kaveckė [15] the implementation of green logistics in the organization highlights a number of advantages, such as an increase in the volume of goods delivered on time, better use of capacities, promotion of the quality of products or services, reduction of material purchase costs, energy costs, waste treatment and reducing their emissions taxes.

According to [3] the main principles of green logistics should be: application of an integrated approach in managing logistics flows; rational use of resources (production, finance, energy, information); minimum raw materials and packaging, the use of non-recyclables; maximum use of production waste, containers and packaging, as secondary raw materials or their environmentally friendly disposal; environmental education and personnel responsibilities increase; implementation of innovative technologies in order to reduce the burden on the environment, etc.

4 Green Logistics Marketing

Green marketing can be defined as an element of a sustainable sustainability strategy. Green marketing includes areas such as green transportation, green products, green packaging, energy-saving operations, green packaging, and transportation pollution control. The modern consumer cares about environmental protection, cares about preserving the environment for future generations. The modern consumer is concerned about the earth's resources, he draws public attention to environmental protection [18].

Rodrigue et al. [13] observed that the quality of transport logistics is critical to the success of many organizations. By applying the principles of green marketing, transport companies can achieve environmental goals faster and transport cargo much safer. Thanks to green marketing, the company's competitive advantage can increase.

Sarkar [19] analyzes that green marketing includes green packaging, environment friendly distribution, safe transportation of cargo. All these initiatives can improve the environmental performance of the organization and its supply chain. Menon and Menon [9] notice that environmental protection marketing is characterized by an innovative and technological solution meet environmental needs, focus on entrepreneurship and convergence of social, environmental and economic indicators. Companies differ in the degree of application of their environmental principle marketing.

Baker and Sinkula [1] created the tool for ecological marketing and empirically found that environmental marketing has a positive effect on the capabilities of companies, e.g., success in new product development.

Skačkauskienė and Vilkaitė-Vaitonė [23] mentioned that three important aspects can be seen in the definitions of green marketing. The first aspect is the links between green marketing and the process approach. According to this approach, green marketing includes various smaller processes that lead to the sale of products and generation of environmental benefits. Another important aspect is based on holistic thinking. This means that green marketing can be seen as different elements system. The third aspect is the environmental benefits generated by green marketing.

Skačkauskienė and Vilkaitė-Vaitonė [23] noticed that there is sufficient reason to believe that green marketing is beneficial at the organizational level in the following aspects:

- strengthening of relations with consumers;
- increase in profit;
- a significant contribution to the achievement of the organization's goals;
- strengthening of competitive advantages;
- cost reduction;
- increasing brand reputation.

European Center for Quality [4] mentioned that one of the main tools of green marketing is various badges that reflect approach to environmental protection. It will encourage buyers to pay attention to the goods, make it easier recognize them among others. It should also be remembered that everything should be presented on the package needs information, for example, if it is a food product, then on its packaging all products used in production and the product should be listed energy value.

Green marketing is the result of 21st century marketing, which created the conditions for the formation of specific markets that include green, organic products and the development trends of green products in the fight against environmental problems and air pollution.

5 Conclusions

Recently, social actions and initiatives have appeared on the market, aimed at reducing the impact of damage to the environment, gaining popularity. Some market participants, seeing rarer than usual ways of forming corporate distinctiveness, are also exploring opportunities to copy similar activities, such as green marketing. Companies that develop new and improved products and services that take the environment into account provide access to new markets, increase their profitability and have a competitive advantage over companies that are not concerned with the environment.

Analyzing the scientific works of foreign authors, it was noticed that the term green logistics is used as a term for ecological, term of coherence in logistics. The scientific literature distinguishes the main levels of sustainable development, which include: ability to invest, innovativeness, productivity of economic activity, quality assurance of services, reduction of air pollution, use of renewable resources, corporate social responsibility, competence of employees, reduction of road accidents.

Radavičiūtė and Jarašiūnienė [12] discussed general green logistics measures that could help solve the aforementioned problems: intermodal transport promotion, route optimization, use of cargo bikes, green carriers and greater public sector involvement.

Green marketing reflects the approach to the development of ecological products and services and the creation of new ecological ones, which are beneficial not only to the environment, consumers, but also to the company itself, since it brings more profit in the long term, since the interest in ecological products increases every year.

References

1. Baker, W.E., Sinkula, J.M.: Environmental marketing strategy and firm performance: effects on new product performance and market share. J. Acad. Mark. Sci. **33**(4), 461–475 (2005)
2. Barysienė, J., et al.: Analysis of the current logistics and transport challenges in the context of the changing environment. Transport **30**(2), 233–241 (2015). https://doi.org/10.3846/16484142.2015.1046403
3. Dzwigol, H., Truskina, N., Kwilinski, A.: Green logistics as a sustainable development concept of logistics. Systems in a circular economy. In: Conference paper. Innovation Management and information Technology impact on Global Economy in the Era of Pandemic (2021)
4. European Center for Quality. Žaliasis Tinklinis Marketingas (2016)
5. Herrmann, F.F., Barbosa-Povoa, A.P., Butturi, M.A., Marinelli, S., Sellitto, M.A.: Green supply chain management: conceptual framework and models for analysis. Sustainability **13**, 8127 (2021). https://doi.org/10.3390/su13158127
6. Jefimovaitė, L., Vienažindienė, M.: Modeling the implementation of green logistics principles: theoretical aspect. Modeling the implementation of green logistics principles: theoretical aspect. Res. J. Public Secur. Public Order **26**, 93–107 (2021)
7. Kardelis, K.: Mokslinių tyrimų metodologija ir metodai. 2-asis pataisytas ir papildytas leidimas. Kaunas (2002)
8. Kumar, A.: Green Logistics for sustainable development: an analytical review. IOSRD Int. J. Bus. **1**(1), 7–13 (2015)
9. Menon, A., Menon, A.: Enviropreneurial marketing strategy: the emergence of corporate environmentalism as market strategy. J. Mark. **61**(1), 51–67 (1997)
10. Mesjasz-Lech, A.: Efektywność ekonomiczna i sprawność ekologiczna logistyki zwrotnej, (43–46). Published by Technical University of Czestochowa, Czestochowa (2011)
11. Lew, A.F.R., Chewand, B.C., Hamid, S.R.: Green logistics implementation factors: a study on a global logistics provider. J. Adv. Manuf. Technol. Special Issue iDECON **12**(1(1)), 115–128 (2017)
12. Radavičiūtė, G., Jarašiūnienė, A.: Žaliosios logistikos taikymo reikšmė kelių transporte. Transporto inžinerija ir vadyba. XXII jaunųjų mokslininkų konferencija „Mokslas – Lietuvos ateitis“ (2019)
13. Rodrigue, J.-P., Slack, B., Comtois, C.: Green logistics. In: Brewer, A.M., Button, K.J. and Hensher, D.A. (eds.) Handbook of Logistics and Supply-Chain Management, Vol. 2, Emerald Group Publishing Limited, Bingley, pp. 339–350 (2017). https://doi.org/10.1108/9780080435930-021
14. Pazirandeh, A., Jafari, H.: Making sense of green logistics. Int. J. Product. Perform. Manag. **62**(8), 889–904 (2013). https://doi.org/10.1108/IJPPM-03-2013-0059
15. Paužuolienė, J., Kaveckė, I.: Žaliosios logistikos taikymo svarba: vartotojų nuomonės tyrimas. Regional Format. Dev. Stud.. **36**, 61–68, (2022). https://doi.org/10.15181/rfds.v36i1.2388
16. Pillay, K., Mbhele, T., B.: The challenges of green logistics in the Durban road freight industry. Environmental Economics, 6(1), 64–73, (2015)
17. Popescu (married Bîzoi), A.C., Sipoș, C.A.: Green logistics – a condition of sustainable development. Revista Econ. **67(**4), 112–126 (2015)
18. Saaria, U.A., Mäkinena, S.J., Baumgartner, R.J., Hillebrand, B., Driessen, P.H.: How consumers' respect for nature and environmental self-assets influence their car brand experiences. J. Cleaner Prod. **261** (2020)
19. Sarkar, A.N.: Green supply chain management: a potent tool for sustainable green marketing. Int. J. Environ. Sci. Manag. Eng. Res. **1**(4) (2012)

20. Saroha, R.: Green logistics & its significance in modern day systems. Int. Rev. Appl. Eng. Res. **4**(1), 89–92 (2014)
21. Seroka-Stolka, O.: The development of green logistics for implementation sustainable development strategy in companies. Procedia - Social and Behavioral Sciences **151**, 302–309. 1st International Conference Green Cities 2014 – Green Logistics for Greener Cities (2014). https://doi.org/10.1016/j.sbspro.2014.10.028
22. Seroka-Stolka, O., Ociepa-Kubickab, A.: Green logistics and circular economy. Transp. Res. Proc. **39**, 471–479 (2019). https://doi.org/10.1016/j.trpro.2019.06.049
23. Skačkauskienė, I., Vilkaitė-Vaitonė, N.: Žaliasis marketingas Lietuvoje: kritinis vertinimas ir plėtros galimybės. Mokslo studija. Vilnius (2022)
24. Tüzün Rad, S., Gülmez, Y.S.: Green logistics for sustainability. Int. J. Manag. Econ. Bus. **13**,(3), 603–614 (2017)
25. Zhang, G., Zhao, Z.: Green packaging management of logistics enterprises. In: 2012 International Conference on Applied Physics and Industrial Engineering, Physics Procedia vol. 24, pp. 900 – 905 (2012)
26. Zowada, K.: Green logistics: the way to environmental sustainability of logistics. empirical evidence from polish SMEs. Eur. J. Sustain. Dev. **9**(4), 231–240 (2020). https://doi.org/10.14207/ejsd.2020.v9n4p231

Restriction of Mobility Due to Follow-Up Measures Caused by COVID-19

Vladimíra Štefancová[1](✉), Kristián Čulík[2], Borna Abramović[3], and Adriana Pálková[1]

[1] Department of Railway Transport, University of Žilina, Univerzitná 1, 01026 Žilina, Slovakia
vladimira.stefancova@fpedas.uniza.sk, adriana.palkova@stud.uniza.sk

[2] Department of Road and Urban Transport, University of Žilina, Univerzitná 1, 01026 Žilina, Slovakia
kristian.culik@fpedas.uniza.sk

[3] Faculty of Operation and Economics of Transport and Communications, University of Žilina, Univerzitná 1, 01026 Žilina, Slovakia
borna.abramovic@fpz.unizg.hr

Abstract. The unexpected arrival of the COVID-19 pandemic significantly affected the normal course of traffic. Public transport authorities were forced to face this situation and come up with solutions to ensure basic transport services. With the worsening epidemiological situation, the demands of the passengers themselves also changed. The mandated government measures were intended to mitigate the risk of infection in order to ensure the necessary mobility. The difficulty of implementing the measures required a quick response. Due to the constantly changing situation, the crisis team met to guide specific procedures to ensure the necessary mobility and ensure basic transport service. This article deals with the evaluation of the impact of the COVID-19 pandemic and government measures from the perspective of transport service providers. It aims to outline the most important areas that had an impact on mobility. The results of this article can be used in further in-depth research and applied in the next wave of the pandemic.

Keywords: Mobility · COVID-19 · Transportation · Traffic service

1 Introduction

The previous perception and organization of transport had to be reevaluated due to the onset of the COVID-19 pandemic. Based on this pandemic situation, the European Union adopted the decision to close the external borders. Subsequently, local measures of the states were proposed. The imposed lockdown led to a subsequent direct impact on the daily mobility of citizens [1]. Based on data from mobile phones, data on mobility within the entire European Union was recorded. The study confirmed that the given measures had a huge impact on mobility within the European Union [2]. The restriction of mobility

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 627–633, 2023.
https://doi.org/10.1007/978-3-031-25863-3_60

during pandemic waves has been globally associated with a change in traffic behavior [3].

During the COVID-19 pandemic, there was a decrease in public transport in the Slovak Republic. The mobility of the inhabitants was influenced by the preference for individual transport and walking [4]. The change in passenger mobility in the Slovak Republic was confirmed based on the movement of citizens at public transport stations. The results of the research reflect the impact of the adopted government measures on mobility and the percentage changes shown in the Fig. 1 [5].

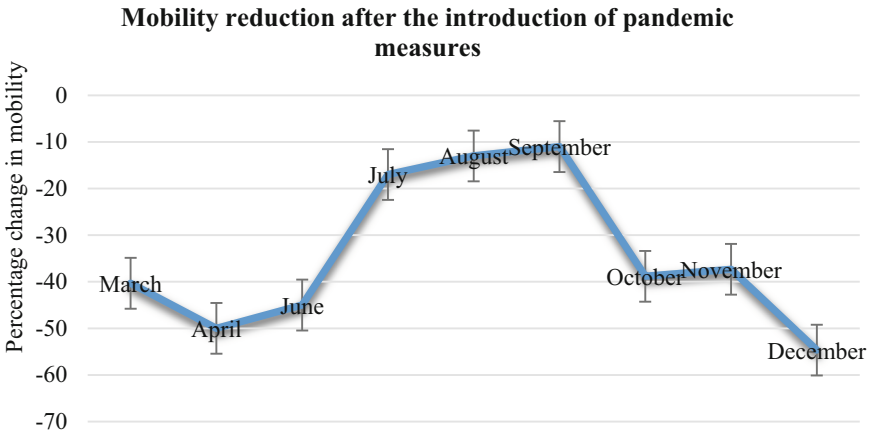


Fig. 1. Reduction of mobility due to the COVID-19 pandemic and introduced government measures in the Slovak Republic in 2020.

The mentioned decrease in mobility was compared with January 2020. The mobility reduction is visible in all months in 2020. The most significant decrease was recorded especially in the spring and winter months. Overall mobility also declined due to the imposition of a state of emergency and the declaration of a curfew, which led to the closure of schools and a preference for online teaching and home office [5]. This had a certain advantage because reduced mobility reduces the number of road accidents [6]. The preference for working from home and regulations for students to study from home significantly influenced the need for travel. Based on this, the use of shared mobility services decreased [7]. Even though the patterns of human mobility have changed due to the impact of COVID-19, a certain group of people has remained disadvantaged. Working from home was not possible due to the certain nature of the work or the citizens in the front line ensuring basic needs. However, not all of them could afford to exclude public transport and it was necessary to ensure basic transport services for them even during the pandemic [8]. The traveling public felt afraid of the risk of contagion and the atmosphere in public transport was deteriorating. The effort of transport institutions was therefore to ensure primary transport service while respecting the established government measures. Due to the impact of the pandemic situation and the announcement of subsequent government measures, management in the field of transport changed from standard to crisis management.

2 The Situation of Providing Transport Services During the COVID-19 Pandemic

The provision of transport services represents the basic satisfaction of transport needs [9]. To achieve effective service of the territory, it is necessary to properly delegate and coordinate individual activities between the Ministry of Transport, self-governing regions, cities, integrated transport systems or transport companies in cooperation with the needs of the traveling public [10].

The COVID-19 pandemic has highlighted the necessity of even better mutual coordination during the lockdowns and after the introduction of subsequent anti-pandemic measures. Figure 2 shows the relationship between transport service providers:

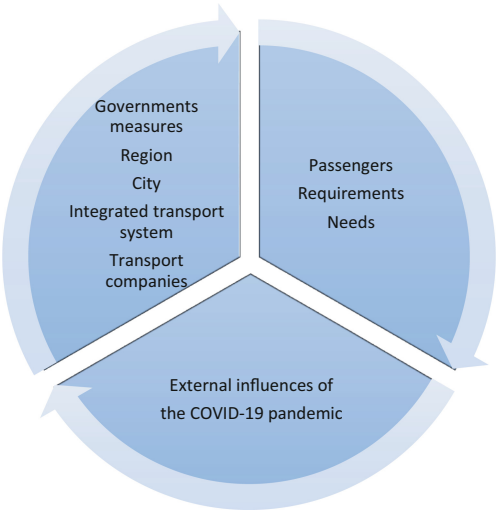


Fig. 2. Interconnection between transport service providers and passenger requirements and the influence of the external environment.

In connection with the pandemic situation and measures of the Slovak government, a relationship between mobility and demand for transport was noted [11]. The regions had to respond quickly to the government's anti-pandemic measures as well as to the needs and demands of the citizens. In cooperation with cities, integrated transport systems, or individual transport service providers, they processed the mandated government measures respecting the needs of citizens to maintain basic transport services. Rapidly changing information often caused unclear situations for which the crisis team had to meet regularly. The regions aimed to reverse the drop in transport performance and ensure a sufficient and safe transport offer to maintain mobility. The meeting of the crisis staff served to guide and solve the problems that arose due to the impact of the pandemic measures ordered during the pandemic situation.

The decline in passenger performance between 2019 and 2020 in a selected region located in Slovakia is recorded in Table 1 [12].

Table 1. Comparison of the transport performance across the different modes of transport during the pandemic situation.

Mode of transport	Transport performance		Decline [%]
	2019	2020	
Bus transport	472	283	40.0
Railway transport	141	72	48.5
Individual car transport	2,574	2,286	11.2

Figure 3 shows the passenger traffic before and during the pandemic situation in a selected area within the Slovak Republic. This figure displays the transport performance of individual and public passenger transport, and it clearly shows that during the pandemic situation, public transport experienced the greatest decline [12].

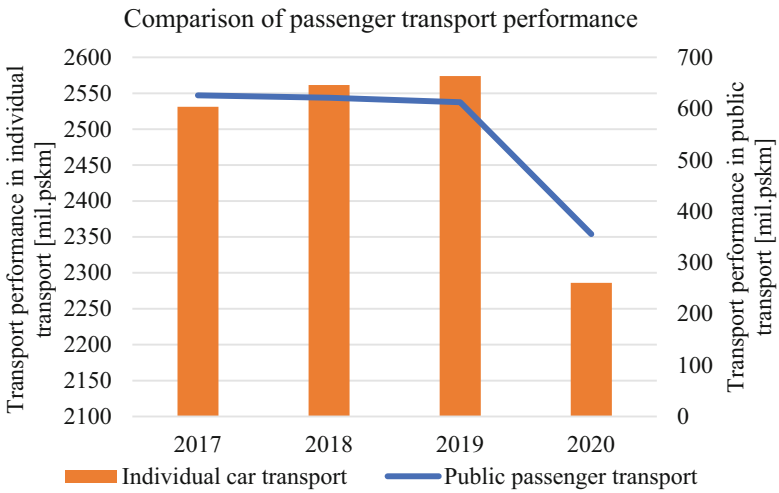


Fig. 3. Passenger transport performance within the selected region.

3 Results

In this chapter, the attitudes of transport providers to the pandemic situation are collected. Representatives of regions, cities, integrated transport systems, and transport companies were approached. Through guided interviews, their view on the course of mobility during the pandemic period was recorded. Based on the collected information, this chapter summarizes the significant impacts of the COVID-19 pandemic and the established regulations on ensuring mobility. The following Table 2 summarizes the most important milestones of the application of the measures and their impact on mobility.

Table 2. Comparison of the most significant attitudes from the point of view of passengers and transport service operators.

Transport service operators	Traveling public
• Change of travel schedule due to mobility restrictions • Transition of the timetable to holiday mode • Limitation of connections due to the curfew • Changing the mode of transport regularly • Lack of drivers due to quarantine • Skipping the front rows of seats behind the driver • Compliance with spacing • Necessity to wear a mask and use disinfection • Cleaning of public transport with ozone • Cancellation of the possibility to buy a ticket from the driver • Purchase of fares using a transport or bank card	• Lack of information due to the constantly changing situation • Change in the method of purchasing travel documents • Lack of transport connections during the off-peak hours • Fear of infection • Unwillingness of all passengers to comply with all regulations (wearing respiratory protection equipment, use of disinfection)

During the pandemic period, short-term or long-term measures were introduced. They significantly influenced the organization and functioning of transport. Based on the situation, there were changes in planning and coordination of transport. As the epidemiological situation and measures were constantly changing, some schools were closed accordingly. Due to the closure of schools and the preference for home offices, there was a limitation on mobility. The self-governing region communicated with the municipalities of the region, and they solved the issues of the lack of transport services in the given location. After evaluation, the requirements were incorporated into the timetables. The travel schedule was developed based on current measures. Transport coordinators were forced to adjust the timetable. In most cases, it was switched to holiday mode. In the case of the opening of some school facilities, this mode was supplemented with booster connections during the morning and afternoon rush hours. Mobility was also significantly affected by the announcement of an evening curfew. In the case of requests to fulfill basic transport needs on the part of passengers, they were dealt with promptly. Since there was a reduction of connections, especially during off-peak hours, the offer of connections for occasional passengers who traveled irregularly was reduced. The providers of transport services have experienced operational and technical problems when creating extraordinary timetables. Due to the outage of public transport drivers, it was difficult to fit the program in such a way that they sat the shifts while respecting the rest and breaks for the drivers. Due to many employees in quarantine, it was necessary to solve the transport process operationally. Based on guided interviews with representatives of cities, regions, transport companies, and integrated transport systems, the following emerged in Table 3.

Table 3. Impact of the COVID-19 and measures on mobility.

Important attributes during pandemic situation
• Reduced mobility • Decrease in the number of passengers • The need to respond promptly to organizational changes in transport • Necessity of timely and effective communication between all organizational bodies • Limitation of the range of performance (insufficient supply of connections in off-peak hours) • Changing the travel mode to a holiday mode • Deviation of passengers from public transport (influence of home office preference or replacement by shared or individual transport) • Procurement of disinfectants and protective equipment for drivers and passenger • Marking of information brochures about the necessity to observe distances in public transport

4 Conclusion

The outbreak of the COVID-19 pandemic brought with it the necessity of changing the organization and functioning of transport. This post aimed to outline the main areas that affected mobility during the pandemic.

Some of the measures that were introduced during the pandemic could remain even after it has passed. From the point of view of transport service providers, a timely response to the changing situation is a prerequisite for mitigation and better adaptation. More regular and thorough cleaning of public transport, as well as the wearing of masks or respirators to protect the upper respiratory tract during the flu season, would be beneficial overall and make public transport safer. It would lead to the protection of drivers and passengers themselves, and from the point of view of safety, public transport would be more competitive. The lack of up-to-date data on mobility and transport relations was considered one of the significant bottlenecks. Although to a certain extent, the carriers had at their disposal the development of the number of passengers, there was a lack of an overall evaluation of the traffic intensity and mutual connection between all entities. Because the pandemic had a significant impact on mobility, in the future it is necessary to deal with the design of an effective model for the correct prediction of disease outbreaks with an overview of the spread and consequences [13]. Predictions and consequences of the pandemic situation represent an important prerequisite for future development. Several studies deal with this issue through machine learning models [14, 15]. In order to ensure better planning of traffic service, it would be advisable to set up a system of regular collection of traffic data and interconnect databases. On the other hand, it was very necessary to be able to inform the passengers themselves about the changes on time. During the pandemic, passengers were informed about the offer of transport services through various communication channels such as bulletin boards, text messages, local radio, and social networks depending on the technical capabilities of the given territory. During the pandemic situation, a subsection related to the issue of COVID-19 was created on the pages of several cities. In certain regions, citizens were informed about current information in this way. In an effort to support mobility and the use of public transport, it would be appropriate to ensure the same conditions for passengers throughout the

Slovak Republic. The present time gives room for the creation of a mobile application that would collect and link up-to-date information on all important matters in a unified space.

Acknowledgements. This publication was created thanks to support under the Operational Program Integrated Infrastructure for the project: Identification and possibilities of implementation of new technological measures in transport to achieve safe mobility during a pandemic caused by COVID-19 (ITMS code: 313011AUX5), co-financed by the European Regional Development Fund.

References

1. Shibayama, T., Sandholzer, F., Laa, B., Brezina, T.: Impact of covid-19 lockdown on commuting: A multi-country perspective. Eur. J. Transp. Infrastruct. Res. **21**(1), 70–93 (2021)
2. Linka, K., Peirlinck, M., Kuhl, E.: The reproduction number of COVID-19 and its correlation with public health interventions. Comput. Mech. **66**(4), 1035–1050 (2020). https://doi.org/10.1007/s00466-020-01880-8
3. Stipic, D., Bradac, M., Lipic, T., Podobnik, B.: Effects of quarantine disobedience and mobility restrictions on COVID-19 pandemic waves in dynamical networks. Chaos, Solitons Fractals **150**, 111200 (2021)
4. Harantová, V., Kalašová, A., Skřivánek-Kubíková, S., Mazanec, J., Jordová, R.: The impact of mobility on shopping preferences during the COVID-19 pandemic: the evidence from the Slovak republic. Mathematics **10**(9), 1394 (2022)
5. Brídziková, M.: Vplyv prijatých protipandemických opatrení na mobilitu obyvateľov v Slovenskej republike. Mladá Veda **9**(1), 45–57 (2021)
6. Ballay, M., Macurová, L., Kohút, P., Copiak, M.: Development of road safety status and the evaluation criterion causes of specific traffic accidents. In: Transport Means - Proceedings of the International Conference, pp. 765–770. Kaunas, Lithuania (2018)
7. Kubaľák, S., Kalašová, A., Hájnik, A.: The bike-sharing system in Slovakia and the impact of COVID-19 on this shared mobility service in a selected city. Sustainability **13**(12), 6544 (2021)
8. Chang, S., et al.: Mobility network models of COVID-19 explain inequities and inform reopening. Nature **589**(7840), 82–87 (2021)
9. Mašek, J., Kendra, M.: Koncepty dopravnej obslužnosti územia v nákladnej a osobnej doprave. Perner's Contacts **3**(3), 1–9 (2008)
10. Poliak, M., Semanová, Š: Obstarávanie dopravnej obslužnosti. Perner's Contacts **8**(1), 1–6 (2013)
11. Konečný, V., Brídziková, M., Senko, S.: Impact of COVID-19 and anti-pandemic measures on the sustainability of demand in suburban bus transport. the case of the Slovak republic. Sustainability **13**(9), 4967 (2021)
12. Pálková, A.: Measures to support the introduction of IDS in the self-governing region Banská Bystrica. Published diploma thesis (2022)
13. Ardabili, S.F., et al.: COVID-19 outbreak prediction with machine learning. Algorithms **13**(10), 249 (2020)
14. Pinter, G., Felde, I., Mosavi, A., Ghamisi, P., Gloaguen, R.: COVID-19 pandemic prediction for hungary A hybrid machine learning approach. Mathematics **8**(6), 890 (2020)
15. Akour, I., Alshurideh, M., Al Kurdi, B., Al Ali, A., Salloum, S.: Using machine learning algorithms to predict people's intention to use mobile learning platforms during the COVID-19 pandemic: machine learning approach. JMIR Med. Educ. **7**(1), e24032–e24032 (2021)

Study of Technological Literacy Competencies of Logistics Specialists of a Transport Company

Kristina Vaičiūtė[1](✉) and Irina Yatskiv[2]

[1] Vilnius Gediminas Technical University, Saulėtekio ave. 11, 10223 Vilnius, Lithuania
kristina.vaiciute@vilniustech.lt
[2] Transport and Telecommunication Institute, Lomonosova iela 1, Riga 1019, LV, Latvia
Jackiva.I@tsi.lv

Abstract. The development of the latest technologies shapes the values, qualities and mindset of every logistics specialist in a transport company. In order to remain competitive in the labor market, logistics specialists must constantly acquire new technological skills. The existing knowledge of the logistics specialist helps to solve the problems that arise during the work, but the unqualified technological knowledge of the logistics specialists of the transport companies disrupts the operation of the organization's processes. Raising the competences of logistics specialists should focus on providing entrepreneurial and technical skills that would enable logistics specialists to adapt to new technologies. The growing popularity of the Internet of Things, cloud computing and other technological innovations make it easier to manage software, so digital and technical skills are becoming an integral part of the operations of transport companies. The article analyzes the main criteria of technological literacy competence of logistics specialists of transport companies, which should be developed in the future.

Keywords: Logistics specialist · Transport Company · Technological literacy · Multi-criteria evaluation method

1 Introduction

The continuous innovativeness of technologies affects the logistics collaboration and the organization of the transport service. According to Taguma et al. [1], in order to remain competitive in the labor market, employees must constantly acquire new technological skills, which requires employee flexibility, a positive attitude to lifelong learning, and curiosity. Raising the competences of employees should be focused on providing creative, entrepreneurial and technical skills that would give employees the opportunity to move to new professional opportunities and adapt to new technologies [2]. Coetzee [3] states that the increasing use of technology in logistics activities increases the anxiety of logistics professionals, which raises the performance problems of the transportation service arising from the excessive use of advanced technology devices. According to Aloqaili et al. [4], the selection of suitable technological development for transport companies becomes a less complicated process than presenting the technologies to be

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 634–644, 2023.
https://doi.org/10.1007/978-3-031-25863-3_61

implemented to logistics specialists. The authors claim that, in order to quickly and efficiently carry out transportation processes, it is necessary for logistics specialists in the transportation market environment to manage the transportation process with their technological knowledge [4]. Robots can increase the efficiency and ease of work, but they still cannot be as creative as humans [5]. Software technology can count, add, subtract, multiply, divide, search, compare, compile and analyze patterns with large amounts of data at a speed that is incomprehensible to the worker. However, errors occur in the listed processes, which neither robots nor software can solve, so human problem-solving and rational decision-making skills are demonstrated here [6].

Globalization, technical and technological improvement, and the desire to gain a foothold in the market economy pose new challenges for transport companies. Companies are engaged in a constant competitive battle. In a constantly changing environment, logistics specialists, i.e., human resources become the most important and active part of the system, determining the efficiency of the organization's activities [7].

The object of this research is the competences of transport company logistics specialists (technological literacy) and the purpose is to conduct a study of the technological competence of logistics specialists of a transport company. Regarding the relevance of the study, it can be noted that in today's international environment, every transport company providing logistics services must ensure technology management capabilities and the company's logistics specialists should be able to make the right decisions related to technology management.

2 Competences of Logistics Specialists of Transport Companies

The innovativeness of production processes, work productivity and production quality directly depend on the competences and qualifications of logistics specialists. In order to work successfully in a profession in which technological development is constantly carried out, logistics specialists must acquire more than one competence and qualification, thus constantly updating their knowledge, skills and abilities; or acquire new ones. [8, 9]. According to Savanevičienė et al. [10], Skirmantienė et al. [11], Palšaitis et al. [12], the following types of specialist competence can be distinguished:

1. Professional (specialized) competence, which includes all the knowledge and preparation needed to perform specific professional tasks.
2. Management (operational) competence, which is understood as the ability to act in an organized manner, to integrate part or all other competences.

After analyzing the content of competencies required for a logistics specialist according to Katiniene et al. [13], Vaičiūtė et al. [14], Palšaitis et al. [15] the following main groups of competences can be distinguished:

1. Special competences (to understand the principles of logistics and transport activities, i.e., the competences required to perform the work).
2. Analytical competencies (required to create an optimal route, select cargo criteria, determine customer needs, i.e., competencies of knowledge of analysis, synthesis, modelling methodologies).

3. Personal competences (communication, cooperation with clients, i.e., self-management competences) [13].

In summary, it can be said that a logistics specialist working in a transport company must have a good knowledge of all the main processes taking place in a transport company.

2.1 Technological Literacy Competencies of Logistics Specialists

Technological literacy skills include cutting-edge knowledge, technical, media and coding skills, process understanding, and IT security awareness [16]. The existing knowledge of the logistics specialist helps to solve the problems that arise during the work [17]. El-Farr [17] states that no matter how important knowledge is, logistics professionals cannot know it all. Pulakas et al. [18] state that after the implementation of technology development, it is no longer enough for a logistics specialist to know only one area, it is necessary to constantly acquire new technological skills. Pedron's [19] research revealed the assumption that technological development did not make it difficult, but improved the quality of work of employees, facilitating their work and reducing the amount of work. As automated devices outsource monotonous and physically demanding tasks in the logistics process, tasks requiring creativity and emotional intelligence have been outsourced to technologically literate workers [19]. When robotizing and automating workplaces, it is important for employees to constantly update their technical and digital skills [20]. Thanks to technological skills, workers are able to operate automated devices used in production [21]. Knowles-Cutler and Lewis [22] states that the need for technological skills will decrease over time due to the accelerating impact of technological development on the development of artificial intelligence, which will be able to perform various technical tasks without human assistance [22]. Berkup [23], Bongomin et al. [24] state that technological literacy refers to the knowledge of digital information and IT devices, which is increasingly important in today's digitized business and learning environment. The authors argue that technological literacy is comparable to digital literacy in that an employee who is technologically or digitally literate is able to think critically and communicate using technology.

In summary, it can be stated that the technological literacy of logistics specialists is defined in the scientific literature as a person's ability to evaluate, acquire and transmit information in a digital environment.

3 Research Methodology

The measurement of competences is complicated, therefore it is not uncommon to judge competence based on simple, easily expressed indicators, which often do not give the whole picture. Quantitative research proposed by scientists Kardelis [25], Tidikis [26] and many others, and a questionnaire (as research method) were chosen to evaluate of transport company technological literacy competencies of logistics specialists and Multi-Criteria Evaluation Method – for ranking.

Based on the Multi-Criteria Evaluation methodology, the expert group n quantifies m objects. Results of evaluation form a matrix of n rows and m columns [27]. Evaluation values can be − indicator units, unit parts, percentages, in a ten-point system. Ranking is a procedure in which the most important indicator is given a rank of *R*, equal to one, the second indicator is given a second rank, and the last indicator is given a rank of m (m is the number of benchmarks). The average of the sum of the ranks is calculated [28]:

$$\sum\nolimits_{i=1}^{m} R_{ij} = \frac{1}{2}n(m+1). \tag{1}$$

where n – the expert group n quantifies objects; m – is the number of benchmarks.

Having expert evaluation indicators, the consistency of their opinions is determined by calculating the concordance coefficient W of the Kendall ranks. The expert assessments can be considered coordinated and the significance of the concordance coefficient can be determined using the Pearson criterion χ^2 (3). The lowest value of the Concordance coefficient $W_{\min}$ is calculated (4).

$$W = \frac{12S}{n^2 m\left(m^2-1\right)} = \frac{12S}{n^2\left(m^3-m\right)}. \tag{2}$$

If S (variance) is the real sum of the squares calculated according to formula (1), then the concordance coefficient (2; 4), in the absence of related ranks, is defined by the ratio of the obtained S to the corresponding maximum $S_{\max}$ (5):

$$\chi^2 = n(m-1)W = \frac{12S}{nm(m+1)}. \tag{3}$$

$$W_{\min} = \frac{\chi^2_{v,\alpha}}{n(m-1)}. \tag{4}$$

$$S_{\max} = \frac{n^2 m\left(m^2-1\right)}{12}. \tag{5}$$

To achieve the aim of the research, the factors determining the efficiency of the technological literacy competencies of logistics specialists of transport companies were investigated.

The experts were asked to assess the main factors determining the efficiency of the technological literacy competencies of logistics specialists of transport companies:

a) management of technological processes of the organization;
b) knowledge of the implementation of new technological systems;
c) technological management of the transportation process;
d) software technical problem solving ability;
e) ability to analyze and compare technological models;
f) awareness of IT security;
g) understanding of transport management of the systems coding.

The distribution of the factors determining the efficiency of the technological literacy competencies of logistics specialists of transport companies according to the above-mentioned criteria (a–g) was evaluated by experts with points from 1 to 7: 1 being the most important, 7 being the least important.

The second stage the experts assessed the main criteria of competencies of logistics specialists of transport companies:

a) be able to cooperate with clients;
b) be able to make an optimal route;
c) to be able to determine the needs of clients;
d) to understand the principles of logistics and transport activities;
e) be able to select cargo criteria;
f) able to perform specific work in the transport / logistics field;
g) to be able to use logistics information systems.

The distribution of the factors determining of competencies of logistics specialists of transport companies according to the abovementioned criteria (a–g) was evaluated by experts with points from 1 to 7: 1 being the most important, 7 being the least important.

4 Results of the Research

The current study involved 8 experts, all of whom have management experience in land transport (Decision Makers) for 3 to 10 years. The experts agreed (75.6%) that logistics specialists lack the most knowledge about the management of new technologies.

4.1 Efficiency of the Technological Literacy Competencies

Distribution of the expert ranks of factors determining the efficiency of the technological literacy competencies of logistics specialists of transport companies according to the above-mentioned criteria (a–g) is shown in Fig. 1.

The data of the analysis and calculation of the distribution of the ranks of the eight experts were listed in Table 1.

The concordance coefficient W was calculated according to formula (2) when there are no associated ranks.

$$W = \frac{12S}{n^2\left(m^3 - m\right)} = \frac{12 \times 838}{8^2\left(7^3 - 7\right)} = 0.4676.$$

The impact of technological development is important factor determining the main efficiency of the technological literacy competencies of logistics specialists of transport companies is 7 the number $m > 7$. The weight of the concordance coefficient χ^2 is then calculated according to formula (3) and a random value is obtained.

$$\chi^2 = n(m-1)W = \frac{12S}{nm(m+1)} = \frac{12 \times 838}{8 \times 7(7+1)} = 22.446.$$

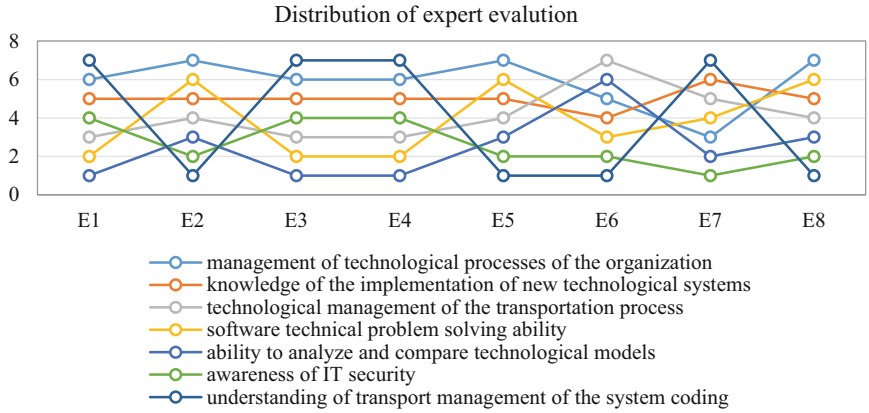


Fig. 1. Distribution of ranks of factors determining the efficiency of the technological literacy competencies of logistics specialists of transport companies (compiled by the Authors).

Table 1. Ranking of the importance of the factors determining the efficiency of the technological literacy competencies of logistics specialists of transport companies (compiled by the Authors).

Ranking formulas	Factor designation symbol ($m = 7$)						
	a	b	c	d	e	f	g
$\sum_{i=1}^{n} R_{ij}$	28	44	16	17	41	42	36
$\overline{R}_j = \frac{\sum_{i=1}^{n} R_{ij}}{n}$	3.5	5.5	2	2.125	5.125	5.25	4.5
$\sum_{i=1}^{n} R_{ij} - \frac{1}{2}n(m+1)$	–4	12	–16	–15	9	10	4
$\left[\sum_{i=1}^{n} R_{ij} - \frac{1}{2}n(m+1)\right]$	16	144	256	225	81	100	16

χ^2 calculated value was 22.446 it was higher than the critical value of (12.5916) that is why the opinion of the respondents is considered to be compatible, and the average ranks show the general opinion of the experts:

$$W_{\min} = \frac{\chi^2_{v,\alpha}}{n(m-1)} = \frac{12.5916}{8(7-1)} = 0.2623 < 0.4676.$$

The minimum value of the concordance coefficient $W_{\min}$ was calculated according to formula above, $W_{\min} = 0.2623 < 0.4676$, so that the opinions of all the 8 respondents on the 7 main criteria determining the importance of efficiency of the technological literacy competencies of logistics specialists of transport companies, which are important, are still considered harmonized.

The indicators of the importance of the factors determining of efficiency of the technological literacy competencies of logistics specialists of transport companies (Q_j) are calculated. The obtained data are presented in Table 2.

According to expert assessments and calculations, the rankings of the importance of the factors determining of efficiency of the technological literacy competencies of logistics specialists of transport companies are:

1. Technological management of the transportation process (c).
2. Software technical problem solving ability (d).
3. Management of technological processes of the organization (a).
4. Understanding of transport management of the system coding (g).

Table 2. The main indicators of the importance of efficiency of the technological literacy competencies of logistics specialists of transport companies Q_j (compiled by the Authors).

Indicator marker	Factor designation symbol ($m = 8$)							Sum
	a	b	c	d	e	f	g	
q_j	0.1250	0.1964	0.0714	0.0759	0.1830	0.1875	0.1607	1.00
d_j	0.8750	0.8036	0.9286	0.9241	0.8170	0.8125	0.8393	6.00
Q_j	0.1458	0.1339	0.1548	0.1540	0.1362	0.1354	0.1399	1.00
Q_j'	0.1607	0.0893	0.2143	0.2098	0.1027	0.0982	0.1250	1.00
Factor layout	3	7	1	2	5	6	4	

4.2 Criteria of Competencies of Logistics Specialists of Transport Companies

The experts assessed the main criteria of competencies of logistics specialists of transport companies and the distribution of ranking of criteria (a–g) is show in Fig. 2.

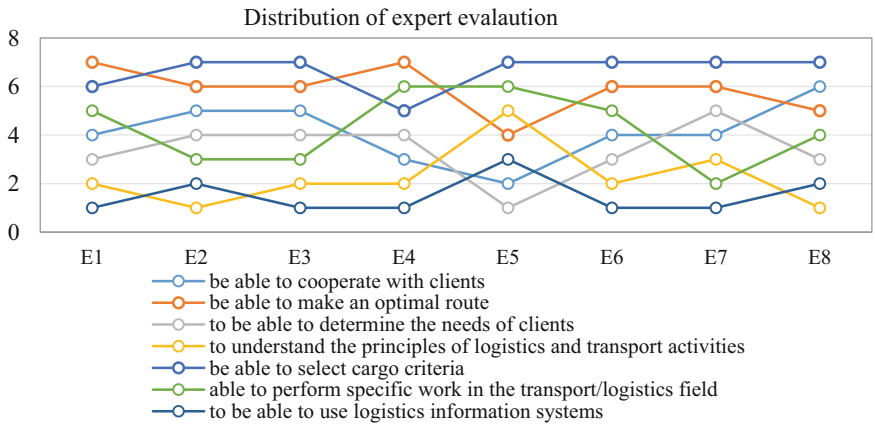


Fig. 2. Distribution of ranks of components of competencies of logistics specialists of transport companies (compiled by the Authors).

The data of the analysis and calculation of the distribution of the rankings based on the answers of the eight expert questionnaires were listed in Table 3.

The concordance coefficient W was calculated according to formula (2) when there are no associated ranks.

$$W = \frac{12S}{n^2\left(m^3 - m\right)} = \frac{12 \times 1292}{8^2\left(7^3 - 7\right)} = 0.7209.$$

Table 3. Ranking table of the main components of competencies of logistics specialists of transport companies (compiled by the Authors).

Ranking formulas	Factor designation symbol ($m = 7$)						
	a	b	c	d	e	f	g
$\sum_{i=1}^{n} R_{ij}$	33	47	27	18	53	34	12
$\overline{R}_j = \frac{\sum_{i=1}^{n} R_{ij}}{n}$	4.125	5.875	3.375	2.25	6.625	4.25	1.5
$\sum_{i=1}^{n} R_{ij} - \frac{1}{2}n(m+1)$	1	15	–5	–14	21	2	–20
$\left[\sum_{i=1}^{n} R_{ij} - \frac{1}{2}n(m+1)\right]^2$	1	225	25	196	441	4	400

The number of important main components of competencies of logistics specialists of transport companies (m) is 7, i.e. $m > 7$. Then the weight of the concordance coefficient χ^2 is calculated according to formula (3) and a random quantity is obtained.

$$\chi^2 = n(m-1)W = \frac{12S}{nm(m+1)} = \frac{12 \times 1292}{8 \times 7(7+1)} = 34.607.$$

χ^2 the calculated value of 34.607 was higher than the critical value (equal to 12.5916), therefore the opinion of the respondents is considered to be consistent, and the average ranks show the general opinion of the experts.

$$W_{\min} = \frac{\chi^2_{v,\alpha}}{n(m-1)} = \frac{12.5916}{8(7-1)} = 0.2623 < 0.7209.$$

The lowest value of the concordance $W_{\min}$ coefficient less than the concordance coefficient W ($0.2623 < 0.7209$). Consequently, the views of all 8 respondents on the 7 key components of competencies of logistics specialists of transport companies, which are important, are still considered harmonized.

The indicators of the components of competencies of logistics specialists of transport companies are calculated – Q_j. The obtained data are presented in Table 4.

Table 4. The main indicators of the important components of the components of logistics specialists of transport companies (compiled by the Authors).

Indicator marker	Factor encryption symbol ($m = 7$)							Sum
	a	b	c	d	e	f	g	
q_j	0.147321	0.209821	0.120536	0.080357	0.236607	0.151786	0.053571	1.00
d_j	0.852679	0.790179	0.879464	0.919643	0.763393	0.848214	0.946429	6.00
Q_j	0.142113	0.131696	0.146577	0.153274	0.127232	0.141369	0.157738	1.00
Q_j'	0.138393	0.075893	0.165179	0.205357	0.049107	0.133929	0.232143	1.00
Factor layout	4	6	3	2	7	5	1	

Based on expert assessments and calculations, the order of importance of the main components of competencies of logistics specialists of transport companies is as follows:

(g) to be able to use logistics information systems;
(d) to understand the principles of logistics and transport activities;
(c) to be able to determine the needs of clients;
(a) be able to cooperate with clients.

The analysis of the research results revealed that the components of competencies of logistics specialists of transport companies are related to the application of the technological literacy competencies between communication networks in improving the quality of service in the transport and logistics system.

5 Conclusions

The article analyzes the criteria of technological literacy competence of logistics specialists of transport companies, which should be developed in the future and used next qualitative methods: questionnaire of high level experts and Multi-Criteria Evaluation Method.

After processing the results of the survey, it was found that logistics specialists (75.6%) lack the most knowledge about the management of new technologies. The research revealed the order of importance of the factors determining of efficiency of the technological literacy competencies of logistics specialists of transport companies and the top-3 factors are: a) technological management of the transportation process; b) software technical problem solving ability; c) management of technological processes of the organization. It was, also, stated that the most important indicators of the components of competencies is ranking according to next order: a) to be able to use logistics information systems; b) to understand the principles of logistics and transport activities; c) to be able to determine the needs of clients; d) be able to cooperate with clients.

It can be said that this study reaffirms competencies of logistics specialists of transport companies manage the importance of information and data processing for the company's operations and the quality of customer service. Appropriate of efficiency of the

technological literacy competencies of logistics specialists of transport companies and possibilities to work with data allow to perform other actions – to model, evaluate, visualize.

References

1. Taguma, M., Feron, E., Lim, M.H.: Future of Education and Skills 2030. Conceptual learning framework. Concept note: Skills for 2030. In: 8th Informal Working Group (IWG) Meeting 29–31 October 2018. Paris, France: OECD Conference Centre (2018). https://static1.squarespace.com/static/5e26d2d6fcf7d67bbd37a92e/t/5e411f365af4111d703b7f91/1581326153625/Education-and-AI.pdf
2. Berger, T., Frey, C.B.: Future shocks and shifts: challenges for the global workforce and skills development: key messages. (OECD Internal Working document). 34. OECD Conference Centre, Paris (2015). http://www.oecd.org/education/2030-project/about/documents/Future-Shocks-and-Shifts-Challenges-for-the-Global-workforce-and-Skills-Development.pdf
3. Coetzee, M.: Psychological career resources of working adults: a South African survey. SA J. Ind. Psychol. **34**(2), 10–20 (2008). https://doi.org/10.4102/sajip.v34i2.491
4. Aloqaili, S., Alharthy, R., Alsaudon, S., Alshaalan, R.: Technology in work place. Riyadh, Saudi Arabia: College of Business Administration. Princess Nourah bint Abdulrahman University (2019). https://www.researchgate.net/publication/342106878_Technology_in_the_workplace
5. Egcas, R.A., Garganera, J.L.: Impact of alternative learning system to the out-of-school-youths, Kasambahay, indigenous people and children-in-conflict with-the law. Asia Pacific J. Multidiscipl. Res. **7**(3), 15–21 (2019)
6. Du, L., Wang, Z., Wang, Y., Di, W., Lu, L.: Survey of research progress on target detection and discrimination of single-channel SAR images for complex scenes. J. Radars **9**(1), 34–54 (2020). https://doi.org/10.12000/JR19104
7. Chlivickas, E., Papšienė, P., Papšys, A.: Žmogiškieji ištekliai: strateginio valdymo aspektai [Human recources: Strategic management aspects. Verslas, vadyba ir studijos. Bus. Manag. Educ. **8**(1), 51–65 (2009). https://doi.org/10.3846/bme.2010.04
8. Laužackas, R.: Vocational training methodology: monograph [Profesinio rengimo metodologija: monografija]. Vytautas Magnus University [Vytauto Didžiojo universitetas]. (2005). https://hdl.handle.net/20.500.12259/41757
9. Fokienė, A., Sajienė, L.: Portfolio method in assessment of non-formal and informal learning achievements [Portfolio metodas vertinant neformaliojo ir savaiminio mokymosi pasiekimus]. Quality of higher education [Aukštojo mokslo kokybė], **6**, 141–159 (2009). (In Lithuanian)
10. Savanevičienė, A., Stukaitė, D., Šilingienė, V.: Development of strategic individual competences. Eng. Econ. **58**(3), 81–88 (2008)
11. Vaičiūtė, K., Skirmantienė, J., Domanska, L.: Assessment of transport specialists' competencies in transport/logistics companies. In: TRANSBALTICA 2017. Transportation Science and Technology: Proceedings of the 10th International Scientific Conference May 4–5, 2017, pp. 628–634. Amsterdam: Elsevier Ltd. (2017). https://doi.org/10.1016/j.proeng.2017.04.423
12. Palšaitis, R., Čižiūnienė, K., Vaičiūtė, K.: Improvement of warehouse operations management by considering competencies of human resources. In: TRANSBALTICA 2017. Transportation Science and Technology: Proceedings of the 10th International Scientific Conference, vol. 187, 4–5 May 2017, pp. 604–613. Amsterdam: Elsevier Ltd. (2017). https://doi.org/10.1016/j.proeng.2017.04.420
13. Katinienė, A., Jezerskė, Ž, Vaičiūtė, K.: Research on competencies of logistics specialists in transport organisations. J. Bus. Econ. Manag. **22**(5), 1308–1322 (2021). https://doi.org/10.3846/jbem.2021.15299

14. Skirmantienė, J., Vaičiūtė, K.: Competence evaluation of transport management specialists: research on graduates' attitudes registered at labour exchange. In: The 9th International Scientific Conference "Business and Management 2016", 12–13 May 2016, pp. 1–9. Technika, Vilnius (2016). https://doi.org/10.3846/bm.2016.55
15. Palšaitis, R., Čižiūnienė, K., Vaičiūtė, K.: Social competencies and perspectives of human resources in logistics organization. In: The 9th International Scientific Conference "Business and Management 2016", 12–13 May 2016, pp. 1–11. Technika, Vilnius (2016). https://doi.org/10.3846/bm.2016.52
16. Kaur, R., Awasthi, A., Grzybowska, K.: Evaluation of Key skills supporting industry 4.0—a review of literature and practice. In: Grzybowska, K., Awasthi, A., Sawhney, R. (eds.) Sustainable Logistics and Production in Industry 4.0. E, pp. 19–29. Springer, Cham (2020). https://doi.org/10.1007/978-3-030-33369-0_2
17. El-Farr, H.: Knowledge work and workers: A critical literature review. Working Paper Series. Leeds University Business School, 1(1), pp. 1–15. (2009)
18. Pulakos, E.D., Arad, S., Donovan, M.A., Plamondon, K.E.: Adaptability in the workplace: development of a taxonomy of adaptive performance. J. Appl. Psychol. **85**(4), 612 (2000). https://doi.org/10.1037/0021-9010.85.4.612
19. Pedron, Z.: The skills revolution of the 21st century: it's time to re-calibrate. On Research. J. EU Bus. School **1**, 20–28 (2018). Home/Downloads/ONRESEARCH.research-journal.issue-1.pdf
20. Tsekeris, C.: Surviving and thriving in the fourth industrial revolution: digital skills for education and society. Homo Virtualis **2**(1), 34–42 (2019). https://doi.org/10.12681/homvir.20192
21. Dittrich, P.-J.: Reskilling for the Fourth Industrial Revolution: Formulating a European Strategy. Jacques Delors Institute, Berlin (2016)
22. Knowles-Cutler, A., Lewis, H.: Deloitte. Official site. Talent for Survival: Essential skills for humans working in the machine age (2016). https://www2.deloitte.com/content/dam/Deloitte/uk/Documents/Growth/deloitte-uk-talent-for-survival-report.pdf
23. Berkup, S.: Working with generations X and Y in generation Z period: management of different generations in business life. Mediterr. J. Soc. Sci. **5**(19), 218–229 (2014). https://doi.org/10.5901/mjss.2014.v5n19p218
24. Bongomin, O., Ocen, G.G., Nganyi, E.O., Musinguzi, A., Omara, T.: Exponential disruptive technologies and the required skills of industry 4.0. J. Eng. **2020**, 4280156 (2020). https://doi.org/10.1155/2020/4280156
25. Kardelis, K.: Research methodology and methods [Mokslinių tyrimų metodologija ir metodai]. Vilnius: Science and Encyclopedia Publishing Center [Mokslo ir enciklopedijų leidybos centras] (2016). In Lithuanian
26. Tidikis, R.: Methodology of Social Sciences Research. Publishing Centre of the Law University of Lithuania, Vilnius (2003). In Lithuanian. https://repository.mruni.eu/handle/007/MRU
27. Sivilevičius, H.: Application of expert evaluation method to determine the importance of operating asphalt neixing plant quality criteria and rank correlation. Baltic J. Road Bridge Eng. **6**(1), 48–58. (2011). https://doi.org/10.3846/bjrbe.2011.07
28. Podvezko, V.: Agreement of expert estimates. Technol. Econ. Dev. Econ. **11**(2), 101–107 (2005)

Analysis of International Air Hubs: A Competitiveness Review

Aya Medany[1](✉), Ilmars Blumbergs[1], and Khaled Elsakty[2]

[1] Riga Technical University/Aeronautics Institute, Transport Department, Riga, Latvia
aya.medany@olympian.org, ilmars.blumbergs@rtu.lv
[2] Arab Academy for Science, Technology and Maritime/Logistics and International Transportation, Transport Department, Giza, Egypt
khaled.sakty@aast.edu

Abstract. The air transport industry is characterized by the consequences of the speedy and momentous impacts of surrounding actions and economic and social changes. An airport hub serves as a center point that connects everyone and everything. Because they protect the financial interests of airlines and satisfy the connectivity requirements of both passengers and cargo, hubs continue to play a significant role in aviation. An efficient hub airport with enough extra space will increase passenger options and encourage airline competition by allowing additional competitors, routes, and frequencies. The airport networks need to apply the developed management and use its features to try to arrive at the optimum results and used its facilities such as: (geographical, capital, the ability for multi-model transports, ready to apply with the future technology, ready to welcome the companies such as FedEx and DHL, applying e-airport with e-airline with e-freight with e-AWB). This helps to achieve maximum growth and to be able to face rapid growth. Future airport networks need to reach all sites, so they should employ several different transmission technologies. Accordingly, this paper aims to compare the competitiveness of the busiest hub in each continent or region in 2019 for cargo and passengers which will be Hong Kong airport (HKIA) for Asia, Frankfurt hub (Fraport) for Europe, in Africa Addis Ababa air hub (ADD) and Cairo international airport hub (CAI), while for middle east will be Dubai airport (DXB).

Keywords: Addis Ababa airport · Air hub · Air Transport Logistics · Cairo Airport · Frankfurt airport · Hong Kong airport · Hub competition and competitive factors

1 Introduction

The standard for airport management effectiveness reflects an airport's ability to maintain its management system or adapt to modern changes. Infrastructure capabilities and the future of the airport will be impacted by management decisions on the future strategic orientation. The major goal of this study is to contrast the strengths of Hong Kong, Dubai, and Frankfurt International Airport with those of Cairo International Airport

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 645–654, 2023.
https://doi.org/10.1007/978-3-031-25863-3_62

and Addis Ababa International Airport. The factors that contribute to the strengths and weaknesses are also identified. To put it another way, why do some airports become more interconnected and crucial to systems than others. Typically, the issue with the air transportation network is its complicated network [3]. Qualitative (subjective) measures began to make an appearance in airport benchmarking surveys as the commercial nature of airports became more and more significant. These measures most frequently assessed specific aspects of airport service quality (ASQ), such as security, check-in, cleanliness, transit and passport control waiting times, seats, and parking availability. Another group of qualitative studies uses a range of techniques, such as the straightforward weighted mean, regression analysis, and fuzzy multicriteria analysis, to derive an overall index of an airport's level of service (LOS). However, qualitative metrics almost primarily focus on how passengers view airports, ignoring the requirements and viewpoints of other airport users and stakeholders [6]. The remainder of the paper is structured as follows: The literature review will be covered in the second section, research methodology, and air hub performance criteria. The third section will discuss the Comparison of the global air hubs based on the developed criteria, Airport size, and Constituents, passengers and cargo air traffic in the group of hubs, Geographical Flight Duration between the hubs. The statical outcomes will be covered in the fourth part. The research recommendations will be covered in the fifth part, and the last section is where the conclusion is.

This research problem identified in this paper and has addressed how an efficient hub airport with enough extra capacity will encourage airline competition and allow for new entries, routes, and frequencies. The best airport can be determined based on the volume of travelers as well as its excellence and accomplishment in facilities, operations, customer services, retail, community relations, and environmental awareness.

2 Literature Review

According to the findings of some studies, the significance of an airport within the air transportation network and the possibility that an airport may be skipped or bypassed when connecting travelers from an origin to a destination are related concepts that are both closely related to the measures of airport centrality. In their analysis of the global air transport networks during 12 years at the country level, Wandelt and Sun (2015) identified nations and flight connections that were topologically crucial in an unweighted network and functionally crucial in a weighted network. Recently, they analyzed the topological characteristics of eight domestic air transport networks during the same 12-year period with differences in passenger flow [5]. They demonstrated that the majority of networks displayed distinct seasonal traffic patterns and that there was a 95% similarity between two consecutive months for all networks. To study the route evolution of the Chinese air transport network in response to deregulation, competition, and airline reorganization over 18 years, Wang et al. (2016) employed market competition and concentration indexes. In addition, Allroggen et al. (2015) evaluated the link quality and hub centrality at airports around the world in terms of frequency, directness, and market accessibility after proposing an air connectivity index. The effect of network changes on an air port's ability to be globally connected was assessed at the route level and was restricted to direct or one-stop connections. Although these studies used a variety

of centrality indicators and network metrics as proxies for various characteristics of air transport networks, they largely ignored the question of whether those measurements could reflect the connection exemplified by the passenger flows and (ii) explain how an airport's connectedness has grown or shrunk over time [3].

Different approaches could be used to evaluate hub connectivity and its strategic importance to network performance. In most cases, it alludes to the quantity and quality of suitable indirect connections made available through the evaluated airline hub. Airline management can improve airline hub connections without adding more flights by coordinating flight schedules. The amount that hub schedule coordination adds to hub connectivity may therefore be determined quantitatively. It offers insight into the range of connecting options that are accessible to passengers as well as the competitive position or connectivity premium of an airport or airline [7].

2.1 Research Methodology

The study uses a descriptive-analytical research methodology with a quantitative approach, by gathering numerical information about the size of the airport hub, number of passengers, number of cargo and the geographical distance between the main international transit hubs for the group hubs in the study which are (Hong Kong, Frankfurt, Addis Ababa, Cairo and Dubai). And it is also based on earlier analyses, studies, publications, and reports on the topic.

3 World Air Hub Comparison Based on Airport Size and Constituents

3.1 Hong Kong Airport (HKIA Airport) – Asia

HKIA opened on 6th July 1998, now it is connected to 220 destinations worldwide and operated by over 120 airlines, over 78,000 staff work at HKIA, 71.5 million passengers handled in 2019, and 4.8 million tons of cargo and airmail moved in the same year. The Total airport size area equals 1,255 hectares which is equal to 12.55 km^2 with a floor area of approximately 730,000 m^2.

3.2 Frankfurt Airport (Fraport Airport) – Europe

One of the most significant hubs in the global logistics system is Frankfurt Airport, which is centrally placed in Europe. It is connected to 306 destinations worldwide. Frankfurt is one of the top 10 airports in the world for airfreight and is the largest in Europe. With a total area of 1.49 km2, it includes the perishable center only in the cargo city North, which has 9,000 square meters of space for storing perishable goods, and the hub of the pharmaceutical industry with more than 7,000 sqm. In 2019, more than 182 million people traveled via airports where Fraport has at least a 50% interest.

3.3 Addis Ababa Airport (ADD Airport) – Africa

For the past 44 years, Addis Ababa Airport has functioned as the country's main international entry point. There are roughly 13,942 employees at Addis Ababa Airport. It covers an area of some 35 km square and the size of the freight terminal is 14,000 m^2. ADD welcomed more than 12 million passengers to be ranked number 3rd continentally for Africa in 2019, and was ranked fourth in Africa in 2016 after handling 211,543 metric tons of goods.

3.4 Cairo Airport (CAI Airport) – Africa

Cairo International Airport ranked second busiest airport in the continent after Johannesburg International airport in South Africa. it covers an area of some 37 km square. And the cargo terminal only sizes 55,000 m square. CAI welcomed more than 17 million passengers in 2018 and handled 313,561 metric tons of goods in 2016 to be ranked number one in Africa. Cairo Airport employs approximately 9,000 employees. It is connected to 73 destinations worldwide.

3.5 Dubai Airport (DAX Airport) – Middle East

In 2019, DXB provided 86.4 million passengers with connections to more than 240 locations on six continents, 95 countries, and more than 100 airlines. Dubai International airport is 29.1 km^2 and although the cargo port is only 35,000 square meters in size, it can handle 3.1 million tons of cargo yearly, placing it among the top 10 cargo hubs worldwide in terms of international freight flow.

4 Passengers and Cargo Air Traffic in the Group of Hubs

Figure 1 finalized civil international air traffic passengers' statistics for the group of hubs for the past 10 years.

Passengers' traffic in Dubai airport reached 2018 to 89 million passengers, Hong Kong reached 74 million then Frankfurt airport 70 million, and boing down to Africa, Cairo reached 18 million, and Addis Ababa 12 million. Different targets and strategies can vary by billions to the economics of their own countries.

Figure 2 finalized cargo international air traffic statistics for the group of hubs for the past 10 years.

In terms of passenger numbers, there is a significant difference across the five air hubs, in 2018 Hong Kong airport transported the highest number among the five hubs with 5 million tons while in 2017 Dubai airport transported 2.6 million tons, Frankfurt 2.2 million tons going to Africa with the lowest number of cargos between the targeted hubs with 431 thousand tons by Addis Ababa and 362 thousand tons by Cairo airport even if they are the highest number between the African countries.

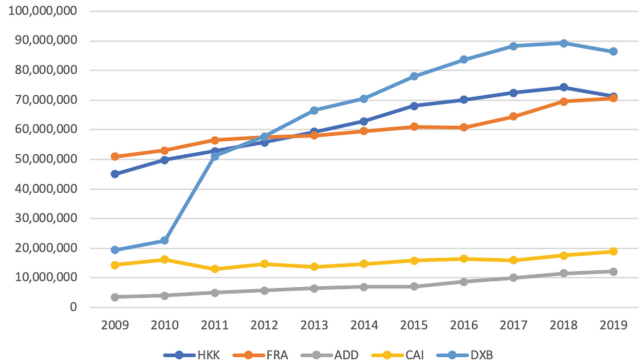


Fig. 1. Passengers' air traffic.

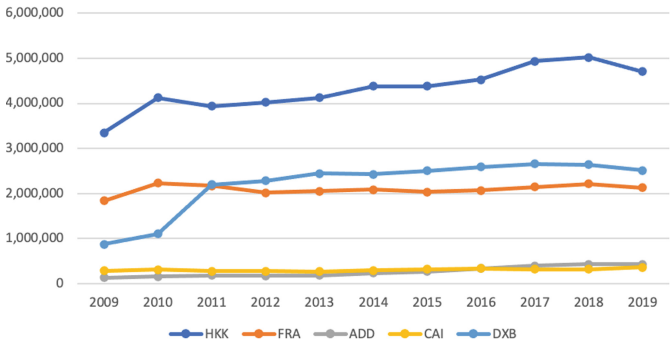


Fig. 2. Cargo air traffic.

5 Geographical Flight Duration Between the Hubs

Numerous spatial factors, the most significant of which is location, affect people's mobility. Because the significance of a place is more heavily influenced by the function of human variables in that place, the idea of strategic location is not always a perfect explanation for development [1].

Geographically speaking, the airport is well-positioned to develop into a hub. Given its geographic location, it is well suited to serve numerous airlines that require technical stops or transit. The length of long-haul flights increases as aircraft performance increases over time, and the likelihood of operating long-haul direct flights also increases [2]. From Table 1 we can find the importance of the geographical airports when the investments of any international company can put in mind, Addis Ababa is the farthest country from the busiest hub in the world, it has the advantage of having the youngest fleet and a lot of destination comparing to other airlines in the same region, but for air transport goods, it will not be the best destination to take as a hub, because most of the cargo transported by air is high value or perishables which need very fast transportation.

Table 1. Flight duration to the world's busiest airport in a different region.

	Tokyo Haneda	London Heathrow	Doha	Atlanta	Sydney	Johannesburg	*Total hours*	*Average hours*
HKG	4.40 h	12.55 h	8.55 h	20.13 h	9.05 h	12.55 h	*68.43*	*11.405*
FRA	13.32 h	1.25 h	5.50 h	10.20 h	21.55 h	10.25 h	*63.27*	*10.545*
Addis Ababa	15.36 h	7.40 h	4.20 h	18.32 h	20.35 h	5.25 h	*72.08*	*12.013*
CAI	14.6 h	5.10 h	3.05 h	15.20 h	18.10 h	8.10 h	*64.1*	*10.668*
Dubai	9.55 h	7.50 h	1.10 h	18.25 h	13.50 h	8.15 h	*59.15*	*9.858*

Cairo Airport and Frankfurt airport are approximately the same summations of time, but there is a huge difference in the facilities and technology that the Frankfurt hub has. From the time value, they are equal but for the quality value, they are not, that's why the study is focusing on the different hubs in a different region with the same capabilities so it can give the society of Air transport what they deserve. While Hong Kong hub is moderate in distance, it's not the shortest but also not the longest. Dubai Airport, a commercial city with a focus on international air travel, has strived to be the world's preferred air travel hub while having the shortest summations of time.

6 Statistical Results

Science's field of statistics deals with gathering, organizing, analyzing, and extrapolating data from samples to the entire population. Additionally, statistical tests are used to determine whether a distributional hypothesis about one or more populations or samples should be accepted or rejected. The parametric test, a type of statistical test that makes assumptions about the distribution of the variables (the unknown parameter of interest) and the estimation of the parameter, is one of the tests that the study used. It has the advantage of being precise in its assumptions, which enables it to draw more accurate conclusions and perform tests for misspecification. The statistical tests known as parametric tests, among other presumptions, assume that the data roughly follow a normal distribution (examples include z-test, t-test, and ANOVA). The z-test and the t-test are the appropriate tests to use when comparing the means of two groups. While ANOVA is a statistical method for comparing the means of an outcome variable of interest across two or more groups, it also allows for the simultaneous testing of several null hypotheses.

6.1 One-Way ANOVA Test for Number of Passengers

It is clear from the results of Table 2 that there are statistically significant differences according to the airport Group at a confidence level of 99%, where the significance of the test has a value of 0.000 which is less than 0.01 for No of passengers, this difference is in favor of the Dubai airport with mean 64,823,536.9, then Hong Kong airport with mean 61,966,636.9, then Frankfurt airport with mean 60,177,309.5, then Cairo airport and Addis Ababa Airport with mean 15,592,799.6 and 7,110,253.1 respectively.

Table 2. One Way ANOVA Test for Number of passengers according to airport.

	N	*Mean*	*Std. Deviation*	*F Test*	*P_value*
Hong Kong airport	11	61,966,636.9	10,116,866.9	55.962**	0.000
Frankfurt airport	11	60,177,309.5	6,143,499.2		
Addis Ababa airport	11	7,110,253.1	2,878,714.2		
Cairo Airport	11	15,592,799.6	1,710,742.3		
Dubai Airport	11	64,823,536.9	25,024,827.8		

** Significant at 1% level.

6.2 One-Way ANOVA Test for Number of Cargo

It is clear from the results of Table 3 that there are statistically significant differences according to the airport Group at a confidence level of 99%, where the significance of the test has a value of 0.000 which is less than 0.01 for No of Cargo, this difference is in favor of the Hong Kong airport with mean 4,318,390.4, then Dubai airport with mean 2,202,478.4, then Frankfurt airport with mean 2,088,581.8, then Cairo airport and Addis Ababa Airport with mean 307,268.4 and 267,429.5 respectively.

Table 3. One Way ANOVA Test for Number of Cargo according to airport.

	N	*Mean*	*Std. Deviation*	*F Test*	*P_value*
Hong Kong airport	11	4,318,390.4	481,197.8	239.708**	0.000
Frankfurt airport	11	2,088,581.8	109,791.0		
Addis Ababa airport	11	267,429.5	113,928.3		
Cairo Airport	11	307,268.4	28,995.5		
Dubai Airport	11	2,202,478.4	618,547.0		

** Significant at 1% level.

6.3 One-Way ANOVA Test for Number of the Total Revenue

It is clear from the results of Table 4 that there are statistically significant differences according to the airport Group at a confidence level of 99%, where the significance of the test has a value of 0.000 which is less than 0.01 for the Total revenue, this difference is in favor of the Dubai airport with mean 22,991.61, then Frankfurt airport with mean 2,831.20, then Hong Kong airport with mean 1,988.08, then Addis Ababa airport and Cairo Airport with mean 0.176 and 0.001 respectively.

Table 4. One Way ANOVA Test for total revenue to the airport.

	N	*Mean*	*Std. Deviation*	*F Test*	*P_value*
Hong Kong airport	11	1,988.082	514.117	151.294**	0.000
Frankfurt airport	11	2,831.209	563.061		
Addis Ababa airport	11	0.176	0.081		
Cairo Airport	11	0.001	0.001		
Dubai Airport	11	22,991.615	5,872.780		

** Significant at 1% level.

6.4 Correlation Between the Number of Passengers, Number of Cargo, and the Total Revenue for the Airport's Group

Table 5 shows that there is a significant correlation between the Number of passengers and the Number of Cargo at a level of confidence of 99%, the correlation is a positive value of 0.824 and is very strong, also there is a significant correlation between Number of passengers and Total revenue at the level of confidence of 99%, the correlation is a positive value with 0.594 and moderate. Also, there is no significant correlation between the Number of Cargo and Total revenue because the significantly greater than the 0.05 level.

Table 5. The correlation matrix between the Number of passengers, Cargo, and Total revenue.

	Number of passengers	Number of Cargo	Total revenue
No of passengers	1	.824**	.594**
No of Cargo	.824**	1	0.247
Total revenue	.594**	0.247	1
**. Correlation is significant at the 0.01 level (2-tailed)			

** Correlation is significant at a 1% level.

7 Research Recommendations

1. Based on the existing cargo alliances, which are primarily developed from existing passenger alliances such as Sky Team Cargo from Sky and WOW from Star Alliance members and the number of destinations that can be reached, a cargo alliance to/from Africa that unites airways from different contents needs to be established.
2. In air transport, the infrastructure needs special qualities to minimize the logistics chains' need to be restructured to serve the quickly expanding e-commerce market and present a new opportunity for growth.

3. Business executives or policymakers can utilize the study's findings to pinpoint the key areas for competition and collaboration. For instance, the data may give a clearer understanding of the locations and airport specifications required to entice airlines to operate new international routes.
4. However, if developed nations like Germany or China came and invested in the developed country, it would have a significant impact and fall under their control.
5. Establishing a logistical system for the whole marketing chain, from the farm to the final destination.

8 Conclusion

A crucial component of global supply chains is now air freight. Air cargo has become an essential part of global supply chains and is anticipated to continue expanding due to factors such as the tightening of product life cycles, the drop in inventory levels, and the increasing competition between airlines and airports. The demand for the benefits that air freight offers, such as speed and dependability, has intensified airline competitiveness. While the competition for airport hubs is influenced by a variety of elements, including infrastructure, airport growth, size, customer service needs, technology for security checks, and the number of destinations that the local airline business can offer. The expansion of markets and just-in-time and e-commerce are only a few of the ways that new industrial organizational principles have made air cargo a valuable asset for global trade. Future development in air cargo transportation will face significant capacity issues at major airports, particularly in Africa, and in making the best use of the available land. In the coming decades, a several of factors will give African nations the chance to reverse the trend. Africa has an enormous untapped human potential that must be utilized for the benefit of aviation generally and the economic prosperity of African nations specifically. African nations will have the chance to change the course of history due to several causes over the coming decades.

Therefore, to create a successful hub, airport operators must be adept at planning their business operations 10 to 20 years in advance. Facilities are also one of the services provided by the airport and have developed into a differentiator among rival airports. Facility optimization includes reducing expenses, turnaround times for airlines, and processing times for freight and passengers. This could help the airport hub run more efficiently and provide higher-quality passenger experiences. One of the most important factors is how well a hub supports passenger and freight operations, especially early morning long-haul arrivals and nighttime freighter services.

The study created and developed the criteria that must be checked before investing in any air hub, and from the framework, it can evaluate SWOT analysis easily to ensure the increase of the economic return. The study compared the five main hubs (Hong Kong, Frankfurt, Addis Ababa, Cairo, and Dubai airports).

References

1. Al-Mehairi, J.M.: Dubai's geographic location and its advantages for the air transportation industry. Arab World Geogr. **19**(3–4), 352–367 (2016)
2. Bardai, A.M., et al.: A review of Kuala Lumpur International Airport (KLIA) as a competitive South-East Asia hub. IOP Conf. Series: Mater. Sci. Eng. **270**(1) (2017). https://doi.org/10.1088/1757-899X/270/1/012039
3. Cheung, T. K. Y., Wong, C. W. H., Zhang, A.: The evolution of aviation network: Global airport connectivity index 2006–2016. Transportation Research Part E: Logistics and Transportation Review, 133 (January 2019), 101826. (2020). https://doi.org/10.1016/j.tre.2019.101826
4. Chung, T.W., Lee, Y.J., Jang, H.M.: A Comparative analysis of three major transfer airports in Northeast Asia focusing on Incheon international airport using a conjoint analysis. Asian J. Shipping Logistics **33**(4), 237–244 (2017). https://doi.org/10.1016/j.ajsl.2017.12.007
5. Malighetti, P., Martini, G., Redondi, R., Scotti, D.: Integrators' air transport networks in Europe. Netw. Spat. Econ. **19**(2), 557–581 (2018). https://doi.org/10.1007/s11067-018-9390-5
6. Paraschi, E.P., Georgopoulos, A., Papatheodorou, A.: Abiotic determinants of airport performance: insights from a global survey. Transport Policy, 85(August 2018), 33–53. (2020). https://doi.org/10.1016/j.tranpol.2019.10.017
7. Yang, H., Liu, W.: Dual-hub connectivity: a case study on China Eastern Airlines in Shanghai. European Transport Research Review, 11(1) (2019). https://doi.org/10.1186/s12544-019-0364-
8. Yuan, X.-M., Low, J.M.W., Tang, L.C.: Roles of the airport and logistics services on the economic outcomes of an air cargo supply chain. Int. J. Prod. Econ. **127**, 215–225 (2010)

Assessment of the Link Between the Integration of Technological Development of a Transport Company and Marketing in the Supply Chain

Kristina Vaičiūtė(✉), Ernestas Vaičius, Liudmila Burinskienė, and Darius Bazaras

Vilniaus Gediminas Technical University, Saulėtekio Ave. 11, 10223 Vilnius, Lithuania
{kristina.vaiciute,liudmila.burinskiene,
darius.bazaras}@vilniustech.lt

Abstract. The following article examines the problem of technological development of transport companies and how it is connected with marketing in supply chain management and the use of technological development as one of the tools to ensure the competitiveness of transport companies. Modern supply chains of transport companies receive an enormous flow of information, consequently, their management and marketing applications cannot be completed without the availability and use of information technologies and telecommunications. Based on the analysis of literature sources, an expert assessment questionnaire was formed and prepared with the concepts of actions and explanations, as well as a compilation of possible expert interviewees. During the structural analysis of the technological development of the companies, the components of the technological development process of the transport company in the supply chain and the determining factors that influence the technological development of the transport company in marketing in the supply chain are identified. In addition, an expert assessment questionnaire is made according to the selected quality criteria. After processing the data of the expert survey, the criteria are arranged and the research results are presented. Conclusions and suggestions are presented at the end of the article.

Keywords: Supply chain · Transport · Development · Technological · Marketing · Multi-criteria evaluation

1 Introduction

In the modern world, transport companies (in the text TC) have to implement any measures to survive competition's under market of the transport conditions. Such measures can range from: The expansion of supply chain (in the text SCh) technology and the application of marketing, which allows for better communication between SCh participants, to reducing costs and solving inventory problems, and remaining a competitive participant in that SCh. Therefore, such integration enables the TC in the SCh to manage cost factors and quality assurance of the service performed. The integration of new technologies provides an opportunity to purchase products and services provided in the SCh at competitive prices. The expansion of new technologies in the SCh paves the road for

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 655–663, 2023.
https://doi.org/10.1007/978-3-031-25863-3_63

the new production and cheaper goods and the accumulation of capital consequently; it allows the greater international competitiveness of individual countries in the SCh itself [1].

The transportation company's SCh management focus began when transportation companies began to improve inventory management, production planning, and control. The objective of SCh management was to improve production efficiency and ensure that capital assets and technological capabilities are used effectively, including the smooth flow of information through SCh technologies that are linked and accessible to suppliers and customers [2, 3]. As highlighted by Pero and Lamberti [4]. In the early stages of a transport company's new service development, SCh management and marketing are isolated from each other, and when there is a need to win back customers or a desire to overcome market competitiveness problems, marketing is combined with supply chain management. At that time, a strong interdependence occurs, as SCh management and marketing constantly exchange information, participate in management decisions and develop joint plans. Williams and Moore [5] defined information circulating in the SCh as information consisting of previously or currently collected data about a specific partner company. Technological developments (in the text TD) allow marketing to obtain information about the purchasing history and demographics of an individual partner company in the SCh or the financial situation of the company. Meaning that in SCh management, TC focus on their core competencies, but also have relationships with other supplier organizations that are involved in that supply chain. Therefore, the act of outsourcing involves the TC in cooperation with other organizations and various information will be exchanged for marketing. The possibility of the TD processes of TC is related to the supply chain participants' ability to obtain specific information through the equipment [6]. When integrating marketing into the SCh, it is necessary to implement the main measures: the possibilities of applying marketing through technology and managing the costs of providing quality services [6, 7]. Even when a transport company's supply chain is dominated by a product-based strategy, the opportunity to increase the profit of the TC becomes shorter and harder to achieve. Therefore, a minor disruption in the availability of a product or service has a significant impact on the financial return of the TC. As a result, the supply chain has become a crucial tool, and to be able to participate in it, you need to have the latest technologies, which provokes TC to expand and, at the same time, invest in technological capabilities [2]. Alvarado and Kotzab [8], define SCh management as the integration of business processes among channel members to achieve better performance of the entire channel system. Parente, et al. and Herrmann, et al. [9, 10] discussed that from a marketing point of view, supply chain management means managing internal and external customer relationships, which provokes connections between supply chain and marketing activities. A balance between client requirements and SCh capabilities needs to be made between TC supply chain participants, which also requires investment in the transport company's TD. When marketing activities limit the ability of a transportation company's SCh to meet demand, the company incurs additional costs. Planning for transportation company supply chain management should take into account all related management costs, and marketing initiatives should be evaluated, including recognition of these costs throughout the transportation company' SCh, related to the timing of marketing activities, taking into account the impact on the SCh and the overall

profitability of the initiative [11, 12]. Therefore, the TD and the creation or implementation of an interactive delivery system among all participants in the supply chain contribute significantly to increasing Market Responsiveness. Customer expectations (i.e., know-what) can be met by sharing the necessary knowledge about client requirements among all actors in the SCh, which in turn promotes firms' dynamic capabilities and responsiveness (i.e., know-how) to these expectations. Not all members of the supply chain monitor and implement marketing activities and customer requirements for the supply chain or ongoing information disruptions. TC can strategically exploit the implications of supply chain management to achieve the competitive advantage needed to meet client needs and the needs of the transportation market. In addition, TC should also pursue their goals by taking into account the goals of their customers [13]. Kumar et al. [14] recommend that future researchers re-examine supplier, customer, and internal integration. Integration and collaboration using innovative technologies with other companies, especially in the supply chain, can be explored in various forms. Thus, in summary, it can be stated that the main criteria for the study of the components of the TD and marketing interface of the TC in the SCh are: database design in the supply chain; modelling of data about companies involved in the supply chain; entering and updating data of cooperating companies in the supply chain; adaptation of communication networks to access databases; entering and updating marketing data in the supply chain of companies; realization of various other functions.

The object of this study is the link between the TD of TC and the integration of marketing in the SCh. Investigating the impact of marketing on the components of TD on the quality assurance of services provided by the TC in the supply chain. The authors applied research methodologies: analysis of scientific literature, grouping, and ranking of indicators.

2 Research Methodology

Quantitative research and a questionnaire survey method proposed by researchers [1, 9] were chosen to evaluate the interaction of the transport company's TD integration with marketing in the SCh. Based on the literature analysis, an expert assessment questionnaire was prepared with the concepts of factors – explanations and a list of experts to be interviewed was compiled. One of the most significant characteristics of experts is competence; naturally, the experts were required to have competence and experience in the field under investigation. When creating the questionnaires, attention was paid to the formulation of the questions. Questions are formulated clearly, and ambiguity is avoided when it is not clear exactly what is being asked.

After the survey of experts, the received data is processed. Processing is necessary to received summarized data. Experts' evaluations are obtained from completed questionnaires and entered into a table if the number of experts is greater than two and W the concordance coefficient shows the level of compatibility of the group of experts.

A panel of experts n appreciates m factors. Assessments form a matrix [15].

The rank sums of the average is calculated (1) [16]:

$$\sum\nolimits_{i=1}^{n} R_{ij} = \frac{1}{2} n(m+1). \tag{1}$$

where n – the expert group n quantifies objects; m – is the number of benchmarks.

The expert assessments can be considered coordinated and the significance of the concordance coefficient W (2) can be determined using the Pearson criterion:

$$W = \frac{12S}{n^2 m\left(m^2 - 1\right)} = \frac{12S}{n^2\left(m^3 - m\right)}. \tag{2}$$

where S- variance.

3 Results of the Research

In this current study were interviewed 8 experts the experience no less 3 years of decision makers of logistics. Experts agreed (86.5%) that marketing for TC influences TD in the supply chain.

The experts evaluated the marketing determining factors in the transport company's TD supply chain:

a) for cost management;
b) to ensure the quality of transportation services;
c) for increasing international competitiveness;
d) for the transmission of marketing information;
e) for the transmission of information flow about the product;
f) for the transfer of information flow about the client/partner;
g) information on customer preferences for transfers.

Distribution of the expert's important indicators according to the above criteria (a–g) is shown in Fig. 1.

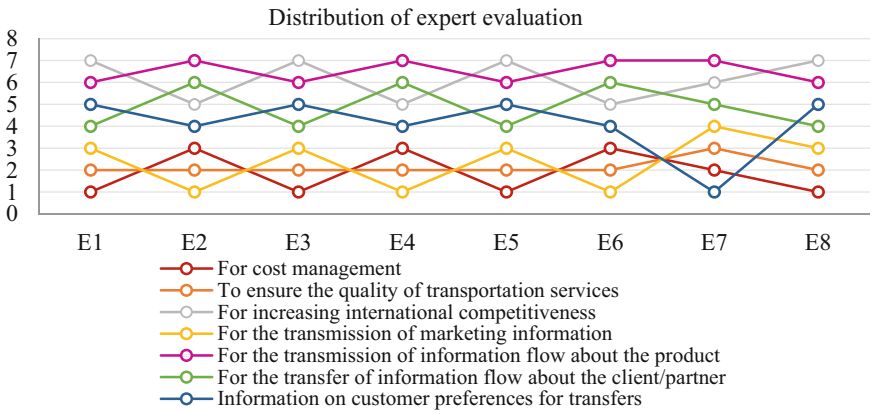


Fig. 1. Distribution of Ranks of Factors (prepared by the Authors).

The indicators of the experts of the ranking calculation is presented in Table 1.

Table 1. The ranking of the indicators determining marketing in the transport company's TD SCh (prepared by the Authors).

Formulas	The symbol for factors designation ($m = 7$)						
	(a)	(b)	(c)	(d)	(e)	(f)	(g)
$\sum_{i=1}^{n} R_{ij}$	15	17	49	19	52	39	33
$\overline{R}_j = \frac{\sum_{i=1}^{n} R_{ij}}{n}$	1.875	2.125	6.125	2.375	6.5	4.875	4.125
$\sum_{i=1}^{n} R_{ij} - \frac{1}{2}n(m+1)$	–17	–15	17	–13	20	7	1
$\left[\sum_{i=1}^{n} R_{ij} - \frac{1}{2}n(m+1)\right]^2$	289	225	289	169	400	49	1

The W was calculated according to Eq. (3) when there are no associated ranks.

$$W = \frac{12S}{n^2\left(m^3 - m\right)} = \frac{12 \times 1422}{8^2\left(7^3 - 7\right)} = 0.7935. \tag{3}$$

The impact of TD is important indicators determining marketing in the transport company's TD supply chain is 7. According to Eq. (4) is calculated the Pearson criterion χ^2 (when m > 7).

$$\chi^2 = n(m-1)W = \frac{12S}{nm(m+1)} = \frac{12 \times 1422}{8 \times 7(7+1)} = 38.089. \tag{4}$$

The opinion of the experts is considered to compatible in that χ^2 calculated and $\chi^2 = 38.089 > 12.5916$, and the average ranks show the general opinion of the experts:

$$W_{\min} = \frac{\chi^2_{v,\alpha}}{n(m-1)} = \frac{12.5916}{8(7-1)} = 0.2623 < 0.7935. \tag{5}$$

After calculating the concordance coefficient $W_{\min} < 0.7935$ (5), the experts' opinions about the determining marketings criteria of the transport company's TD in the SCh are still considered harmonized.

The indicators of the factors determining main marketing's criteria the transport company's TD in the supply chain Q_j. Are presented in Table 2.

According to expert assessments and calculations, the rankings of the importance of the factors determining marketing in the transport company's TD supply chain are:

- for cost management;
- to ensure the quality of transportation services;
- for the transmission of marketing information;
- information on customer preferences for transfers;
- for the transfer of information flow about the client/partner.

The experts evaluated the main aspects of the transport company's integration of TD with marketing:

Table 2. The indicators of the importance of the factors determining main marketing's criteria determining the transport company's TD in the SCh $Q_{j.}$ (prepared by the Authors).

Indicator marker	The symbol for factors designation ($m = 7$)							Sum
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	
dj	0.933	0.924	0.7813	0.9152	0.768	0.826	0.853	6
qj	0.067	0.076	0.2188	0.0848	0.232	0.174	0.147	1
Q_j	0.156	0.154	0.1302	0.1525	0.128	0.138	0.142	1
$Q_{j'}$	0.219	0.210	0.0670	0.2009	0.054	0.112	0.138	1
Layout	1	2	6	3	7	5	4	

a) information exchange is necessary for supply chain management;
b) for collecting customer requirements and information;
c) for identifying supply chain opportunities;
d) examining the impact on the SCh and the overall profitability of the initiative;
e) to collect information about customers;
f) for modelling companies involved in the supply chain;
g) for data entry and management of cooperating companies in the supply chain.

The distribution of the components of the TC integration of TD with marketing according to the above-mentioned criteria (a–g) was evaluated by experts from 1 to 7: 1 – most important, 7 – not important is shown in Fig. 2.

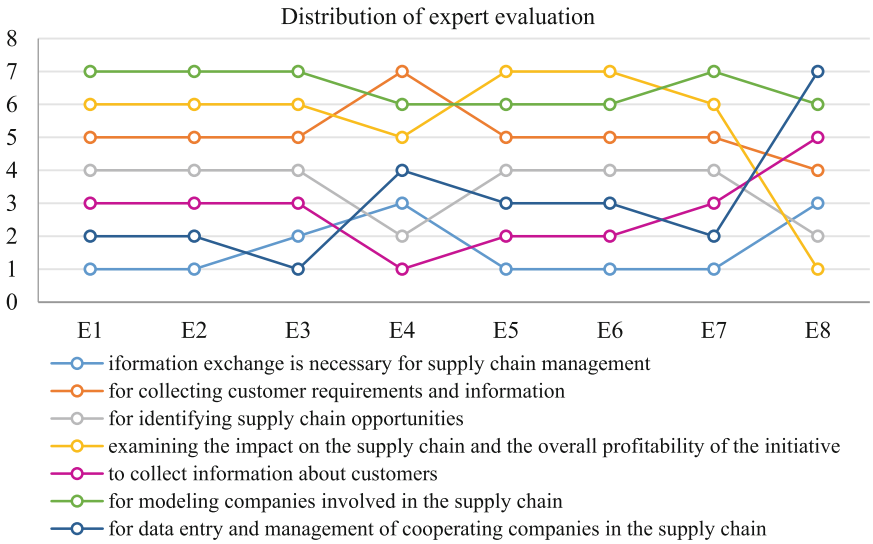


Fig. 2. Distribution of transport company's marketings integration of TD ranks according to experts (prepared by the Authors).

The ranking of the data of the calculation expert indicators is presented in Table 3.

Table 3. Ranking of the main factors of TC integration of TD with marketing (prepared by the Authors).

Formulas	The symbol for factors designation ($m = 7$)						
	(a)	(b)	(c)	(d)	(e)	(f)	(g)
$\sum_{i=1}^{n} R_{ij}$	13	41	28	44	22	52	24
$\overline{R}_j = \frac{\sum_{i=1}^{n} R_{ij}}{n}$	1.625	5.125	3.5	5.5	2.75	6.5	3
$\sum_{i=1}^{n} R_{ij} - \frac{1}{2}n(m+1)$	–19	9	–4	12	–10	20	–8
$\left[\sum_{i=1}^{n} R_{ij} - \frac{1}{2}n(m+1)\right]^2$	361	81	16	144	100	400	64

W (the concordance coefficient) was calculated according to Eq. (6) when there are no associated ranks.

$$W = \frac{12S}{n^2\left(m^3 - m\right)} = \frac{12 \times 1166}{8^2\left(7^3 - 7\right)} = 0.65067 \tag{6}$$

According to Eq. (7) is calculated the Pearson criterion χ^2 (when m > 7).

$$\chi^2 = n(m-1)W = \frac{12S}{nm(m+1)} = \frac{12 \times 1166}{8 \times 7(7+1)} = 31.231 \tag{7}$$

The Pearson criterion χ^2 31.231 > 12.5916 therefore the opinion of the experts is considered to be harmonized.

$$W_{\min} = \frac{\chi^2_{v,\alpha}}{n(m-1)} = \frac{12.5916}{8(7-1)} = 0.2623 < 0.6506 \tag{8}$$

The lowest value $W_{\min}$ less than the concordance coefficient W (0.2623 < 0.6506). Consequently, the views of all respondents on the 7 key criterias to the above are still harmonized.

The calculated factors Q_j of TD integration of the transport company with marketing are presented in Table 4.

The expert assessments and calculations, the order of the main factors TC integration of TD with marketing is as follows:

- information exchange is necessary for supply chain management;
- to collect information about customers;
- for data entry and management of cooperating companies in the supply chain;
- for identifying supply chain opportunities;
- for collecting customer requirements and information.

The results of the analysis study revealed that the links between the integration of TD of TC with marketing in the supply chain are related to the provision of information to improve service quality and increase competitiveness.

Table 4. The indicators of the important components of a transport company's integration of technological development with marketing (prepared by the Authors).

Marker	The symbol for factors designation ($m = 7$)							Sum
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	
q_j	0.058	0.183	0.125	0.1964	0.098	0.232	0.107	1
d_j	0.942	0.817	0.875	0.8036	0.902	0.768	0.893	6
Q_j	0.157	0.136	0.146	0.1339	0.150	0.128	0.149	1
Q_j'	0.228	0.103	0.161	0.0893	0.188	0.054	0.179	1
Factors rank of importance	1	5	4	6	2	7	3	

4 Conclusions

After processing the results of the survey, it was found that marketing for TC influences TD in the supply chain (86.5%).

The research revealed that the order of importance of the factors determining the efficiency of TD of TC with marketing in the supply chain is: 1) Information exchange is necessary for supply chain management; 2) to collect information about customers; 3) for data entry and management of cooperating companies in the supply chain; 4) for identifying supply chain opportunities; 5) for collecting customer requirements and information.

It was stated that the order of the indicators of the factors determining main marketing's criteria determining the transport company's TD in the supply chain in terms of importance is as follows: 1) for cost management; 2) to ensure the quality of transportation services; 3) for the transmission of marketing information; 4) information on customer preferences for transfers; 5) for the transfer of information flow about the client/partner.

In summary, it can be said that marketing and technological changes are mostly connected through the organization and exchange of information flows. This can be linked to the assumption that marketing usually carries a certain informational load to the user, which directly participates in the formation of the user's need, supports and modifies this need taking into account market changes and the opportunities of market participants.

References

1. Çalışkan, H.: Technological change and economic growth. Procedia Soc. Behav. Sci. **195**, 649–654 (2015). https://doi.org/10.1016/j.sbspro.2015.06.174
2. Stevens, G.C., Johnson, M.: Integrating the Supply Chain … 25 years on. Int. J. Phys. Distrib. Logist. Manage. **46**(1), 19–42 (2016). https://doi.org/10.1108/IJPDLM-07-2015-0175
3. Skačkauskienė, I., Vilkaitė-Vaitonė, N.: Žaliasis marketingas Lietuvoje: kritinis vertinimas ir plėtros galimybės. Mokslo studija. Vilnius (2022)

4. Pero, M., Lamberti, L.: The supply chain management-marketing interface in product development: an exploratory study. Bus. Process. Manag. J. **19**(2), 217–244 (2013). https://doi.org/10.1108/14637151311308295
5. Williams, Z., Moore, R.: Supply chain relationships and information capabilities: the creation and use of information power. Int. J. Phys. Distrib. Logist. Manage. **37**(6), 469–483. (2007). 10. 1108
6. Lovelace, R., Parkin, J., Cohen, T.: Open access transport models: a leverage point in sustainable transport planning. Transp. Policy **97**, 47–54 (2020). https://doi.org/10.1016/j.tranpol.2020.06.015
7. Ma, P., Wang, H., Shang, J:. Supply chain channel strategies with quality and marketing effort-dependent demand. Int. J. Prod. Econ. **144**(2), 572–581 (2013). https://doi.org/10.1016/j.ijpe.2013.04.020
8. Paužuolienė, J., Kaveckė, I.: Žaliosios logistikos taikymo svarba: vartotojų nuomonės tyrimas. Regional Formation Dev. Stud. **36**(1), 61–68 (2022). https://doi.org/10.15181/rfds.v36i1.2388
9. Alvarado, U.Y., Kotzab, H.: Supply chain management: the integration of logistics in marketing. Ind. Mark. Manage. **30**(2), 183–198 (2001). https://doi.org/10.1016/S0019-8501(00)00142-5
10. Parente, D.H., Lee, P.D., Ishman, M.D., Roth, A.V.: Marketing and supply chain management: a collaborative research agenda. J. Bus. Ind. Mark. **23**(8), 520–528 (2008). https://doi.org/10.1108/08858620810913335
11. Herrmann, F.F., Barbosa-Povoa, A.P., Butturi, M.A., Marinelli, S., Sellitto, M.A.: Green supply chain management: conceptual framework and models for analysis. Sustainability **13**, 8127 (2021). https://doi.org/10.3390/su13158127
12. Vokurka, R.J., Lummus, R.R.: Balancing Marketing and Supply Chain Activities. J. Mark. Theory Practice **6**(4), 41–50. (1998). https://www.jstor.org/stable/40469935
13. Jefimovaitė, L., Vienažindienė, M.: Žaliosios logistikos principų įgyvendinimo modeliavimas: teorinis aspektas. Viešasis saugumas ir viešoji tvarka (26) (2021)
14. Aljanabi, A.R.A., Ghafour, K.M.: Supply chain management and market responsiveness: a simulation study. J. Bus. Ind. Mark. **36**(1), 150–163 (2021). https://doi-org.nlhhg.idm.oclc.org/
15. Kumar, V., Jabarzadeh, Y., Jeihouni, P., Garza-Reyes, J.A.: Learning orientation and innovation performance: the mediating role of operations strategy and supply chain integration. Supply Chain Manage. **25**(4), 457–474 (2020). doi:https://doi.org/10.1108/SCM-05-2019-0209
16. Kardelis, K.: Mokslinių tyrimų metodologija ir metodai [Research methodology and methods]. Vilnius: Mokslo ir enciklopedijų leidybos centras [Science and Encyclopedia Publishing Center] (2016)
17. Tidikis, R.: Socialinių mokslų tyrimų metodologija. Vilnius: Lietuvos Teisės Universitetas (2003). https://repository.mruni.eu/bitstream/handle/007/15459/Tidikis_tyrimu_metodologija.pdf?sequence=1&isAllowed=y
18. Sivilevičius, H.: Application of expert evaluation method to determine the importance of operating asphalt mixing plant quality criteria and rank correlation. Baltic J. Road Bridge Eng. **6**(1), 48–58 (2011). https://doi.org/10.3846/bjrbe.2011.07
19. Podvezko, V.: Agreement of expert estimates. Technol. Econ. Dev. Econ. **11**(2), 101–107 (2005). https://doi.org/10.1080/13928619.2005.9637688

Railway Transport

Identification and Classification of Soft Targets in Railway Infrastructure

Simona Slivkova[1](✉) and Lenka Michalcova[2]

[1] Faculty of Safety Engineering, VSB – Technical University of Ostrava, Lumirova 630/13, 700 30 Ostrava, Czech Republic
simona.slivkova@vsb.cz

[2] Faculty of Transportation Sciences, Czech Technical University in Prague, Konviktska 20, 110 00 Prague 1, Czech Republic
brehovska@fd.cvut.cz

Abstract. The protection of soft targets has recently come to the interest of a range of experts, government organizations, and companies. This is happening in relation to current developments in the security situation. Ensuring the protection of soft targets is the primary interest of all the entities involved. For establishing effective protection, it is, however, necessary to correctly recognize which element could be attacked i.e. which can be identified as a soft target. The basis for identifying a soft target is its definition, which is however not precisely defined and is perceived differently by different experts. In view of this fact, there is no specific process for identifying soft targets in railway infrastructure. At the same time, it is visible from history that railway transport becomes a target for terrorist attacks. This article, therefore, focuses on the possibility of identifying soft targets in railway infrastructure. The first part gives some results of analysis of possible approaches and criteria for identifying soft goals, focusing on the area of railway infrastructure. On the basis of the results of the analysis, criteria are subsequently determined and a process for identification of soft targets in railway infrastructure is proposed. This method allows assessors to gain the list of railway stations, which are classified into two categories of soft targets.

1 Introduction

Railway transport is a complex system, whose essence is the transport of people and freight using railway transport routes, railway transport resources, energy, and manpower on railway tracks [1]. Railway transport has become one of the most important ways of transporting people and freight by land. For instance, within NATO, railway transport forms one of the principal ways of transporting armed forces [2]. Since 2008 railway transport has also been classified as one of the sectors of critical European infrastructure [3]. Railway transport is also a necessary condition for increasing the competitiveness of a state [4].

The world security situation with regard to terrorism is constantly worsening and the number of violent attacks is increasing. The organizers of such attacks are increasingly motivated to aim them at unprotected places with high concentrations of people, regardless of whether they are politically or religiously symbolic [5].

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 667–676, 2023.
https://doi.org/10.1007/978-3-031-25863-3_64

As a result of their importance, transport systems often number among the targets of terrorist attacks, mainly due to their high impact on a social, economic, psychological, and political level [6, 7].

History has recorded for instance these attacks on transport systems [8]:

- Bologna, Italy, railway station, 1980, 85 killed, 200 injured.
- Madrid, Spain, train, 2004, 191 killed, 1800 injured.
- London, England, metro, 2005, 56 killed, 784 injured.
- Volgograd, Russia, train station, 2013, 23 killed, 72 injured.

An overview of historical instances of attacks on transport systems from 1970 to 2019 is presented in Fig. 1.

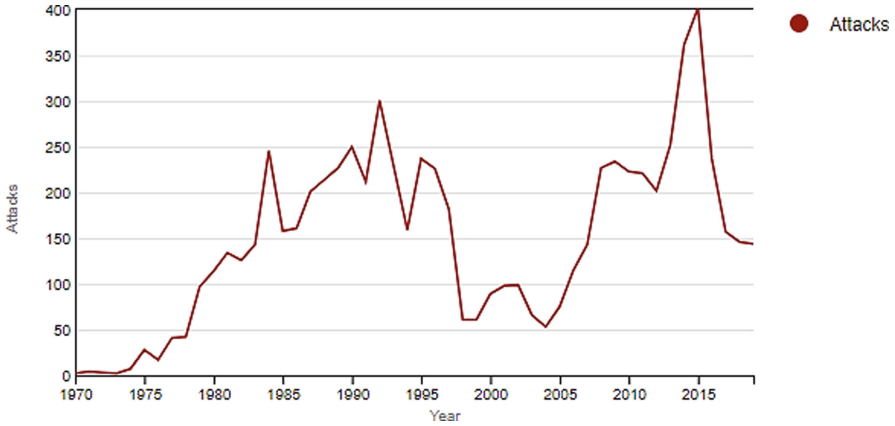


Fig. 1. Overview of attacks on transport systems in history [8].

For setting effective protection of soft targets it is necessary to correctly identify which elements can be regarded as soft targets. Currently, there are no comprehensive standards or binding regulations which define the criteria for determining soft targets, as exist for instance in the protection of critical infrastructure. It can be said that there are currently only recommended criteria, defined on a general level [9].

The basic parameters for identifying soft targets are primarily derived from the definition of a soft target. Available definitions describe soft targets as a place with high vulnerability, but a low level of protection. Such a general definition is however difficult to use in the process of identifying soft targets. In this respect, the following article focuses on more detailed possibilities for identification and subsequent classification of soft targets in railway infrastructure. A list of specific identified soft targets is not the aim of this article.

With regard to previous research [10, 11], railway stations are primarily regarded as soft targets in the area of railway infrastructure. However, as has already been mentioned, this list is very general. There is no existing approach that would more precisely specify which railway stations could be soft targets.

Therefore, the aim of this article is to present a method for identifying soft targets in railway infrastructure with the help of criteria that were established on the basis of an analysis of various approaches.

2 Identification of Soft Targets in Railway Infrastructure

The following text introduces some possible methods of identification and subsequently presents a suggested method and criteria for identifying soft targets.

2.1 Methodology

The following text presents an analysis of chosen methods and approaches which can be used for identifying soft targets. As part of the analysis, both general methods and methods prepared directly for the problems of soft targets were incorporated. The text below only presents the principal results of the analysis of suitable methods.

There currently exist many usable methods. Some methods are simple and quick, and some are very complicated as they are based on fuzzy logic, machine learning, or artificial intelligence. A basic overview of such methods can be found for instance in research by Lapkova, Kotek, and Kralik [12].

Amongst foreign approaches a lot of literature focused on the protection of soft targets can be found. The majority of this literature does not however deal more closely with how to identify or determine a soft target. As a rule, the sources use a general definition of a soft target.

This approach is for instance used by The EU's guidelines for security at major events [13]. According to this document, soft targets are not just places where large events potentially susceptible to threats are to be held. The guidance also identifies public places, fan zones, public vantage points, town squares, transport and evacuation routes, and means of public transport.

A similar list is offered for example in the document Soft targets and crowded places security plan overview [14]. Here soft targets are primarily crowded places, such as sports venues, shopping centers, schools, and transport systems, which are easily accessible to a large number of people and have limited security or protective measures, which makes them vulnerable to attack.

A range of documents can be found which provide a more detailed approach to the identification, and also individual criteria for identifying soft targets.

One of the better-known approaches to identifying soft targets is the CARVER method. The word CARVER is an acronym for [15]:

- criticality;
- accessibility;
- recuperability;
- vulnerability;
- effect on population;
- recognizability.

The method can be used for identifying the place of a possible attack. It thus helps in choosing the best targets or components for a possible attack.

Blahova [16] presents the calculator MIST (Methods of identification of soft targets), which assesses the most vulnerable soft targets according to the following factors:

1. the accessibility factor and the security level;
2. renewability factor;
3. vulnerability factor;
4. influence on people's lives;
5. factor detect;
6. recognition factor;
7. attractiveness factor/symbolism;
8. performance factor and time;
9. frequency factor;
10. response time factor of integrated rescue system.

The calculator is derived from the original CARVER method and is supplemented by other important factors which are used to assess soft targets.

Fundamental documents concerning the issue of soft targets in the Czech Republic is Soft targets protection concept [17]. In the methodology it is stated that for the selection of suitable security measures it is more effective to assess each target individually, taking into account its function, particularly with clarification of factors relevant to security. Two basic criteria have an impact on these factors; the attractiveness of the target from the attacker's point of view and the actual possibility of securing it. The following are considered diagnostic factors [17]:

- openness to the public;
- security personnel;
- amount and concentration of people;
- police presence;
- media presence;
- symbolism of the target.

From many other publications, various approaches can be found by fulfilling a range of criteria. In the case of the previously-mentioned article [12] they are for instance:

– concentration of people;
– security measures against violent attacks;
– attractiveness.

Zeman's study [18] assessed soft targets from a vulnerability viewpoint. The vulnerability was here measured by lethality i.e. the average number of victims caused by terrorist attacks against each type of soft target. Vulnerability is then given by:

1. concentration of people;
2. effectiveness of security measures;

3. quality of execution of terrorist attacks.

The methods mentioned were chosen only for illustration. From the above-mentioned list, it is evident that the possible outline of criteria is wide but inconsistent. It also lacks a comprehensive process for identifying elements that could be soft targets. For these reasons, the article presents a proposal for the process of identifying soft targets in railway infrastructure.

2.2 Criteria of Identifying Soft Targets

From an analysis of potential approaches and criteria for identifying soft targets, basic criteria were chosen, which are then used in the proposed process of identifying soft targets in railway infrastructure. A list of the chosen criteria is given below. The characteristics of the chosen criteria are in bold, and these criteria are then included in the proposed process (see sub-Chapter 2.3).

One of the major criteria that were discovered in carrying out the analysis was the level of security measures. Although this criterion significantly contributes to the resilience of the railway infrastructure [19], with regard to the specificity of this issue, this criterion is however not further included in the assessment. The basic level of security measures at railway stations is practically uniform (stations have both public and private places) and small variations (use of cameras, security guards) are not comprehensively assessable because this information is not kept as a statistic.

Number of People. The concentration of people always expresses the number of people who are or can be found in a given place [12, 18]. With regard to railway infrastructure, it is about the number of people (passengers) in a given railway station.

This criterion cannot however be precisely determined, as it is variable over time, in different time periods, and during various service disruptions. It is however possible to use values of average daily passenger numbers. In this article, we use the figures for the 100 stations in the Czech Republic with the highest average daily number of passengers in 2019 for trains belonging to the carrier ČD, a.s. It can be assumed that this information will also be available for other years and other countries.

For processing this type of data it is necessary to use a statistical concept. The data only contain values for the 100 stations with the highest average daily number of passengers in 2019. For further work, it would be appropriate to scale these values.

For the purposes of scaling data, the quartile statistical method was used. Quartile deviation is one of the measures determining the variability of features in the statistical features of an aggregate. Three quartiles divide a statistical aggregate into quarters. On the basis of these quarters, three possible categories for assessing these criteria in the identification of soft targets in railway infrastructure were set.

– Category A: average daily number of passengers $\geq$ value Q3.
– Category B: average daily number of passengers $\geq$ value Q2 and $<$ Q3.
– Category C: average daily number of passengers $\geq$ value Q1 and $<$ Q2.

Attractiveness of Soft Target. Another important criterion is attractiveness [12, 16]. Primary attractiveness in terms of railway stations lies in the location of the given station within the railway network, i.e. attractive stations are:

1. Railway stations in regional capitals.
2. Railway hubs – stations where a larger number of tracks meet are regarded as railway hubs. These stations are also often identified as critical infrastructure elements [20], which increases their attractiveness in terms of the impacts caused by the failure of the element [21].

The attractiveness of a given railway station can also be increased by the presence of other attractive elements in close vicinity to the station. The following can also be attractive:

- Railway stations which are close to an important shopping center.
- Railway stations which are close to an important cultural center.
- Railway stations which are close to an important employer.

The proximity of these elements needs to be compared using a map interface, also with regard to other potential territorial risks [22].

Transport Infrastructure of Connecting Operators. The second view of attractiveness is also the presence of transport infrastructure of connecting operators in the vicinity of the station. The transport infrastructure of connecting operators can be classified on several levels:

1. Terminal – important public transport hubs which integrate several municipal public transport stops and long-distance bus transport stops are usually labeled as transport terminals.
2. (Bus) stations – bus stations are purpose-built thoroughfares with a larger number of bus stops and a dispatch building.
3. Stop – a stop is a marked place for public transport vehicles to stop and for passengers to enter, leave or change vehicles within a bus, tram, or trolleybus transport.

With regard to these characteristics, the following categories can also be seen within the transport infrastructure of connecting operators:

1. Category E: there is a transport terminal near the train station.
2. Category F: there are two or more stops for various types of connecting transport (municipal, long-distance, trolleybus, bus, tram, metro).
3. Category G: there is one connecting transport stop near the station.

2.3 Process of Identifying Soft Targets

The proposed process for the identification of soft targets in railway infrastructure includes all the criteria determined above. The whole process is represented in Fig. 2.

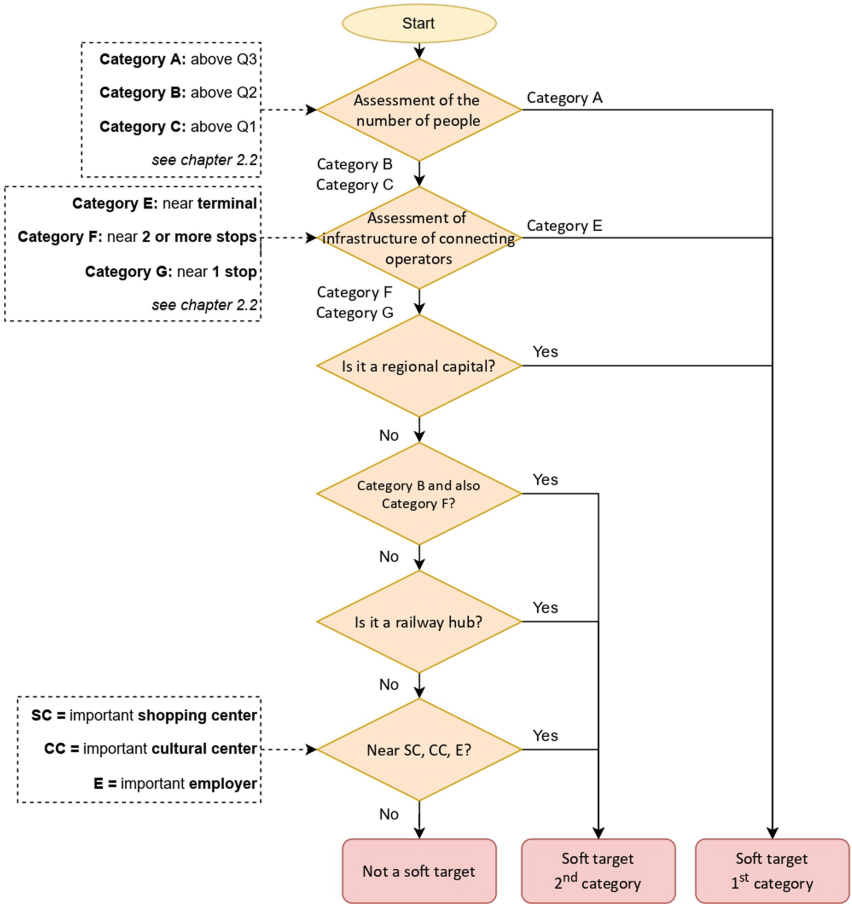


Fig. 2. Diagram of identification of soft targets in railway infrastructure.

The 1st step is assessing the number of people who for the purposes of this process are divided into categories A, B, and C. These categories are specified in the previous chapter. From this assessment, all stations in category A come out as a soft target (category A = average daily number of passengers ≥ value Q3).

The 2nd step is assessing connecting transport infrastructure. Again, the criteria were further specified in the chapter above. Here, stations are assigned to categories E, F, and G. Stations in category E are soft targets, i.e. stations that have a transport terminal nearby.

Subsequently, in the 3rd step stations in regional capitals become soft targets. The Czech Republic is divided into a total of 14 regions, and each region has a regional capital. The 3rd step identifies the most important town in the given region.

The 4th step defines as soft targets those stations which are both category B (average daily number of passengers ≥ value Q2 and < Q3) and category F (there are two or more stops for various types of connecting transport in the vicinity of the station).

The 5th step identifies transport hubs as soft targets (stations where a larger number of tracks meet).

And the final the 6th step focuses on stations that have an important element nearby (shopping center, cultural center, and important employer).

Stations that become soft targets within one criterion (step) do not go forward to assessment of other criteria (steps).

3 Classification of Soft Targets

In the diagram of the process of identification of soft targets in railway infrastructure (Fig. 2), the classification of soft targets into two categories is evident: Soft targets the 1st category and Soft targets the 2nd category.

This classification reflects the basic significance of a soft target. The purpose of classification will be seen more closely in setting security measures for the given categories of soft targets, which will be created in the following parts of the research.

The 1st category includes railway stations which are defined/identified as a soft target according to the following criteria: Category A in the assessment of the number of people, Category E in the assessment of the infrastructure of connecting operators, and regional capital. For these stations, it is necessary to provide significant security measures, because due to their nature they may become the target of an attack.

The 2nd category includes railway stations which are defined/identified as a soft target according to the following criteria: Category B and also Category F, railway hub, and important shopping center, important cultural center, or important employer nearby. These stations also need to be protected using security measures. It is not however necessary to set equally strict criteria as in the 1st category. It is however necessary to observe the current situation at the station and if necessary react to changes.

4 Results of the Process of Identification of Soft Targets

On the basis of the findings, which were gained from an analysis of possible approaches and criteria, a process for identifying soft targets in railway infrastructure was proposed. This process contains both basic criteria for the general identification of soft targets and specific criteria related to railway infrastructure. The process is set in such a way as to reflect existing and usable data. The possible number of people in the station is assessed, as well as around the station (connecting transport infrastructure, important shopping or cultural center, important employer) and the character of the station (station in the regional capital, railway hub).

The application of the proposed process is sequential, whereby every station goes through the whole process. If within one of the steps, a station is determined as a soft target in the 1st or the 2nd category, it does not continue to the other assessment steps and its assessment is complete.

This process was applied to the territory of the Czech Republic as part of the project activity. The values for the 100 stations in the Czech Republic with the highest average daily number of passengers in 2019 for trains belonging to the carrier ČD, a.s. were used as input data. All these stations have gone through the proposed soft target identification

process. The result is the identification of 30 soft targets in the 1st category and 20 soft targets in the 2nd category. Specific data and a specific list of stations is not the result of this publication with regard to the protection of this information.

The results of the process will be used in other parts of the research in the field of soft target protection, where security measures for the 1st and the 2nd categories of soft targets will be determined.

5 Conclusions

Correct identification of the soft target is the basis for determining the protection of the soft target. Therefore, the Authors provide a methodological overview for the identification of soft targets of railway infrastructure. Based on the analysis of possible methods and approaches, the authors propose a process for identifying soft targets. The design of the process and its first application were carried out in the conditions of the Czech Republic. Specific values are not given in this article due the protection of data. The proposed approach can also be adjusted according to the needs of different country railways. Furthemore it is also possible to transfer the established approach to other fields.

Funding. This work was supported by the Technology Agency of the Czech Republic [grant number CK01000015].

References

1. Zangani, D., Fuggini, C.: Towards a new perspective in railway vehicles and infrastructure. In: Procedia - Social and Behavioral Sciences, Genova, Italy, vol. 48, pp. 2351–2360 (2012). https://doi.org/10.1016/j.sbspro.2012.06.1206
2. Vlkovsky, M., Ivanusa, T., Neumann, V., Foltin, P., Vlachova, H.: Optimizating Cargo security during transport using dataloggers. J. Transp. Secur. **10**, 63–71 (2017). https://doi.org/10.1007/s12198-017-0179-4
3. Council Directive 2008/114/EC of 8 December 2008 on the identification and designation of European critical infrastructures and the assessment of the need to improve their protection. European Council, Brussels, Belgium (2008). 8 p.
4. Transport policy of the Czech Republic for the period 2014 - 2020 with a view to 2050. Ministry of Transport of the Czech Republic, Prague. Approved by Resolution of the Government of the Czech Republic No. 449 of 12 June 2013 (2013). 89 p.
5. Leitner, B., Luskova, M.: Assessing security of soft targets using complex systems analysis methods. In: Hofreiter, L., Berezutskyi, V., Figuli, L., Zvaková, Z. (eds.) Soft Target Protection. NSPSSCES, pp. 241–255. Springer, Dordrecht (2020). https://doi.org/10.1007/978-94-024-1755-5_19
6. Hedel, R., Boustras, G., Gkotsis, I., Vasiliadou, I., Rathke, P.: Assessment of the European Programme for Critical Infrastructure Protection in the Surface Transport Sector. Int. J. Crit. Infrastruct. **14**(4), 311–335 (2018). https://doi.org/10.1504/IJCIS.2018.095616
7. Szatmari, M., Leitner, B.: Threat assessment of railway stations as a tool for increasing of soft targets security level. In: Proceedings of 24th International Scientific Conference. Transport Means 2020, Kaunas, Lithuania. pp. 119–125 (2020)
8. GTD: The Global Terrorism Database. The National Consortium for the Study of Terrorism and Responses to Terrorism (START) (2019). https://www.start.umd.edu/gtd/about/

9. Apeltauer, T., et al.: Soft Target Protection. Leges, Prague (2019). 171 p.
10. Slivkova, S., Rehak, D., Michalcova, L., Pittner, R.: Threat assessment of the railway infrastructure soft targets. In: Prentkovskis, O., Yatskiv (Jackiva), I., Skačkauskas, P., Junevičius, R., Maruschak, P. (eds.) TRANSBALTICA 2021. LNITI, pp. 429–438. Springer, Cham (2022). https://doi.org/10.1007/978-3-030-94774-3_42
11. Rehak, D., Flynnova, L., Slivkova, S.: Concept of resistance in the railway infrastructure elements protection. In: Prentkovskis, O., Yatskiv (Jackiva), I., Skačkauskas, P., Junevičius, R., Maruschak, P. (eds.) TRANSBALTICA 2021. LNITI, pp. 419–428. Springer, Cham (2022). https://doi.org/10.1007/978-3-030-94774-3_41
12. Lapkova, D., Kotek, L., Kralik, L.: Soft targets – Possibilities of their identification. In: 29th DAAAM International Symposium on Intelligent Manufacturing and Automation, 9 p. (2018). https://doi.org/10.2507/29th.daaam.proceedings.053
13. Statewatch: Security of the spectacle - The EU's guidelines for security at major events (2012). 36 p.
14. Department of Homeland Security: Soft targets and crowded places security plan overview. U. S. (2018). 26 p.
15. Headquarters Department of the Army: Target analysis process. Special Operations Forces Intelligence and Electronic Warfare Operations, Appendix D. Washington, DC (1991). 7 p.
16. Blahova, M.: Software methodology for soft target identification baset on Methods of identification of soft targets. Trilobit 1 (2020). 7 p.
17. Ministry of the Interior of the Czech Republic: Concept of protection of soft targets for the years 2017–2020. Czech Republic, Prague (2017). 32 p.
18. Zeman, T.: Soft targets: definition and identification. AARMS **19**(1), 109–119 (2020). https://doi.org/10.32565/aarms.2020.1.10
19. Slivkova, S., Rehak, D., Nesporova, V., Dopaterova, M.: Correlation of core areas determining the resilience of critical infrastructure. In: 12th International Scientific Conference on Sustainable, Modern and Safe Transport (TRANSCOM 2017), Procedia Engineering, vol. 192, pp. 812–817 (2017). https://doi.org/10.1016/j.proeng.2017.06.140
20. Dvorak, Z., Sventekova, E., Rehak, D., Cekerevac, Z.: Assessment of critical infrastructure elements in transport. In: 10th International Scientific Conference Transbaltica 2017: Transp. Sci. Technol. Procedia Eng. **187**, 548–555 (2017). https://doi.org/10.1016/j.proeng.2017.04.413
21. Rehak, D., Novotny, P.: Bases for modelling the impacts of the critical infrastructure failure. Chem. Eng. Trans. **53**, 91–96 (2016). https://doi.org/10.3303/CET1653016
22. Bernatik, A., Senovsky, P., Senovsky, M., Rehak, D.: Territorial risk analysis and mapping. Chem. Eng. Trans. **31**, 79–84 (2013). https://doi.org/10.3303/CET1331014

Assessment of the On-Board Energy Storage Parameters of the Locomotive for Rail Quarry Transport

Ievgen Riabov[1](✉), Liliia Kondratieva[1], Liliia Overianova[1], and Sergiy Goolak[2]

[1] National Technical University "Kharkiv Polytechnic Institute", 2, Kyrpychova str., Kharkiv 61002, Ukraine
overanova@ukr.net

[2] State University of Infrastructure and Technologies, 9, Kyrylivska str., Kyiv 04071, Ukraine

Abstract. The use of on-board energy storage on a locomotive for rail quarry transport is considered. Three scenarios of energy consumption in the power supply of traction electric drive and auxiliary locomotive systems using on-board energy storage system (OESS) are considered. For each of the scenarios, simplified mathematical models of processes have been developed, which describe the energy exchange in the traction and auxiliary systems during exploitation of OESS. The input data for the calculations are the dependence of the power at wheel of locomotive on time, which is determined by the results of solving the traction task for the section railway line. Calculations has been made for the studied scenarios of OESS operation using data of locomotive operation at PJSC "Poltava Ferrexpo Mining". It is defined that the parameters of OESS depend on the energy consumption scenario. It is proposed to use OESS on the locomotive with electric traction drive based on induction motors for PJSC "Poltava Ferrexpo Mining" according to energy consumption scenarios, which provide power from OESS during shunting and power from OESS when shunting with co-powered from the catenary for guide lifts.

Keywords: Rail quarry transport · Electric traction system · Onboard energy storage · Traction asynchronous electric drive

1 Introduction

The decarbonization of the economy and the achievement of climate neutrality have been identified as a priority in the National Economic Strategy until 2030 [1], which is developed taking into account the European Green Deal. Accordingly, enterprises of different sectors of the economy of Ukraine have formulated their own programs for greening production processes, in which the priority is the introduction of innovative technologies at all stages of production. For domestic rail transport, achieving the goals of climate neutrality is primarily associated with the further spread and development of electric traction, which has high energy and environmental efficiency [2].

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 677–688, 2023.
https://doi.org/10.1007/978-3-031-25863-3_65

Reducing energy consumption and reducing the carbon footprint are urgent challenges today. In the traction rolling stock of rail transport, these problems are solved by implementing modern equipment, facilities and by optimizing energy consumption. In the last case, an important energy saving technology is the use of energy storage devices to store recuperation energy [3–5]. Therefore, this research work conducted for such a locomotive, the traction system of which is included on-board energy storage system (OESS). Determination of OESS parameters is related to the analysis of energy processes in the traction electric drive of rolling stock [6–10]. The analysis is based on mathematical modeling of rolling stock movement and energy processes in its traction system [11, 12]. This allows the use of detailed mathematical models, the parameters of which are determined from the characteristics of rolling stock and its equipment. Processing of experimental data on energy consumption of rolling stock is performed in [13]. At the stage of creation of the locomotive the estimation of technical parameters of OESS is possible with use of the first approach described above in case of simplification of mathematical model.

The purpose of the work is to substantiate the possibility of using and to propose a procedure for determination of the parameters of the OESS locomotive for rail quarry transport.

2 Research Material

The procedure of assessment of technical parameters will be carried out on the example of a locomotive for PJSC "Poltava Ferrexpo Mining". The system of electric traction of alternating current of 10 kV, 50 Hz is applied at this enterprise. Traction units OPE1A (M) are operated on electrified lines. Transportation of rock mass is carried out by constantly formed trains of 14 dump trucks 2VS105. The weight of the loaded dump truck is 156 tons. The speed limit is 20 km/h. According to the results of the analysis of site profiles, it was found that the estimated (managerial) ascension is about 40‰. Lifting length – 450 m, on the ascension there is a curve with a radius of about 500 m. There are also sections with a slope of 30‰ with a length of (500…600) m. The profile of the section of the track is shown in Fig. 1.

The maximum calculated traction characteristic of a 16-axle two-section locomotive (one of the possible options for creating a locomotive with a traction electric drive based on induction motor) is shown in Fig. 1. Calculations were performed in [14] taking into account recommendations [15–17].

When transporting the mass can be divided into four stages during one passage:

1. movement from the crushing plant to the unloading point;
2. shunting under load;
3. movement from the unloading point to the crushing plant;
4. shunting during unloading.

Figure 2 shows the dependence of the tangential power for the studied locomotive during on site working. The dependence is obtained by calculating the traction task.

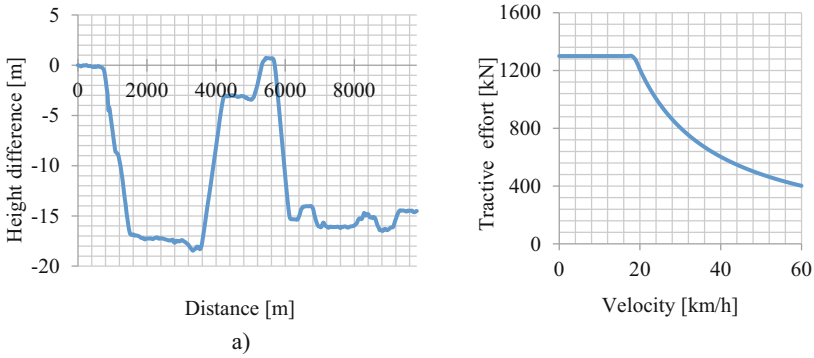


Fig. 1. Input data: a) – track profile, b) – traction characteristic of the locomotive.

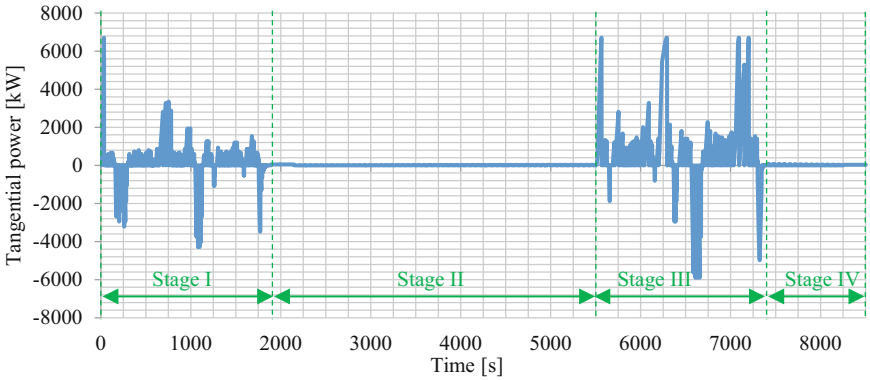


Fig. 2. Dependence of power at wheel on time: Stage I is movement from the crushing plant to the unloading point; Stage II is shunting under load; Stage III is movement from the unloading point to the crushing plant; Stage IV is shunting during unloading.

The total duration of the passage is 8,512 s, the duration of the half-passage from the crushing plant to the unloading point in the opposite direction is 1,813 and 1,915 s, respectively, the duration of loading is 3,613 s, unloading is 1,524 s.

To assess the parameters of OESS, modeling for several scenarios of energy consumption on the locomotive has been performed. The following scenarios describes the simplest ways to manage energy consumption from OESS. When estimating energy consumption, it is necessary to take into account the power of locomotive auxiliary systems, which is consumed by motor-fans for cooling traction motors, cooling system of transformer and traction converters, compressor, etc.

The average power of auxiliary systems assuming as the following: during motion on the section – 250 kW; during loading dump cars – 50 kW, during unloading – 100 kW. Consequently, three scenarios of locomotive OESS were considered.

The 1st Scenario. In traction mode during movement on the railway section, the locomotive receives power from the catenary. In case of shunting during loading and unloading, the power supply of the traction electric drive and auxiliary systems is carried

out only from OESS. In the electrodynamic braking (EDB) mode, the recuperation energy is used to power the locomotive auxiliary systems and charge the OESS. In this case, if the power during recuperation is less than the power of auxiliary systems, the required energy is consumed by OESS. If the recuperation power exceeds the total power of the auxiliary systems and OESS - the electrodynamic brake starts working.

Scenario 2. In traction mode, the locomotive is powered by the catenary while the power consumption is below a certain level. If the set power supply level of the traction electric drive and auxiliary systems of the locomotive is exceeded, it is carried out from the catenary and OESS. Shunting during loading and unloading in EDB mode – simplify the 1st Scenario.

The 3rd Scenario. The locomotive is powered by OESS, if the power does not exceed a certain value. When it is exceeded, the traction and auxiliary systems of the locomotive are fed together from the OESS and the catenary. Shunting during loading and unloading in EDB mode – simplify the 1st Scenario.

The direction of energy flows for each scenario is shown in Fig. 3.

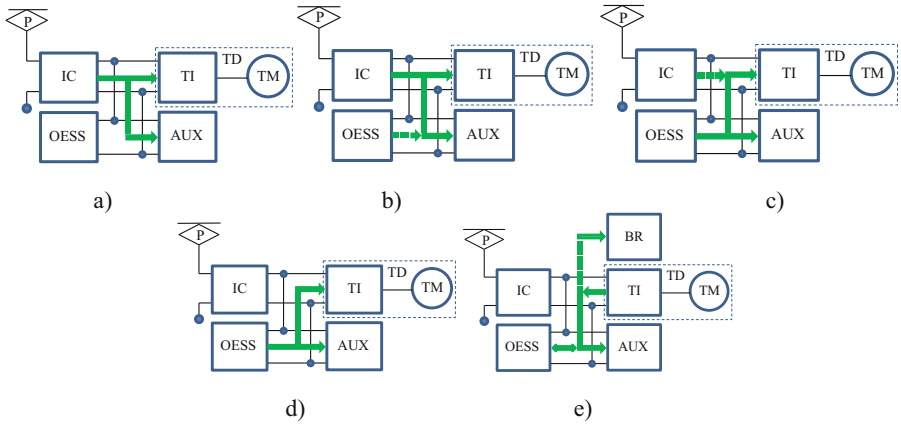


Fig. 3. Schemes of energy exchange in locomotive traction electric drive and auxiliary systems: a) – traction mode when movement on the site for the 1st Scenario; b) – traction mode when movement on the site for the 2nd Scenario; c) – traction mode when driving on the site for the 3rd Scenario; d) – traction mode when maneuvering; e) – electrodynamic braking mode: P – pantograph, IC – input converter, OESS – onboard energy storage system, TI – traction inverter, TM – traction motor, TD – traction electric drive, AUX – auxiliary locomotive systems, BR – braking resistor.

For the 1st Scenario the mathematical description of the above processes has the form for traction mode during movement on the railway section:

a) power consumed from the input converter:

$$p_{in}(t) = \frac{p_k(t)}{\eta_T} + p_{aux}(t); \tag{1}$$

where $\eta_T = f(p_k(t))$ the average efficiency of the traction electric drive in the traction mode, assuming equal to 0.9; $p_{aux}(t)$ – power consumed by locomotive auxiliary systems,

b) power consumed by traction electric drive and locomotive auxiliary systems from OESS

$$p_{oess}(t) = 0. \tag{2}$$

For the 2nd Scenario the mathematical description of the above processes has the form for traction mode:

1. power consumed from the input converter:

$$p_{in}(t) = \begin{cases} \dfrac{p_k(t)}{\eta_T} + p_{aux}(t), & \left(\dfrac{p_k(t)}{\eta_T} + p_{aux}(t)\right) \le P_{IN} \\ P_{IN}, & \left(\dfrac{p_k(t)}{\eta_T} + p_{aux}(t)\right) > P_{IN} \end{cases} \tag{3}$$

where P_{IN} – the maximum power consumed by the input converter.

2. power consumed by traction electric drive and locomotive auxiliary systems from OESS:

$$p_{oess}(t) = \begin{cases} 0, & \left(\dfrac{p_k(t)}{\eta_T} + p_{aux}(t)\right) \le P_{IN} \\ \dfrac{p_k(t)}{\eta_T} + p_{aux}(t) - P_{IN}, & \left(\dfrac{p_k(t)}{\eta_T} + p_{aux}(t)\right) > P_{IN} \end{cases} \tag{4}$$

For the 3rd Scenario the mathematical description for traction mode during movement on railway section:

1. power consumed from the input converter:

$$p_{in}(t) = \begin{cases} 0, & \left(\dfrac{p_k(t)}{\eta_T} + p_{aux}(t)\right) \le P_{OESS} \\ \dfrac{p_k(t)}{\eta_T} + p_{aux}(t) - P_{OESS}, & \left(\dfrac{p_k(t)}{\eta_T} + p_{aux}(t)\right) > P_{OESS} \end{cases}. \tag{5}$$

2. power consumed by OESS:

$$p_{oess}(t) = \frac{p_k(t)}{\eta_T} + p_{aux}(t). \tag{6}$$

For all scenarios in traction mode when shunting during loading and unloading:

1. power consumed from the input converter:

$$p_{in}(t) = 0, \tag{7}$$

2. power consumed by traction electric drive and locomotive auxiliary systems from OESS:

$$p_{oess}(t) = \frac{p_k(t)}{\eta_M} + p_{aux}(t), \tag{8}$$

where $\eta_M = f(p_k(t))$ – the average efficiency of the traction electric drive in the traction mode during maneuvering, assuming equal to 0.3.

For EDB mode the processes that take place in the traction and auxiliary systems of the locomotive are described by the following expressions:

1. power consumed from the input converter:

$$p_{in}(t) = 0 \tag{9}$$

2. power consumed by traction electric drive and locomotive auxiliary systems from OESS:

$$p_{oess}(t) = \begin{cases} -(p_{aux}(t) - p_k(t) \cdot \eta_B), \quad p_k(t) \cdot \eta_B \leq p_{aux}(t) \\ p_k(t) \cdot \eta_B - p_{aux}(t), \quad (p_k(t) \cdot \eta_B > p_{aux}(t)) \wedge (p_k(t) \cdot \eta_B - p_{aux}(t) < P_{OESS}) \\ P_{OESS}, \quad p_k(t) \cdot \eta_B - p_{aux}(t) \geq P_{OESS} \end{cases} \tag{10}$$

where $\eta_B = f(p_k(t))$ – The efficiency of the traction electric drive in the EDB mode, takes equal to 0.9; P_{OESS} – rated power of OESS. The sign "minus" corresponds to the mode of energy consumption from OESS.

3. recuperation power consumed by locomotive auxiliary systems:

$$p_a(t) = \begin{cases} p_k(t) \cdot \eta_B, \quad p_k(t) \cdot \eta_B \leq p_{aux}(t) \\ p_{aux}(t), \quad p_k(t) \cdot \eta_B > p_{aux}(t) \end{cases} \tag{11}$$

4. power of the braking resistor:

$$p_{br}(t) = \begin{cases} 0, \quad p_k(t) \cdot \eta_B \leq (p_{aux}(t) + P_{OEES}) \\ p_k(t) \cdot \eta_B - p_{aux}(t) - P_{OEES}, \quad p_k(t) \cdot \eta_B > (p_{aux}(t) + P_{OEES}) \end{cases} \tag{12}$$

OESS energy "at the terminals" is calculated by expression:

$$e_{oess}(t) = \begin{cases} E_p + \eta_{OESS} \int\limits_0^{t_p} p_{oess}(t)dt, & p_{oess}(t) > 0 \\ E_q - \int\limits_0^{t_q} |p_{oess}(t)|dt, & p_{oess}(t) < 0 \end{cases} \tag{13}$$

where η_{OESS}

- the average efficiency of the drive (OESS with matching converter (if available)), it was taken equal to 0.95; E_p, E_q
- the energy of the storage before the p-th and q-th stage of charging and discharging, respectively; t_p, t_q
- the duration of the p-th and q-th stages of charging and discharging, respectively.

Conditions $p_{oess}(t) > 0$ corresponds to the charge of the drive, the condition $p_{oess}(t) < 0$ – discharge.

EDB is not used during maneuvering.

The OESS parameters are determined by the following expressions.

Power P'_{OESS} is defined by (20) as the maximum value.

Energy accumulated in OESS in EDB mode:

$$e'_{oess}(t) = E_p + \eta_{OESS} \int\limits_0^{t_p} p_{oess}(t)dt, \quad p_{oess}(t) > 0. \tag{14}$$

The operating energy consumption of the drive is determined by the expression:

$$E_{OESS} = \frac{E_{\max} - E_{\min}}{\eta_{OESS}}. \tag{15}$$

where $E_{\max}$, $E_{\min}$ – the largest and smallest values of OESS energy, which are determined by dependence $e_{oess}(t)$, calculated according (23); η_{OESS} – OESS efficiency.

The energy to be stored in the storage system before the start of the movement is determined by preliminary calculation, provided that the initial energy of the OESS is zero:

$$E_0 = |E_{\min}|. \tag{16}$$

Calculations of energy process parameters are performed for several OESS rated power values. The results of calculations are in Figs. 4, 5 and 6.

Figure 4 shows results for the 1st Scenario. As it is seen the energy consumed by OESS does not depend on its power (Fig. 4a). This is due to the conditions of the scenario for which the calculations were performed: energy is consumed by OESS during maneuvering, and therefore is of constant importance. The total energy consumed by OESS during shunting is 139 kWh.

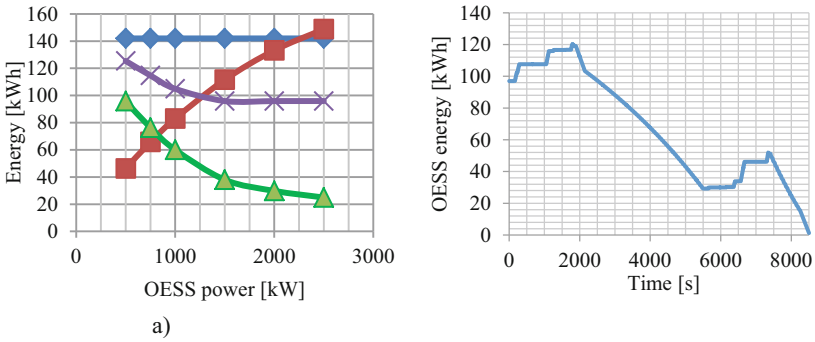


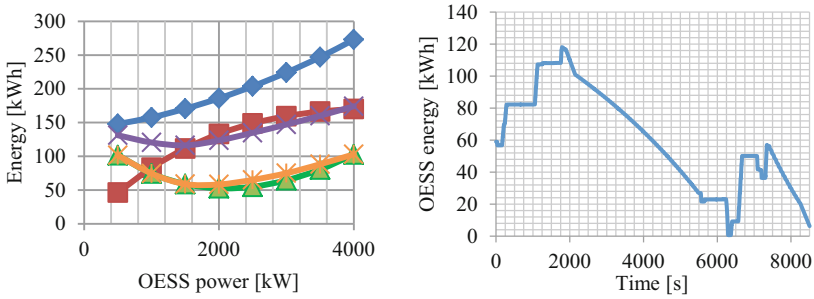
Fig. 4. Results of calculations for the 1st Scenario: a) – calculations of energy process parameters: energy consumed by OESS is a blue line, the energy that OESS can accumulate during recuperation is the orange line, working energy consumption - green line, the initial energy is the purple line; b) – dependence of OESS power and energy at nominal OESS power of 500 kW.

As the power of the OESS increases, the energy that can be accumulated in the EDB mode increases. Also, as the capacity of the OESS increases, the operating energy consumption and the initial energy that the OESS must have before starting to movement. As it is seen from Fig. 4, when the OESS power is 2,500 kW, the energy that can be accumulated during EDB exceeds the energy that will be consumed when powered by OESS. However, in the case under study, the maximum power consumption in shunting mode is about 400 kW. Therefore, the feasibility of using OESS with a capacity that is several times higher than the capacity of auxiliary systems needs further study.

In Fig. 4b shows the dependences for OESS energy at a nominal OESS power of 500 kW. It follows from Fig. 4b that the drive is charged with a power of 500 kW in EDB modes, and discharge, when shunting with a maximum power of about 480 kW. To ensure the operation of the locomotive during the passage, the initial energy must be 96 kWh. The total energy that OESS can accumulate while movement is 46 kWh. OESS charging takes place in EDB modes. Discharge of OESS is mainly during shunting at the overload point and the crushing plant.

Figure 5 shows results for the 2nd Scenario. Analysis of dependences of Fig. 5a shows that with increasing power, energy consumption with OESS increases. The energy consumed during shunting does not change and is 139 kWh. The rest goes to compensate for the energy required to power the locomotive systems in excess of power in modes when the power consumption exceeds the maximum power that can be consumed by the locomotive from the catenary. As the OESS capacity increases, the energy consumption of the OESS increases nonlinearly. At the same time, the curve of energy dependence that OESS can accumulate on its power has the effect of "saturation" - at a power of more than 2,500 kW, growth is very slow. It is noteworthy that the difference between the energy consumed by OESS and the energy that can be stored by OESS has a minimum in the power range of 1,500…2,500 kW. That is, in this range will have place the most efficient use of the drive. The minimum values of the initial energy also fall on this power range, and the minimum operating energy consumption falls on the range of 1,000…2,000 kW.

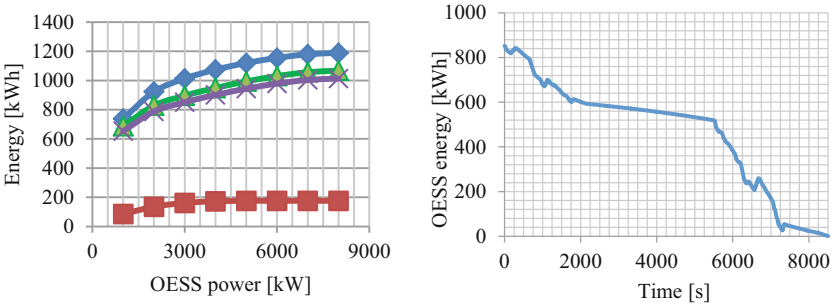
Based on these conditions, it is possible to consider rational for the 2nd Scenario power OESS close to 1,500…2,000 kW.



a)

Fig. 5. Results of calculations for the 2nd Scenario: a) – calculations of energy process parameters: Energy consumed by OESS is a blue line, the energy that OESS can accumulate in the EDB mode at a given power is the red line; the difference between the energy consumed by OESS and the energy that OESS can store is the green line; operating energy intensity of OESS is a purple line; the initial energy of OESS is the orange line; b) – dependence of OESS energy at nominal OESS power of 2,000 kW.

In Fig. 5b dependence of OESS power and energy for the 2nd Scenario at nominal OESS power of 2,000 kW is presented. From Fig. 5b it follows that the combined power supply of the locomotive from the traction network and OESS is carried out at acceleration during the movement on the guide lifts. Calculations show that the energy consumption for this is 46.9 kWh. The rest of the OESS energy is used to power the locomotive during shunting from loading and unloading. Figure 6 shows results for the 3rd Scenario.



a) b)

Fig. 6. Results of calculations for the 3rd Scenario: a) – calculations of energy process parameters: the energy consumed by OESS is the blue line; the energy that OESS can accumulate during recuperation is the red line; operating energy consumption - green line; the initial energy is the purple line; b) – dependence of OESS energy at OESS rated power of 3,000 kW.

Analysis of the dependences in Fig. 6a shows that the curves have a "saturation" effect at a power of more than 3,000 kW, it growth is very slow. This can be explained by the fact that a significant part of the energy consumed by locomotive systems is consumed at less than 3,000 kW. Higher power is required only when accelerating and driving on guide slopes. Accordingly, the energy accumulation does not increase at a power of more than 3,000 kW. The dependences (Fig. 6b) show that the main energy consumption is provided by OESS. The most intensive energy consumption occurs during the movement of a loaded train.

3 Discussion of Results

Studies confirm the possibility of using OESS on a locomotive for quarry rail transport. The considered scenarios of OESS application and the calculations carried out in accordance with preliminary estimation of the main technical parameters of OESS - energy consumption and capacity. For the 1st Scenario, in which OESS is mainly used for autonomous maneuvering, the OESS's operating capacity is estimated at approximately 150 kWh at 500 kW.

For the 2nd Scenario, in which the energy of the OESS is used to power the traction and auxiliary systems of the locomotive and autonomous movement during maneuvering, the energy consumption of the OESS is about 200 kWh at a power of 2,000…2,500 kW. That is, to implement this scenario, the power of OESS should be about a third of the nominal power of the locomotive.

In the 3rd Scenario, where the locomotive systems are mainly powered by OESS, its operating energy consumption is about 800…900 kWh at a power of 2,500…3,000 kW. That is, the power of OESS is 30… 50% of the nominal power of the locomotive.

Definitely, the technical parameters of OESS depend on the scenario of its application. In particular, in the case of power supply of the traction electric drive from OESS, its power reaches 30…50% of the nominal power of the locomotive. The energy intensity of OESS also significantly depends on the energy consumption scenario.

For the studied locomotive for PJSC "Poltava Ferrexpo Mining", where the movement is carried out by electrified tracks, it was possible to consider it appropriate to use OESS in the 1st and the 2nd Scenarios. It is advisable to increase the energy consumption of OESS to ensure the operation of the locomotive at least during the shift.

The obtained preliminary technical parameters make it possible to select the type of OESS and determine the circuitry of using it on the locomotive. It should be noted that the considered scenarios do not describe all possible energy consumption options. Therefore, further research aimed to increase accuracy of research results is needed and should be based on refined mathematical models.

4 Conclusions

After the preliminary assessment of the parameters of the OESS locomotive for quarry railway transport three scenarios of energy consumption are considered: the first, the use of OESS to supply the locomotive systems during maneuvering; the second, power supply of locomotive systems from OESS during shunting and limiting the power of

the input converter; the third, power supply of locomotive systems when shunting from OESS as the main source of energy. For each of these scenarios, mathematical models were developed that describe the processes of energy transition, and calculations of OESS parameters were performed.

The estimation of OESS parameters is performed on the basis of the dependence of the tangential power obtained when solving the traction problem and the power consumed by the locomotive auxiliary systems. It is discovered that for the 1st and the 2nd Scenarios the energy intensity of OESS is 150…200 kWh, for the third – 900 kWh. The power of OESS for the 1st Scenario is about 500 kW, for the 2nd and the 3rd – 2,500 … 3,000 kW.

According to the results of the research, the technical feasibility of using OESS on a locomotive for quarry railway transport is substantiated. It is proposed to use OESS in the 1st or the 2nd Scenario and increase the energy intensity of OESS to be able to work during the shift without charging from an external source.

Further research should focus on optimizing energy consumption based on refined mathematical models.

Acknowledgement. The Authors express their sincere gratitude to the Chief Engineer of the Railway Department of PJSC "Poltava Ferrexpo Mining" S.V. Mosin and the director of LLC "Nikolaev locomotive repair plant" S.V. Roi and for promoting the study, including up-to-date information on the real needs in the rolling stock of Ukrainian mining enterprises.

References

1. Postanova KMU vid 03 bereznia 2021 r. № 179 Pro zatverdzhennia Natsionalnoi ekonomichnoi stratehii na period do 2030 roku (Resolution of the Cabinet of Ministers of March 3, 2021 № 179 "On approval of the National Economic Strategy for the period up to 2030". (in Ukrainian). https://www.kmu.gov.ua/npas/pro-zatverdzhennya-nacionalnoyi-eko-a179. Accessed 10 Jun 2022
2. Getman, H., Vasiliev, V.: Analyz rezervov snyzhenyia enerhoemkosty zheleznodorozhnыkh perevozok na hornodobyvaiushchykh predpryiatyiakh (Analysis of reserves for reducing the energy intensity of railway transportation at mining enterprises). Electromagnetic Compatib. Safety Railw. Transp. **17**, 61–67 (2019). (in Russian)
3. Best Practices and Strategies for Improving Rail Energy Efficiency. https://railroads.dot.gov/elibrary/best-practices-and-strategies-improving-rail-energy-efficiency. Accessed 10 Jun 2022
4. Kuznetsov, V., et al.: Method of selecting energy-efficient parameters of an electric asynchronous traction motor for diesel shunting locomotives - case study on the example of a locomotive Series ChME3 (ЧМЭ3, ČME3, ČKD S200). Energies **15**(1), 317–336 (2022). https://doi.org/10.3390/en15010317
5. Morea, D., Elia, S., Boccaletti, C., Buonadonna, P.: Improvement of energy savings in electric railways using coasting technique. Energies **14**, 8120–8135 (2021). https://doi.org/10.3390/en14238120
6. Spiryagin, M., Wu, Q., Wolfs, P., Sun, Y., Cole, C.: Comparison of locomotive energy storage systems for heavy-haul operation. Int. J. Rail Transp. 1–15 (2017). https://doi.org/10.1115/JRC2017-2217
7. Omelyanenko, V., Riabov, I., Overianova, L., Omelianenko, H.: Traction electric drive based on fuel cell batteries and on-board inertial energy storage for multi unit train. Electr. Eng. Electromechan. (4), 64–72 (2021). https://doi.org/10.20998/2074-272X.2021.4.08

8. Yatsko, S., Sidorenko, A., Vashchenko, Y., Liubarskyi, B., Yeritsyan, B.: Method to improve the efficiency of the traction rolling stock with onboard energy storage. Int. J. Renewable Energy Res. **9**(2), 848–858 (2019)
9. Buriakovskiy, S., Maslii, A., Pomazan, D., Overianova, L., Omelianenko, H.: Multi-criteria quality evaluation of energy storage devices for rolling stock using Harrington's desirability function. In: 2020 IEEE 7th International Conference on Energy Smart Systems ESS 2020, pp. 158–163 (2020)
10. Mayrink, S., Oliveira, J., Dias, B., Oliveira, L., Ochoa, J., Rosseti, G.: Regenerative braking for energy recovering in diesel-electric freight trains: a technical and economic evaluation. Energies **13**(4), 963–979 (2020). https://doi.org/10.3390/en13040963
11. Petrenko, A., Liubarskiy, B., Pliugin, V.: Determination of railway rolling stock optimal movement modes. Electr. Eng. Electromechan. (6), 27–31 (2017). https://doi.org/10.20998/2074-272X.2017.6.04
12. Bureika, G., Vaičiūnas, G.: Investigating the impact of track gradients on traction energy efficiency in freight transportation by railway. WIT Trans. Ecol. Environ. **143**, 461–472 (2011). https://doi.org/10.2495/ESUS110391
13. Kostin, N., Nikitenko, A.: Avtonomnost rekuperatyvnoho tormozhenyia – osnova nadezhnoi i enerhoeffektyvnoi rekuperatsyy na elektropodvyzhnom sostave postoiannoho toka (Autonomy of recuperative braking - the basis of reliable and energy-efficient recuperation on the electric composition of direct current). Railway Transp. Ukraine **3**, 15–22 (2014). [in Russian]
14. Riabov, I., Mosin, S., Overianova, L., Kondratieva, L., Demydov, O., Goolak, S.: Otsinka tekhnichnykh parametriv lokomotyva dlia zaliznychnoho kariernoho transport (Assessment of the technical parameters of the locomotive for railway quarry transport.). Transport Systems and Technologies, (39), 83–100 (2022). (in Ukrainian). https://doi.org/10.32703/2617-9040-2022-39-9
15. Kamaev, A., Apanovich, N., Kashev, V., et al.: Konstruktsyia, raschet y proektyrovanye lokomotyvov: Uchebnyk dlia studentov vtuzov, obuchaiushchykhsia po spetsyalnosty «Lokomotyvostroenye» (Construction, calculation and design of locomotives: A textbook for university students majoring in "Locomotive"): Mashinostroenie, 351 (1981)
16. Goolak, S., Tkachenko, V., Šťastniak, P., Sapronova, S., Liubarskyi, B.: Analysis of control methods for the traction drive of an alternating current electric locomotive. Symmetry **14**, 150–168 (2022). https://doi.org/10.3390/sym14010150
17. Slashchov, V.: Tiahovi ta halmovi rozrakhunky na reikovomu transporti: Navch. posib (Traction and brake calculations on rail transport: Textbook Way): East Ukrainian nat. Univ. V.Dalia, 232 (2005). (in Ukrainian)

Study on Measurement Repeatedness of Vertical Impacts on Rail of Loaded and Empty Wagons

Gediminas Vaičiūnas(✉) and Stasys Steišūnas

Vilnius Gediminas Technical University, Saulėtekio al. 11, 10223 Vilnius, Lithuania
{gediminas.vaiciunas,stasys.steisunas}@vilniustech.lt

Abstract. The paper investigates the question of the repeatedness of the results of the measurement of the impact of a wagon wheel on the rail. It is examined how the dispersion of the impact values depends on whether the wagon is loaded or empty. The ratio of the total width of the two middle quartiles to the median is used as a parameter to assess the predictability of the effect of wagon wheel damage on vertical impacts. The results of field tests were used for the research, and conclusions were presented.

1 Introduction

The interaction of the wheels of the rolling stock with the rails depends on various operational characteristics. In part, this depends on the characteristics of the rail, such as the reinforcement of the rails [1]. It is, therefore very important to provide appropriate requirements for the design of railways [2]. Relevant railway elements, such as rail fasteners, are first modelled [3]. The effect of the wheel on the railway track structure also has its advantage - the magnitude of the effect can be determined from the deformations of the track structure [4]. However, this is not the only way to measure wheel impact force on the rail [5]. One effect is due to the orderly construction of the rail and the other to the presence of damage [6]. It is also affected by wheel surface damage [7]. The impact of damage to the wheel rolling surface is transmitted to other rail vehicle structures [7]. But the wheelset itself is most affected [8]. This effect also depends on the general condition of the rail vehicle [9]. Rolling stock traction sand systems have an impact [10]. However, track or wheel damage is one aspect, and the other aspect is the different wheel loads when the wagon is loaded or empty. [11]. The wear of the rails also depends on it [12]. Different analytical methods are used to predict rail wear [13]. Sometimes it is possible to conduct field research on this phenomenon [14]. As for rolling stock with wheel damage hunts, while rolling, the contact of the damage with the rail and the forces caused is different each time. By measuring these forces, a large scatter of values is obtained. However, this dispersion is slightly different under different operating conditions. In some operating conditions, the force measurement results correlate better with the magnitude of the damage, in others - worse. This study examines how the scattering of impact force values depends on whether the wagon is loaded or empty.

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 689–695, 2023.
https://doi.org/10.1007/978-3-031-25863-3_66

2 Equipment and Methodology of the Test

The Atlas LG system (Fig. 1) is used to measure the forces caused by wheel damage, which determines the impact force on the rail. System sensors are installed on the rails, from which information is read and processed by dedicated equipment.

Fig. 1. ATLAS – LG measuring system.

More information about the measurement ATLAS-LG system can be found in the literature [15]. This study examines data from tests on the wagon in two different wheel damage cases. In the first case – the wheel has two breaks of 20 × 10 × 4 mm and 15 × 40 × 3 mm size. In the second case – the wheel has a flat of 2.0 mm and a break of 30 × 40 × 2 mm.

3 The Process of the Experiment and the Analysis of the Results

The values of the maximal vertical forces when the wagon is loaded are plotted in Fig. 2 in the form of a BOX and whisker graph.

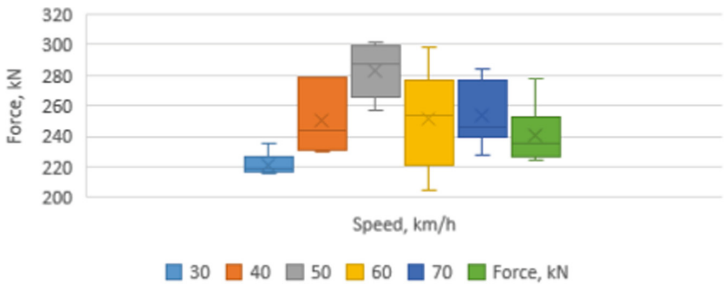


Fig. 2. Values of maximal vertical forces when the wagon is loaded.

The authors of the article created graphs for all test cases as follows:

1. values of maximal vertical forces when the wagon is loaded;
2. values of the maximal vertical forces when the wagon is empty;
3. values of average vertical forces when the wagon is loaded;
4. values of average vertical forces when the wagon is empty.

Figure 2 shows one example of the graphs listed above.

The Authors proposed to calculate the ratio of the total width of the two middle quartiles to the median in estimating the wagon wheel damage magnitude:

$$Q_M = \frac{Q_U - Q_L}{M} \rightarrow min, \tag{1}$$

where Q_U – upper quartile; Q_L – lower quartile: M – median (Fig. 2).

This indicator name is sometimes abbreviated to "indicator Q_M "for simplicity. In the formula [1], both the median and the mean of the values can be used as the value of M. The same principle must be followed in all calculations. The lower value of the indicator Q_M causes the better the repeatedness of the measured vertical force. The value of Q_M is calculated under different operating conditions of the rolling stock (in this case, different speeds). Comparing the Q_M values in different cases determined which conditions are best suited to relate the magnitude of the damage to its influence on the rail. The results of the calculations are summarized in Table 1.

Table 1. Summary of the indicator Q_M values according to the operating conditions.

Speed, km/h	1st case of wheel damage				2nd case of wheel damage			
	Maximal vertical force		Averaged vertical force		Maximal vertical force		Averaged vertical force	
	Loaded wagon	Empty wagon	Loaded wagon	Empty wagon	Loaded wagon	Empty wagon	Loaded wagon	Empty wagon
30	0.045	0.244	0.040	0.034	0.110	0.207	0.021	0.043
40	0.192	0.166	0.030	0.100	0.376	0.117	0.063	0.040
50	0.122	0.124	0.043	0.172	0.629	0.217	0.080	0.035
60	0.224	00.13	0.026	0.126	0.411	0.124	0.041	0.016
70	0.147	0.362	0.101	0.114	0.432	0.156	0.087	0.048
80	0.109	0.118	0.108	0.110	0.606	0.132	0.110	0.176

Based on the data in Table 1, the changes of the indicator Q_M on running speed are plotted (the graphs use the averaged Q_M values according to the first and second damage cases). The dependence of the values of the indicator Q_M on the running speed when measuring the maximal forces is given in Fig. 3.

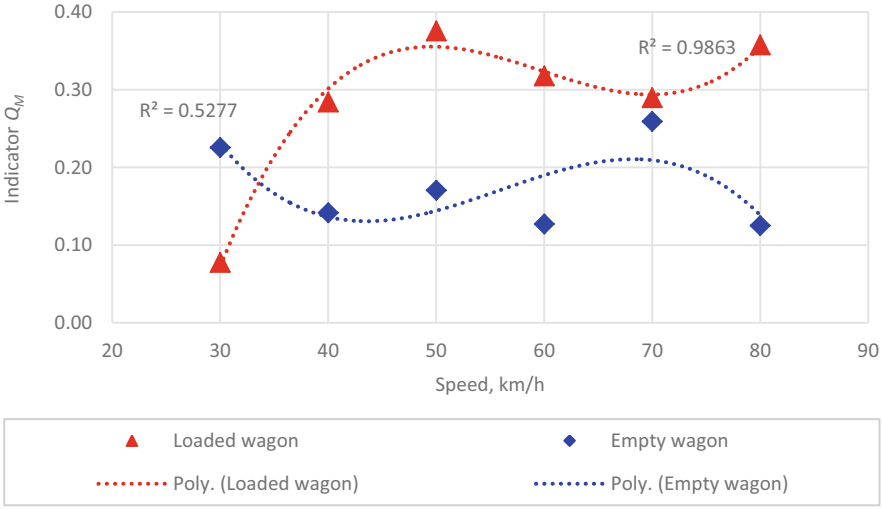


Fig. 3. Dependence of the indicator Q_M values on running speed when measuring maximum forces.

Figure 3 shows that in most cases, the values of the indicator Q_M are lower when the wagon is empty. Then the value of the indicator Q_M is about 0.15–0.2 and depends weakly on the speed. When the wagon is loaded, the Q_M increases with increasing wagon speed. To equalize the scales of the two graphs in Fig. 3 (to correctly compare the trends in the change of indicator Q_M on the speed of the empty and loaded wagons), the data are normalized. The normalized values of the indicator Q_M according to the maximal forces are given in Fig. 4.

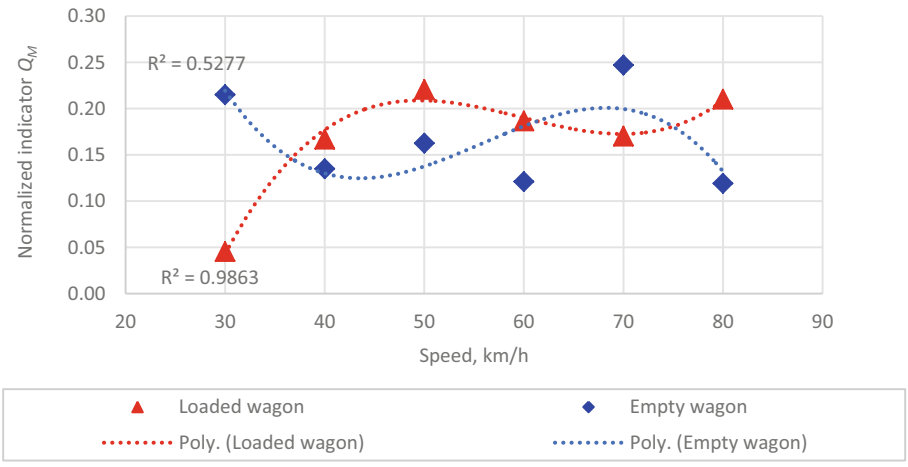


Fig. 4. Dependence of the indicator Q_M normalized values on running speed when measuring maximal forces.

The lower value of the indicator Q_M causes the better the repeatedness of the measured vertical force. Two main conclusions can be drawn from the data in Fig. 4. First – the predictability of the effect of wagon wheel damage on vertical forces correlates better with the wagon running speed when the wagon is loaded. Secondly – reducing the train speed from 80–90 km/h to 50–60 km/h does not improve the correlation of wheel damage magnitude with the vertical forces. It is necessary to reduce the speed to 30–40 km/h to improve it. This is especially evident in Fig. 4 in the case of a loaded wagon. Because there are several defects in the running surface of the wheel, the values of the indicator Q_M do not consider the entire wheel-rail interaction in terms of maximal impact forces. Therefore, in the following study, the wheel impact forces were measured over the entire running surface and averaged. The dependence of the indicator Q_M values on the running speed, when measured forces are averaged, is given in Fig. 5.

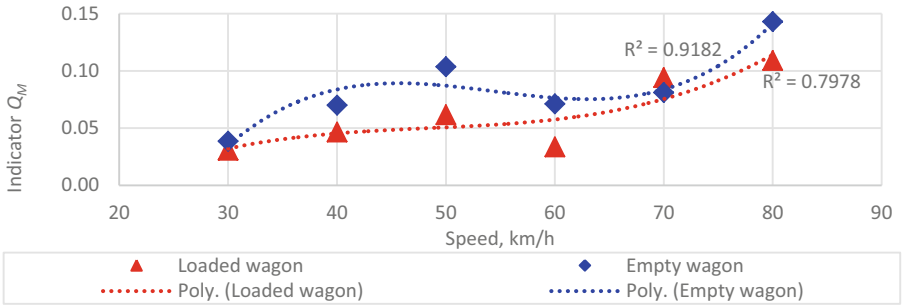


Fig. 5. Dependence of the indicator Q_M values on running speed when measuring averaged forces.

It can be seen from Fig. 5 that the indicator Q_M values of the loaded and empty wagons do not differ much. The third-degree polynomial is a better-matched dependence of the indicator Q_M on the speed when the wagon is empty. The researchers decided

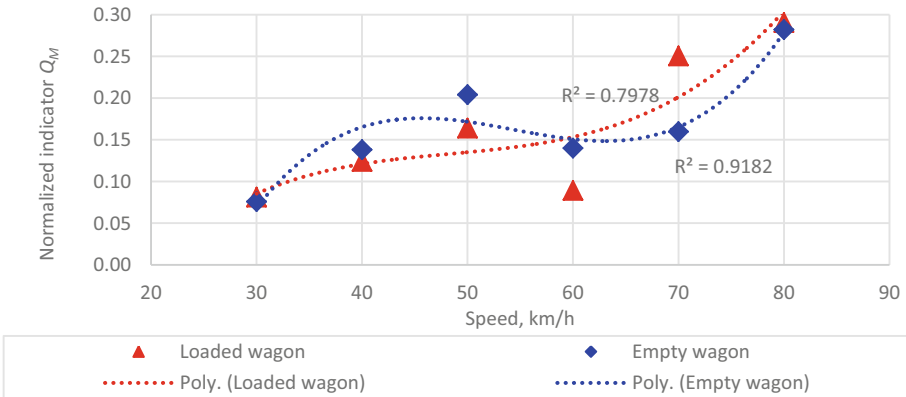


Fig. 6. Dependence of the indicator Q_M normalized values on running speed when measuring average forces.

to conclude according to the normalized values. The normalized values of the indicator Q_M by averaged forces are given in Fig. 6.

The data in Fig. 6 shows that the predictability of the effect of wagon wheel damage on the averaged values of the vertical forces correlates better with the wagon running speed when the wagon is empty. The best predictability is at a wagon speed of 30 km/h. The same goes for an empty and loaded wagon.

4 Conclusions

1. The ratio of the total width of the two middle quartiles to the median – the indicator Q_M – can be used as a parameter to assess the predictability of the effect of wagon wheel damage on vertical forces.
2. It is sometimes appropriate to use its normalised values to unify the range of variation of the indicator Q_M under different conditions (convenience of analysis).
3. The dependence of the indicator Q_M (according to the maximum forces) on the speed is minimal. For an empty wagon, this indicator ranges from 0.1 to 0.21. Its dependence on speed is hard to clear.
4. The dependence of the indicator Q_M (according to the average forces) on speed is quite apparent. The indicator Q_M correlates better with the running speed when the wagon is empty. The authors propose to describe this correlation in the third-degree polynomial. In this case coefficient of determination R^2 is equal to 0.7978 and 0.9182.
5. Reducing train speeds from 80–90 km/h to 50–60 km/h does not improve the correlation of the magnitude of wagon wheel damage with measured vertical forces. This does not improve the quality of the determination of the magnitude of possible wheel damage. It is necessary to reduce the speed to 30–40 km/h to improve the correlation of the magnitude of wheel damage with the vertical forces.

References

1. Dersch, M.S., Silva, M.T., Edwards, J.R., Lima, A.D.O.: Analytical nonlinear modeling of rail and fastener longitudinal response: 036119812110693 (2022). https://doi.org/10.1177/03611981211069350
2. Edwards, J.R., Cook, A., Dersch, M.S., Qian, Y.: Quantification of rail transit wheel loads and development of improved dynamic and impact loading factors for design **232**, 2406–2417 (2018). https://doi.org/10.1177/0954409718770924
3. Trizotto, M., Dersch, M.S., Edwards, J.R., Lima, A.: Analytical elastic modeling of rail and fastener longitudinal response **2675**, 164–177 (2021). https://doi.org/10.1177/0361198120985848
4. Cortis, D., Bruner, M., Malavasi, G.: Development of a wayside measurement system for the evaluation of wheel-rail lateral contact force. Measurement **159**, 107786 (2020). https://doi.org/10.1016/J.MEASUREMENT.2020.107786
5. Boronenko, Y., Rahimov, R.: Waail Mahmod Lafta: develop a new approach measuring the wheel/rail interaction loads. In: Proceedings 2021 Joint Rail Conference JRC 2021 (2021). https://doi.org/10.1115/JRC2021-58471

6. Dersch, M.S., Trizotto, M., Edwards, J.R., Oliveira, A.D.: Quantification of vertical, lateral, and longitudinal fastener demand in broken spike track: inputs to mechanistic-empirical design (2021). https://doi.org/10.1177/09544097211030736
7. Maglio, M., Pieringer, A., Nielsen, J.C.O., Vernersson, T.: Wheel–rail impact loads and axle bending stress simulated for generic distributions and shapes of discrete wheel tread damage. J. Sound Vib. **502**, 116085 (2021). https://doi.org/10.1016/J.JSV.2021.116085
8. Jastremskas, V., Vaičiūnas, G., Černašejus, O., Rudzinskas, V.: Investigation into the mechanical properties and metal creaks of a diesel locomotive wheel. Vilnius Gedim. Tech. Univ. **25**, 287–292 (2011). https://doi.org/10.3846/TRANSPORT.2010.35
9. Juršėnas, V., Vaičiūnas, G.: A survey of methods used for assessing the performance of diesel locomotives. Transport **22**, 28–30 (2007). https://doi.org/10.1080/16484142.2007.9638092
10. Gorbunov, M., et al.: Estimation of sand electrification influence on locomotive wheel/ rail adhesion processes. Eksploat. i Niezawodn. **21**, 460–467 (2019). https://doi.org/10.17531/EIN.2019.3.12
11. Radmehr, A., Ahangarnejad, A.H., Pan, Y., Hosseini, S.M., Tajaddini, A., Ahmadian, M.: Wheel-rail contact patch geometry measurement and shape analysis under various loading conditions. In: 2020 Joint Rail Conference JRC 2020. (2020). https://doi.org/10.1115/JRC2020-8042
12. Yılmaz Sönmez, H., Öztürk, Z.: Effects of traffic loads and track parameters on rail wear: a case study for Yenikapi-Ataturk airport light rail transit line. Urban Rail Transit. **6**, 244–264 (2020). https://doi.org/10.1007/S40864-020-00136-1/TABLES/20
13. Jagadeep, B., Kiran Kumar, P., Subbaiah, K.V.: Stress Analysis on Rail Wheel Contact. Int. J. Res. Eng. **95**, 319–325 (2018)
14. Nafari, S.F., Gül, M., Hendry, M.T., Otter, D., Cheng, J.J.R.: Operational vertical bending stresses in rail: real-life case study. J. Transp. Eng. Part A Syst. **144**, 05017012 (2017). https://doi.org/10.1061/JTEPBS.0000116
15. Bureika, G., Levinzon, M., Dailydka, S., Steisunas, S., Zygiene, R.: Evaluation criteria of wheel/rail interaction measurement results by trackside control equipment. Int. J. Heavy Veh. Syst. **26**, 747–764 (2019). https://doi.org/10.1504/IJHVS.2019.102682

Improving Noise Immunity of Audio Frequency Track Circuits Using Neural Networks and Data Classification

Inna Saiapina(✉), Halyna Holub, and Ivan Kulbovskyi

State University of Infrastructure and Technologies, Kyrylivska Street, 9, Kyiv 04071, Ukraine
inna.saiapina@gmail.com, {golub.galina,kulbovskiy}@ukr.net

Abstract. Track circuits are key elements of railway automation systems, and train safety depends on their reliable operation. During the operation, they are exposed to numerous noises. The article considers a method to improve noise immunity of audio frequency track circuits (AFTC) so that the influence of noise can be reduced by opening the transmission path at the input of a track receiver in the intervals between signal current pulses. It allows to increase the signal-to-noise ratio at the input of a track receiver from 10% to 30%, depending on the noise parameters and the useful signal level. To eliminate noise in the intervals between pulses of the useful signal more effectively, a method of adaptive delay line control is proposed, which will allow to correct adaptively the interval of opening the transmission path, adjusting it to the parameters of the AFTC: the length of the rail line, the carrier frequency of the signal, the insulation resistance and the frequency of the modulating signal. A series of studies was conducted using simulation; according to the results of the studies, a database was created with tables of concordance of the values of the AFTC operation parameters with the signal transmission time. Once the data classification problem was solved, the optimal model structure based on neural networks was chosen, which implements the adaptive delay line control method.

Keywords: Audio frequency track circuit · Noise immunity improvement · Neural networks · Data classification · Simulation modeling

1 Introduction

Track circuits are designed to detect the presence of a train on a section of track. The safety of train traffic and railway automation systems' operation depends on their reliability. Audio-frequency track circuits, which can be utilized in high-speed railways, are commonly used in Ukraine, like in many other countries. Track circuits operate in difficult conditions, as they are affected by numerous noises. The noise is greatly caused by the influence of reverse traction current passing through the rails and traction network, as well as pulse and fluctuation noise. The operation of locomotives with asynchronous electric drives, the use of centralized electric heating of passenger trains, the use of thyristor pulse control of traction motors create dangerous noise, including in the operating frequency range of AFTC [1, 2]. Therefore, the issue of increasing their noise immunity is very relevant.

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 696–705, 2023.
https://doi.org/10.1007/978-3-031-25863-3_67

2 Background and Related Work

Today, the technical and software development level is sufficient for employing advanced technologies to solve problems related to the modernization of AFTC. For example, due to many years of research, French scientists have developed a jointless UM71 track circuit with a low modulation frequency, demonstrating good noise immunity characteristics [3, 4]. Chinese researchers took the French prototype as the basis to develop the ZPW-2000A jointless track circuit, which retains the technical advantages of UM71 while showing increased reliability [5].

Numerous studies of AFTC are explicitly devoted to the problem of noise immunity in their operation. In [6], it is noted that electromagnetic noise and adverse weather conditions can significantly change the parameters of the signal current. Using an automatic system for diagnosing the parameters of the AFTC operation based on neuro-fuzzy logic is proposed to eliminate adverse impacts. In [7], the authors analyze the effect of ambient temperature on the reliability of AFTC operation using a linear regression model. However, that paper does not offer any means to improve the reliability of AFTC in severe conditions. To reduce the probability of error in detecting a signal from the track receiver, in [8], it is suggested to use statistical methods based on determining the mutual correlation function of the reference and received signals. This method has proved to be effective with white Gaussian noise. In [9], a study was conducted to improve the noise immunity of a track receiver by using various methods of modulation and demodulation of the rail line control signal. The obtained results show that expanding the spectrum of the frequency-shift keying signal leads to an increase in the power of harmonic noise, which will fall into the bandwidth of the track receiver. In the case of correlation reception, the best stability is provided with phase-shift keying and the poorest one – with amplitude-shift keying.

A promising trend is the introduction of the latest Artificial intelligence (AI) technologies and algorithms to improve fault identification, fault prediction and noise immunity of AFTC [6]. To solve these problems, researchers use such tools as neural networks [10, 11], neuro-fuzzy logic [7], deep belief network [5], the combined decision tree algorithm and the set theory [12], the support vector machine algorithm [13], and the dynamic time transformation algorithm [14]. In [15], automated noise detection is proposed by applying a wavelet transform and using a neural network classifier. The authors of the article [10] propose using recurrent neural networks with long short-term memory based on the use of available data to improve the reliability of AFTC operations. They also simulate the signal voltage by constructing a mathematical model of an AFTC.

The use of up-to-date technologies can significantly increase the reliability of an AFTC, so the problem of finding optimal methods for those types of AFTC used in the Ukrainian railways is urgent.

The signal current of TRC-3 audio frequency track circuits, which are commonly used in the Ukrainian railways, is a signal of a carrier audio frequency modulated by pulses with a frequency of 8 or 12 Hz. In the intervals between these pulses, a useful signal is not received, although noise may occur, which will have an adverse impact on the track receiver. Therefore, to avoid the effect of this noise, a method is proposed to improve noise immunity of audio frequency track circuits, which allows opening the transmission path at the input of a track receiver in the intervals between signal current

pulses [16]. To implement this method, it is proposed to introduce an adjustable delay line, a single pulse generator and a controlled electronic key to the AFTC equipment (see Fig. 1).

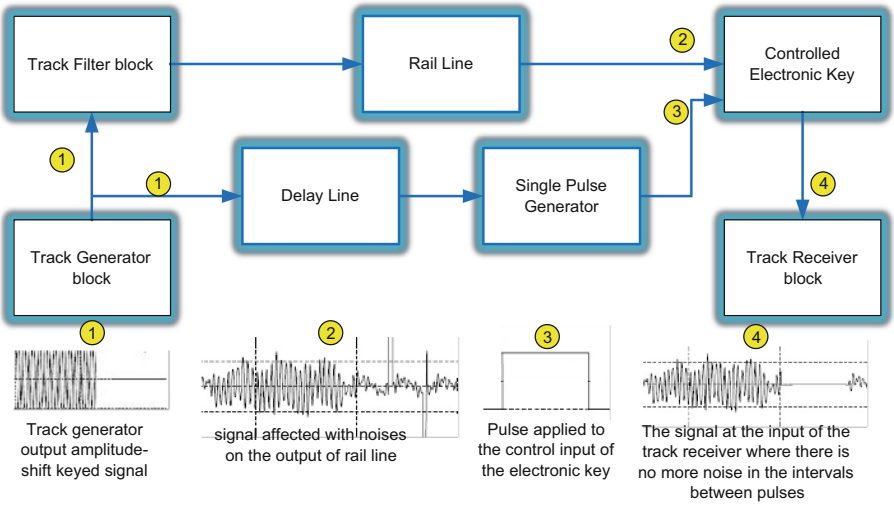


Fig. 1. Implementation structure of the method to improve AFTC noise immunity.

The track generator simultaneously sends a signal to two outputs: to the rail line and to the delay line. The delay line is supposed to synchronize the opening of the electronic key at the input of the track receiver with the interval between the signal current pulses. I.e., the delay line delays the signal for the period of time it takes for the signal current to travel from the output of the track generator through the rail line to the input of the track receiver. A single pulse generator generates the pulse that controls the opening of the electronic key. It should be noted that the pulse duration of the single pulse generator must correspond to the frequency of modulation of the signal current. The delay line must be adjusted for the time of passage of the signal current in the AFTC so that, on the one hand, to prevent the opening of the key during the current pulse, or otherwise, the track circuit may seem false occupied. On the other hand, the influence of maximum noise on the track receiver should be excluded. The time of passage of the signal current in the track circuit is a variable value that depends on the operating conditions of the AFTC. The more accurately this time is determined, the higher the noise immunity of the AFTC can be provided. To solve the problem of accurately determining the delay time t_d for the delay line, it is proposed to develop a neural network based method for adaptive control of the delay line, which essentially means precisely adjusting the signal delay time depending on the parameters of the AFTC operation: the frequency of the carrier signal f_C, the length of the rail line l_{RL}, the insulation resistance R_I and the modulation frequency f_M.

3 Research Method

A large array of data is required to train neural networks, which might be problematic since numerous measurements must be performed on AFTC sections that are constantly involved in the transportation process. Italian researchers in the paper [17] note that simulation of the AFTC operation under various operating conditions can be very helpful for obtaining data, which can replace a series of previous measurements.

A simulation model of the AFTC operation was developed to obtain the necessary data using the Matlab and Simulink mathematical software complex (see Fig. 2). The model structure consists of blocks that simulate the operation of a track generator, a track filter, link lines for centralized equipment placement, track transformers, rail lines of adjacent track circuits, a cable line and a track receiver. The track generator unit is represented by a carrier frequency generator, a pulse generator, and a manipulator. The carrier frequency generator generates a sinusoidal signal of a given frequency and amplitude, which is sent to the first input of the manipulator. A pulse signal with a modulation frequency is sent to the second input of the manipulator. The manipulator multiplies a sinusoidal carrier frequency signal by a pulse signal that is generated with a modulation frequency. The track filter unit uses capacitive, active and reactive resistance elements. The cable and rail line blocks are based on the line model with distributed parameters.

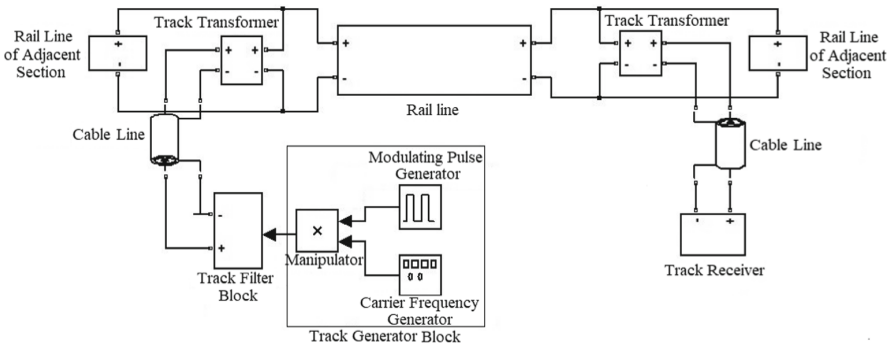


Fig. 2. Structure of the TRC-3 audio frequency track circuit simulation model.

The impact of rail lines of adjacent sections on the AFTC functioning due to the impact of resistances of adjacent sections of the rail lines on the transmitted signal through propagation constant is taken into account.

Using the Mann-Whitney, Fisher, and Student criteria, the insignificance of differences in signal levels at the input of a track receiver obtained both in simulation and in a real device is justified with a confidence probability of 95%. This indicates that the developed model is adequate for the real sample.

A series of studies were conducted using the developed model; according to the results of the studies, a relational database was created with tables of concordance of the values of the AFTC operation parameters based on 521 measurements. The following values were used for simulation. TRC-3 signal current frequencies: 420 Hz, 480 Hz,

580 Hz, 720 Hz and 780 Hz; the rail line lengths: 0.2 km, 0.5 km, 0.8 km and 1 km; insulation resistance: 0.85 Ω·km, 1 Ω·km, 2 Ω·km, 10 Ω·km, 25 Ω·km and 50 Ω·km; frequency of modulation 8 or 12 Hz.

The t_d value was obtained based on the difference in the phase of the signal current between the initial phase at the output of the track generator and the phase at the input of the track receiver. As a result of the simulation, the minimum signal delay time of 0.246 ms corresponds to a signal with a frequency of 780 Hz with a rail line length of 0.2 km and an insulation resistance of 50 Ω·km. The maximum delay time of 0.927 ms corresponds to a signal with a frequency of 420 Hz with a rail line length of 1 km and an insulation resistance of 0.85 Ω·km.

The delay line adaptive control method requires an accuracy of less than a millisecond in determining t_d. The neural network training, validation and test input sample x that corresponds to a certain t_d output value, has the following structure:

$$x = |f_{Ci}\, l_{RLi}\, R_{Ii}\, f_{Mi}|, \tag{1}$$

where i is the number of the parameters combination in the input sample.

The required high accuracy of the output t_d value and its dependence on four parameters from the input sample leads to the complexity of the neural network structure, which could satisfy the requirements. To search for a simpler model structure that could implement the delay line adaptive control method, the dataset of the AFTC data mining parameters was performed. Using MS Excel Data Mining package, data was classified based on the decision tree algorithm to determine key input parameters affecting the t_d value (see Fig. 3). During the classification, the algorithm divided the range of t_d values into five intervals, each representing a certain colour on the histogram of the decision tree (see Table 1). The classification results show that the main parameter affecting the t_d value is the frequency of the carrier signal f_C. So it was decided to choose the model structure of an adaptive delay line control device containing five multilayer perceptrons with one hidden layer for each of the five f_C values used in TRC-3. So each perceptron is responsible for determining t_d for one of the f_C values. It was implemented using the Matlab software package together with Simulink and Neural Network Toolbox extensions (see Fig. 4). Due to the model structure where separate neural network is created for each of the five f_C values used in TRC-3, the accuracy of the result is increased and the simulation error is reduced. It also made possible to reduce the complexity of the neural networks structure and simplify perceptrons' training (Fig. 5).

Carrier signal frequency verification blocks of adaptive delay line control device model (Fig. 4) check whether the f_C parameter in the input data sample match the corresponding frequency of the neural network. If it does, then the output of the verification block receives a logical 1, otherwise – a logical 0. Thus, blocks *I1–I5* reset their outputs unless the signal f_C matches, and the adder output receives only the t_d value (in ms) from the neural network, which gives an accurate result for this particular f_C of the signal based on the analysis of the other three input parameters: l_{RL} (in km), R_I (in Ω·km) and f_M (in Hz). All neural networks are multilayer perceptrons with direct signal propagation and reverse error propagation. The activation function is a smooth and continuous hyperbolic tangent function. Neural networks 1–4 have fifteen neurons in a hidden layer and were trained using the Levenberg-Marquardt algorithm [18, 19]

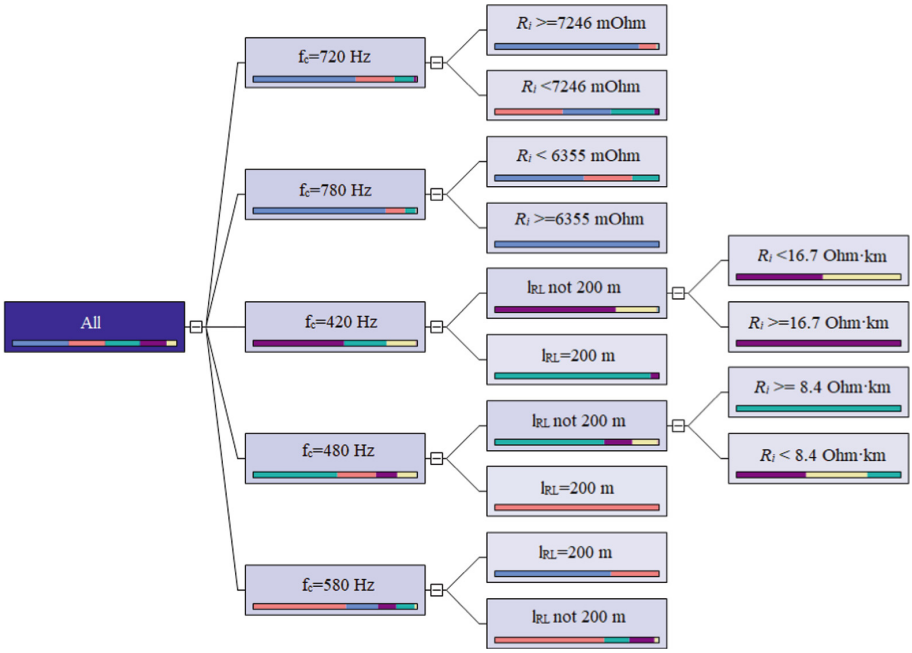


Fig. 3. Decision tree for the delay time parameter obtained from data classification results.

which is applied to optimize the parameters of nonlinear regression models. To train the neural network 5 with twenty neurons in a hidden layer, which adapts the delay value for signals with a carrier frequency of 720 Hz, the best result was obtained with the Bayesian regularization [20] for adjusting weights and offsets, which is based on the Levenberg-Marquardt algorithm. This method minimizes the combination of error squares and weights to obtain the best generalizing properties of the neural network. The number of neurons in the hidden layer and the training method were selected experimentally to meet the required training accuracy (Fig. 5). The simulated dataset of 521 parameters combination for neural networks 1–4 was divided into 3 sets: training dataset (70%), validation dataset (15%), and testing dataset (15%). For neural network 5 it was divided as 70% for training dataset and 30% for testing dataset due to Bayesian regularization method where validation is disabled by default so that training can continue until an optimal combination of errors and weights is found.

4 Research Results

The effectiveness of the introduction of an adjustable delay line, a single pulse generator and an electronic key for improving AFTC noise immunity is based on comparing signal-to-noise ratio (SNR) without using the proposed decision with the SNR while using it [21]

$$SNR_{db} = 10 \cdot \lg\left(\frac{P_{signal}}{P_{interference}}\right), \tag{2}$$

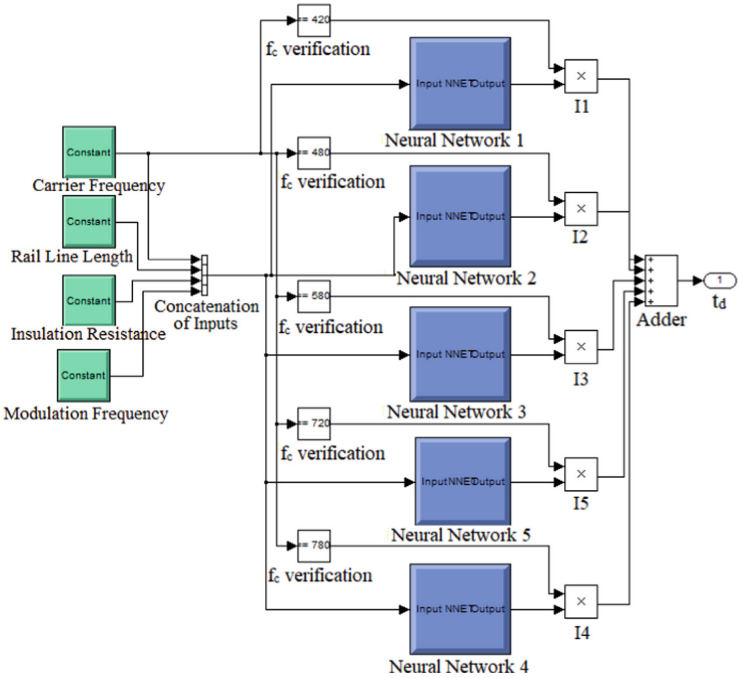


Fig. 4. Structure of the adaptive delay line control device model.

Table 1. Data mining designations.

t_d interval, ms	Number of t_d values corresponding to the interval	Probability, %	Histogram
< 0.35	118	32.06	
0.35-0.47	83	22.8	
0.47-0.56	79	21.75	
0.56-0.67	59	16.46	
>=0.67	23	6.93	

where P_{signal} is the average power dissipated by the signal; $P_{interference}$ is the average power dissipated by the interference signal; SNR_{dB} is a signal-to-noise ratio, calculated in dB.

To define P_{signal} and $P_{interference}$, simulation modeling of the AFTC operation under affection of noises from reverse traction current, thyristor regulation, pulse interference, and fluctuation interference was carried out. The proposed implementation of the method of AFTC noise immunity improvement (Fig. 1) makes it possible to increase the signal-to-noise ratio at the input of a track receiver from 10% to 30%, depending on the noise parameters and the useful signal level.

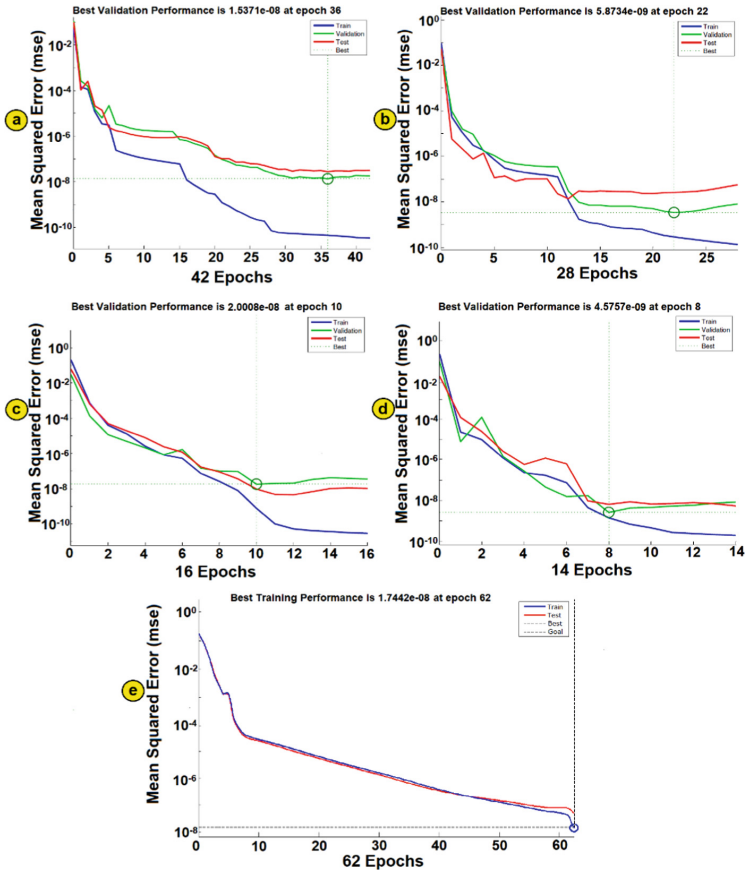


Fig. 5. Neural Networks training, validation and test results: a) the 1st Neural Network; b) the 2nd Neural Network; c) the 3rd Neural Network; d) the 4th Neural Network; e) the 5th Neural Network.

To estimate the maximum efficiency of the proposed adaptive delay line control method, let assume that during the normal operation, the delay line will be set to the average delay time of $t_{d\,average} = 0.4546$ ms. The obtained delay times suggest that this method for TRC-3 allows to increase the accuracy of the time interval up to 0.47 ms.

The proposed solutions for improving the noise immunity of AFTC can be used on tracks equipped with TRC-3 with centralized placement of equipment.

5 Conclusions

The Authors consider a method to improve noise immunity of audio frequency track circuits that helps reduce the effect of noises by opening the transmission path at the input of a track receiver in the intervals between signal current pulses. The implementation of the proposed method allows for an increase in the signal-to-noise ratio at the input

of a track receiver from 10% to 30%, depending on the noise parameters and the useful signal level.

To eliminate noise in the intervals between pulses of the useful signal more effectively, a method of adaptive delay line control is proposed, which will allow adapting delay time parameters depending on the length of the rail line. The carrying signal frequency, the insulation resistance and the frequency of the modulating signal. Using the results of the data containing information classification on the impact of AFTC operation parameters on signal transmission time, the optimal model structure based on neural networks implementing the adaptive delay line control method was selected. The model is based on neural networks with direct signal propagation and reverses error propagation. The Levenberg-Marquardt algorithm and the Bayesian regularization were used for training. The adaptive delay line control method for TRC-3 with a carrier signal frequency from 420 Hz to 780 Hz, a rail line length from 200 m to 1,000 m, and an insulation resistance from 0.85 Ω·km to 50 Ω·km allows for an increase in the accuracy of setting the delay line time interval up to 0.47 ms.

References

1. Havrilyuk, V.I., Shcheka, V.I., Meleshko, V.V.: Testing new types of rolling stock for electromagnetic compatibility with signaling and communication devices. Sci. Transp. Prog. **5**(59), 7–15 (2015). (in Russian). https://doi.org/10.15802/stp2015/55352
2. Havryliuk, V.: Model of propagation of traction current harmonics from trains to a track circuit receiver. In: 2021 Asia-Pacific International Symposium on Electromagnetic Compatibility (APEMC), pp. 1–4 (2021). https://doi.org/10.1109/APEMC49932.2021.9597152
3. Park, K.B., Park, J.Y., Jang, M.S., Lim, M.S., Kim, S.H.: A study on the internal modeling of track circuit (UM71-C) on HSL. In: Proceedings of. KIEE Conference Korean Institute of Electrical Engineers, pp. 1130–1131 (2006). (in Korean)
4. Debiolles, A., Oukhellou, L., Aknin, P., Denoeux, T.: Track circuit automatic diagnosis based on a local electrical modelling. In: Proceedings of WCRR, pp. 4–8 (2006)
5. Zheng, Z., Dai, S., Xie, X.: Research on fault detection for ZPW-2000A jointless track circuit based on deep belief network optimized by improved particle swarm optimization algorithm. IEEE Access. **8**, 175981–175997 (2020). https://doi.org/10.1109/ACCESS.2020.3025628
6. Havryliuk, V.: ANFIS based detecting of signal disturbances in audio frequency track circuits. In: 2020 IEEE 2nd International Conference on System Analysis & Intelligent Computing (SAIC), pp. 1–6 (2020). https://doi.org/10.1109/SAIC51296.2020.9239127
7. Huang, Z., Li, S., Wei, X.: Analysis of temperature impact on audio frequency track circuits using linear regression model. In: AIP Conference Proceedings vol. 1834, p. 020019 (2017). https://doi.org/10.1063/1.4981558
8. Goncharov, K.V.: The correlated track receiver of tone track circuits. Sci. Transp. Prog. **38**, 188–193 (2011). (in Russian). https://doi.org/10.15802/stp2011/6837
9. Goncharov, K.V.: Comparative analysis of modulation and demodulation methods of the control signals of rail line. Sci. Transp. Prog. **42**, 12–19 (2012). (in Russian). https://doi.org/10.15802/stp2012/9223
10. de Bruin, T., Verbert, K., Babuška, R.: Railway track circuit fault diagnosis using recurrent neural networks. IEEE Trans. Neural Netw. Learn. Syst. **28**(3), 523–533 (2017). https://doi.org/10.1109/TNNLS.2016.2551940
11. Huang, Z.W., Wei, X.Y., Liu, Z.: Fault diagnosis of railway track circuits using fuzzy neural network. J. China Railw. Soc. **34**(11), 54–59 (2012). (in Chineese). https://doi.org/10.3969/j.issn.1001-8360.2012.11.009

12. Zhu, W.B., Wang, X.M.: Research on fault diagnosis of railway jointless track circuit based on combinatorial decision tree. J. China Railw. Soc. **40**(7), 74–79 (2018). (in Chineese). https://doi.org/10.3969/j.issn.1001-8360.2018.07.011
13. Zhang, M.: Railway track circuit fault diagnosis based on support vector machine with particle swarm optimization. In: 2013 International Conference on Electrical, Control and Automation Engineering, pp.113–117. DEStech Publications, Lancaster (2013)
14. Dong, W.: Fault diagnosis for compensating capacitors of jointless track circuit based on dynamic time warping. In: Mathematical Problems in Engineering, vol. 2014, pp. 2–13. Hindawi Publishing Corporation, New York (2014)
15. Havryliuk, V.: Audio frequency track circuits monitoring based on wavelet transform and artificial neural network classifier. In: 2019 IEEE 2nd Ukraine Conference on Electrical and Computer Engineering (UKRCON), pp. 491–496 (2019). https://doi.org/10.1109/UKRCON.2019.8879833
16. Saiapina, I.O.: Improvement of methods and means to increase audio frequency track circuits noise immunity. thesis of Ph.D. Ukrainian State University of Railway Transport, Kharkiv (2017). http://lib.kart.edu.ua/bitstream/123456789/4080/1/dis_Saiapina.pdf.pdf. Accessed 15 June 2022. (in Ukrainian)
17. Mariscotti, A., Ruscelli, M., Vanti, M.: Modeling of audio frequency track circuits for validation, tuning, and conducted interference prediction. IEEE Trans. Intell. Transp. Syst. **11**(1), 52–60 (2010). https://doi.org/10.1109/TITS.2009.2029393
18. Levenberg, K.A.: Method for the solution of certain problems in least squares. Q. Appl. Math. **2**. 164–168 (1944)
19. Ranganathan, A.: The Levenberg-Marquardt algorithm. Tutor. LM Algorithm. **11**, 101–110 (2004)
20. Foresee, F.D., Hagan, M.T.: Gauss-Newton approximation to Bayesian learning. In: Proceedings of the International Joint Conference on Neural Networks, pp. 1930–1935. Institute of Electrical and Electronics Engineers, San Jose (1997)
21. Saiapina, I., Babaiev, M., Ananieva, O.: Reducing noise influence on an audio frequency track circuit. MATEC Web Conf. **294**, 03015 (2019). https://doi.org/10.1051/matecconf/201929403015

Comparison of Railway Development in the Countries of the World

Gediminas Vaičiūnas(✉)

Vilnius Gediminas Technical University, Saulėtekio Av. 11, 10223 Vilnius, Lithuania
gediminas.vaiciunas@vilniustech.lt

Abstract. According to the author, the development of the railway system in a country is best determined by the ratio of the length of the railway to the area of that country, the population and the gross domestic product. Using this principle, the author analyzes the railway development of the 10 longest railway states in the world. The regularity of the length of the state railways correlated with the railway development indicators calculated by the author was observed in the research. In the case of the 10 countries with the longest railways, the values of the railway development indicator proposed by the author vary according to the law close to the normal distribution.

Keywords: Development of rail transport · Indicator of the development · Length of railways

1 Introduction and Literature Review

The development of rail transport and the construction of new railway lines require research into the rail network in those areas. Depending on the nature of the area, the railway network faces corresponding problems. For example, countries close to the seas or oceans may face the problem of the impact of floods on the rail network. [1]. Countries with fast-growing economies face challenges to the dynamics of the rail network [2]. Countries at the crossroads of transport corridors face a priority problem [3]. Countries with large areas and long railway lines are looking at the specifics of high-speed trains [4]. The multiplicity of carriers and trains raises the issue of scheduling [5]. The question arises as to how to group carriers, how to create clusters [6]. Issues of competition and cooperation between carriers are addressed [7]. Planning work on the rail network is important to achieve competitiveness [8]. The issue of transport corridors differs slightly in different parts of the world, for example Europe is now focusing on integration [9]. It is very important to integrate the countries of Eastern Europe into a common railway network [10]. Therefore, a strategic approach to multi-criteria decisions is becoming relevant [11]. To this end, interactive maps are developed and strategically evaluated [12]. Information technology also occupies a recent place in e-business logistics [13]. Depending on the specifics of the area, other railway issues

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 706–715, 2023.
https://doi.org/10.1007/978-3-031-25863-3_68

may arise. In mountainous areas, for example, locomotive wheel flanges are worn and metal fatigue is more common on plains [14]. In countries where railways are electrified and electric vehicles are used, their operation is different from in countries where diesel vehicles are used [15]. However, one of the most common questions about railways in different countries is the assessment of the development of the railway system in the country.

2 Methodology of Investigation

The purpose of this study is to compare the development of railways in the largest railway countries. In order to evaluate the development of railways in one or another country, it is first necessary to choose evaluation criteria. According to the author, the development of the railway system in a country is best determined by the ratio of the length of the railway to the area of that country, the population and the gross domestic product. This opinion is based on the fact that the number of inhabitants, the gross domestic product and the area of the country are sub-basic indicators determining the size of the state (or other unit). Accordingly, the ratio of railway length to the above-mentioned indicators shows the development of railways in the country in relation to other indicators of that country. Various methods are available to summarize the meanings of these relationships. In this case, the author tends to underestimate the method, and chooses one of the simplest - the geometric mean method. Its essence is that after normalizing the values of the considered indicators, their geometric mean is calculated (according to each alternative), and a priority order of alternatives is formed based on the value of the mean.

First of all, data are collected and analyzed: length of railways, area of countries, population, gross domestic product. This study collects data from about 10 countries with the longest rail length in the world. Then the ratio of the length of the railway to the area of the country, the population and the gross domestic product is calculated. Each relative indicators has different units of measurement. To summarize them, they are normalized. The arithmetic and geometric mean of the normalized values are calculated. Based on these values, conclusions are drawn about the development of railways in one country or another in the world. The course of the research conducted based on this principle and the results obtained are presented below in the article.

3 Research Progress and Results

The length of the railway in one country or another is generally considered to be the main indicator of the development of the railway system. The TOP 10 countries in the world in terms of railway length are shown in Fig. 1.

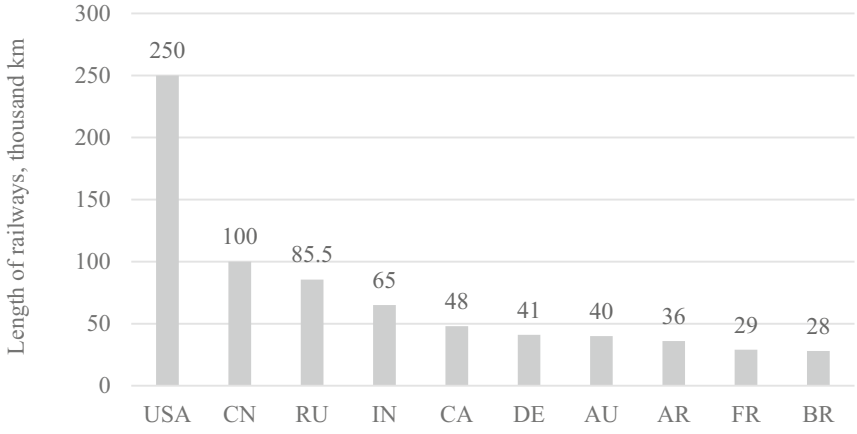


Fig. 1. Countries with the longest railways in the world.

Naturally, the United States is in first place, China in second place and Russia in third place. One of the factors determining the need for a railway network in a country is the size of the country. The area of the countries shown in Fig. 1 is shown in Fig. 2, respectively.

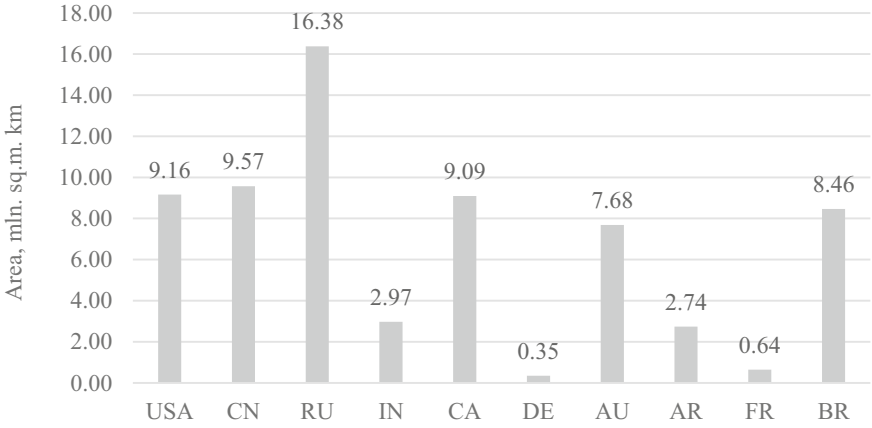


Fig. 2. Area of countries with the most developed railway system.

It should be noted that the first three countries are the same in terms of area, only the order of the countries differs - here: Russia, China, USA. Another reason for the development of the railways is the population. The population of the countries with the most developed railway system is shown in Fig. 3.

Fig. 3. Population of countries with the most developed railway system.

In addition to the first three of countries with the most developed railway system, Brazil appears here, and it also has a large population (more than 200 million). China has by far the largest population (close to 1.5 billion), followed by the United States (over 300 million). The possibility of developing the railway system is largely determined by the country's economic development. It is usually defined as gross domestic product. The gross domestic product of the countries with the most developed railway system is shown in Fig. 4.

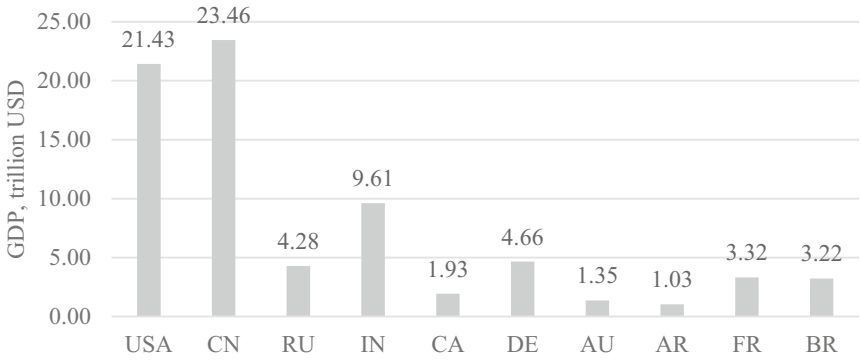


Fig. 4. Gross domestic product of countries with the most developed railway system.

In terms of gross domestic product, the world leaders are the US and China. As can be seen from the data in Figs. 1, 2, 3 and 4, the development of railways is related to indicators such as the area of the country, the population, the gross domestic product, but these values are not always correlated. It is therefore interesting to examine relative indicators such as the length of the railway per unit area, population, or unit of domestic product. The length of the railway per unit area by country is shown in Fig. 5.

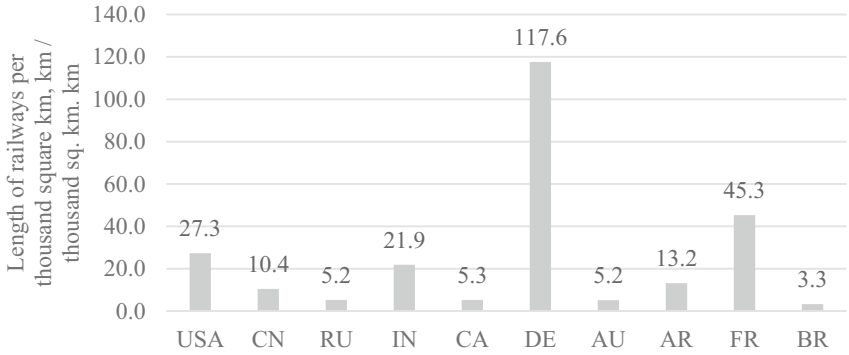


Fig. 5. Length of railway per unit area.

Figure 5 shows that Germany, France and the United States account for the largest share of the country's railway area. Meanwhile, countries such as Russia or Australia have a low rate in this respect, as these countries have a very large area compared to the other countries in question. The length of the railway per million inhabitants of the country is shown in Fig. 6.

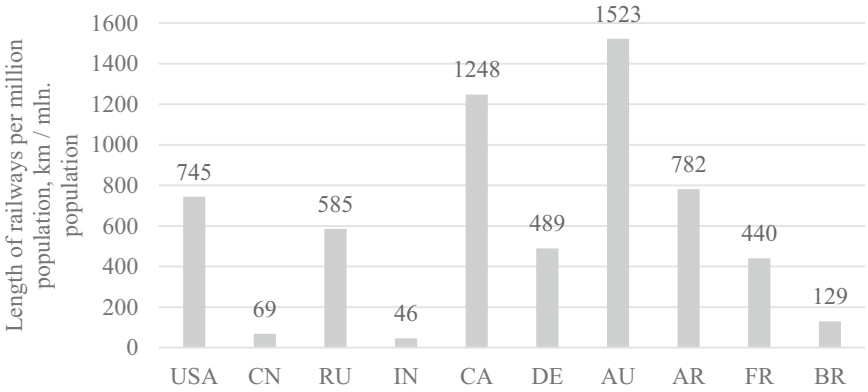


Fig. 6. The length of the railway per million inhabitants of the country.

The length of railways per million inhabitants is highest in Australia, Canada, Austria and the United States. Australia is a large but not very densely populated country, so the railway has a large population of one million. Understandably, China or India, due to its large population, have a lower rate. Assessing the development of the railways in terms of their economies requires an assessment of their GDP. The length of the rails flowing to the country's BVB unit is shown in Fig. 7.

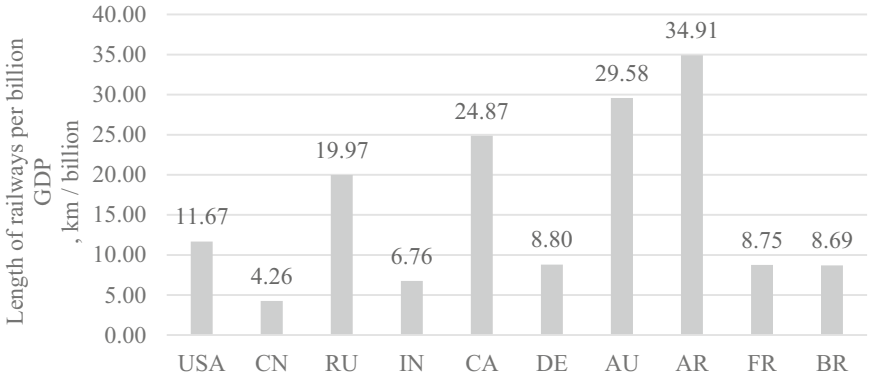


Fig. 7. Length of railways flowing to the country's BVB unit.

Austria, Australia, Canada and Russia lead in terms of the length of railways flowing to the country's BVB unit. These are countries with a well-developed railway system but relatively low GDP. To summarize the various ratios, they can be normalized first. The normalized values of the railway length per unit area are shown in Fig. 8.

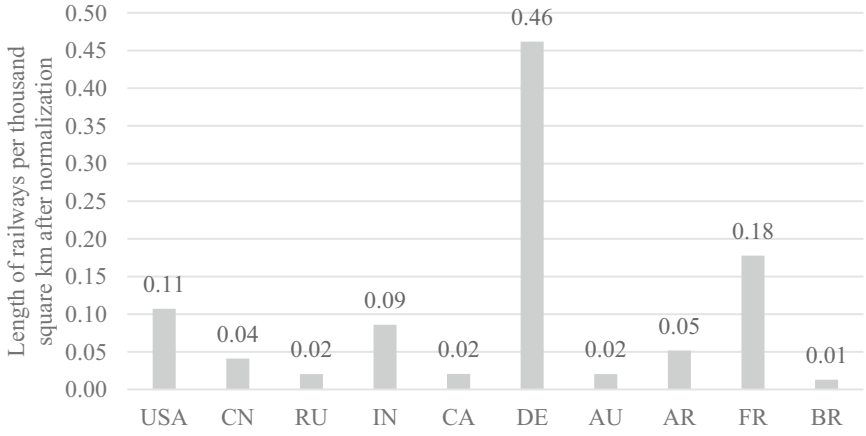


Fig. 8. Length of railways flowing to the country's BVB unit.

Austria, Australia, Canada and Russia lead in terms of the length of railways flowing to the country's BVB unit. These are countries with a well-developed railway system but relatively low GDP. To summarize the various ratios, they can be normalized first. The normalized values of the railway length per unit area are shown in Fig. 8.

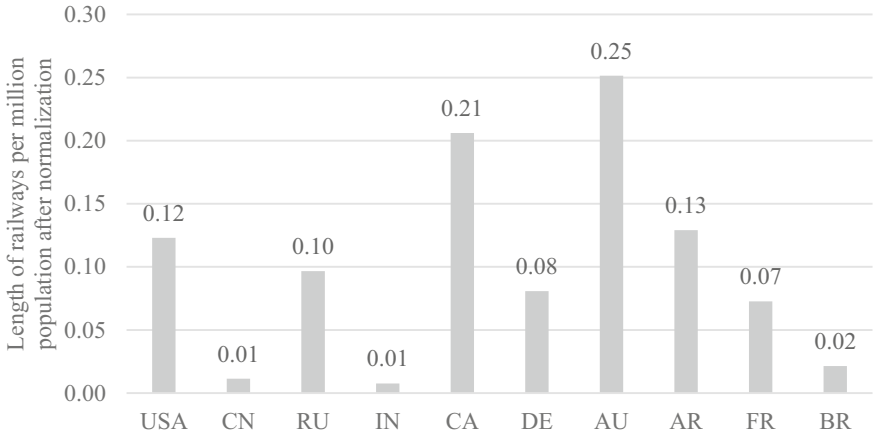


Fig. 9. The normalized ratio of railway length to population.

The format of the graph in Fig. 9 is similar to the graph in Fig. 6, only the sum of the values in Fig. 9 is equal to 1. The normalized values of the length of the railway per unit of GDP of the country are shown in Fig. 10.

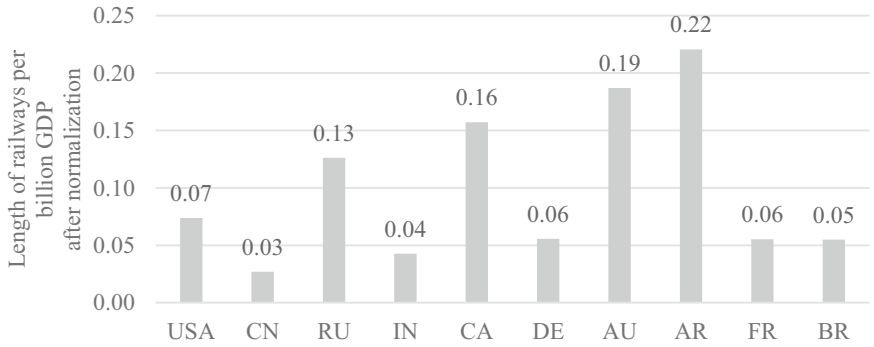


Fig. 10. The normalized values of railway length per unit of GDP of the country.

The shape of the graph in Fig. 10 is similar to the graph in Fig. 7, only the sum of the values in Fig. 10 is equal to 1. The graphs in Figs. 8, 9, and 10 are in the same format as the graphs in Figs. 8, 6, and 7. However, in Figs. 8, 9, and 10, the sum of the values is equal to 1 because the values of the ratios are normalized. After normalizing the values of the relative indicators, they can be generalized to each other. This cannot be done without normalizing the values, as different indicators have different physical meanings. On the one hand, the arithmetic mean of the normalized values can be calculated by summing. However, since normalized indicators are relative, a geometric mean is usually calculated in such cases. Therefore, the decision-making method is called the geometric mean method. Figure 11 shows the values of the arithmetic means and geometric means of the normalized values of the relative railway development indicators.

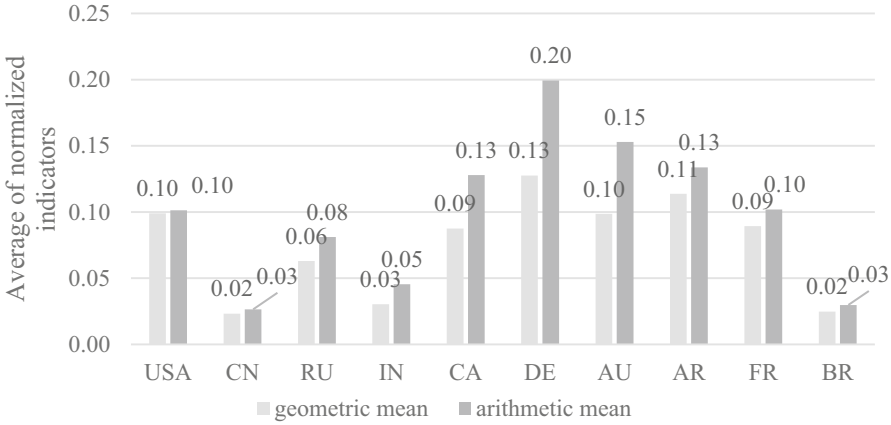


Fig. 11. Averages of normalized values of ratios.

Based on the data in Fig. 11, the development of railways in the countries can be compared with other indicators of these countries (such as country area, population, GDP). It should be noted that the scatter of the geometric mean values is monthly than that of the arithmetic mean values. When examining the values of the arithmetic mean, more pronounced peaks are observed. Although it is more mathematically correct to derive the values of the geometric mean (since normalized ratios are considered). The geometric average shows that the development of railways (in relation to other indicators of the country) is highest in Germany and Austria, followed by the USA, Australia and France. It is interesting to note that in Fig. 11 the countries are in descending order of the length of the railway network (the largest in the US and the shortest in Brazil). If the US indicator is ignored, the normal distribution law can be observed in Fig. 11. Consequently, the countries with the average length of the railway network (looking at the 10 main countries) have the best developed railway performance in terms of other indicators.

4 Conclusions

It is not sufficient to estimate the length of the railway network in that country alone to assess the development of the railways in one country or another. The length of the railway network needs to be assessed in relation to other indicators in the country.

In order to estimate the length of the railway network in relation to other indicators of the country, such indicators as the area of the country, the population, and the GDP of the country can be used.

After calculating the ratio of the length of the railway network to the area of the country, population and GDP, the level of railway development in the country can already be seen in relation to other indicators, but it is not possible to summarize them due to differences in their physical meaning.

In order to summarize the relative indicators, such as the ratio of the length of railways in the country to the area of the country, the population, the country's GDP, it

is necessary to normalize the value of the indicators. The arithmetic, and preferably the geometric mean, of the normalized values can then be calculated.

The analysis of the 10 countries with the longest railway network in the world shows that the countries with the average length of the railway network (out of the 10 countries examined) have the best railway development in terms of other indicators. The exception is the United States, which has a good track record in terms of other indicators.

References

1. Lamb, R., Garside, P., Pant, R., Hall, J.W.: A probabilistic model of the economic risk to Britain's railway network from bridge scour during floods. Risk Anal. **39**(11):2457–2478 (2019). https://doi.org/10.1111/risa.13370
2. Huang, Y., Lu, S., Yang, X., Zhao, Z.: Exploring railway network dynamics in China from 2008 to 2017. ISPRS Int. J. Geo-Inf. **7**(8), 320 (2018). https://www.mdpi.com/2220-9964/7/8/320/htm
3. Vaičiunas, G., Steišunas, S.: Investigation of priority directions of rail Baltica extension from Warsaw. Proc. Eng. **187**, 40–45 (2017)
4. Xu, G., Yang, H., Liu, W., Shi, F.: Itinerary choice and advance ticket booking for high-speed-railway network services. Transp. Res. Part C Emerg. Technol. **95**, 82–104 (2018)
5. Zhang, C., Gao, Y., Yang, L., Gao, Z., Qi, J.: Joint optimization of train scheduling and maintenance planning in a railway network: a heuristic algorithm using Lagrangian relaxation. Transp. Res. Part B Methodol. **134**, 64–92 (2020)
6. Nežerenko, O., Koppel, O.: Formal and informal macro-regional transport clusters as a primary step in the design and implementation of cluster-based strategies. Transp. Telecommun. **16**(3), 207–216 (2015)
7. Saeedi, H., Wiegmans, B., Behdani, B., Zuidwijk, R.: Analyzing competition in intermodal freight transport networks: the market implication of business consolidation strategies. Res. Transp. Bus Manag. **23**, 12–20 (2017)
8. Consilvio, A., Di Febbraro, A., Meo, R., Sacco, N.: Risk-based optimal scheduling of maintenance activities in a railway network. EURO J. Transp. Logist. **8**(5), 435–465 (2018). https://doi.org/10.1007/s13676-018-0117-z
9. Sładkowski, A., Cieśla, M.: Analysis and development perspective scenarios of transport corridors supporting Eurasian trade. In: Sładkowski, A. (ed.) Transport Systems and Delivery of Cargo on East–West Routes. SSDC, vol. 155, pp. 71–119. Springer, Cham (2018). https://doi.org/10.1007/978-3-319-78295-9_2
10. Miljković, M.M., Gavrilović, B.J., Vujačić, J.P.: The trans-European transport corridors: contribution to economic performances of European regions. Industrija. **46**(2), 173–187 (2018). https://aseestant.ceon.rs/index.php/industrija/article/view/18043
11. Munier, N., Hontoria, E., Jiménez-Sáez, F.: Strategic Approach in Multi-Criteria Decision Making, vol. 275, ISOR. Springer, Cham (2019). https://doi.org/10.1007/978-3-030-02726-1
12. Abastante, F., Günther, F., Lami, I.M., Masala, E., Pensa, S., Tosoni, I.: Analytic network process, interactive maps and strategic assessment: the evaluation of Corridor24 alternative development strategies. In: Lami, I.M. (ed.) Analytical Decision-Making Methods for Evaluating Sustainable Transport in European Corridors. SSISS, vol. 11, pp. 205–232. Springer, Cham (2014). https://doi.org/10.1007/978-3-319-04786-7_12

13. Frąś, J., Scholz, S., Olsztyńska, I., Frąś, J., Scholz, S., Olsztyńska, I.: Modern information technologies in the logistics of e-business. Res. Logist. Prod. **7**(4), 285–297 (2017)
14. Jastremskas, V., Vaičiūnas, G., Černašejus, O., Rudzinskas, V.: Investigation into the mechanical properties and metal creaks of a diesel locomotive wheel. Vilnius Gediminas Tech. Univ. **25**(3), 287–292 (2011). https://www.tandfonline.com/doi/abs/10.3846/transport.2010.35
15. Juršėnas, V., Vaičiūnas, G.: A survey of methods used for assessing the performance of diesel locomotives. Transport. **22**(1), 28–30 (2007). https://www.tandfonline.com/action/journalInformation?journalCode=tran20

Changes in the Passenger Sector in the COVID-19 Era

Agata Pomykala(✉)

Railway Research Institute, 50, Chlopickiego, 04-275 Warsaw, Poland
apomykala@ikolej.pl

Abstract. The article presents the changes that took place on the rail passenger transport market in 2020 – the first year of the SARS-CoV-2 pandemic, with particular emphasis on rail passenger transport in Poland. The considerations concern passenger transport segments represented by: PKP Intercity – a long-distance operator, SKM Warszawa, working as a agglomeration operator. The analysis of the available data shows that: regardless of the market segment, the year 2020 for railway companies was characterized by significant declines in the volume of transports which reached the lowest level in March and April. Those changes were correlated with the level of restrictions on the people's movement. While preparing the article, the data and available sources were used and the methods of analysis and synthesis in addition. The results are presented in tabular form and the text is enriched with graphs.

Keywords: Transportation · Railway · Passenger sector · COVID-19

1 Introduction

The results of research on the impact of COVID-19 on the transport sector have been published since the beginning of 2020 by organizations representing urban transport, road, railway and aviation. COVID-19 is also of interest to worldwide researchers from a variety of research communities and research positions. Concerning mobility and transport, many papers were published describing the phenomena occurring in different countries, e.g. in France [1], in Germany [2] and in Sweden [3]. Research carried out in parallel on almost all continents provides a rare opportunity to observe the same phenomenon in different environments and contribute to understanding different aspects of the coronavirus impact (more generally) on society. Research conducted in the USA suggests that crowded spaces play a more important role than population density in the spread of COVID-19 and the type of occupation, while the patterns of commuting to work do not play a significant role [4]. When looking for ways to reduce the spread of SARS-CoV-2, attempts are made to identify the important growth factors, routes, and methods of its transmission. There are opinions among the authors pointing to the leading role of public transport systems [5], as well as denying them [6].

The German Koch Institute indicated that 0.2% of traceable outbreaks in Germany were linked to transport, and involved fewer people per outbreak than those infrequently

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 716–725, 2023.
https://doi.org/10.1007/978-3-031-25863-3_69

affected settings [7]. French Public Institute on Health Information showed that only 1.2% of Covid-19 clusters were linked to transport (land, air, and sea). They mainly come from workplaces (24.9%), schools and universities (19.5%), healthcare venues (11%), temporary public and private events (11%), and family gatherings (7%) [8]. In the UK, an analysis has shown that the risk of contracting Covid-19 while traveling by train is 1 in 11,000 journeys (equivalent to a chance of less than 0.01%, lower than the probability to die in a road accident). With a face covering, it's 1 in 20,000 journeys, or 0.005% [9].

2 Characteristics of the Transport Sector

2.1 The Situation in the EU27

Railway Transport. In early 2020 international railway traffic was stopped in almost all countries, and domestic one decreased by approximately 80% for all national rail services during lockdowns [10]. Passenger services suffered more than freight, but the pandemic affected both types of transport. The loss in the first half of 2020 a passenger rail transport level broke down to 40% in comparison to 2019, and at the end of 2020 – 41%. In 2020 railways lost € 26 billion in revenue in the European Union (EU27), including passenger service – € 24 billion and freight – € 2 billion [11]. Figure 1 presents the percentage of losses in the subsequent months of the second half of 2020 for passenger services.

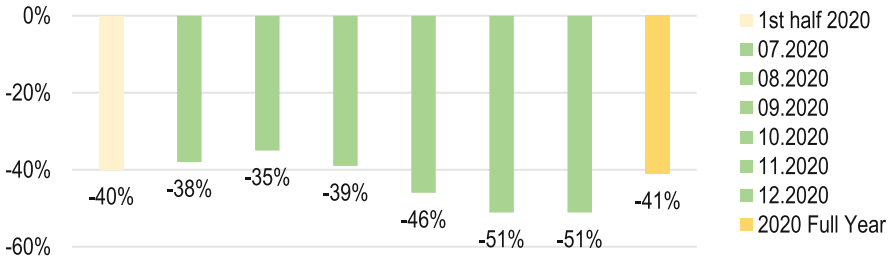


Fig. 1. Losses 2020/2019 in Passenger Services, Source: own elaboration based on [11].

In the transport of goods, the situation throughout 2020 was significantly better than in the transport of passengers, nevertheless in the period January-June the result was 15% lower than that obtained in the comparable period of 2019. The loss at the end of the year was 11%.

Road Transport. Global road transport activity was almost 50% below the 2019 average by the end of March 2020 [24]. During the March/April lockdown, some European toll operators lost up to 90% of traffic and 80% of revenue [12]. The decrease in road traffic reduction compared to the previous year in individual cities around the world differed significantly depending on the severity of infections and the adopted regulations helpful in limiting the spread of the virus. Sweden was the least restrictive of mobility,

not introducing travel bans, but only recommending behaviours limiting the spread of the virus. In comparison of presented periods of time, the decrease in traffic in Stockholm is lower than in others cities. Weekly mobility patterns in the week to the average traffic figures from the same week one year earlier are presented in Table 1.

Table 1. Road traffic reduction related to SARS-CoV-2 in selected cities in selected periods of national emergency, year-on-year.

City	16–22.03.20	11–17.05. 20	6–12.07.20	31.08–6.09.20	19–25.10.20
Barcelona, Spain	−73%	−65%	−31%	−38%	−35%
Manchester, UK	−67%	−53%	−53%	−42%	−42%
Stockholm, Sweden	−48%	−29%	−39%	−10%	−3%
Madrid, Spain	−86%	−73%	−59%	−59%	−32%
Milan, Italy	−74%	−61%	−42%	−35%	−29%

Source: own elaboration based on data [13] [accessed 20.05.2021].

Ban of public transport and international movements across Europe, with the highest impact on the tourism sector, caused significant drops in turnover in road transport: bus & coach urban/local −42%, bus & coach intercity −70%, bus & coach tourism −82%, taxi −60% [10, 14]. The total loss in freight and passenger transportation in 2020 was almost $ 1 trillion [15].

Air Transport. Since 2019, total air connectivity has declined by 68% in Frankfurt, 67% in London, 67% in Paris, 66% in Istanbul, 64% in Moscow, and 53% in Amsterdam [16]. Aviation has been in its gravest moment in history with a collapse in air travel demand globally. Its recovery will be vulnerable and volatile, severely hampered by the resurgence of the outbreak across regions alongside stricter travel restrictions with:

- Overall reduction of 50% of seats offered by airlines.
- Overall reduction of 60% passengers (−2,699 million).
- Approx. USD 371 billion loss of gross passenger operating revenues of airlines.
- Airport revenue USD 125 billion [17].

In all regions passenger revenue losses were recorded: Africa – USD 14 billion, Asia/Pacific – USD 120 billion, Europe – USD 100 billion, Latin America/Caribbean – USD 26 billion, Middle East – USD 22 billion, North America – USD 88 billion [17].

2.2 The Situation in Poland

In Poland, road and air transport almost was frozen, carrying in the weakest month – May 2020 – only 4,986 and 7,000 passengers, respectively. In the rail sector, the worst month was April 2020, when 6,097 people were transported [18].

Significant decreases were recorded in all branches as compared to the corresponding period of the previous year. In aviation, in the worst month, the volume of transport was only half a percent of the result achieved in 2019, in rail −23%, and in the road −21.7%. The comparison every month is shown in Fig. 2.

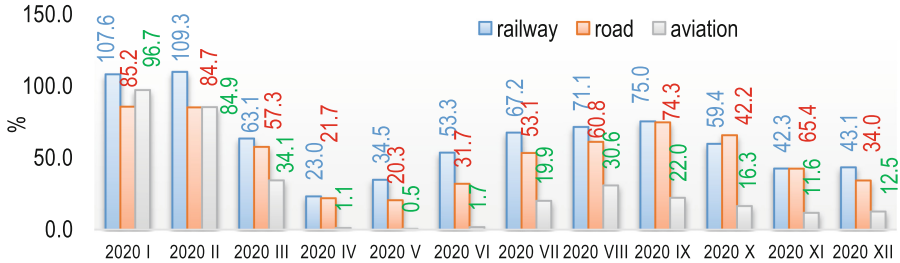


Fig. 2. Change in the number of passengers in relation to the corresponding period of the previous year, Source: own elaboration based on data [18].

Modal Share in Poland. The year 2020 brought changes not only in the number of passengers but also in the inter-industry division. There has been a decline in the share of road and air transport and an increase in the share of rail in the transport market. Although the number of passengers traveling by trains decreased significantly - exceeding 207 million, the share of railways increased by 5% compared to the previous year, and by 10% compared to 2018. In road transport, the reduction in the number of travelers in 2020 by over 125 million resulted in a decrease in the share by 3.2% compared to 2019. The biggest losses were recorded in the aviation sector, whose share, with the number of passengers of 4 million passengers, decreased by 2/3. Figure 3 shows the changes in modal split in Poland in 2020 compared to the previous years.

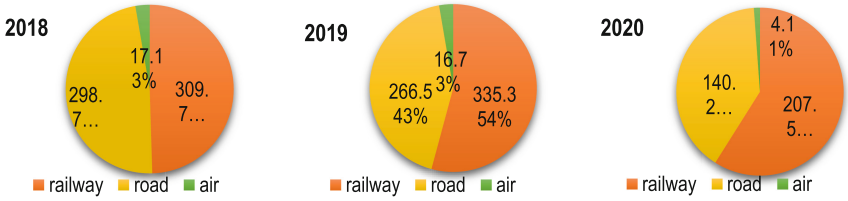


Fig. 3. Modal split in Poland in 2018–2020; number of passengers in M, Source: own elaboration based on data [18].

Changes in Mobility. The regulations introduced in the early stages of COVID-19 development were aimed at stopping the spread of the pathogen. They are mainly concerned with increasing the social distance, limiting the number of people gathering in place, and the movement of people. During the first wave of disease, the most significant decrease in mobility was recorded in places such as restaurants, shopping centers, museums, libraries, and cinemas. However, in the following weeks, there was an increased chance in the mobility of Poles. Since April 20, Poland has started the phase of lifting some of the restrictions related to the coronavirus epidemic, which has resulted in increased mobility in shops and parks. Table 2 shows changes for each day compared to a baseline value which is the median value, for the corresponding day of the week, during the 5-weeks 03.01–06.02 in 2020.

Table 2. Community mobility changes due to the coronavirus (COVID-19) outbreak in Poland from February to June 2020.

29.03.2020	11.04.2020	30.04.2020	7.05.2020	21.05.2020	23.06.2020
Retail and recreation					
−78%	−76%	−28%	−32%	−16%	1%
Parks					
−59%	−57%	25%	16%	47%	89%
Transit points, incl. Railway/metro station, bus/taxi stop, motorway parking space, car rental					
−71%	−64%	−44%	−46%	−38%	−23%
Workplaces					
−36%	−48%	−38%	−32%	−27%	−21%
Residential					
13%	17%	10%	12%	9%	4%

Source: own elaboration based on data [13].

Throughout the year, changes in the average travel distance of passengers in rail transport were observed compared to 2019. The highest difference – nearly 30% was in April 2020, when Poland was subject to the travel ban. The following months brought a gradual improvement in the situation. The following months brought a gradual improvement in the situation. In August 2020, the average length of a train journey was 4.5% lower than in the corresponding month in 2019. The data on different months is presented in Fig. 4.

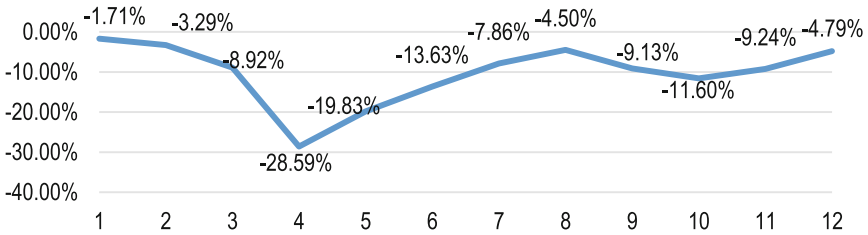


Fig. 4. Average distance changes 2020/2019, Source: own elaboration based on data [19].

As is seen in Fig. 4, the arrival of the autumn (second) Covid-19 wave shortened the trips: in October by over 9%, and in November by 11.6% compared to 2019.

3 Anti-covid-19 Regulations in Poland

The specificity of SARS-CoV-2 is, among others elements, is related to its easily penetration of the human body and quick replication. In the first period of the epidemic, there was no verified information on what type of remedial actions would bring the most reliable results. Governments of countries affected by COVID-19 made decisions aimed at limiting the development of the epidemic and protecting the population based on the experiences of others regions and recommendations of international organizations. In Poland, the restrictions, introduced for the first time in March, generally concerned reducing crowds of people in public spaces, lowering social mobility, and increasing the possibility of keeping distance between people. The introduction and subsequent elimination of restrictions were associated with an increase of infections during the first and second waves of Covid-19. From 04.03.2020 till the end of 2020, the total number of cases in Poland reached over 1,295 million (number of tests taken 7,204 million). According to the Ministry of Health, more than 28,5 thousands infected patients died and most of them had been suffering from concurrent diseases [20].

4 Changes in the Polish Passenger Rail Transport Market in 2020

The need to contain the spread of SARS-CoV-2 coronavirus infections has resulted in significant restrictions on the movement of people on almost all continents. The passenger transport sector was severely affected and all Polish operators suffered as a result of the restrictions introduced and the stay-at-home order. The transport performance measured in the pass-km decreased by 42.65% compared to 2019, and the operational performance measured in the train-km by 6.29%. The drastic drops in the volume of transport, especially during the first wave of diseases, had influence on the results obtained by transport companies. The impact of measures to prevent the spread of SARS-CoV-2 appeared as early as mid-March. Also, others limitations were introduced in the operation of international connections, and in consequence, operators providing services only in the field of international connections, i.e. Leo Express and UBB, suspended their performance in the second quarter of 2020.

4.1 Long-Distance Transport

Since 2015 PKP Intercity, the largest Polish carrier operating long-distance transport, has been constantly improving its offer, which resulted in a stable increase in operational performance and transport performance. In 2020 the decrease was related to the suspension or the shortening of train runs. The performances decreased by 9.45% and 47.2%, respectively. The significant difference is related to the drastic reduction in the number of passengers with a slight reduction in the number of trains launched. Due to the introduced administrative restrictions on the permissible number of passengers on board the train, the transport performance decreased by nearly 50%: from almost 11,650 million pass-km to only 6,150 million pass-km. The comparison of the operating performance in 2015–2020 is shown in Fig. 5, and the transport performance in Figure 6.

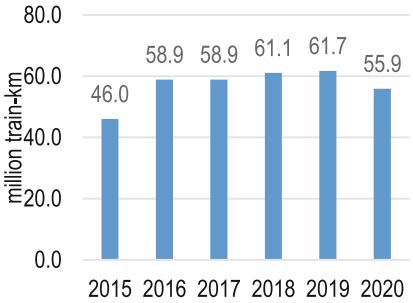


Fig. 5. PKP Intercity operational performance changes in 2015–2020. Source: own elaboration based on data [21].

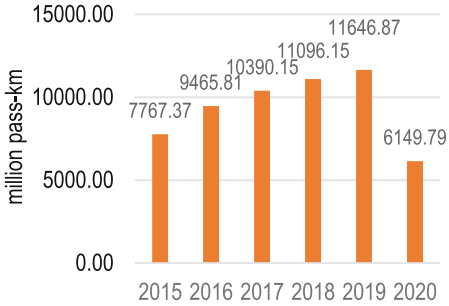


Fig. 6. PKP Intercity transport performance changes in 2015–2020. Source: own elaboration based on data [21].

The number of PKP Intercity passengers in April was over 90% lower than in the same month of 2019. In May, a slight increase in the total number of passengers (9,802,624) was recorded, which initiated a slow improvement in the situation and a relative stabilization during the holiday season. In the fall, the number of travelers again fell significantly due to the development of the second wave of the epidemic. In November and December, they exceeded 50% concerning the respective periods of the previous year. In the passenger rail transport market, the share of PKP Intercity fluctuated and depended mainly on periodic travel bans, restrictions on the activities of entities providing accommodation services and restrictions on access to recreation and sports areas. In early 2020, the share of PKP Intercity was comparable in the share in January and February 2019: the difference was 0.36% and 0.27%, respectively. In March (the first month of the disease in Poland and the introduction of restrictions in movement), there was a decrease by 0.7%. Changes in the share of this company compared to 2019 are shown in Fig. 7.

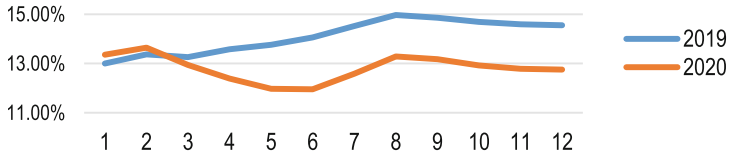


Fig. 7. PKP Intercity share in terms of number of passengers in 2019–2020. Source: own elaboration based on data [21].

As is seen in Fig. 7, the following months, usually characterized by an increase in PKP Intercity's market share, in 2020 were characterized by a decrease in the share of this company: in April by 1.19%, in May by 1.79%, in June by 2.10%, in July by 1.93%, in August and in September by 1.68%, in October by 1.77 and in November and December by 1.8%.

4.2 Agglomeration Transport

Local government company - SKM in Warsaw (SKM) servs four lines in the Warsaw agglomeration. In 2020, the distance of travel of SKM trains was over 15 million km, and number of passengers was over 14.9 million. In 2019, over 22 million passengers used the services of this agglomeration railway, which means a decrease of 32% [22]. The worst months in terms of the number of passengers were April and May, when only 580,847 and 851,472 travelers, respectively, used the services of SKM. These numbers show a decline in the number of SKM train users by 67.6% in April and 53% in May. In the following months, along with the elimination of the restrictions of the first wave of COVID-19, the number of travelers became to increase slowly just to second wave of pandemic. In August, the number of passengers amounted to just over 1,300 thousand. Which means a decrease by 18% compared to the same month of the previous year. In the following months, the situation worsened along with the administrative introduction of mobility restrictions and the number of cases. It is true that in September the number of passengers increased to almost 1.5, but the decrease compared to September 2019 was 21.5%. In October, the drop in the number of travelers amounted to nearly 38%, and in November to over 53%. A comparison of the number of SKM Warszawa passengers in the subsequent months of 2019 and 2020 is shown in Fig. 8.

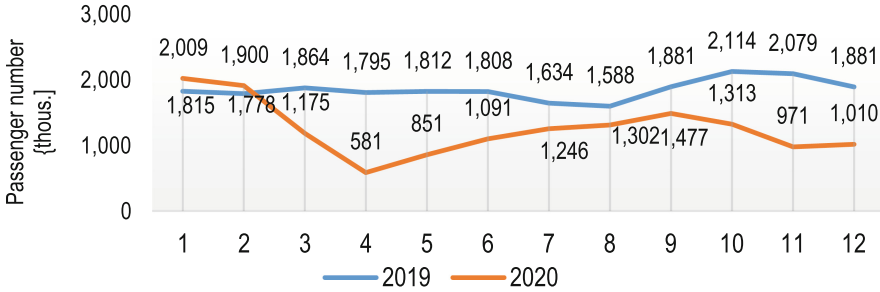


Fig. 8. Comparison of SKM Warszawa passengers number in 2019 and 2020. Source: own elaboration based on data [22].

Changes in the number of passengers influenced the volume of transport performance, which decreased by 32.3% compared to 2019. The change in the number of trains launched and the length of the routes in which they ran affected the size of operational performance. The change was slightly more than 15% (a decrease from 4.1 million train-km in 2019 to 3.5 million train-km in 2020. The difference between transport performance and operational performance is mainly related to the reduction in the total capacity of trains to 50% in the most restrictive period of the pandemic. Figure 9 shows the changes in the volume of transport performance expressed in pass-km in the period 2015–2020 and Fig. 10 - the comparison of the operational work volume.

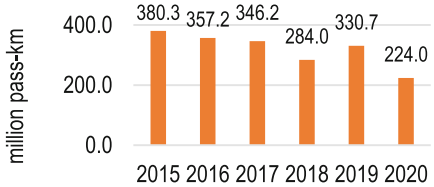


Fig. 9. SKM Warszawa transport performance changes in 2015–2020. Source: own elaboration based on data [21].

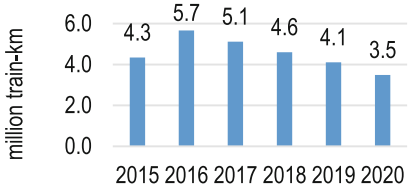


Fig. 10. SKM Warszawa operational performance changes in 2015–2020. Source: own elaboration based on data [21].

5 Conclusion

The crisis that followed the appearance of the SARS-CoV-2 coronavirus also manifested itself in transport, particularly affecting the passenger sector. Mobility restrictions imposed on society due to the need to prevent the spread of the pathogen drastically reduced travel. The aviation sector was the most affected. In Poland, COVID-19 influenced the modal split, the share of railways increased by 5% compared to 2019. The year 2020 for railway companies was characterized by significant declines, which reached the lowest level during the first wave of COVID-19. The volumes of transport are correlated with the level of applicable restrictions on the people's movement. The sudden introduction of restrictions resulted in a sharp reduction in the number of travelers and the number of transports. During the first wave, both long-distance and agglomeration carriers recorded a significant drop in passengers. Later on, i.e. in the summer months, the stability of transport increased. The autumn wave affected more long-distance than agglomeration transport.

From the first days of the epidemic, public transport was identified as a potential source of infection. Although rail operators have reduced the risk of transmission of infection, and studies conducted in various countries have shown that public transport does not have a particular impact on the spread of COVID-19, the negative opinion about transport in this regard does not change. There seems to be no good information campaign to show that carriers have taken steps to limit virus transmission and that travel is safe.

References

1. Guan, L., Prieur, C., Zhang, L., Prieur, C., Georges, D., Bellemain, P.: Transport effect of COVID-19 pandemic in France. Annu. Rev. Control **50**, 394–408 (2020). https://doi.org/10.1016/j.arcontrol.2020.09.009
2. Anke, J., Francke, A., Schaefer, L.-M., Petzoldt, T.: Impact of SARS-CoV-2 on the mobility behaviour in Germany. Eur. Transp. Res. Rev. **13**(1), 1–13 (2021). https://doi.org/10.1186/s12544-021-00469-3
3. Dahlberg, M., et al.: Effects of the COVID-19 pandemic on population mobility under mild policies: causal evidence from Sweden. arXiv (2020)
4. Almagro, M., OraneHutchinson, A.: The determinants of the differential exposure to COVID-19 in New York city and their evolution over time. J. Urban Econ. **123**, 103293 (2020). https://doi.org/10.1016/j.jue.2020.103293
5. Harris, J.E., et al.: The Subways Seeded the Massive Coronavirus Epidemic in New York City. Social Science Research Network. No. 3574455 (2020)
6. Furth, S.: Automobiles Seeded the Massive Coronavirus Epidemic in New York City. Market Urbanism (2020)
7. Robert Koch Institut: Epidemiologisches Bulletin. Infektionsumfeld von COVID-19 Ausbrüchen in Deutschland (2019)
8. IAPT: Transport, Public transport is COVID-safe. Brussels, pp. 1–6 (2020)
9. Hunt, M.: Covid-19 Transmission Rates on Rail. London (2020)
10. UIC Covid-19 Task Force Management of Covid-19. First estimation of global economic impact of Covid-19 on Rail Transport, Paris (2020)
11. CER: COVID Impact Tracker: a bleak first quarter for railways (2021). https://www.cer.be/media/press-releases/cer-covid-impact-tracker-bleak-first-quarter-railways
12. Roads to Recovery after the pandemic, 11 Jan 2021 (2021). https://www.worldhighways.com/feature/roads-recovery-after-pandemic
13. https://www.statista.com
14. IRTU: COVID-19 Impact on the Road Transport Industry (2020). https://www.iru.org/resources/iru-library/covid-19-impact-road-transport-industry-update-november-2020
15. IRU Annual Report 2020 - Executive Summary, Geneva, 5AD. https://www.iru.org/resources/iru-library/iru-annual-report-2020
16. IATA: European Air Transport COVID-19 Impacts and Recovery to be Worse than other Regions (2020). https://www.iata.org/en/pressroom/pr/2020-12-10-01/
17. ICAO: Economic Impacts of COVID-19 on Civil Aviation (2020). https://www.icao.int/sustainability/Pages/Economic-Impacts-of-COVID-19
18. Statistical Bulletin No. 12/2020, Warsaw (2020)
19. UTK: Monthly statistics 2020, Warsaw (2021)
20. FB Ministry of Health. https://www.gov.pl/web/koronawirus/wykaz-zarazen-koronawirusem-sars-cov-2
21. UTK: Przewozy pasażerskie 2016–2020, Warszawa (2017, 2018, 2019, 2020)
22. SKM: SKM in 2020, Warszawa (2021)

Implementing Intelligent Monitoring of the Technical Condition of Locomotive Hydraulic Transmissions

Boris Bondar[1], Oleksandr Ockasov[1], Viačeslav Petrenko[2](✉), and Michail Martishevskij[1]

[1] Ukrainian State University of Science and Technologies, Lazariana st. 2, 49010 Dnipro, Ukraine

[2] Vilnius Gediminas Technical University, Plytinės st. 27, 10105 Vilnius, Lithuania

viaceslav.petrenko@vilniustech.lt

Abstract. The study is aimed at replacing outdated approaches in the organization of maintenance of the locomotive fleet. The article presents a comparative analysis of maintenance strategies for traction rolling stock. The necessity of introducing control over the technical condition of locomotives to ensure the transition to a preventive maintenance system is substantiated. Directions of research - adjustment of the existing volumes and frequency of repairs, the introduction of individual repair strategies, the introduction of adapted and flexible approaches to the maintenance of locomotives. To improve the efficiency of monitoring the technical condition of locomotives, the use of factor analysis methods is proposed. The purpose of using factor analysis methods is to reduce the number of analysed parameters, while the information content of monitoring the technical condition should not decrease. The results of applying the method of principal components to assess the technical condition of the hydraulic transmission of a diesel locomotive during testing are presented. It is proposed to use the concept of latent diagnostic parameters to assess the technical condition of locomotive units. Considering the physical meaning of the processes occurring in the hydraulic transmission, as a result of the analysis, three groups of latent parameters were identified: "Load", "Losses", "Input". These parameters characterize the technical condition of the hydraulic transmission. Each of the latent parameters includes information from a group of physical process sensors. The implementation of the considered approach will ensure the effective use of monitoring results and a gradual transition to predictive maintenance.

Keywords: Rail vehicle · Hydraulic transmission · Maintenance strategy · Principal components analysis · Latent diagnostic features · Parameter informativeness

1 Introduction

The world's leading transport and industrial companies are investing significant funds in the modernization of approaches to servicing fixed assets. The efficient use of fixed assets

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 726–736, 2023.
https://doi.org/10.1007/978-3-031-25863-3_70

is one of the key points in the transition to Industry 4.0 and Industry 5.0 technologies. The basic technologies of the future are autonomous robotics, simulation modelling, horizontal and vertical systems integration, augmented reality, Internet of things, cloud technologies, additive manufacturing, cybersecurity, and big data. All these technologies are gradually being introduced by global transport companies in the fields of design, production, operation, and maintenance of locomotives.

The research aimed at replacing outdated approaches in organizing the maintenance of a locomotive fleet is being carried out by scientists from Ukraine and abroad. The primary areas of the research are the adjustment of the existing volumes and repair frequency, the introduction of individual repair strategies, and the introduction of adapted and flexible approaches to the maintenance of locomotives.

Researchers [1] define the following paradigms of approaches in managing the condition of technical objects: a maintenance system before failure (reactive maintenance), a planned preventive maintenance system (preventive maintenance), a maintenance system by condition (predictive maintenance), an integrated management system of technical condition (prescriptive maintenance system). The considered paradigms have found their application in the development of control systems for the technical condition of traction rolling stock. In works [2, 3], the analysis of approaches to the organization of maintenance of locomotives was carried out. The comparative analysis of rolling stock maintenance strategies is given in Table 1.

The main factor influencing the feasibility of using a locomotive maintenance strategy is the comparison of the costs upon implementing the strategy with the economic benefit of implementation. Despite the development of complex intelligent systems, for a part of the equipment of locomotives, it is rational to use reactive and preventive approaches. This is due to the fact that not all locomotive nodes are equipped with modern technical condition control systems. The decision on the need to install control and monitoring systems for the technical condition of nodes depends on the technical capability of measuring important control parameters, the cost of control tools, and the number of risks associated with the malfunctions emergence of the node being monitored. With regard to the complexity of a locomotive as a technical system, in many cases, a combination of several strategies is used to organize locomotive maintenance.

The choice of locomotive maintenance strategy requires a systematic approach and analysis of a large number of factors. As a criterion in substantiating the maintenance strategy, researchers propose to use the criterion of minimizing specific consumption for the performance of routine activities [3, 4]. The papers [5, 6] propose criteria for minimizing the costs of routine activities while ensuring a prescribed level of reliability. The criteria for choosing the system parameters of the predictive maintenance, taking into account the failure impact of dependent nodes, are considered in [7]. Theoretical foundations for choosing the parameters of an intelligent strategy in locomotive maintenance using fuzzy logic approaches are discussed in [8, 9].

Table 1. Rolling stock maintenance strategies.

Strategy and its characteristics	Reactive	Preventive	Predictive	Recommendatory
Advantages	Minimal costs for organizing maintenance. Full use of the node resource	Simplicity in scheduled maintenance and repair High equipment reliability	Reducing the costs of scheduled maintenance	Personalized repair
Disadvantages	Significant costs for eliminating the consequences of failure	Incomplete use of the locomotive node resource, significant costs	The sharp increase in the number of unscheduled repairs	Significant costs for equipment and personnel
Criteria for the organization of the maintenance system	The locomotive's ability to perform the work	The prescribed level of locomotive reliability	Maximum usage of the residual node life. Minimum preventive maintenance and repair works	Risk minimization Continuous improvement and optimization of the maintenance and repair system
Maintenance tasks during operation	Maintenance and repair works are not performed	Periodic maintenance and repair, control of the condition of the nodes	Residual life prediction (failure point prediction)	Avoid repeat failures
Performing repairs	Elimination of failure and its consequences	Constant list of maintenance and repair works. Scheduled repairs Absence of Individual approaches	Orientation to the scheduled replacement of nodes, More inspections – fewer repairs	Individual approach to locomotive maintenance
Technologies used, Methods	Aggregate repair method, Forming the emergency stock and revolving fund	Reliability analysis, Periodic diagnostics	Equipment monitoring, Optimization of maintenance and repair works	IIoT, Big Data, ML, risk analysis

Most of the methods for choosing the parameters concerning the maintenance strategy are based on the use of statistical data on the reliability of rolling stock in the

operation and are focused on optimization criteria. Optimization criteria are the adjustment of overhaul periods and repair volumes, taking into consideration: operating conditions, repair organization, reliability level, minimizing maintenance costs, minimizing the number of unscheduled repairs, and life cycle costs. In addition to using the optimization approach, methodologies of conditionally oriented service have recently become widespread. [10–15] RCM (Risk Centered Maintenance), RBM (Risk Based Maintenance), RAMS (Reliability, Availability, Maintainability and Safety).

In [16], the authors reviewed methods for predicting the technical condition of railway automation nodes using a limited amount of statistical data. The use of statistical data on the reliability of rolling stock when calculating the parameters of the maintenance system has a number of problems and contradictions formulated in [17, 18]. Let us consider the contradictions from the viewpoint of maintenance and repair of locomotives.

Complexity – the locomotive consists of a significant number of interacting elements (nodes and systems), which makes it difficult to identify the causes and types of failures, as well as factors affecting the development and manifestation of failures. That is, performing the failure cause analysis of locomotives in operation is extremely difficult.

The size and variability of the research object. Despite the fact that the number of locomotive series operated by railway companies is not large, and the number of locomotives of one series can reach hundreds of units, the sizes of statistical samples of locomotive equipment failures are not always representative. In addition, locomotives are not put into operation at the same time and operate under different conditions. Therefore, the failure analysis of the locomotive fleet for calculating the parameters of the maintenance system can be based on incorrect or outdated data.

Failure documentation – at failure documentation, a functional failure, as a rule, is registered. A functional failure [17] is understood as the fact of a failure emergence, that is, the residual life of the node becomes equal to zero and further operation of the locomotive is impossible or not advisable. At the same time, from the viewpoint of the effective organization of the locomotive maintenance system, the most important is the potential failure. The potential failure is the fact about the beginning of the defect growth. The task of the locomotive technical condition management system is to detect potential failure, predict the residual life, and determine the moment in performing the maintenance and repair works according to the condition of maximum usage of the residual life while minimizing the risk from the emergence of a functional failure. Thus, the registration of functional failures by the operating organization does not provide sufficient information about the development of the failure.

Reznikov's contradiction [18] is also well-known; its main provisions for the locomotive facilities are formulated as follows:

- gathering information about critical failures is inadmissible and is evidence of a dysfunctional locomotive fleet maintenance system. Critical failures lead to a reduction in the service life of nodes and units of locomotives;
- there is no such reduction in the service life of the locomotive equipment that any operating organization will agree to obtain failure data for the development of a maintenance system;

- defining the form of link between the characteristics of reliability and the equipment operating time of the locomotive requires a significant amount of data. The repetition of critical failures is inadmissible, that is, the data will be missing.

The analysis carried out allows us to conclude that in order to transfer to a predictive and recommendatory strategy, it is necessary to additionally use other approaches, namely: controlling the technical condition of locomotive nodes in real-time (monitoring), identifying anomalies in the operation of locomotive equipment based on monitoring results, determining the moment in the emergence of potential failure, predicting the residual life of the node. The linkage of the stages in the transition to a preventive locomotive maintenance strategy is shown in Fig. 1.

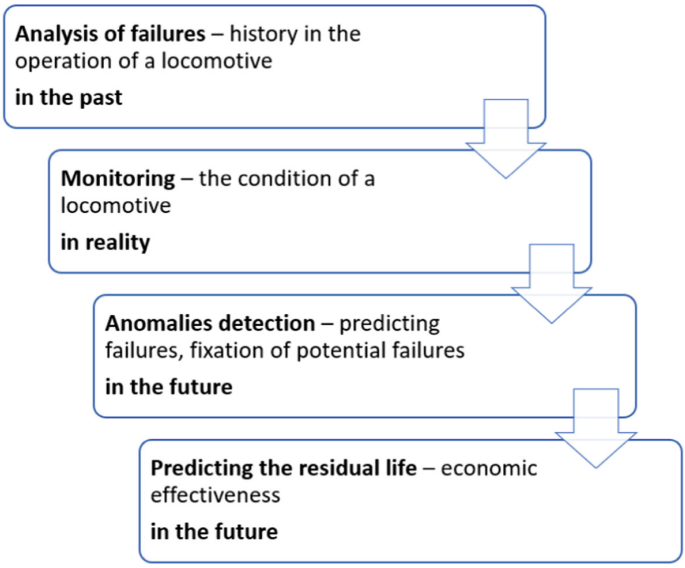


Fig. 1. The linkage of stages in the transition to a preventive locomotive maintenance strategy.

The basic stage for the transition to a preventive maintenance system is the introduction of systems for monitoring the technical condition of the locomotive. Monitoring is understood as the process of continuous surveillance of the technical condition and processes occurring in the operation of the locomotive or its node. At the same time, monitoring can be implemented both continuously during operation using built-in (on-board) control systems, and periodically during bench tests, equipment performance testing, etc. Features in the use of intelligent technologies when choosing locomotive maintenance strategies are given in [19].

The amount and completeness of data obtained from monitoring systems of technical conditions should be sufficient to solve the problems of detecting anomalies in the operation of equipment and predicting the residual life. On the other hand, when operating a locomotive, modern control and monitoring systems generate a huge amount of data. The information-measuring system of the locomotive measures, processes, and controls

such a number of parameters, the changing volume, and velocity of which significantly exceeds the person's ability to conduct an analysis. In this regard, the task arises of choosing the control parameters of locomotive nodes when monitoring the technical condition.

The choice of control parameters is carried out from the viewpoint of maximizing information about the technical condition of the monitoring object. When choosing the control parameters of locomotive nodes, the following requirements must be taken into account:

- the number of control parameters should be minimal, and at the same time, sufficient to obtain complete and reliable information about the technical condition of the monitoring object;
- the parameters controlled during monitoring should minimally correlate with each other.

2 Research Methods Used for the Investigation

Modern locomotives are equipped with hundreds of sensors. An increase in the number of control points (signals) leads to a complication and an increase in the cost of the diagnostic system. Moreover, there is a certain number of control points, upon reaching which, the information content and the depth of diagnosis increase slightly. In this case, it becomes necessary to reduce the number of control points (diagnostic signs) in such a way that the necessary and sufficient amount of information is provided to determine the technical condition of the object being diagnosed.

In the tasks of diagnostic monitoring, in most cases, the dynamics of variables are studied, which at different control points are formally considered as separately analyzed values.

Preliminary processing of diagnostic information in diagnostic systems is based on the formalization of initial features and allocation of the space of valuable features from the viewpoint of diagnosing. Among these methods, mathematical methods for assessing the informativeness of diagnostic features are distinguished. In this case, traditional methods based on dispersion, regression, correlation analysis, an information-theoretic approach grounded on the calculation of conditional probabilities and the amount of information, and multivariate statistical analysis are used.

The paper [20] proposes the use of factor analysis methods for processing the results of monitoring and diagnosing locomotive equipment. The purpose of factor analysis is to detect latent variables or factors that explain the structure of correlations in a set of variables. Factor analysis is often used to reduce the dimensionality of data in order to find a small number of factors that contain most of the dispersion (information) obtained from the analysis of a significantly larger number of explicit variables. In other words, factor analysis means a set of methods that, on the basis of actually existing links of features, objects, or events, make it possible to identify latent (hidden and inaccessible for direct measurement) generalizing characteristics of the organized structure and development mechanism of the studied events or processes. A block diagram explaining the formation of latent diagnostic features is shown in Fig. 2.

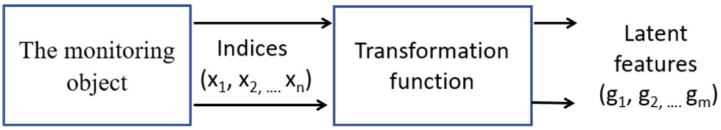


Fig. 2. Block diagram of the forming latent diagnostic features.

The principal components method is used as a transformation function [21, 22]. As a result of applying the principal component method, the initial set of diagnostic parameters is transformed into a set of latent diagnostic parameters of a lesser dimension. At the same time, the latent diagnostic parameters obtained as a result of the transformation do not correlate with each other and allow you to save the amount of diagnostic information not less than the prescribed one.

Examples of using the principal component method for diagnosing equipment failures in engineering are presented in [23–26]. The results of these works allow us to assert the effectiveness of using the method to determine the malfunctions of complex technical objects.

The results of monitoring the technical condition of the control object are an n-dimensional vector. Vector X is a set of control parameters received from sensors installed on the object:

$$X = \{x_1, \ldots, x_n\}. \tag{1}$$

As a result of using the principal components method, the initial vector X is transformed into a vector G:

$$G = \{g_1, g_2, \ldots, g_n\}. \tag{2}$$

Each element g_n of the set G is a latent diagnostic parameter:

$$g_n = \sum_{i=1}^{n} x_i \cdot a_i, \tag{3}$$

where x_i – the measured value of the control parameter; a_i – factor loading of the parameter; n – dimension of the initial set of diagnostic parameters.

With further analysis, the dimension of the vector G is reduced to m (where $m \leq n$). When reducing the dimension of the set of latent control parameters, condition (4) is used:

$$\sum_{i=1}^{m} D(g_i) \leq \alpha, \tag{4}$$

where α – the prescribed percentage of the initial information preservation about the condition of the control object; $D(g_i)$ – the amount of information per component.

As a result of applying condition (4), the dimension of the initial set of control parameters is declining, while retaining the prescribed level of informativeness about the

equipment condition. The set G includes only m of significant components, in addition, each component includes m of the most informative control parameters.

Significant latent diagnostic parameters are determined from the condition (5):

$$g_i = \sum x_i \cdot a_i, \tag{5}$$

where m – the number of significant components determined by the rock scree method [21, 22].

The principal components having been formed using condition (5) are latent diagnostic parameters. The latent diagnostic parameter means a parameter that does not physically exist, and at the same time, it contains information characterizing the monitoring object status. Using the principal component method enables the no-correlation condition between latent parameters. From a technical viewpoint, each latent parameter characterizes one of the groups of physical processes in the monitoring object's functioning.

In calculating the value of the latent diagnostic parameter, m of control parameters x_i is used, the values of factor loadings of which are maximum.

3 Results

The papers [20, 27] highlight the preliminary results of the authors' bench tests of diesel hydraulic transmissions, UGP 750–1200 type. During the tests, the following diagnostic parameters are recorded: voltage U_m and armature current I_m of the drive electric motor, voltage U_{gen} and armature current I_{gen} of the loading E-motor. For hydraulic transmission, the input parameters are the rotating velocity w_m and the torque M_m on the shaft of the drive electric motor, the rotating velocity w_{ci} and the pump impeller torque M_{ci}. The output parameters of the hydraulic transmission during testing are the rotating velocity w_{ct} and the turbine wheel torque M_{ct}, which corresponds to the rotating velocity and armature torque of the load generator. The oil temperature at the inlet t_{in} and outlet t_{out} of the hydraulic transmission, the temperature t_{tcf} and the oil pressure p_{tcf} in the hydraulic unit are also recorded. Additionally, the calculated parameters were taken into account. Drive electric motor power P_m and load generator power P_{gen}. The temperature of the oil in the hydraulic apparatus/the power of the generator t_{tcf}/P_{gen} ratio. The transfer ratio of the rotating velocity (w_{ci}/w_{ct}) of turbine wct and pump wheels w_{ci}.

When processing the experimental data obtained as a result of the tests, the conformance inspection of the data with the normal distribution law and the data set clearance from outliers using the 3σ method was conducted. For the correct using the principal components method, the data were normalized by the maximum-minimum technique.

Using the principal components method, three latent diagnostic features were identified. The volume of information attributable to the first three latent features of hydraulic transmissions that have passed the tests is in the range from 86 to 92%.

With regard to the factor loadings of control parameters in the composition of the components and the physical meaning of the processes occurring in the hydraulic transmission, the components are named: "Load", "Losses", "Input".

The results of applying the above methodology for processing test results on the example of one of the diesel hydraulic transmissions, UGP 750–1200 type are at Table 2.

Table 2. Factor loading of control parameters for hydraulic transmission.

Component	Factor loading of a diagnostic parameter									
	U_{gen}	I_{gen}	U_m	I_m	w_{ct}	t_{tcf}	p_{tcf}	t_{inp}	t_{out}	P_m
Load	0.24	0.27	-	-	-	-	0.39	-	-	-
Losses	-	-	-	-	-	0.56	-	0.39	0.45	-
Input	-	-	0.60	0.05	0.44	-	-	-	-	-

On the example of the considered transmission, the equations of latent diagnostic parameters (components) are as follows:

$$\begin{aligned} Load &= 0,24 \cdot U_{gen} + 0,27 \cdot I_{gen} + 0,39 \cdot p_{tcf}, \\ Losses &= 0,56 \cdot t_{tcf} + 0,39 \cdot t_{inp} + 0,45 \cdot t_{out}, \\ Input &= 0,60 \cdot U_m + 0,05 \cdot I_m + 0,44 \cdot w_{ct}. \end{aligned} \tag{6}$$

The numerical values of the components are dimensionless values. Using the values of the components and factor loadings, a comparison and evaluation of the technical condition of hydraulic transmissions during tests on the bench are performed.

4 Conclusions

Using the proposed approach, the dimension of the initial set of control parameters was reduced from 13 control parameters to three latent diagnostic parameters. Dimensionality reduction of the initial set of control parameters makes it possible to simplify the analysis of the technical condition both in manual and automatic modes. It is easier for the operator controlling the condition of the monitoring object to analyze a smaller number of parameters. When using intelligent monitoring systems, reducing the number of parameters cuts down on time expenses spent on analysis, reduces the requirements for the computing power of the system, and simplifies the interpretation of the results.

A further direction for continuing research using latent diagnostic parameters is the usage of anomaly search methods using artificial intelligence technologies. Dimensionality reduction of the initial set of control parameters will simplify the classification and analysis of the technical conditions of control objects, and use statistical methods for searching for anomalies. The proposed method can be applied in the analysis of the results of testing and diagnosing any nodes of locomotives and the locomotive as a whole.

The implementation of the considered approach will ensure the effective use of monitoring results and a gradual transition to predictive maintenance. The advantage of monitoring the condition of equipment in operation is the ability to detect any unusual features in the behaviour of the object in operation, while there is no need to accumulate large amounts of statistical data on equipment failures.

References

1. Lee, J., Ni, J., Singh, J., Jiang, B., Azamfar, M., Feng, J.: Intelligent maintenance systems and predictive manufacturing. ASME. J. Manuf. Sci. Eng. **142**(11), 110805 (2020). https://doi.org/10.1115/1.4047856
2. Tartakovskyi, E., Ustenko, O., Puzyr, V., Datsun, Y.: Systems approach to the organization of locomotive maintenance on Ukraine railways. In: Sładkowski, A. (ed.) Rail Transport—Systems Approach. SSDC, vol. 87, pp. 217–236. Springer, Cham (2017). https://doi.org/10.1007/978-3-319-51502-1_5
3. Bodnar, B., Ochkasov, O.: System choice of the technical maintenance of locomotives equipped with on-board diagnostic systems. In: Proceedings of 21st International Conference on Transport Means 2017, 20–22 September 2017, Juodkrante, Lithuania. - Part I. -Kaunas: Kaunas University of Technology, pp. 43–47 (2017)
4. Bosov, A.A.: Theoretical foundations and methodology for calculating rational planned restoration of locomotives and cars: Abstract of a Thesis of Doctor of Technical Sciences: 22 May 2007. Leningrad: Leningrad Institute of Railway Transport Engineers, 30 p. (1986)
5. Hryshechkina, T.: Mathematical model of the rational maintenance system of railway transport technical objects. Transp. Syst. Transp. Technol. Iss. **14**, 30–35 (2017). https://doi.org/10.15802/tstt2017/123165
6. Increasing operational reliability of locomotives by implementing a rational maintenance system: Ph.D. thesis in Engineering: 05.22.07/Bodnar Yevhen Borysovych; the Dnipropetrovsk National University of Railway Transport named after V. Lazarian. – Dnipropetrovsk, p. 161 (2004)
7. Bosov, A.A., Hryshechkina, T.S., Savchenko, L.M.: Mathematical modeling of a technical object dependent failures. Sci. Transp. Prog. Iss. **28**, 129–132 (2009)
8. Datsun, Y.: The choice of the strategy of the technical service and repair of locomotives based on the methods of fuzzy logic. Bull. Volodymyr Dahl East Ukr. Natl. Univ. **218**(1), 77–80 (2015)
9. Datsun, Y.M.: Research of the operation of a fuzzy classifier for determining strategies for maintenance and repair of locomotive nodes. Railw. Transp. Ukr. **5**, 51–54 (2015)
10. Grenčík, J., Poprocký, R., Galliková, J., Volna, P.: Use of risk assessment methods in maintenance for more reliable rolling stock operation. MATEC Web Conf. **157**04002 (2018). https://doi.org/10.1051/matecconf/201815704002
11. Jaiswal, V., Banodha, V., Patel, P.: Risk assessment in maintenance work at diesel locomotive workshop. Int. J. Emerg. Technol. **5**(1), 59 (2014)
12. Bodnar, B., Bolzhelarskyi, Y., Ochkasov, O., Hryshechkina, T., Černiauskaitė, L.: Determination of integrated indicator for analysis of the traffic safety condition for traction rolling stock. In: Intelligent Technologies in Logistics and Mechatronics Systems (ITELMS 2018): The 12th International Science Conference, 26–27 April 2018, Panevėžys, pp. 45–54. Kaunas University of Technology, Panevėžys (2018)
13. Xu, S., Chen, C., Lin, Z., Zhang, X., Dai, J., Liu, L.: Review and prospect of maintenance technology for traction system of high-speed train. Transp. Saf. Environ. **3**(3), 1–20 (2021). https://doi.org/10.1093/tse/tdab017
14. Bulakh, M., Okorokov, A., Baranovskyi, D.: Risk system and railway safety. IOP Conf. Ser. Earth Environ. Sci. **666**(4), 042074 (2021). https://doi.org/10.1088/1755-1315/666/4/042074
15. Lakin, I.K., Abolmasov, A.A., Melnikov, V.A.: Risk management model to prevent locomotive malfunction. World Transp. Transp. **4**, 130–136 (2013)
16. Moiseenko, V., Kameniev, O., Gaievskyi, V.: Predicting a technical condition of railway automation hardware under conditions of limited statistical data. Eastern-Eur. J. Enterp. Technol. **3**(9–87), 26–35 (2017). https://doi.org/10.15587/1729-4061.2017.102005

17. Moubray, J.: Reliability-Centered Maintenance. Industrial Press Inc., New York (2001)
18. Resnikoff, H. L.: Mathematical Aspects Of Reliability-Centered Maintenance. United Airlines Inc., San Francisco (1977)
19. Ochkasov, O., Shvets, O., Cerniauskaite, L.: Usage of intelligent technologies in choosing the strategy of technical maintenance of locomotives. Technologijos ir Menas = Technol. **8**, 68–71 (2017)
20. Bodnar, B., Ochkasov, O.: Devising a procedure to form the diagnostic parameters for locomotives using a principal components analysis. East. Eur. J. Enterp. Technol. **2**(1(110)), 97–103 (2021). https://doi.org/10.15587/1729-4061.2021.230293
21. Yin, S., Ding, S.X., Xie, X., Luo, H.: A review on basic data-driven approaches for industrial process monitoring. IEEE Trans. Indus. Electron. **61**(11), 6418–6428 (2014). https://doi.org/10.1109/TIE.2014.2301773
22. Jolliffe, I.T., Cadima, J.: Principal component analysis: a review and recent developments. Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. **374**(2065), 20150202 (2016). https://doi.org/10.1098/rsta.2015.0202
23. Nadir, F., Elias, H., Messaoud, B.: Diagnosis of defects by principal component analysis of a gas turbine. SN Appl. Sci. **2**(5), 1–8 (2020). https://doi.org/10.1007/s42452-020-2796-y
24. Mnassri, B., Ananou, B., Ouladsine, M.: Fault detection and diagnosis based on PCA and a new contribution plot. IFAC Proc. Vol. **42**(8), 834–839 (2009). https://doi.org/10.3182/20090630-4-ES-2003.00137
25. Doorsamy, W., Cronje, W.A.: A method for fault detection on synchronous generators using modified principal component analysis. In: 2015 IEEE International Conference on Industrial Technology (ICIT), Seville, Spain, pp. 586–591 (2015). https://doi.org/10.1109/ICIT.2015.7125162
26. Zheng, M., Wu, L., Li, L., Liu, C., Wang, L., Sun, S.: A modified method for fault detection and isolation of redundant Inerial measurement unit in dynamic environment. In: 2017 36th Chinese Control Conference (CCC), Dalian, pp. 6998–7002 (2017). https://doi.org/10.23919/ChiCC.2017.8028460
27. Bodnar, B., Ochkasov, O., Bobyr, D., Korenyuk, R., Bazaras Ž.: Using the self-braking method when the post-overhaul diagnostics of diesel-hydraulic locomotives. In: Proceedings of the 22nd International ScienceConference on TYransport Means 2018, 03–05 October 2018, Trakai, Lithuania. Kaunas University of Technology, Klaipėda University, JSC Lithuanian Railways (AB Lietuvos Geležinkeliai). Kaunas, Pt. II, pp. 914–919 (2018)

Methodological Framework for Assessing and Strengthening the Resistance of Railway Critical Infrastructure Elements

David Rehak[1], Lucie Flynnova[1](✉), and Abdollah Malekjafarian[2]

[1] Faculty of Safety Engineering, VSB – Technical University of Ostrava, Lumirova 630/13, 700 30 Ostrava, Czech Republic
lucie.flynnova@vsb.cz

[2] Structural Dynamics and Assessment Laboratory, School of Civil Engineering, University College Dublin, Dublin 04V1W8, Ireland

Abstract. The concept of resilience is one of the crucial factors for protecting elements of railway critical infrastructure. The resilience of prevention is generally known as a key phase from time perspective. This is determined by resistance which can be defined by the ability of the system to prevent occurring of disruptive events. Increasing the level of critical infrastructure elements resistance could minimize the likelihood of disruptive events and resulting damages. Currently, however there is no comprehensive procedure for strengthening the resistance in the railway critical infrastructure sector. This paper considers methodology for assessing and strengthening resistance in the critical infrastructure systems and its applicability when compiling functional procedures for assessing and strengthening resistance of railway critical infrastructure elements. The essence of this paper is also the definition of methodological-logical framework with all its requirements for defining a suitable procedure included. The methodological framework is composed of semi-quantitative methods that can be applied in the prevention phase or transformed into the given phase. The framework as the main starting point is developed. Basic findings into perception of the new concept of critical infrastructure resistance are provided.

Keywords: Critical infrastructure · Railway infrastructure · Resilience · Resistance of elements

1 Introduction

Railway systems play a critical role on European Transport networks. Due to its importance, railway infrastructure is also classified as the European critical infrastructure sub-sectors. Therefore, it is important that its elements should be protected as a matter of priority. The application of resilience concept is one of the factors which has been used in protecting systems for critical infrastructure elements. In most of the current definitions, resilience is determined by three main factors: robustness, recoverability and adaptability [1]. Several recent studies [2–4] suggest that the key factors of resilience

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 737–745, 2023.
https://doi.org/10.1007/978-3-031-25863-3_71

should be widened to include a fourth determining factor which is resistance. In the context of critical infrastructure resilience, the term resistance can be defined as the ability of a critical infrastructure elements to prevent disruptive events [2]. Resistance includes measures of a preventative nature determining security resistance and structural resistance [3]. The main essence of dealing with critical infrastructure resistance is increasing its level. In addition, it is necessary to continuously assess resistance to ensure its high level. The assessment should also identify the weak points, which are subsequently strengthened by implementing a range of appropriate tools.

This paper proposes a framework for the process of assessing and strengthening resistance which is comprised of four main steps: the 1st step, railway critical infrastructure elements, the 2nd step, threats to them, the third step, the elements resilience and the 4th step, the methodology of the process of assessing and strengthening the resistance of railway critical infrastructure. The proposed methods usable for the individual steps of the given framework were selected on the basis of their semi-quantitative nature and the possibility of transformation for use in the prevention phase. These areas are further detailed in the following sections.

2 Description of Railway Infrastructure

Railway infrastructure is understood as all routes and fixed transport installations necessary for the operation of trains and the safety of their operation. This mainly includes ground area, track and track bed, engineering structures (e.g., bridges, tunnels, culverts, structures for protection against falling stones and avalanches and retaining walls), superstructures (e.g., rails, turntables and points), level crossings (including equipment for ensuring the road traffic safety), safety signaling, telecommunication and lighting installations and others [5].

These railway infrastructure elements can be classified into three groups from a structural viewpoint [2, 6]:

1. Line elements are lines that ensure transfer, delivery or transit between two elements/places which are physically separate from each other. They are a fundamental group in relation to all surface and point elements. Line elements of the railway transport sector are inter-station sections or individual tracks.
2. Point elements form a closed unit which fulfils its function for a specific line element or several line elements needs (e.g., points where one track turns or two tracks cross each other). They are individual pieces of equipment or other smaller system elements, such as railway equipment (communication equipment, safety equipment, electrical equipment, signalling systems, points systems and so forth), railway structures, stops or crossings.
3. Surface elements have the surface unit character in which several line and point elements can work at the same moment (at least one line and two point elements). In comparison with line and point elements, they can be perceived as the most complicated subgroup. Due to the presence of multiple elements in the same place could be crucial and the effects of disruption to their functioning can accumulate further. Primarily classified railway junctions, crossings with crossing safety equipment and train stations with station safety equipment are examples of this group.

3 Threats to Railway Infrastructure

Railway infrastructure elements are continuously threatened by the impact of dangers of a naturogenic and anthropogenic nature, which subsequently initiate a range of disruptive events. These can have a serious negative impact on infrastructure functionality, and also on the safety and health of passengers. Within the framework of railway infrastructure protection, the prevention phase is therefore key, including thorough identification and analysis of dangers which can cause such a disruptive event.

Threats affecting railway infrastructure elements can be subdivided into two fundamental groups according to their origin: the first one are the threats in the railways and railway transport area and the second is dangers arising outside of the track perimeter, i.e. resulting from surrounding environment [2].

The first sub-group of threats affecting railway infrastructure elements are threats arising within the track perimeter, i.e., having their origin in railway transport. These threats are defined by Regulations on railway safety [7] and classifies them as accidents, serious accidents and emergencies. It specifically refers to for instance a collision between railway vehicles or an obstruction in a clear cross-section; accidents on a level crossing (including accidents involving pedestrians on level crossings); accidents caused by moving a railway vehicle; railway vehicle fires; escape of dangerous substances during transport; track breakage; track buckling and other track misalignment; fires and explosions within the track perimeter; failures of signaling system.

The second sub-group is threats arising from the surrounding environment, which usually do not originate in railway transport, but can threaten it through their impact. These threats can be classified as naturogenic-abiotic (i.e., flooding, flash floods, extreme winds, heavy rain and so forth) and biotic (i.e., epidemics), anthropogenic-technogenic (i.e., special floods, functionality disruptions in important electronic communication systems, power cuts and so forth) and sociogenic (i.e., illegal activities, including terrorism) [8].

As a result of their interconnection with other infrastructure and their open nature, railway infrastructure elements are exposed to a range of disruptive events and thus require a high safety level. One of the possible approaches to the critical infrastructure elements protection is the concept of resilience.

4 Railway Critical Infrastructure Resilience and Resistance

The concept of resilience is an important factor in the critical infrastructure elements protection system against the negative effects of disruptive events. It should however be constantly ensured, i.e., in the phase before the occurrence of the disruptive event, during the actual event and as well in the phase after its negative effects come to an end. In its current concept, resilience is however seen as a state formed by repressive factors (i.e., robustness and recoverability) and strengthening factors (i.e., adaptability). Preventative factors (i.e., resistance) that can be used for elements to prepare to disruptive events are currently absent in the present resilience concept. Due to this reason, it is highly important to focus on this group of factors which determine the critical infrastructure elements resistance and strengthen resilience in preventive phase [2].

4.1 Railway Critical Infrastructure Resilience

The term resilience was first defined in 1973 by Holling [9], in relation to the resistance and stabilisation of ecological systems, as a measure of the persistence of the system and its ability to absorb disruptions without significant changes to the state of the system. Later the term resilience started being used in other fields of science, such as for instance economics, psychology and sociology, and later also engineering. Within the critical infrastructure context, the term resilience was first used and defined in the document Critical Infrastructure Resilience Final Report and Recommendations in 2009 [1], where resilience was defined as the ability of a critical infrastructure element to minimise the impact of a disruptive event and shorten the time it lasts. Resilience effectiveness is then conditional on the ability of a system to anticipate, absorb, adapt and then quickly recover from the negative effects of potential disruptive events. Currently, in the present concept, three components determine resilience, these are robustness, recoverability and adaptability [1].

4.2 Railway Critical Infrastructure Resistance

The term resistance in the relation to term resilience was first defined by Sugden [10], who in his article dealt with the relationship and difference between the resilience and resistance of ecosystems. Sugden defines resistance as a measure of how the ecosystem changes after a deviation, for instance the foreign species introduction. Resilience is therefore the extent to which the ecosystem is able to recover after removing the cause of the change.

The term resistance appears in a whole range of scientific disciplines, for instance ecology [11, 12], medicine [13, 14], sociology [15, 16] and recently also in engineering, specifically in the field of critical infrastructure resistance [2–4].

Resistance of critical infrastructure can be defined as the ability of critical infrastructure element to prevent disruptive events [2]. Resistance includes measures of a preventative nature determining security resistance and structural resistance. Regarding to security resistance, the element is able to resist the effects of negative factors using a range of safety measures. The second of them, structural resistance, is the element's ability to resist the negative effects on the basis of its location inside the system, construction and the used technology [17].

Resistance is determined by the four following factors [2]:

1. Crisis preparedness which means a set of preventive measures for increasing the preparedness of an element for disruptive events occurrence [18]. Amongst these measures are for instance threat analysis and safety planning, including crisis preparedness plans and emergency plans.
2. Anticipation ability which is the ability of an element to anticipate the occurrence of potential disruptive events, thus allowing prevention and timely reaction of the disruptive event occurrence. For that, it is possible to use for instance a resilience disruption indication system [19]. Other measures are for instance regular checks, reconnaissance or the use of software applications enabling disruptive events prediction.

3. Physical resistance which is understood as the structural qualities of buildings and technology employed, which through their material and construction resistance resist the negative effects of the influence of threats, and in this way prevent the occurrence of disruptive events [20].
4. Safety measures which are a set of and technical means and regime and organisational measures for increasing the safety of elements against disruptive events [18]. Amongst safety measures are for example entrance checks, alarm systems, guarding of premises or mechanical barrier apparatus [21].

Strengthening individual factors determining resistance leads to an increase in the resistance level and thus in overall resilience. Part of strengthening resistance is increasing protection of elements in the prevention phase, through which the likelihood of the disruptive event occurrence being prevented is increased. Resistance can therefore from a time viewpoint be considered the most significant component of resilience, with its potential suitability the focus of further research.

5 The Proposed Framework for Assessing and Strengthening the Resistance of Railway Critical Infrastructure Elements

The proposed framework for assessing and strengthening resistance is composed of four main components, which are focused on the selection of railway critical infrastructure elements, selection of threats, elements resistance assessment and strengthening the resistance of elements (Fig. 1).

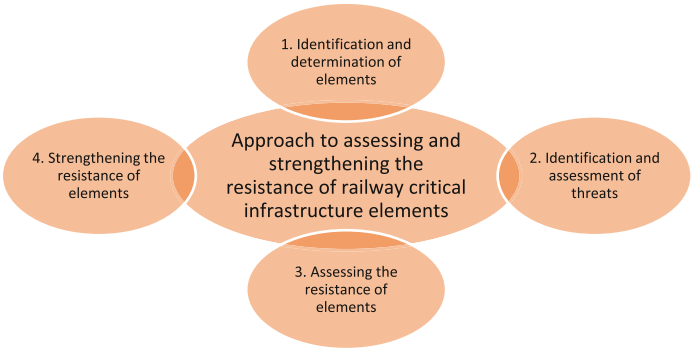


Fig. 1. Framework for assessing and strengthening the resistance of railway critical infrastructure elements.

The basis of this framework is the definition of a methodological concept for creating a custom approach for assessing and strengthening the resistance of railway critical infrastructure elements.

5.1 Identification and Determination of Railway Critical Infrastructure Elements

The first component in the proposed framework includes identifying the elements of the railway infrastructure themselves. Their criticality can be assessed by a whole range of factors. These are for instance assessment of the dependency between individual infrastructures, assessment of the potential effects of disruption to the functionality of elements or their failure, the importance of elements, and predominantly a combination of these factors.

For prioritising elements suitable for assessing resistance, a range of specific methods can be used for identifying and determining critical elements in the area of railway infrastructure. For the purposes of this framework, the RICA tool [6] was chosen as the most suitable method for identifying and determining critical elements of the railway infrastructure, due to its semi-quantitative nature enabling an integral approach to the assessment of the criticality of elements, within which their technical and process aspects are comprehensively assessed factors. The method can be used in the identification phase of the critical element, as well as its determination, and is applicable to point, line and area elements.

5.2 Identification and Assessment of Threats Affecting Elements of Railway Critical Infrastructure

The second component of the proposed framework deals with threats affecting elements of railway critical infrastructure. General and specific methods can be used for identifying and assessing the threats to the railway system. Amongst the general methods are for example FMECA (Failure Mode, Effects and Criticality Analysis) and FMEA (Failure Mode and Effects Analysis) [22].

Currently there are also a range of methods dealing with assessment of risks for protection of critical infrastructure. Amongst them are for instance Better Infrastructure Risk and Resilience (BIRR), CARVER2 and others [23].

Specifically, in the area of railway transport, identification of threats is dealt with by for instance Szatmári and Leitner [24] and Kucera and Dobesova [25]. For this part of the proposed framework, a semi-quantitative assessment of vulnerability and prioritization using the HRVA method [24], which was applied by the authors to the rail transport sector, appears to be the most appropriate. The essence of the method is the prioritization of risks and the identification of vulnerable points in the system, which will enable early prediction of the activation of threats.

5.3 Assessing the Resistance of Railway Critical Infrastructure Elements

The third component of the framework is a methodological apparatus for assessing the resistance of railway critical infrastructure elements. However, in this context, it is necessary to point out that currently there is still no specific method which is oriented exclusively for assessing resistance. All currently available methods are aimed at assessing resilience as a whole, or as individual components, where resistance is assessed as part of the robustness of a critical infrastructure element.

In the context of assessing resilience of critical infrastructure elements, the following can for instance, be classified as the suitable method: Critical Infrastructure Element Resilience Assessment (CIERA) [20]. This methodology defines procedures and criteria for assessing the resilience of elements of critical infrastructure, primarily from technically oriented sectors. As part of the resilience assessment, there is an upward assessment of measurable items, variables, resilience components and the level of resilience of the element itself. However, with a light transformation, the given algorithm can also be used to assess preventive resilience factors, i.e., resistance and its individual variables.

5.4 Strengthening the Resistance of Railway Critical Infrastructure Elements

The final and currently principal component of the framework is employing methods that can be used for strengthening resistance. Similarly, as with assessing resistance, in this case no methods dealing exclusively with strengthening resistance are known. Due to this reason, it is necessary to aim at methods focused on strengthening resilience as a whole. In this section, the article by Rehak et al. can be mentioned as the most effective [26], which provides an overview of internal and external tools suitable for strengthening resilience. Within the application of this method, it is expedient to pay attention in particular to preventive measures which lead to the strengthening of the resistance of railway critical infrastructure elements.

6 Conclusion

The presented methodological framework is an initial step towards the definition of the methods for assessing and strengthening the resistance of elements of railway critical infrastructure. For the individual steps of the framework, one method is always selected, which, with its character, appears to be the most effective for solving the given problem. Research results show that the currently available methods are oriented more towards assessing global resilience, or the robustness of elements which are partially incorporated in resistance factors. For this reason, the baseline factors determining resistance in the sector of railway critical infrastructure were defined in the framework of this article. These factors are crisis preparedness, ability to anticipate, physical resilience and safety measures.

In follow-up research, it is necessary to further explore the definition of the method for assessing and strengthening the resistance of railway critical infrastructure elements. Research should in particular look at the identification and definition of other suitable factors determining resistance and their quantification for the purposes of semi-quantitative assessment. Attention should also be paid to methods suitable for assessing resistance and identifying weak points. Finally, tools suitable for strengthening resistance should be identified, both on a sectoral and elementary level of critical infrastructure.

Funding. This work was supported by the Technology Agency of the Czech Republic under Grant [number CK01000015] and VSB – Technical University of Ostrava under Grant [number SP2022/70]. This publication has also emanated from research conducted with the financial support of Science Foundation Ireland under Grant number 20/FFP-P/8706.

References

1. National Infrastructure Advisory Council: Critical Infrastructure Resilience Final Report and Recommendations. U.S. Department of Homeland Security (2009)
2. Rehak, D., Flynnova, L., Slivkova, S.: Concept of resistance in the railway infrastructure elements protection. In: Prentkovskis, O., Yatskiv (Jackiva), I., Skačkauskas, P., Junevičius, R., Maruschak, P. (eds.) TRANSBALTICA 2021. LNITI, pp. 419–428. Springer, Cham (2022). https://doi.org/10.1007/978-3-030-94774-3_41
3. Rehak, D., Hromada, M., Lovecek, T.: Personnel threats in the electric power critical infrastructure sector and their effect on dependent sectors: overview in the Czech Republic. Saf. Sci. **127**, 104698 (2020). https://doi.org/10.1016/j.ssci.2020.104698
4. Rogers, C.D.F., et al.: Resistance and resilience–paradigms for critical local infrastructure. Municipal Eng. **165**(2), 73–83 (2012). https://doi.org/10.1680/muen.11.00030
5. Commission regulation (EC) No 851/2006, of 9 June 2006, specifying the items to be included under the various headings in the forms of accounts shown in Annex I to Council Regulation (EEC) No 1108/70 (Codified version) (2006)
6. Rehak, D., Slivkova, S., Pittner, R., Dvorak, Z.: Integral approach to assessing the criticality of railway infrastructure elements. Int. J. Crit. Infrastruct. **16**(2), 107–129 (2020)
7. Directive (EU) 2016/798 of the European Parliament and of the Council, of 11 May 2016, on railway safety (recast) (2016)
8. Ministry of the Interior of the Czech Republic: Threat Analysis for the Czech Republic: Final Report. 2015. Approved by Resolution of the Government of the Czech Republic of 27 April 2016, vol. 369, p. 9 (2015)
9. Holling, C.S.: Resilience and stability of ecological systems. Annu. Rev. Ecol. Syst. **4**, 1–23 (1973)
10. Sugden, A.M.: Resistance and resilience. Science **293**(5536), 1731 (2001)
11. Knapp, R.A., Matthews, K.R., Sarnelle, O.: Resistance and resilience of alpine lake fauna tofish introductions. Ecol. Monogr. **71**(3), 401–421 (2001)
12. Mahardja, B., et al.: Resistance and resilience of pelagic and littoral fishes to drought in the SanFrancisco Estuary. Ecol. Appl. **31**(2), e02443 (2021)
13. European Centre for Disease Prevention and Control. https://antibiotic.ecdc.europa.eu/en/get-informedfactsheets/factsheet-experts. Accessed 2 Apr 2021
14. Ddzidic, S., Susković, J., Kos, B.: Antibiotic resistance mechanisms in bacteria: biochemical and genetic aspects. Food Technol. Biotechnol. **46**(1), 11–21 (2008)
15. Baaz, M., Lilja, M., Schulz, M., Vinthagen, S.: Defining and analyzing "Resistance": possible entrances to the study of subversive practices. Altern. Global Local Polit. **41**(3), 137–153 (2017)
16. Hollander, J.A., Einwohner, R.L.: Conceptualizing resistance. Sociol. Forum **19**(4), 533–554 (2004)
17. Lovecek, T., Rehak, D., Siser, A., Hromada, M.: Resistance of passive security elements as a quantitative parameter influencing the overall resistance and resilience of a critical infrastructure element. In: The Tenth International Conference on Emerging Security Information, Systems and Technologies (SECURWARE 2016), France, pp. 200–205 (2016)
18. Rehak, D., Senovsky, P., Slivkova, S.: Resilience of critical infrastructure elements and its main factors. Systems **6**(2), 21 (2018)
19. Splichalova, A., Patrman, D., Kotalova, N., Hromada, M.: Managerial decision making in indicating a disruption of critical infrastructure element resilience. Adm. Sci. **10**(3), 75 (2020)
20. Rehak, D., Senovsky, P., Hromada, M., Lovecek, T.: Complex approach to assessing resilience of critical infrastructure elements. Int. J. Crit. Infrastruct. Prot. **25**, 125–138 (2019)

21. Kampova, K., Lovecek, T., Rehak, D.: Quantitative approach to physical protection systems assessment of critical infrastructure elements: use case in the Slovak Republic. Int. J. Crit. Infrastruct. Prot. **30**, 100376 (2020)
22. BS EN IEC 60812: Failure modes and effects analysis (FMEA and FMECA). European Committee for Electrotechnical Standardization, Brussels, Belgium (2018)
23. Giannopoulos, G., Filippini, R., Schimmer, M.: Risk Assessment Methodologies for Critical Infrastructure Protection. Part I: A State of the Art, Publications Office of the European Union (2012). https://doi.org/10.2788/22260
24. Szatmári, M., Leitner, B.: Vulnerability assessment and risk prioritization with HRVA method for railway stations. Transp. Res. Procedia **55**, 1649–1656 (2021). https://doi.org/10.1016/j.trpro.2021.07.155
25. Kucera, M., Dobesova, Z.: Analysis of the degree of threat to railway infrastructure by falling tree vegetation. ISPRS Int. J. Geo Inf. **10**(5), 292 (2021). https://doi.org/10.3390/ijgi10050292
26. Rehak, D., Slivkova, S., Janeckova, H., Stuberova, D., Hromada, M.: Strengthening resilience in the energy critical infrastructure: methodological overview. Energies **15**(14), 5276 (2022). https://doi.org/10.3390/en15145276

A Reliable Low-Cost Interlocking System for Regional Railway Lines

Petr Šohajek[1], Martin Šustr[2], Pavla Šmídová[3](✉), and Radovan Soušek[2]

[1] Department of Transport Management, Marketing and Logistics, University of Pardubice, Studentská 95, 532 10 Pardubice, Czech Republic
petr.sohajek@student.upce.cz

[2] Department of Aviation Transport, University of Pardubice, Studentská 95, 532 10 Pardubice, Czech Republic
st27535@student.upce.cz, radovan.sousek@upce.cz

[3] Department of Information Technology in Transport, University of Pardubice, Studentská 95, 532 10 Pardubice, Czech Republic
smidova.pavla@gmail.com

Abstract. This article deals with the topic of remote control systems for railway transport with a focus on increasing the safety of transport on regional rail lines and increasing the reliability of the RadioBlock interlocking system to ensure the sustainability of operations on lines with lower traffic volume. The paper provides a general explanation of traffic management through control centres, while also considering the efficiency aspects of remote control, which allows for more efficient operation on lines, which has a direct impact on the maintenance of traffic and services, especially on regional lines. As well, the analytical part of the article is focussed on the RadioBlock interlocking system, including an explanation of its operating procedures and technical shortcomings. The next section presents the characteristics of using radio frequency technology in rail transport. This is followed by a proposal for upgrading the RadioBlock system by implementing radio frequency technology, and a description of the traffic management according to the proposal is also given. The characteristics of the proposed solution are then presented, which enables the safety of train movements without the need to install a costly train protection system, including the acquisition of expensive equipment. There is also a summary of the results obtained and a reflection on the future direction of research in the field of alternative interlocking systems.

Keywords: Remote traffic control · Railways · RadioBlock · ETCS · RFID · Resilience · Safety systems · Interlocking systems

1 Introduction

Many challenges have arisen in railway transport in recent years. One of the challenges is to continue to maintain operations on regional lines with low traffic volumes. Over the past 40 years, operations on many regional lines have been reduced for economic reasons or the jobs of dispatchers and other employees serving at individual rail yards

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 746–755, 2023.
https://doi.org/10.1007/978-3-031-25863-3_72

have been cut. On some lines, in order to save operating costs, modern interlocking equipment has been installed to enable remote control of traffic from central offices. On lines with lower traffic volumes, no equipment was installed and, due to redundancies, normal traffic control was converted to a so-called "simplified traffic control". This consists of staffing the posts required for traffic management only to the extent strictly necessary. This has led not only to a reduction in operating costs on these lines, but also to a significant reduction in operational safety and, at the same time, to a reduction in line capacity and a reduction in the quality of transport services.

Reconstruction works on railway lines are often associated primarily with the deployment of a new control and interlocking system based on advanced technologies. Traffic control by train dispatchers serving at each station is replaced by remote traffic control from a few control centres. This is a trend that has significantly increased the overall efficiency of rail transport in the long term [1]. A significant disadvantage is the relatively high acquisition costs of these interlocking systems. On regional lines, the introduction of modern interlocking systems with remote traffic control brings the greatest savings in operating costs, as regional lines are equipped with obsolete interlocking and signalling equipment that requires more personnel to operate. Investing in the upgrade of equipment on regional lines thus brings the highest cost savings per worker per kilometre of line, while increasing operational safety. Remote control technology allows operations to be maintained on less busy lines serving large areas of a country with lower population densities and fewer freight requirements, using a small number of dispatchers. In the Czech Republic, the RadioBlock Interlocking System (RBS) is used on some regional lines. This paper aims to present a proposal to upgrade the RBS using RFID (Radio Frequency Identification) technology to improve safety and reliability of operations at a sustainable cost for installing RBS on additional lines, including sustainable maintenance, repair and operating costs.

2 Materials and Methods

Our research used empirical and analytical methods to investigate the functioning of transport processes, as well as a quasi-experimental method, which consists of conducting action research. It is a process of systematically collecting data on the operation of the system in relation to the stated aims and objectives, including data collection in a system feedback loop for action planning based on the formulated hypotheses.

2.1 Traffic Management Centre

A remote traffic control system for railway lines is essentially a system in which traffic in a specific area is controlled from control centres on various lines, stations, junctions, sidings and railyards.

According to [1], the Czech infrastructure operator uses Centralised Traffic Control Centres (CTCC) for traffic control on main railway lines and selected regional lines (such as the centres in Prague and Přerov) and Regional Traffic Control Centres (RTCC) for traffic control on regional lines (such as in Volary). In both cases, dispatchers are located in central control centre buildings and each dispatcher controls traffic in a selected area.

Remote traffic control has a three-level structure consisting of a master dispatcher, a traffic dispatcher and a dispatcher. The main advantage of remote traffic control according to [1] is that all three levels of control are located in one room together, so that communication between them is faster and more accurate than in the case of traffic control at each station separately. The RadioBlock System (RBS) has been installed on some regional lines in the Czech Republic, which has a Regional Traffic Control Centre located at the Volary station.

2.2 RadioBlock Interlocking System

A simplified and specific remote traffic control system based on radio block technology has been developed specifically for conditions in the Czech Republic, but is also applicable elsewhere. The RadioBlock system (RBS) is based on similar principles to the European Train Control System (ETCS), but with many simplifications. Interlocking systems such as ETCS are based on data communication between vehicles and control centres via a non-public network and train indication by track circuits, axle counters, track loops, balises or other technologies. The RadioBlock interlocking system is based on wireless communication between vehicles and control centres via public data networks and train indication by GPS position messages and driver input of position codes [2]. This simple system does not achieve the same level of safety, but practical operation has proven it to be a viable and effective solution for interlocking operations on lesser used regional lines.

Characteristics of RBS. The basic components of the RBS are the RadioBlock Centre (RBC) and the RadioBlock Vehicle (RBV). The traffic controller gives the clearance and driving instructions by entering commands into the RadioBlock Centre. The RBV receives the information on the clearance and displays the information on the display to the driver [3]. The driver follows the instructions to drive the train to the point where the clearance ends and from which he makes a voice announcement when he reaches it.

On lines equipped with RBS, communication between the control room and the vehicle is carried out in two ways. In addition to the data communication between the RBC and the RBV, voice communication between the dispatcher and the driver is used in the form of phrases specified in the relevant regulation, for almost all operations, such as announcing the departure of a line section and arranging the train's onward journey [3]. The phrases must contain the train or vehicle number, the type of communication (data or voice), the location in the RBS area (RBS station, position on the line) and, if necessary, the number of the track occupied by the train and the status of the track the train is leaving (the track may be unoccupied or occupied by wagons). The on-board unit communicates with the RBC via the public GSM network. Based on the data entered by the driver and the GPS position received from the RBV, the RBC displays the current position of the vehicle or train to the dispatcher. The dispatcher can also see the track and station yard availability on the RBC displays. Finally, the RBC archives the communication between the dispatcher and the driver [4]. The RBC has an instant overview of all trains and vehicles that:

1. are about to begin travelling in an RBS-controlled area;
2. are about to enter an RBS-controlled area;
3. are about to leave an RBS-controlled area;
4. are moving about within an RBS area;
5. are standing at a particular point within the RBS area.

Before a train begins travelling in an RBS area, all actions necessary to ensure the train's movement must be carried out. First, the train must be logged into the RBS. Once logged in, the train is under the supervision of the traffic controller who controls the designated area. However, logging in does not mean that the train is authorised to move. If the driver tries to move the train without permission, the RBV almost immediately evaluates this as an error condition and stops the vehicle by opening the electro-pneumatic valve on the braking system [4]. The dispatcher only gives permission to travel from one point to another in one direction. The RBV or driver always notifies the dispatcher when such a point is reached. On reaching this point in the station, the driver must enter a unique code into the RBV which is indelibly marked on a steel plate located next to each track. After verification of the data entered by the RBS, the driver requests permission to proceed to the next point by means of a call to the traffic controller. If the next journey is possible, the traffic controller enters the information into the RBC and the RBV allows the driver to continue the journey.

RBS Emergency Communication. Emergency voice communication is only used in special cases, such as:

1. The RBV equipment is broken.
2. Data communication between the RBV and the RBC is interrupted.
3. The vehicle in the RBS area is not equipped with RBV.

In these cases, according to [3], the traffic controller receives only voice information and there is no interaction between the RBC, RBV and the vehicle control system (emergency remote stop of the vehicle is not possible). All decisions and commands issued by the radio block dispatcher must be entered into the RBC, which checks these decisions and prevents collision situations. The dispatcher and the driver communicate together by telephone instead of by data, and each must make a record in writing on their copy of the operating instructions. At the same time, the driver manually enters the commands received by telephone from the dispatcher into the RBV and this alternative method enables the train to travel to the designated point.

2.3 Features of RFID Technology in a Railway Transport System

Radio frequency identification equipment can be used to identify objects using high frequency electromagnetic waves. According to [5], intelligent vehicles should be able to receive information from sensors and RFID tags, and this data will be processed by the central unit of the vehicle and then sent to other vehicles. In line with the previous statement, [6] states that by applying RFID to the rail network and vehicles, information systems may be able to optimise the current traffic situation without human intervention

or provide feedback to the central control centre based on sensor information, thereby improving traffic safety. Other authors, such as [7] and [8], state that for information technology to be truly beneficial, it must be linked to central and supporting information systems.

According to [9], the main benefits include:

- improvement in the quality of service,
- lower rates of human error;
- eliminating paper documentation, etc.;
- the ability to monitor the technical condition of the vehicle and the operating conditions;
- automatic identification can be made without physically touching and without direct visibility between the identifier (tag) and the reader;
- information is provided in real time, which usually affects the quality of operational processes;
- as it is contactless technology, identification of the object does not require precise position or clear visibility;
- unattended operation;
- the option to encrypt data;
- the ability to detect the actual order of the wagons;
- tracking the movement of wagons in the railway system.

Based on the results of RFID technology testing, it has been verified that the read range of an RFID reader is approximately 2 m, depending on the type of tag, antenna, reader, weather, and wave interference from metal objects. During testing at the Volary railway station with the Impinj R420 Speedway Revolution reader and Confidex tags, the following results obtained in heavy rain are shown in Table 1.

Table 1. RFID tag testing.

Tag type	Direction straight, angle 0°	Direction straight, /angle 45°
Survivor	4.2	2.2
Iron-side	2.5	1.9
Iron-side Micro	2.5	1.5
Iron-side Slim	2.3	1.9

It was noticed, that these results meet the requirements for ensuring the reliability and functionality of the proposed solution.

3 Results and Proposal of RBS Upgrades

A single European Train Control System (ETCS) is being implemented in the EU Member States. However, this system is not well suited to ensuring operational safety on

many regional lines, both in terms of infrastructure as well as vehicles. Certain regional lines are of marginal importance in terms of the Europe-wide network, but in terms of the region they are often very important. These are generally lines on which the same set of traction units, numbering in terms of dozens, have been in operation for a long time and which do not generally leave the area. Also, other units enter the area only very rarely. There is therefore no need for an interoperable solution. The regular set of vehicles usually consists of several types of older vehicles which, for various reasons, cannot easily be replaced by a few types of modern vehicles with ETCS already installed. Nor is it practical or even possible to install ETCS on older vehicles.

For this reason, simple and inexpensive solutions for ensuring traffic on these lines have been sought in recent times. One of them is the Czech RadioBlock system. Over time, however, the RBS has become partially obsolete and at the same time certain imperfections in practical operation persist. Based on the analysis of operational experience (local surveys, empirical results, statistical data), the following are examples of some of the shortcomings which have been identified:

I. The system is not 100% reliable in terms of determining the exact position of the train.
II. The reliability of the data communication between the RBC and RBV is only about 80%, blockages occur, for example, in hilly terrain.
III. The system is not able to detect and actually check the track occupancy at a station.
IV. Many operations are dependent on their faultless execution by the operating personnel.

The solution described in this paper should eliminate all the major drawbacks of the RBS and, as a consequence, reduce the risk of human error and increase the safety and continuity of operations.

3.1 Proposal of Upgrading RBS with RFID Technology

Sensing the location of objects including railway vehicles using RFID technology is a long-standing practice in both passenger and freight transport. The core of this proposal is to apply RFID technology to the RBS system to eliminate existing problems caused by inaccurate, erroneous or otherwise inadequate train positioning in the controlled area. Compared to the current state, the RBV would only allow a train to travel if an RFID tag is read and associated with a specific geographic point and also paired with a GPS location.

Vehicle Equipment. An essential part of the RFID implementation should be the upgrade of the in-vehicle equipment, including the installation of an interface between the RBS and the RFID reader. The interface is necessary for the RBV to receive information directly from the infrastructure instead of the driver manually entering codes to determine the train's location. In addition, the RBV data store must be extended and the RBV algorithms must be upgraded to work with an offline network map in which the RFID tag codes would be stored. This would remove the disadvantages of the current position verification via GPS. Pairing the position data from the RFID tags with the

GPS-derived position will ensure that if the tag is moved or removed, the position of the train can still be determined.

Vehicles operating regularly on routes equipped with RBS RFID must be equipped with an RFID reader and other necessary equipment. There are two options for equipping a vehicle with an RFID tag reader. The first option is to install a fixed reader with an antenna on the side of the vehicle or under the vehicle. The second option is to equip the vehicle with a portable RFID reader paired with the RBV.

Infrastructure Facilities. Rail lines equipped with RFID-enabled RBS would be equipped with RFID tags at least at regular train stopping points. For railway stations, all tracks must be fitted with RFID tags, at least at both ends of each track and at locations where trains are required to stop. For tracks with platforms, RFID tags may be placed at the ends of the platforms. To eliminate the effects of weather on reliability, the tag should be placed on the edge of the platforms or on posts located at each track. The installation of tags on sleepers is not recommended by the authors based on their experience for technical and weather related reasons.

3.2 Traffic Management Processes

Communication between driver and controller should be data based. Voice communication should only be used when necessary, such as in an emergency or during a technical fault, and would have to be by means of precise phrases according to the railway carrier's regulations. The proposed method of RBS RFID data communication is explained by an example of a train logging into the RBS, see Fig. 1.

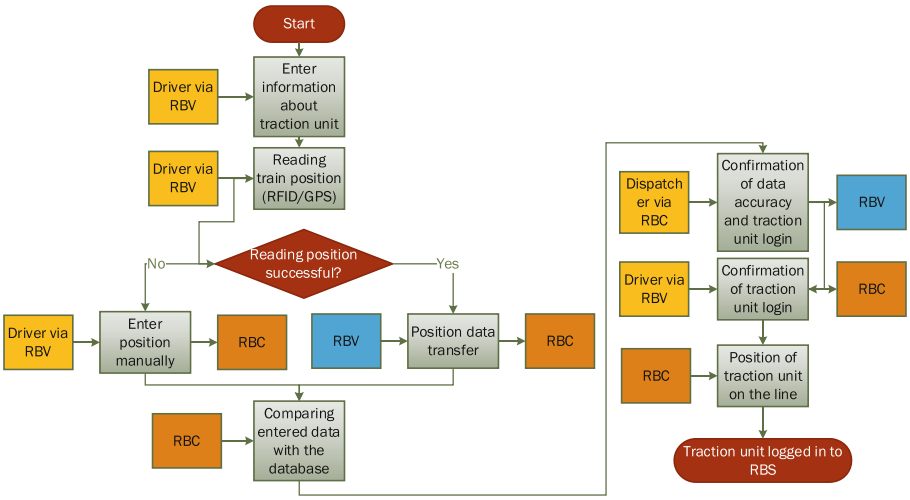


Fig. 1. Algorithm of logging in to RBS.

In order to log the traction unit into the RBS, the driver enters the information into the RBV and reads the RFID tag located at the track. If neither the tag nor the GPS

location can be read, the driver enters the location (such as the station name and track number) manually. The data is then sent to the RBC. The data received by the RBC from the RBV is evaluated and compared with the database. If the data match, the controller confirms the login and the RBC automatically places the traction unit and the train set on a specific track.

In the event of a request for authorisation to move, the driver enters the train information (operational train number and date of operation) into the RBV. If the train has not been entered in the RBV memory, they must enter the train number, date and next stopping point manually. They must also enter into the system whether the track in question remains occupied after the train has left the track or whether any vehicles remain on the track. By confirming the dialogue, the driver sends a request to move the train. The data is then processed by the RBS and transmitted to both parties involved in the communication, who acknowledge or refuse the request. The train will then be able to enter the line section and proceed through the following points on the line to the designated point where its movement authorisation is valid. Each train must stop at a designated point on the line where its movement authorisation ends, such as at a designated platform in a station. Ideally, it should stop as close as possible to the designated point where the RFID tag is located. Once the train has stopped, it reads the RFID tag and the GPS location, the RBV records the event and, after the driver confirms that the data is correct, the RBV sends a message to the RBC. The message confirms that:

- the train has arrived at the designated point (the RBV reads the RFID tag);
- the entire train has released all sections on the line;
- the rear of the train has cleared all collision points.

In case the train had not released the track sections or collision points, the driver would not acknowledge the correctness of the message data on reaching the designated point and would send an error message, whereas the RBC considers the track section as still occupied. This solution allows for the creation of sectional units on the line for increased capacity, including the control of their occupation by the train and further control of the train's direction of travel.

4 Discussion

Despite numerous statements, the topic of real safety improvement on regional lines in the Czech Republic is marginal, except for a period immediately following an accident. The conclusion from the investigation is the following in the case of one of the accidents on a line equipped with RBS according to [10]: "The fundamental cause of the accident was human error – the driver of the train Os 18003. Human error was manifested by overlooking and misjudging the situation". In the case of lines with no interlocking equipment, of which there are dozens in the Czech Republic, according to [11], a frequent cause of an accident is "Failure of the train driver to fulfil their reporting obligation at the station, failure to await the arrival of an oncoming train, failure to request permission for the train to depart and its unauthorised departure into a section of the track occupied by an oncoming train", with a contributing factor being "the absence of technical (interlocking)

equipment to eliminate the possible failure of the human factor". The proposal is not intended to compete with or in any way challenge the introduction of ETCS, but to provide an opportunity to increase safety on regional lines with lower traffic volumes where the installation of ETCS is completely ineffective.

Advantages of RBS with RFID:

- No need to install communication cables along the lines.
- Train signalling is not dependent only on the human factor (elimination of manual data entry).
- The dispatcher has a precise overview of the train's position on the track.
- Hardware upgrade and installation is simple and cheap compared to ETCS solutions.
- Overall lower costs for the operation of the interlocking system.
- Option for remote traffic control from central control centres.
- Increased operational safety on many lines in the foreseeable future.
- Increased resilience and reliability of the existing RBS, as the failure of RFID technology does not have a direct impact on operational safety.

Due to the high cost of implementing a standard remote control system with ETCS, there must be a high volume of traffic on the lines. The proposed modifications to the existing RBS are low-cost and can bring a significant improvement in rail safety on less frequented regional and local lines in the foreseeable future, as opposed to installing an ETCS, regardless of the level installed. The proposal for the implementation of RFID technology is based on a very low cost solution and could be used for traffic management on regional lines even without the use of RBS under certain circumstances.

5 Conclusion

Except for the internal development of interlocking systems by the manufacturer AŽD Prague and the development of a navigation support system for drivers, the Authors are not aware of any development of equipment that would have comparable parameters to the proposal. The Authors have reached the following research outcomes:

1. analysing the current state of operation on lines equipped with RBS;
2. analysing the interlocking equipment and other technical systems contributing to the safety of operation on regional lines in the Czech Republic and Slovakia;
3. analysing the vehicle fleet on regional RBS lines;
4. defining the shortcomings of the existing RBS system;
5. testing the performance of RFID technology in a railway environment;
6. designing algorithms for RFID operation and implementation in RBS, including staff workflows;
7. testing the functionality of the proposed solution in a railway environment.

The oncoming tests are planned on the operation of RFID with RBS in a realistic environment with specific rail vehicles. The idea of linking the RBS with the "Navigation for drivers" application is proposed for the nearest future. The introduction the application 2021 of "Navigation for Drivers" based on timetable data, positions and movements

of individual trains on the lines, alerts the driver to perform actions at individual points on the line and to approaching oncoming trains will be considered.

Acknowledgment. The hardware described in the article has been tested in the Transport Education and Research Centre of the University of Pardubice and within the OLTIS Group. The research has been carried out with the grant under the project "Student Grant Competition 2022".

References

1. Polach, V.: Centrální dispečink Přerov – pilotní projekt. In: Vědeckotechnický sborník ČD č. 22/2006, České dráhy, a. s., Prague (2006). https://vts.cd.cz/documents/168518/195375/2204.pdf/0bd759f3-6be6-4936-8d24-0ea2f1f6cddd. Accessed 11 May 2022
2. Veselý, K., Kačmařík, P., Pavel, M.: Critical safety aspects of GNSS virtual balise for ETCS. Railknowledge bank (2019)
3. SŽDC: Regulation on the Management of Railway Traffic on Lines Equipped with a Radio Block – SŽDC D4. Railway Operation Portal. https://provoz.szdc.cz/portal/Show.aspx?oid=1359773
4. Chrdle, Z.: Vlaky bez strojvedoucích, budoucnost nebo sen? Trains without drivers, the future or a dream? In: 6th Conference European Transport Trends: Will the Czech Republic Remain a Crossroads of Europe? (2017). http://www.top-expo.cz/domain/top-expo/files/smart-city/smart-city-2017/ted/prezentace/05-chrdle_zdenek.pdf. Accessed 16 Mar 2019
5. Senadeera, S., Dogan, N.: Emerging applications in RFID technology. Int. J. Comput. Sci. Electron. Eng. (IJCSEE) **4**(2) (2016). ISSN 2320-4028
6. Hell, P., Varga, P.: Accurate radiofrequency identification tracking in smart city railways by using drones. Interdiscip. Descr. Complex Syst. **16**(3), 333–341 (2018)
7. Balog, M., Mindas, M.: Informatization of Rail Freight Wagon by implementation of the RFID technology. In: Leon-Garcia, A., et al. (eds.) SmartCity 360 2015-2016. LNICSSITE, vol. 166, pp. 592–597. Springer, Cham (2016). https://doi.org/10.1007/978-3-319-33681-7_50
8. Zhang, J., Shao, L.: Research on the railway safety monitoring based on the Internet of Things technology. In: Zhang, R., Zhang, Z., Liu, K., Zhang, J. (eds.) LISS 2013, pp. 921–926. Springer, Heidelberg (2015). https://doi.org/10.1007/978-3-642-40660-7_137
9. Hricova, R.: RFID as a tool of competitiveness increase of rail freight. ACTA TECNOLOGÍA **2**(1), 11–14 (2016)
10. The Rail Safety Inspecton Office: Collision of a passenger train No. 18003 and the freight train No. Mn 88850 between Číčenice and Vodňany stations. Accident and incident investigation report, Prague (2011). https://www.dicr.cz/uploads/Zpravy/MU/DI_Vodnany.pdf
11. The Rail Safety Inspection Office: Collision of the regional passenger train No. 17113 with the regional passenger train No. 17110 between Pernink and Nové Hamry operating control points. Accident and incident investigation report, Prague (2020). https://www.dicr.cz/files/uploads/Zpravy/MU/DI_Pernink_Nove_Hamry_200707.pdf

Revised Estimation of Public Railway Infrastructure Line Capacity: Lithuanian Case

Gintautas Bureika(✉)

Vilnius Gediminas Technical University, Saulėtekio al. 11, 10223 Vilnius, Lithuania
gintautas.bureika@vilniustech.lt

Abstract. The problematic of determination of maximum capacity of Lithuanian Railway lines is considered is this article. Maximum capacity considered the largest number of trains that could run over a railway line, during the scheduled time interval. At the same time, the train traffic should be ensured in a strictly perfect, mathematically defined environment, with the trains running permanently and ideally at minimum headway, i.e., keeping time-based distance between two consecutive trains. Current applied calculation methods and the means of Lithuanian train traffic arranging are revised by estimating the railway traffic irregularity due the features of technical equipment: traction vehicles, signalling, automatic, track, catenary, etc. The maximum potential capacities of three problematic lines of Lithuanian Railways are estimated taking into account the type and power of freight locomotives. Considered railway lines are: "Livintai – Gaižiūnai", "Plungė – Šateikiai" and "Pagėgiai – Tauragė – Viduklė". Finally, basic conclusions and recommendations are given.

Keywords: Railway transport · Line capacity · Traffic schedule · Period · Time interval · Consecutive trains

1 Problematic of Ensuring the Railway Capacity

The railway transport sector consists of railway infrastructure (railway, power supply and signalling/automatic) and rolling stock fleet (rolling stock, road vehicles, depots, etc.). The capacity of a railway line is the maximum number of trains or pairs of trains of a specified mass that can be passed during a unit of time (day, hour, day) ensuring absolute traffic safety. The available technical means of traffic organization (equipment), the type and power of the rolling stock used, technologies and established methods of train traffic organization (e.g., type of traffic schedule) are evaluated.

Many researchers consider the problematic of effective using of railway capacity in different countries. The in-depth research of the main factors affecting railway capacity is being carried out on a few Spanish railway infrastructures [1]. The results exemplify how the capacity diverges with factors such as train speed, arranged stops, train heterogeneity, distance between rail signals, and traffic timetable consistency [1, 10]. Real data from the Swedish rail network, train operation and delays were used by Anders to analyse how different factors influence available capacity and train delays [2]. The second approach of

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 756–764, 2023.
https://doi.org/10.1007/978-3-031-25863-3_73

this researcher was the railway experiments by using simulation tool RailSys, especially the analysis revealed an in-depth understanding of the mechanisms of railway operation on double-track lines. Other paper describes how the UIC 406 method it is expounded in Denmark [8, 9]. The relationship between train delay, traffic volume and train type heterogeneity was investigated in a series of experiments using simulation analysis of trains operating on a single-track rail lines was considered by Dingler [5]. The density of railway level crossings has a considerable influence on the capacity of railway lines due to the speed limitation in them [3, 4].

Theoretical capacity is the number of trains that could run over a route, during a specific time interval, in a strictly perfect, mathematically generated environment, with the trains running permanently and ideally at minimum headway (i.e., temporal interval between two consecutive trains). The main disadvantage of the current Lithuanian railway transport infrastructure is the insufficiency of two-track railways in the entire network. In 2020 two-track lines of Lithuanian Railways accounted for only 23% of the entire national railway network. For this reason, the passing oncoming trains and free passing of slower moving trains raise complications.

The aim of this study was to reveal the inaccuracies of determination the capacity of the lines by Lithuanian Railway Undertaking (thereafter – RU) and to propose the methods of calculating the maximum capacity of the lines and the ways of its realization. The new approach proposed by Author to ensure enlarging the capacity of railway lines is relying on freight locomotive dynamic features: acceleration and potential speed considering the profile of track instead of scheduled time periods.

2 Methodology of Determination of Railway Line Capacity

The capacity of a railway line is the maximum number of freight trains (pairs of trains) of the specified mass and length, which can be passed through this railway line per time unit (day, hour), taking into account the technical equipment of the railway line and the way train traffic is organized. It is possible to extract the available capacity, i.e., the one that is currently available and the necessary capacity required to provide the expected traffic volumes in the nearest future.

Capacity is determined by dividing the time of day available for train traffic by the schedule period. Automation and centralisation of operations could bring useful capacity closer to the maximum calculated, or even to their maximum level. Factors that affect capacity include:

1. rolling-stock;
2. locomotive power (acceleration and potential speed);
3. train length;
4. brake distance;
5. automation and signalling equipment are used in stations and lines;
6. making of schedules (using a certain type of schedule);
7. development of the infrastructure at the stations;
8. availability of platforms;
9. development of railway infrastructure;

10. development of station switcher yard;
11. types of switchers that are used in stations;
12. train traffic planning and organization processes, etc.

The map of the network of Lithuanian Railway lines is presented in Fig. 1.

LATVIA
RUSSIA
POLAND
BELARUS
Priekulė
Rengė
Meitenė
Šarkiai
Joniškis
Biržai
Pasvalys
Pakruojis
Meškučiai
Kuršėnai
Šiauliai
Radviliškis
Pevevėžys
Daugpilis
Zarasai
Turmantas
Visaginas
Anykščiai
Utena
Dūkštas
Rubikiai
Ignalina
Didžiasalis
Adutiškis
Maseluki
Molėtai
Ukmergė
Širvintos
Pabradė
Skersabaliai
Bezdonys
Kyviškės
Kena
Gudonai
Vilnius
Paneriai
N Vilnia
Lentvaris
Trakai
Valčiūnai
Jašiūnai
Vaidotai
Rūdiškės
Valkininkai
Matuizos
Stasylos
Varėna
Marcinkonys
Druskininkai
Porieče
Trakiški
Mockavа
Lazdijai
Šeštokai
Alytus
Kalvarija
Marijampolė
Vilkaviškis
Kybartai
Nesterov
Vinčai
Pilviškiai
Kaunas
Mauručiai
Jūrė
Kaišiadorys
Žaslai
Vievis
Livintai
Gaižiūnai
Kalnėnai
Palemonas
Šakiai
Jurbarkas
Šilainiai
Lukšiai
Žeimiai
Kėdainiai
Dotnuva
Raseiniai
Šilalė
Šilutė
Pagėgiai
Gelgaudiškis
Tauragė
Varlaukis
Viduklė
Šiauliai
Šilutė
Šilalė
Šilainiai
Šilutė
Šilalė
Šilutė
Šilalė
Šilutė
Šilalė

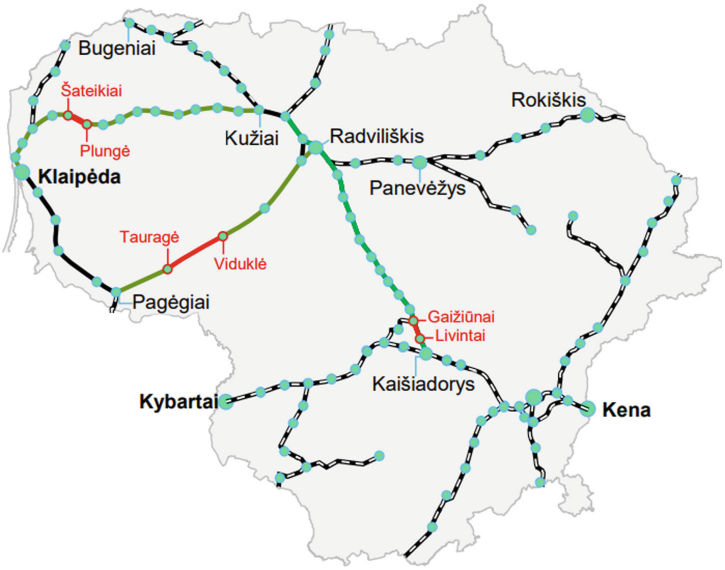


Fig. 2. Three problematic Lithuanian Railway sections: "Kaišiadorys – Radviliškis", "Kužiai – Klaipėda" and "Radviliškis – Pagėgiai" [7].

2. stations – capacity of arrival and departure tracks and switchers;
3. power supply equipment of electrified lines – data of the power supply traction system.

3 Calculations of Line Capacities and Results

3.1 Definition of Traffic Scheduled Periods on Lines

A schedule period is considered to be the time that a railway line is occupied by a group of trains, characteristic of a certain schedule type. It is usually chosen from the four options of passing trains (see Fig. 3), according to which the period T is calculated. These four schemes show different options of possible passing of opposing freight trains through the limiting railway line. The lowest value of scheduled period for calculating the capacity was selected. When drawing up the train traffic schedule, it is necessary to provide for the passage of trains through the limiting line in accordance with the scheme that ensures the highest efficiency.

The line capacity is calculated with a unified mass of the train:

1. The mass of odd direction freight trains is equal to 6,000 t.
2. The mass of even direction trains is equal to 2,500 t.

The unified mass of freight trains is selected from 2020/2021 of the freight train traffic schedule of RU. Schemes of passing trains through the lines of limited capacity are shown in Fig. 3.

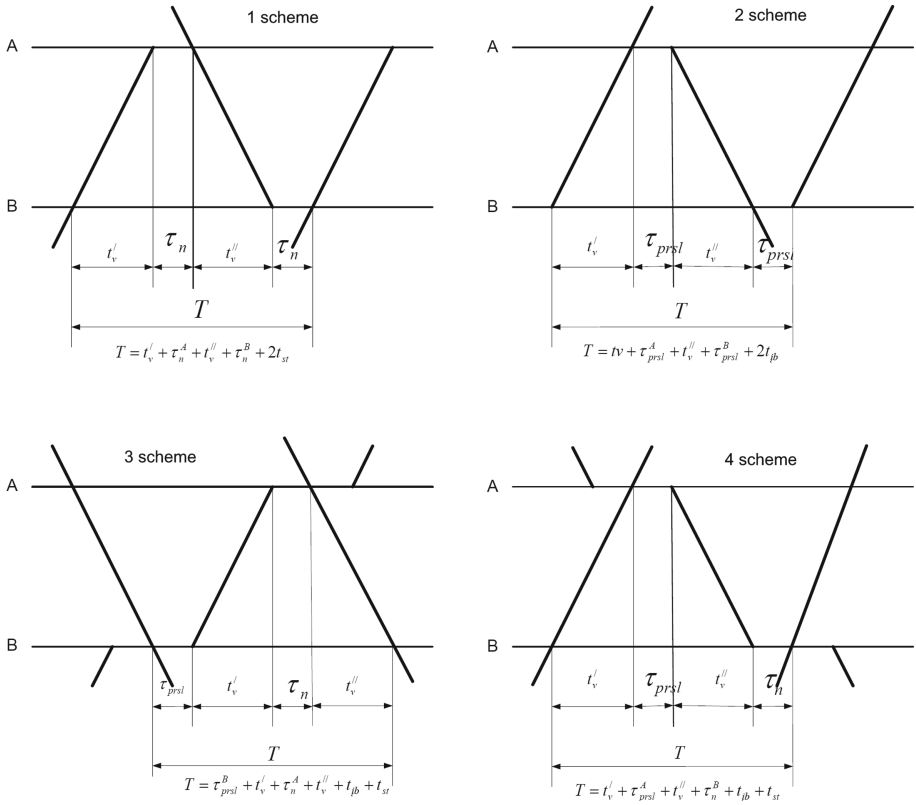


Fig. 3. Schemes of passing trains through the lines of limited capacity: T – period of train traffic schedule, min.; $t_v^{/}$ and $t_v^{//}$ – train running time without braking and acceleration, min.; t_{st} – train braking time, min.; t_{jb} – train acceleration time, min.; T_n – train arriving interval at considering stations A and B, min.; T_{prsl} – train overtaking interval in considering stations A and B, min.

It is also assumed that the throughput is calculated for the main series of freight locomotives used in Lithuanian Railways: 2M62M and SIEMENS ER20CF. The technical characteristics of these locomotives were used in the calculations.

At the railway line "Livintai-Gaižiūnai" the shortest time period is obtained by organizing train traffic according to the 3rd scheme (Fig. 3), and at the line "Plungė – Šateikiai" and "Viduklė – Tauragė" according to the 2nd scheme. The capacity indicators of railway line depend on the types of signalling, automatic and blocking equipment used to manage train traffic at that line, train movement speeds and principles of traffic organization.

3.2 Capacity of Railway Line "Viduklė–Tauragė"

The length of this single-track line is 42.3 km. A semi-automatic blocking is used to organize train traffic, i.e., there can be only one train at a line. Both Viduklė and Tauragė

stations are equipped with electrical centralization of switches and signals. The permitted speed of freight trains at this line is 80 km/h.

The maximum capacity of the line "Viduklė –Tauragė" is calculated according to the Formula (1). It was evaluated the main criteria of the components of development of the Lithuanian Railway technological process [10]:

$$N = \frac{(1440 - t_{tech}) \cdot \alpha_p}{T}; \tag{1}$$

where 1440 – number of minutes per day; t_{tech} – technology breaks of train traffic, min.; α_p – reliability coefficient, estimating the traffic irregularity due the fails of technical equipment (signalling, automatic, track, catenary, etc.); T – period of train traffic schedule, min.

The duration of the technological traffic break on single-track lines is 60 min. The reliability coefficient is 0.96. In this case, the capacity of the line is $N = 13$ pairs of trains, i.e., 13 even and 13 odd trains. Carrying trains with 2M62M or 2ER20CF locomotives and properly repaired infrastructure tracks would increase the capacity of the line up to $N = 16$ pairs of trains.

The throughput of the railway line "Viduklė–Tauragė" is presented in Fig. 4.

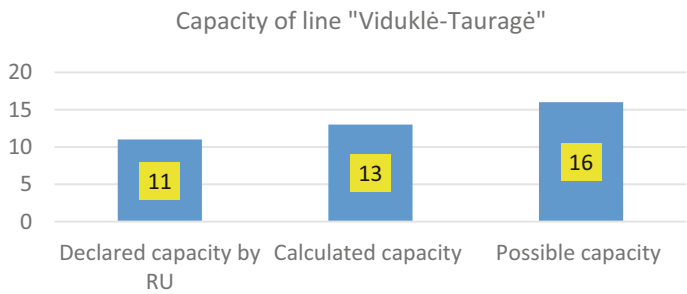


Fig. 4. The capacity of the line "Viduklė – Tauragė" in pairs of trains.

3.3 Capacity of Single-Track Line "Plungė – Šateikiai"

The line "Plungė – Šateikiai" is the limiting line of the railway section "Kužiai – Klaipėda". The line is 13.9 km length. Both stations bordering the line are equipped with microprocessor centralization of switchers and signals. An automatic blocking is used to manage train traffic on the line. This means that the blocks separating the trains from each other are limited by the line traffic lights. The maximum permitted speed for freight trains at this line is 90 km/h.

The line "Plungė – Šateikiai" is single-track and equipped with an automatic blocking, so the capacity is calculated according to the Formula (2) [10]:

$$N = \frac{K \cdot (1440 - t_{tech}) \cdot \alpha_p}{(K - (K-1) \cdot \alpha_{pp}) \cdot (t' + t'' + T_a + T_b) + (K-1) \cdot (I_t' + I_t'') \cdot \alpha_{pp}}; \tag{2}$$

where α_{pp}– set coefficient, equal to proportion of number of trains running in the set and the total number of passing trains; t' and t'' – running time of trains on a line, min.; $I_t^{'}$ and $I_t^{''}$ – interval between the train sets running on even and odd direction, respectively, min.; K – number of trains in the set; T_a and T_b – periods of train traffic schedule, respectively stations A and B, min.

The maximum calculated capacities of the railway line "Plungė – Šateikiai" are shown in Fig. 5.

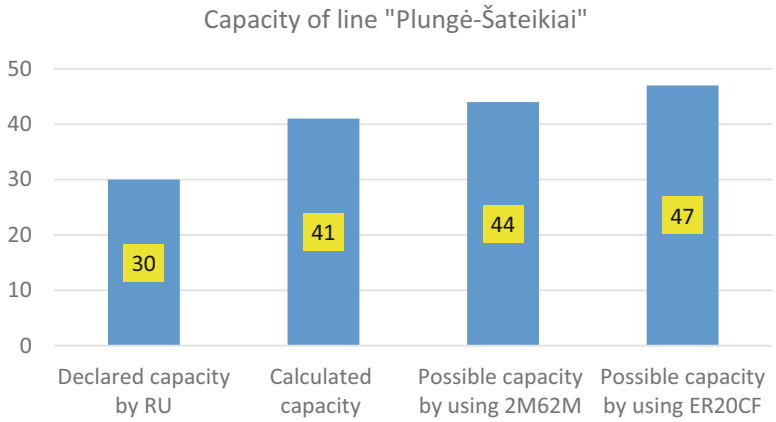


Fig. 5. The capacity of the line "Plungė – Šateikiai" in pairs of trains.

It can be state that Lithuanian RU does not rationally uses the public railway infrastructure, and the chosen method of compiling the service train schedule does not ensure the maximum possible capacity of lines.

3.4 Capacity of Single-Track Line "Livintai – Gaižiūnai"

The limiting single-track line "Livintai – Gaižiūnai" is located on the railway section "Kaišiadorys – Radviliškis". It is equipped with an automatic blocking. "Livintai – Gaižiūnai" line is 11.9 km long. Both stations bordering the line are equipped with microprocessor centralization of switchers and signals. The speed limit for freight trains is 90 km/h. Freight trains in both directions pass through this station at an average speed of 65 km/h. The maximum capacity of the line "Livintai – Gaižiūnai" was calculated according to Formula (2). In order to more efficiently use the automatic blocking at the line, it is necessary to set trains, i.e., allow one-way trains one after the other "in group". Assuming the condition that the number of trains in the set will be two trains, it was gained a theoretical capacity $N = 52$ pairs of trains. Figure 6 shows the capacity diagram for this line "Livintai – Gaižiūnai".

Thus, the method of compiling the official train schedule chosen by the Lithuanian RU for organizing the running of freight trains in problematic (single-track) lines does not ensure the maximum possible capacity.

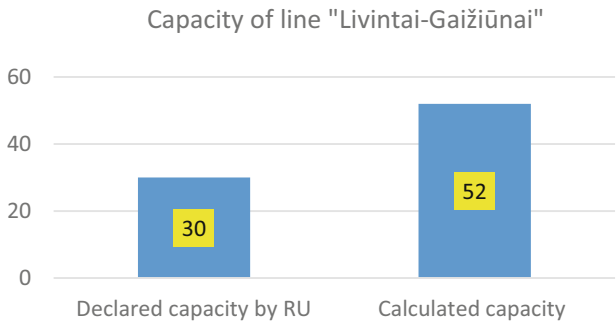


Fig. 6. The capacity of the line "Livintai – Gaižiūnai" in pairs of trains.

4 Conclusions

Insufficient capacity of the public railway infrastructure restricts the competition of the railway transport market and disturbs the liberalization of the activity of the whole transport sector of Lithuania. Incorrect determination of the maximum possible capacity of railway lines does not ensure rational and efficient use of the public infrastructure potential of Lithuanian Railways. The capacity of the railway line "Viduklė–Tauragė" declared and actually implemented by the Lithuanian railway undertaking is 1.5 times lower than the revised capacity, of the line "Plungė –Šateikiai" – 1.6 times and of the line "Livintai – Gaižiūnai" – 1.7 times.

In order to increase the capacity of railway lines with automatic blocking, the arrangers of train traffic by packaging method is applicable. In Lithuanian Railways, the traffic schedule of non-pair trains is not still sufficient applied for increasing the capacity of problematic lines.

References

1. Abril, A., Barbert, F., Ingolotti, L.P., Salido, M.A., Tormos, M.P.: An assessment of railway capacity. In: Transportation Research Part E Logistics and Transportation Review. Published by Elsevier. Online ISSN: 1366-5545 (2008). https://www.researchgate.net/publication/222673865_An_assessment_of_railway_capacity
2. Anders Lindfeldt, A.: Railway capacity analysis: methods for simulation and evaluation of timetables, delays and infrastructure. Doctoral thesis in infrastructure, Stockholm, KTH, p. 77 (2015). http://www.diva-portal.org/smash/get/diva2:850511/FULLTEXT01.pdf
3. Bureika, G., Gaidamauskas, E., Kupinas, J., Bogdevičius, M., Steišūnas, S.: Modelling the assessment of traffic risk at level crossings of Lithuanian railways. Transport **32**(3), 282–290 (2017). Technika, Taylor & Francis, Vilnius, London. ISSN 1648-4142
4. Bureika, G., Komaiško, M., Jastremskas, V.: Modelling the ranking of Lithuanian railways level crossing by safety level. Transp. Probl. = Problemy Transportu: Int. Sci. J. **12**(Special edition) 11–22 (2017). The Silesian University of Technology, Katowice
5. Dingler, M.: Understanding the Impact of Operations and New Technologies on Railroad Capacity, in Civil Engineering. University of Illinois at Urbana-Champaign, Urbana-Champaign (2010)

6. Directive 2012/34/EU of the European Parliament and of the Council of 21 November 2012. Establishing a single European railway area (recast) (2012). https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32012L0034&from=lt
7. JSC "LTG Infra", Capacity analysis in a congested infrastructure. (In Lithuanian: Pajėgumų analizė perpildytoje infrastruktūroje) (2018). http://lginfrastruktura.lt/documents/12778/17719/Pajegumu_analize_2017_2018.pdf/330c70b4-5368-42c8-a56b-f2ddf12ce909
8. Khadem Sameni, M., Landex, A., Preston, J.: Developing the UIC 406 method for capacity analysis. In: Proceedings for 4th International Seminar on Railway Operations Research (2011). http://www.iaror.org
9. Landex, A., Kaas, A.H., Schittenhelm, B., Schneider-Tilli, J.: Evaluation of railway capacity. In: Proceedings of Trafficdays, pp. 1–22. DTU (2006)
10. Ševaldin, D.: Interaction between Lithuanian Railway infrastructure capacity and long and heavy freight train traffic. Master thesis. VILNIUS TECH, p. 70. (In Lithuanian: Lietuvos geležinkelių infrastruktūros pralaidumo bei ilgųjų ir sunkiųjų prekinių traukinių eismo sąveika) (2022)

Innovations and Development of Aerospace Technologies

Influence of the Ground Effect on the Precise Landing of an Unmanned Aircraft

Andrius Dubovas(✉) and Domantas Bručas

Vilnius Gediminas Technical University, Vilnius, Lithuania
{andrius.dubovas,domantas.brucas}@vilniustech.lt

Abstract. This paper examines a multi-rotor unmanned aerial vehicle and the influence of the ground effect on the aircraft during the landing stage. Theoretical and practical research of other authors and results are described. It is briefly discussed how the position of the high-pressure area changes with changing environmental conditions. The study examined the ground effect on the drone at 1/3R - 2R. Calculations show that the propeller thrust increases up to 7%. Also, discussing the results, it has been hypothesized that an increase in thrust near the ground will reduce engine speed, which may directly impact the drone's stability and landing accuracy. Further research is needed to explore this issue further.

Keywords: Unmanned aerial vehicle · Ground effect · Landing accuracy

1 Introduction

1.1 Drone Landing Systems

These days, the use of unmanned aerial vehicles is becoming increasingly popular. These aircraft are used for recreational and targeted missions, and vertical take-off multi-propeller are most commonly used for those tasks. The main advantage of this type of drone is better maneuverability and the ability to land on a smaller site compared to fixed-wing aircraft. Since there are tasks where the pilot cannot visually land the drone, it is essential to ensure that the UAV can land precisely on the selected spot. Various systems, such as video cameras or a GPS RTK system, can be used for this purpose.

The first method uses a camera mounted on a drone. Calibration points are marked at the landing site, which is captured by the video camera as the aircraft approaches the ground, the actual position of the drone is calculated, and the necessary corrections are made. The disadvantage of the system is that the landing site must be prepared before the flight and marked with unique calibration points. Studies have also shown that cameras do not always capture calibration points when using this system [1].

Another method that can be used to improve landing accuracy is satellite navigation. It should be noted that these systems are sufficient for the accuracy of the flight. However, according to the available data [2], the accuracy of the GPS signal alone is not sufficient for the landing of an unmanned aircraft. For this reason, an improved GPS RTK system is used. During static tests, it was found that the error did not exceed 2.5 cm. During dynamic tests, it was found that the system's error did not exceed 3 cm [3].

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 767–772, 2023.
https://doi.org/10.1007/978-3-031-25863-3_74

1.2 Landing Accuracy

Practical studies with commercial drones have shown [4] that imaging systems to improve landing accuracy achieve an accuracy of about 8 cm. The average landing error of a study using an unmanned aircraft with a GPS RTK system ranged from 7 cm to 14 cm [5].

1.3 Ground Effect

The ground effect occurs when the aircraft approaches the ground. The magnitude of the effect depends on the distance between the aircraft propeller and the ground [6]. The distance is calculated by taking the propeller blade as the reference unit. Depending on the aircraft type, this distance varies from 2 to 5 times the blade length when the effect starts. Also, the effect increases proportionally with decreasing distance to the ground [7]. According to the theory of helicopters [8], the maximum value of the ground effect is felt at a distance to the ground equal to half the length of the blade. Similar tendencies are seen with multi-propeller aircraft. The main difference - the strength of the Ground effect, also depends on the number of propellers. Comparing single and four-propeller aircraft, a more robust effect is seen with multi-propeller aircraft [9].

Simplified models are most commonly used in computer modeling studies. It is assumed in the calculations that the airflow moves vertically downwards from the propeller, and the flow rotation influenced by the rotating propeller is not considered [10].

Practical studies also show that reducing the impact of the ground effect reduces the landing error from 14 cm to 7 cm [5]. The study used a platform that was lifted off the ground. The platform itself has many holes that allow air to pass freely. This increased the distance between the propeller blades and the ground, and the platform allowed airflow to move to the ground. The downside to this solution is that a landing pad must be installed before the flight, which is not always possible.

Analysis of aircraft fluctuations at different altitudes has shown that the fluctuations follow a sinusoidal graph. It is also clear from the analysis that the amplitude of the oscillations decreases with increasing altitude. One of the researchers' suggestions is implementing these changes in the drone flight program [11].

2 Ground Effect Simulations

2.1 Methodology

The OpenVSP program is used for theoretical calculations. The drone model is based on a drone made by the company "Up and Above", which can be seen in Fig. 1.

This drone is equipped with EMAX MT4114 engines. These are composed of fifteen-inch two-blade propellers with a pitch of 5.5. The following parameters were used for the calculations:

- Propeller thrust – 10 N;
- Propeller speed – 4,000 rpm;

Fig. 1. Drone used for research.

- Time interval between calculations – 0.00063 s.
- Distance to ground – 1/3R - 2R, where R is the length of the blade.

The Vortex Lattice Method (VLM) was used for the calculations. Calculations were started using a distance equal to 1/3 of the length of the blade. The modification was performed using 25 propeller revolutions. The air density of the standard atmosphere was also used - 1.225 kg/m^3. The following distances were used for the following calculations:

- 1/2R;
- 1R;
- 1 2/3R;
- 2R;

After the first calculations, a difference with the works of other authors was observed. As shown in Fig. 2, the airflow lines do not move vertically downward due to the propeller's rotation but move downward in a spiral until it bounces to the surface.

As seen from the modeling, the high-pressure zone is not concentrated under the central part of the drone. Separate high-pressure zones are formed under each propeller, as shown in Fig. 2, and a higher pressure zone is created directly under propellers. Simulations with crosswind were also performed, the results can be seen in Fig. 3.

The use of 7 m/s wind was chosen for the simulations. In this case, the thrust of the propeller was not observed. Calculations show that the high-pressure area is not concentrated directly under the propellers but moves with the ambient airflow. Areas

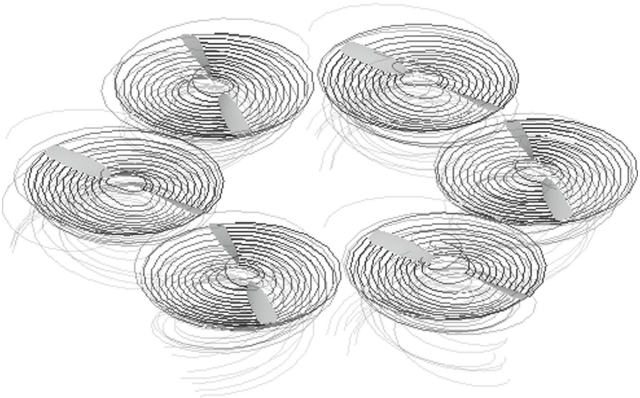


Fig. 2. Ground effect under each rotor.

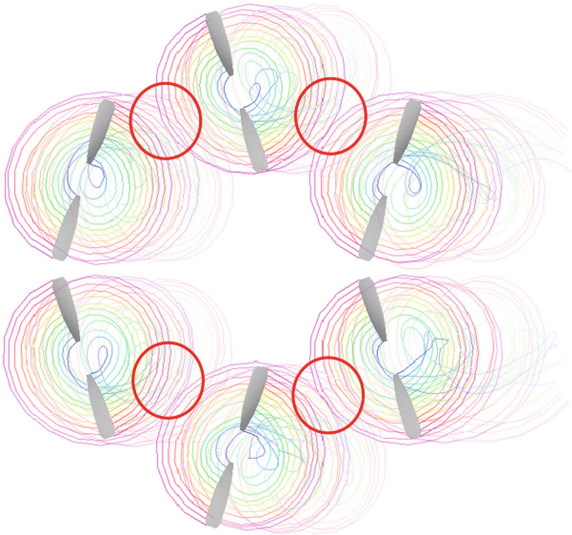


Fig. 3. Ground effect under the influence of wind.

with streams from different propellers are marked in red. Further research is needed to determine how this affects the drone's stability.

Further data analysis observed a variation in propeller thrust at different distances between the propeller and the surface. Figure 4 shows the increase in thrust when the distance between the ground and the propeller is equal to 1/3 of the blade length. Data analysis shows an increase in thrust of up to 7 percent. When comparing results when the distance to the ground was equal to 2R, the increase in thrust was negligible. Further calculations show that the increase in the distance between the propeller and the blades decreases with increasing distance.

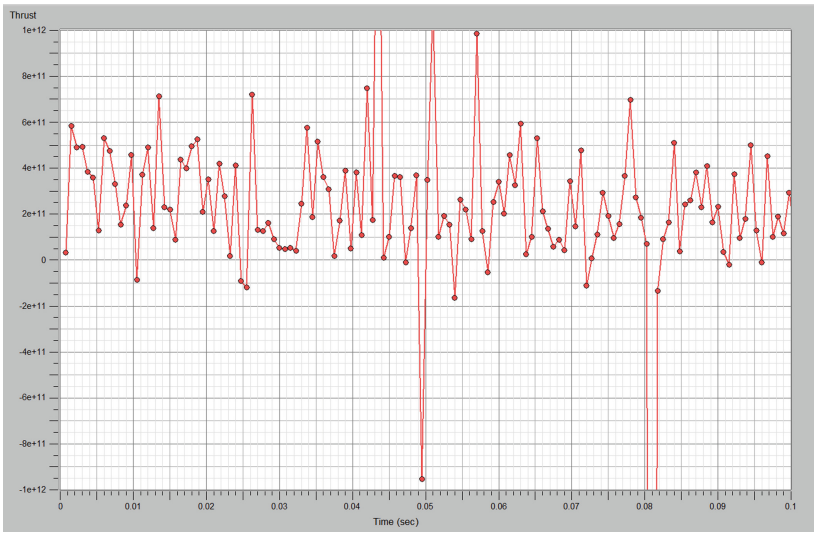


Fig. 4. Propeller thrust when the distance to the ground is equal to 1/3R.

After the calculations, a new hypothesis was created. Increased thrust reduces engine speed, and as the engine speed decreases, the drone's response time to thrust changes increases. As a result, the drone's stability decreases, which has a direct effect on landing accuracy.

3 Conclusions

It can be seen that as the unmanned aircraft approaches the ground, the propeller thrust increases due to the ground effect. This reduces the power required by the motors. On the other hand, at ground distances of 1/3R, lower engine speeds than at cruising altitudes can affect the stability of the aircraft near the ground. For this reason, the accuracy of the landing may be reduced. Further testing is needed to confirm or refuse this hypothesis. Further research is also needed to determine what action needs to be taken to reduce the impact of the land effect.

References

1. Saripalli, S., Montgomery, J.F., Sukhatme, G.S.: Vision-based autonomous landing of an unmanned aerial vehicle. In: Proceedings 2002 IEEE International Conference on Robotics and Automation (Cat. No. 02CH37292), vol. 3, pp. 2799–2804. IEEE (2002)
2. Lebedev, I., Erashov, A., Shabanova, A.: Accurate autonomous uav landing using vision-based detection of aruco-marker. In: International Conference on Interactive Collaborative Robotics, pp. 179–188 (2020). Springer, Cham.Author, F., Author, S., Author, T.: Book title. 2nd edn. Publisher, Location (1999)
3. Eriksson, S.: Real-time kinematic positioning of UAS-possibilities and restrictions (Master's thesis) (2016)

4. Yoakum, C., Cerreta, J.: A review of DJI's mavic pro precision landing accuracy. Int. J. Aviation Aeronautics Aerospace **7**(4). (2020). https://doi.org/10.15394/ijaaa.2020.1524
5. Zukauskas, L.: Research on Real-Time Kinematic Global Positioning System Accuracy Used in Unmanned Aerial Vehicle (2020)
6. Li, J., Lei, G., Xian, Y., Wang, X.: Research on ground effect of shipborne flying-wing UAV. In: Proceedings - 2014 10th International Conference on Computational Intelligence and Security, CIS 2014, pp. 685–688. (2015). https://doi.org/10.1109/CIS.2014.105
7. Merkeliunas, E.: Study of multirotor UAV landing accuracy improvements (2021)
8. https://www.copters.com/aero/ground_effect.html
9. Sanchez-Cuevas, P., Heredia, G., Ollero, A.: Characterization of the aerodynamic ground effect and its influence in multirotor control. Int. J. Aerospace Eng. (2017)
10. Matus-Vargas, A., Rodriguez-Gomez, G., Martinez-Carranza, J.: Ground effect on rotorcraft unmanned aerial vehicles: a review. Intel Serv Robot. **14,** 99–118 (2021). Doi:https://doi.org/10.1007/s11370-020-00344-5
11. Aicha, S., Ahujab, C., Guptac, T., Arulmozhivarmand, P.: Analysis of Ground Effect on Multi-Rotors (2014)

Mathematical Model of Airport Aviation Security

Olena Sokolova, Kostiantyn Cherednichenko(✉), and Viktoriia Ivannikova

National Aviation University, Kyiv 03058, Ukraine
cherednichenko.kostya@gmail.com

Abstract. Nowadays there is a duality in the definition of aviation security. In the study, the authors considered aviation security as a state of protection of aviation security from acts of unlawful interference, which is provided by a set of measures involving human and material resources. Current research on this topic leaves quite unexplored the impact of criminality and economic factors that could potentially affect the level of threats to the airport. Developed multiple regression aviation security model Schiphol Airport clearly demonstrates the importance of such factors, which have been deprived of attention among scientists. Potentially, the model could be expanded by creating a multi-level aviation security model that requires further research (particularly in terms of the Occam razor principle) and a significant sample of statistics. The obtained results confirmed authors assumption about the dependence of acts of unlawful interference and criminality of area in which the airport is located: there is a significant positive correlation; with an increase in criminality there is +0.017 increase in acts of unlawful interference. From a practical point of view, the developed model of aviation security allows to manage and forecast the level of danger in order to ensure the airport operation safety.

Keywords: Aviation security · Safety · Mathematical model · Risk · Interference · Airport

1 Introduction

Today, aviation security in Ukraine is dualistic: ICAO defines it as a combination of measures and human and material resources intended to safeguard civil aviation against acts of unlawful interference; Air Code of Ukraine (ACU) determines it as a protection of civil aviation (CA) from acts of unlawful interference (AUI), which is provided by a set of measures involving human and material resources [1].

Authors believe these statements is insufficiently disclosed and describe only a normative and legal aspects of security. It is recommended to understand this term as follows: according to the ACU, aviation security is one of the areas (subsystems) of civil aviation safety, defined as: "…the state of civil aviation with acceptable level…" [2]; therefore, if the supersystem is considered as a "state", then the subsystem must be interpreted in a similar way. Integrated and supplemented definition of aviation security - the state of

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 773–781, 2023.
https://doi.org/10.1007/978-3-031-25863-3_75

protection of aviation security from acts of unlawful interference, which is provided by a set of measures involving human and material resources. Typically, in order to assess the level of security, a comprehensive model is built, which consist of:

– the surface with a set of "vectors" by which the intruder could attack;
– risk, which is defined as a mathematical expectation (probability) of attack and losses from it;
– human and material resources designed to prevent and protect from attacks on civil aviation infrastructures.

However, in most of the analyzed scientific studies on this topic [2–7], the models of intruders (violators) either limited by the definition of "terrorism", or are not considered at all, which is inaccurate.

Intruders (violators) of aviation security may be divided into the following groups: "insiders" (dismissed employee; employee, responsible for an operational incident); "accidental" intruder (for example, burglars and robbers); terrorists. It should be noted that the last-mentioned group is the smallest in of incidents, but it is the most dangerous one.

The concept of terrorism has a very narrow field of interpretation, so today in counter-terrorism study, scholars use term "violent extremism", which includes "terrorism" [8–11]. Violent extremism (VE) is the phenomenon of non-state actors, or individuals, or organizations, who commit violence or contribute to it for social or political purposes, or promote ideas that rationalize, justify and encourage the mobilization of violence [8]. The VE also includes ideologically motivated crimes, such as hate crimes, which may not reach the threshold of terrorism.

The authors claim it necessary to, firstly, consider the term "violent extremism" in comprehensive model of aviation security; secondly - to analyze potential intruders (violators) by assessing the criminality of the area in which the airport is located.

It is critical to avoid a fundamental attribution error: to claim that airports with higher security and low operations values are "safer" than airports with lower security at higher operations is incorrect. Therefore, it is recommended to add to the complex model such indicators as passenger or freight traffic [12]. Such indicators could be also be used to in order assess the "attractiveness" of an airport for attack.

Also, the economic aspects remain rather unexplored, for example, the expanses on airport's security services and its impact on safety. The concept of CA security has some uncertainty: there is no clear definition "acceptable level" of damage risks, which indicates the diversification of costs dedicated to ensure such level.

2 Results

Schiphol Airport (Amsterdam, Netherlands) operations data was taken in order to create a mathematical model with the above assumptions.

The initial production statistics were taken from Royal Schiphol Group «Traffic Reviews» [13] (Table 1):

Table 1. Initial production statistics Amsterdam Schiphol Airport.

Year	Freight (in million tons) [13]	Passengers (in millions) [13]	Air transport movements (in thousands) [13]
2000	1,222	39,271	414,928
2001	1,180	39,531	416,462
2002	1,240	40,588	401,385
2003	1,310	39,960	392,997
2004	1,420	42,541	402,738
2005	1,450	44,163	404,594
2006	1,530	46,066	423,122
2007	1,610	47,794	401,888
2008	1,570	47,392	428,336
2009	1,290	43,523	418,742
2010	1,510	45,137	386,316
2011	1,520	49,681	420,349
2012	1,480	50,976	423,407
2013	1,530	52,569	409,835
2014	1,630	54,978	404,728
2015	1,620	58,284	424,728
2016	1,670	63,625	460,145
2017	1,760	68,515	484,000
2018	1,720	71,053	476,934
2019	1,570	71,700	496,826
2020	1,400	20,900	227,304
2021	1,670	25,500	266,967

Royal Schiphol Group's Annual Reports were also analyzed [14] on security costs and acts of unlawful interference (Table 2):

Table 2. Dynamics of security costs and AUI of Schiphol Airport.

Year	Aviation security expanses (in millions) [14]	Acts of unlawful interference [14]
2000	198	40
2001	203	42
2002	201	43
2003	199	43
2004	200	44
2005	203	46
2006	204	45
2007	221	40
2008	221	41
2009	241	32
2010	242	31
2011	261	36
2012	247	42
2013	232	23
2014	271	17
2015	238	41
2016	247	47
2017	293	46
2018	300	30
2019	270	35
2020	254	25
2021	243	24

In order to simplify the study, the number of cases of violence in Amsterdam were used as an assessment of criminality [15, 16]: (Table 3)

Table 3. Public violence in Amsterdam.

Year	Number of cases of public violence in Amsterdam [15, 16]
2000	570
2001	539
2002	609
2003	628
2004	646
2005	685
2006	636
2007	500
2008	501
2009	665
2010	585
2011	485
2012	465
2013	380
2014	305
2015	330
2016	295
2017	395
2018	260
2019	335
2020	250
2021	385

The multiple regression model was programmed with RStudio software. The results are presented in Fig. 1.

```
Console  Terminal  Jobs
R 4.1.3 · ~/
> # add Schiphol Airport statistical data
> library(readxl)
> data <- read_excel("C:/Users/Admin/Desktop/Schiphol Airport Data.xlsx")
> View(data)
> # create multiple regression model
> ASmodel <- lm(AUI ~ atMovements + asExp + pubVio, data = data)
> summary (ASmodel)

Call:
lm(formula = AUI ~ atMovements + asExp + pubVio, data = data)

Residuals:
    Min      1Q  Median      3Q     Max
-5.6102 -1.8834 -0.4576  1.9486  7.9347

Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept) 22.385322  11.895286   1.882   0.0761 .
atMovements 34.139122   8.891935   3.839   0.0012 **
asExp       -0.040251   0.030492  -1.320   0.2034
pubVio       0.017426   0.008381   2.079   0.0522 .
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 3.68 on 18 degrees of freedom
Multiple R-squared:  0.8449,    Adjusted R-squared:  0.819
F-statistic: 32.68 on 3 and 18 DF,  p-value: 1.701e-07

> # correlation plots
> library(GGally)
> ggpairs(data)
```

Fig. 1. Coded in RStudio aviation security multiple regression model of Schiphol Airport.

The results may be interpreted as follows:

- adjusted R-squared, which characterizes the accuracy of the model, is 0.819;
- there is positive correlation of AUI number and air transport movements; the significance is high ($p - value = 0.0012 < 0.05$); that means that every 100,000 operations lead to +3.4 AUI.
- negative correlation of AUI number and aviation security expanses; the significance is quite low ($p - value = 0.2034$); that means that every 1,000,000 EUR spent on security leads to the −0.04 of AUI; potentially, low significant may be explained in terms of "security theater" [17].
- positive correlation of AUI number and number of cases of public violence, the significance is quite high ($p - value = 0.0522$); that means that with an increase in criminality there is +0.017 increasement in AUI.

Correlation graphs (Fig. 2):

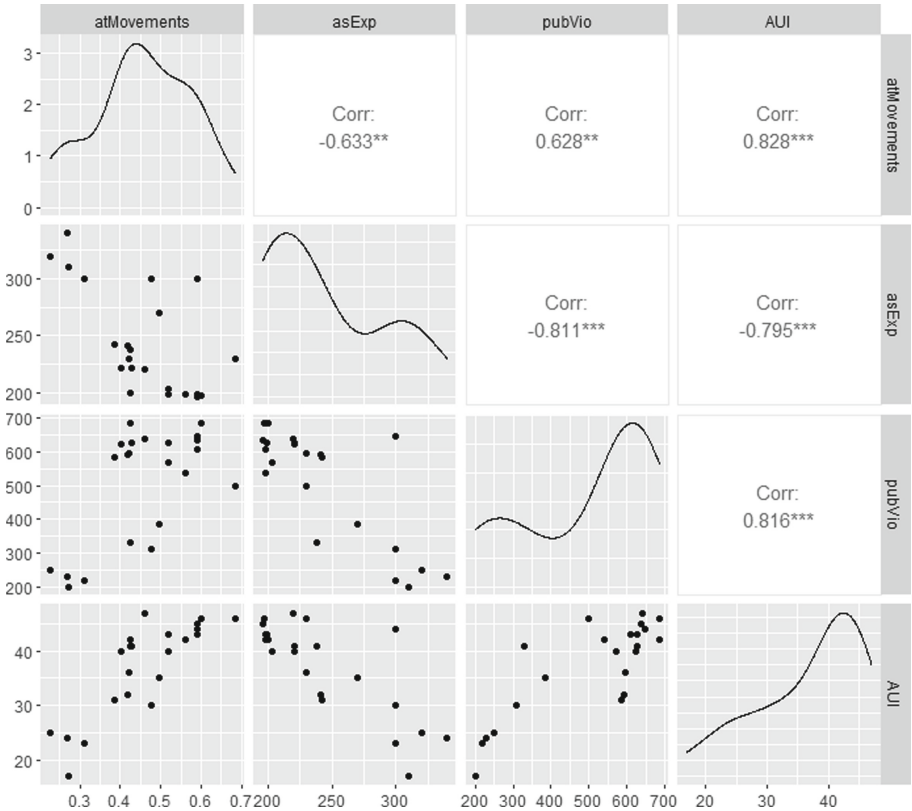


Fig. 2. Correlation of multiple regression model indicators.

The developed model could be presented mathematically:

$$AS_{Schiphol} = 22.3853 + 34.1391 \cdot \alpha - 0.0402 \cdot \beta + 0.0174 \cdot \gamma, \quad (1)$$

where $AS_{Schiphol}$ – acts of unlawful interference of Schiphol Airport; α – number of air transport movement, in millions; β – aviation security expanses, in millions of EUR; γ – number of cases of public violence in Amsterdam.

However, this model has certain disadvantages, namely:

- local optimum problem, which may be corrected in further research by a multi-level model development that includes performance indicators of other airports;
- the accuracy of the model may be improved by increasing the sample of statistical data, particularly, on acts of unlawful interference;
- potentially, such indicators as risk, human and material resources intended for the protection of civil aviation infrastructure may be added to the model in order to improve accuracy.

3 Conclusions

Aviation security should be defined as the state of protection of civil aviation from acts of unlawful interference, which is provided by a set of measures involving human and material resources. Modern researches on this topic are one-sided in aviation security models development: they ignore criminal and economic aspects that could potentially affect number of acts of unlawful interference and the level of threats.

During the study, a mathematical model of airport aviation security of the was developed, which includes the following indicators: 1) acts of unlawful interference of Schiphol Airport; 2) number of air transport movement, in millions; 3) aviation security expanses, in millions of EUR; 4) number of cases of public violence in Amsterdam. Developed with the RStudio multiple regression aviation security model clearly demonstrates the importance of mentioned factors, which have been undeservedly deprived of attention among scientists. Potentially, the model could be expanded (to increase accuracy) by creating a multi-level aviation security model that requires further research (particularly in terms of the Occam razor principle) and a significant sample of statistics.

The obtained results confirmed authors assumption about the dependence of AUI and criminality of area (presented in paper as the number of cases of violence) in which the airport is located: there is a significant ($p - value = 0.0522$) positive correlation; with an increase in criminality there is +0.017 increase in AUI.

From a practical point of view, the developed model of aviation security solves the attribution problem and allows to manage and forecast the level of danger in order to ensure the airport operation safety.

References

1. Cherednichenko, K.: Model of aviation safety intruder. XXII International Scientific and Practical Conference "Flight. Modern problems of science" (2022). https://bit.ly/3zu2I9o
2. Cherednichenko, K., Yanchuk, M.: Mathematical formalization of transport safety assessment (2020). https://bit.ly/3Qf8DF9
3. Lin, H.Z., Wei, J.: Optimal transport network design for both traffic safety and risk equity considerations. J. Clean. Prod. **218**, 738–745 (2019). https://doi.org/10.1016/j.jclepro.2019.02.070
4. Sdoukopoulos, A., Pitsiava-Latinopoulou, M., Basbas, S., Papaioannou, P.: Measuring progress towards transport sustainability through indicators: analysis and metrics of the main-indicator initiatives. Transp. Res. Part D: Transp. Environ. **66**, 316–333 (2019). https://doi.org/10.1016/j.trd.2018.11.020
5. Li, T., Rong, L., Yan, K.: Vulnerability analysis and critical area identification of publictransport system: a case of high-speed rail and air transport coupling system in China. Transp. Res. Part A: Policy Practice **127**, 55–70 (2019). https://doi.org/10.1016/j.tra.2019.07.008
6. McFarlane, P.: Developing a systems failure model for aviation security. Saf. Sci. **124**, 104571 (2020). https://doi.org/10.1016/j.ssci.2019.104571
7. Tamasi, J., Demichela, M.: Risk assessment techniques for civil aviation security. Reliab. Eng. Syst. Saf. **96**, 892–899 (2011). https://doi.org/10.1016/j.ress.2011.03.009
8. Jensen, M., Yates, E., Sheehan, K.: Extremism in the Ranks and After, START: College Park, MD (2021)

9. Szumowska, E., Czernatowicz-Kukuczka, A., Kossowska, M., Król, S., Kruglanski, A.W.: Truth and Significance: A 3N Model (Needs, Narratives, Networks) Perspective on Religion. In: The Science of Religion, Spirituality, and Existentialism, eds. Kenneth Vail III and Clay Routledge, pp. 225–242. Elsevier, London (2020)
10. Karagiannis, E.: European Converts to Islam: Mechanisms of Radicalization. Politics Religion Ideology **13**(1), 99–113 (2012)
11. Leiken, R.: Europe's Angry Muslims: The Revolt of the Second Generation. Oxford University Press, Oxford (2012)
12. Ivannikova, V., Shevchuk, D., Konovalyuk, V., Borets, I., Vysotska, I.: Estimation of the innovative technologies influence on passengers processing procedures at the airport. Transp. Res. Procedia **59**, 127–136 (2021). https://doi.org/10.1016/j.trpro.2021.11.104
13. Royal Schiphol Group. 2000–2021 Royal Schiphol Group traffic and transport figures (2021). https://bit.ly/3mD4IUZ
14. Royal Schiphol Group. 2000–2021 Royal Schiphol Group Annual Report. (2021). https://cutt.ly/bnWh8fi
15. Number of cases of public violence in Amsterdam (2022). https://bit.ly/3zoYhN6
16. Netherlands Crime Rate & Statistics 1990–2022 (2022). https://bit.ly/3myPGzE
17. Schneier, B.: Beyond Fear: Thinking Sensibly About Security in an Uncertain World. Copernicus Books, New York (2003)

Scavenging of a Two-Stroke Engine

Vytautas Rimša(✉)

Department of Aviation Technologies, Antanas Gustaitis Aviation Institute, Vilnius Gediminas Technical University, Linkmenų g. 28, 08217 Vilnius, Lithuania
vytautas.rimsa@vilniustech.lt

Abstract. Investigation of a two-stroke engine scavenging phenomenon remains a significant issue due to its wide application in sports, the military, and other areas. The finite volume method is used to investigate the two-stroke engine scavenging process. Investigated cold flow study of internal combustion engine is targeting the process of identified and improve fluid flow inside the shaft, ports and muffler. The impact of the engine speed is examined it effect to pressure fluctuations and temperature inside engine, investigated sophisticated blades effect to engine scavenging performance for various blade angles and effect on the required torque.

Keywords: Two stroke · Scavenge · CFX · Cold flow · Blades · Torque

1 Literature Review

Sir Dugal Cherk invented the two-stroke engine at the end of the 19th century. Today, two-stroke engines are still used in motorcycles, scooters and small UAVs due to their simple design and high power-to-mass ratio.

There were attempts to use this engine in automobiles; even more, some quite sophisticated machines, such as the Auto-Union, Saab and others, were produced in the 1960s. However, the two-stroke engine-powered car was banished due to stringent ecological requirements, fuel consumption and exhaust emissions [1].

Analysis of engine fluid flow can be done in many ways one of possible solution it is cold flow analysis given by [2] and [3]. This approach reality "simple" here main focus is on gas flow inside ports and cylinder. The other approach consists of numerical analysis of combustion and transient heat transfers processes in the engine [4, 5]. This approach allowed better understand engine performance, but it require extremely high computation resources there for it is performed only after detail investigation of cold flow engine analysis.

[6] showed the process of charge exchange in a two-stroke opposed-piston aircraft diesel engine. While [7] analyzed the performance of a conventional four-stroke engine operating in the two-stroke cycles by direct fuel injection and mechanical air supercharging. Low temperature combustion (LTC) may be the next step for further emission and fuel consumption reduction. However, LTC requires unconventional ignition systems [4]. A simulation model of a propulsion system in waves is presented with an emphasis on modelling a two-stroke marine diesel engine: the framework for building such a model and its mathematical descriptions [5].

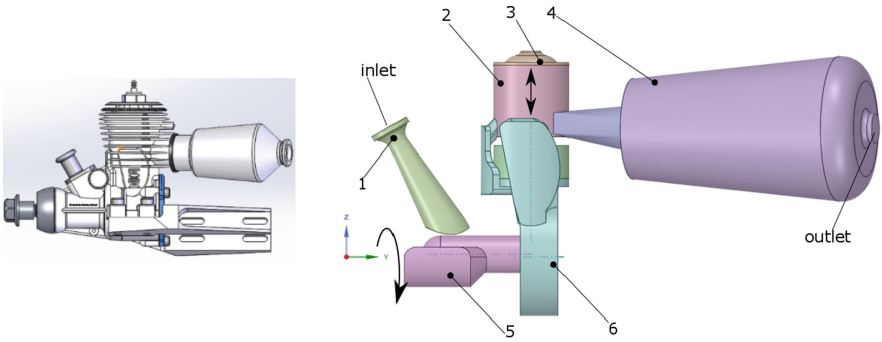
© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 782–789, 2023.
https://doi.org/10.1007/978-3-031-25863-3_76

The engine design optimization was proposed by [6]. Where authors analyzed a two-stroke small aero-engine prototype to improve the engine's performance and optimize the geometric parameters of the scavenging ports by performing one-dimensional (1D) and three-dimensional (3D) computational fluid dynamics (CFD) coupling simulations.

The literature review shows that a two-stroke engine's mathematical and physical modelling is still an important and necessary topic. There are many investigations for reality low speed and high volume automobile or motorcycle engines but nevertheless, it lacks comprehensive data on an extremely small volume and high speed engine performance and scavenging analysis.

2 Object of Investigation

A two-stroke engine "Fora" is under investigation in this paper. The engine is regulated according to FAI rules, available at [7]. According to the rules, the engine is restricted by a maximum inlet diameter of Ø4 mm, maximum restricted outlet muffler diameter of Ø6 mm and maximum engine volume of 2.5 cm^3.



a) b)

Fig. 1. Two-stroke engine "Fora" a) engine general view; d) engine inner solid general elements, where 1 – inlet diffuser; 2 – cylinder with compressible volume in Z-axis respect to time; 3 – head of the cylinder; 4 – muffler; 5 – rotatable shaft in Y-axis; 6 – ports.

2.1 Assumptions and Simplification

The current paper investigates a cold flow engine model with temperature effects due to gas compression/decompression. The shaft body is represented in Fig. 1. The subsequent investigation is carried out: 1. Body 5 rotates around the Y-axis; the rotation speed is 28,000 rpm which is the typical actual engine speed on the ground when the speed of an aircraft zero. 2. The rotation speed of 30,000 rpm is related to the engine speed in the loop, and 3 the rotation speed is 35,000 rpm when the engine exceeds maximum speed when the aircraft flies in the horizontal direction. The cylinder gas in Fig. 1 (body 2)

deforms respectively to the time in the Z-axis direction, simulating piston motion. The numerical model is constrained, so the air that forms the inlet is sucked into a diffuser. At the appropriate time, the air flows into the shaft (body 5) and later through the crankcase ports (body 6). At the appropriate time, it flows into the cylinder (body 2) and then via muffler (body 4) flows to the environment through the outlet.

In this paper, the effect of engine speed on engine head temperature Fig. 1 (body 2) and speed on the outflow of gas from the muffler was analyzed (body 4). It helped to partly validate the numerical model, the validation of which is quite complicated due to its high complicity. In the end, the improvements to a two-stroke engine scavenging process are proposed.

2.2 Mesh

Two types of tetrahedral mesh were created: a 10-node mesh for complicated geometry and hexagonal mesh for simplified geometry. The mesh consisted of 148 k nodes and 434 k elements, the quality of mesh parameter skewness is 0.75, while the maximum value is up to 0.95.

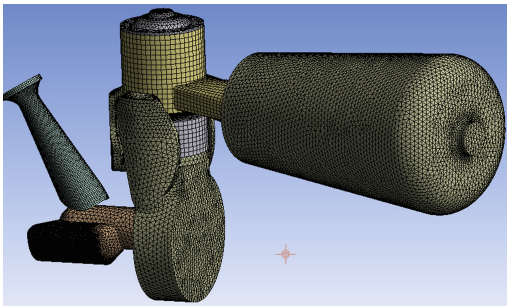


Fig. 2. Engine inner structure mesh.

3 Calculation Results

Due to high complexity, the numerical investigation of a two-stroke engine scavenging process is still a challenging case requiring great computer resources. The acceptable time step was identified. It could be represented as one shaft rotation cycle is equal to 360° degrees or 100 time steps are equal to 3.6°. The current paper investigated two-engine rotations. The first is some specific additional initialization, while the second rotation was measured concerning such output parameters as temperature versus engine speed. It is reflected in Fig. 3. It is seen that with an increase in engine speed, the temperature of an engine drops down. While on the measured surface, the increase in the engine's speed by 20% decreases the engine's temperature by 4%, which is logical as higher speed increases the mass of airflow and causes the decrease in the surface temperature.

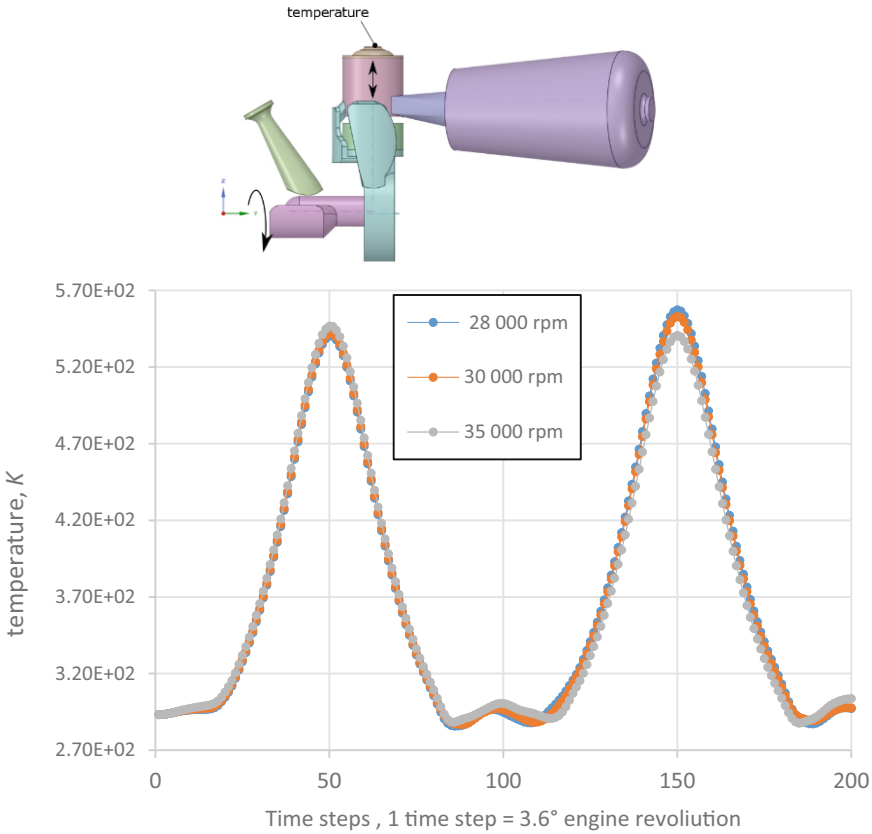


Fig. 3. Engine head temperature versus engine speed.

While Fig. 3 shows pressure in the outlet surface respectfully to the engine speed in this case, pressure fluctuations are much higher than the temperature numbers in Fig. 4. It was affected by high gas compressibility. Similar results are given in Gordon Blair's [11] where the author says that in the *P/Pa* ratio, the It was affected by high gas compressibility 0.75 and the highest value exceeds up to 1.4. The numerical CFD model simulation shows maximum value *P/Pa* = 1.4 at 35,000 rpm and minimum *P/Pa* = 0.687 at 35,000 rpm.

3.1 Investigation of Additional Blades' Effect on Two-Stroke Engine Scavenging Process

One of possible way to increase engine performance is to suck more air inside engine, burn it with more fuel in the cylinder and later push burn out gas for next stroke.

For many years of physical experiments engineers found appropriate timing settings for two stroke engine design.

The new search of increase of engine power is to investigate effectivity of the engine gas flow with added additional "blades" is shown in Fig. 5, and the effect of the blade

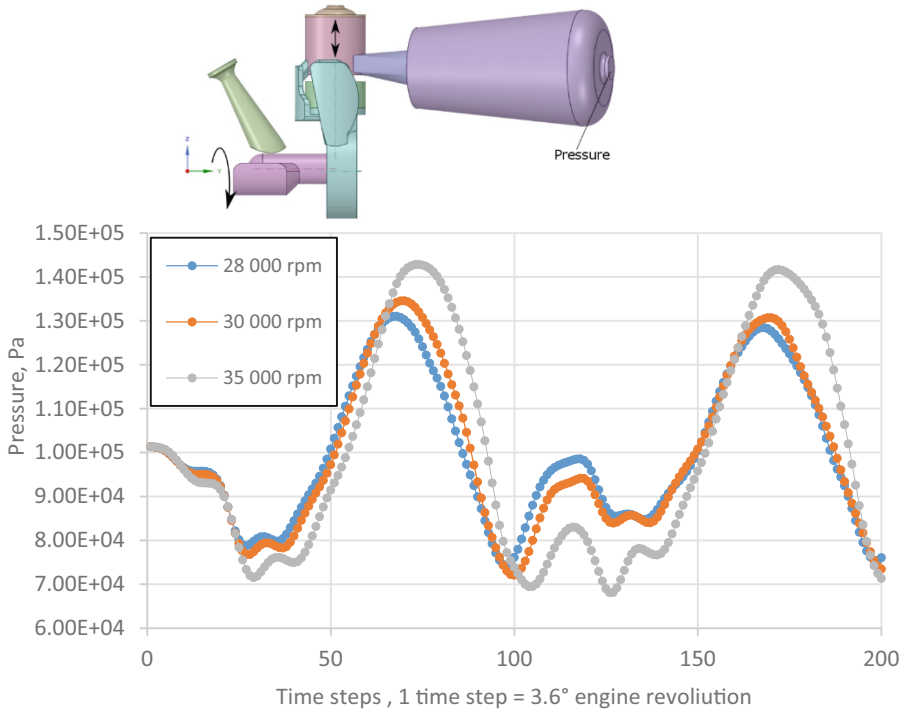
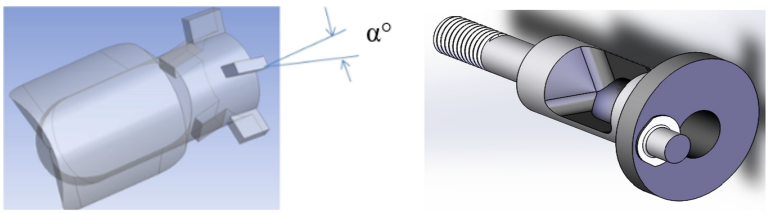


Fig. 4. Engine outlet pressure versus engine speed.



a) b)

Fig. 5. Typical two strike shaft (a); inner volume of shaft with added additional blades (b).

angle $\alpha°$ on the engine scavenging process is investigated. The basic idea of investigation is to calculate contribution of blade elements to engine scavenging process if it helps to suck more air during one engine stroke, and also investigate negative effect –increase require torque to rotate the shaft. Addition these blades during engine rotation additional mix air and fuel mixture also helps to vaporize and prepare the mixture for combustion.

Calculation results (Fig. 6 and Fig. 7) show that small blades angle α below 60° and less are not able to help to suck more air due to reality small angle of attack. It means that require to analyze smaller angle step α between 70° up to 90° also capture all operating engine speed regimes.

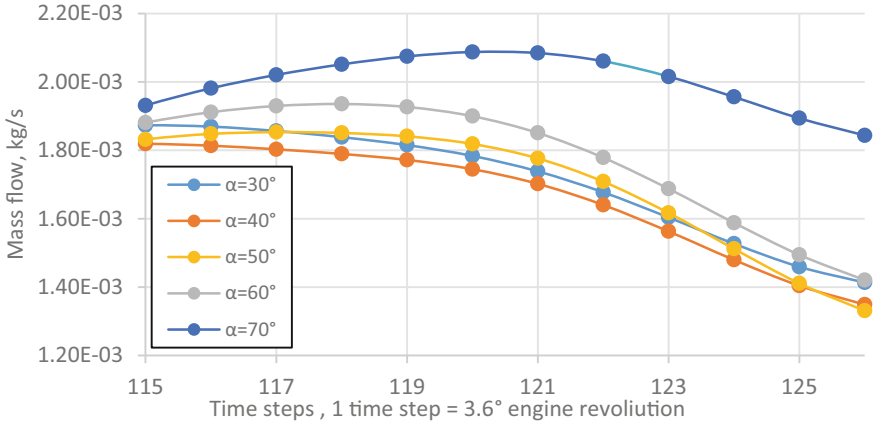


Fig. 6. Air flow debit in the opening position to blade angle.

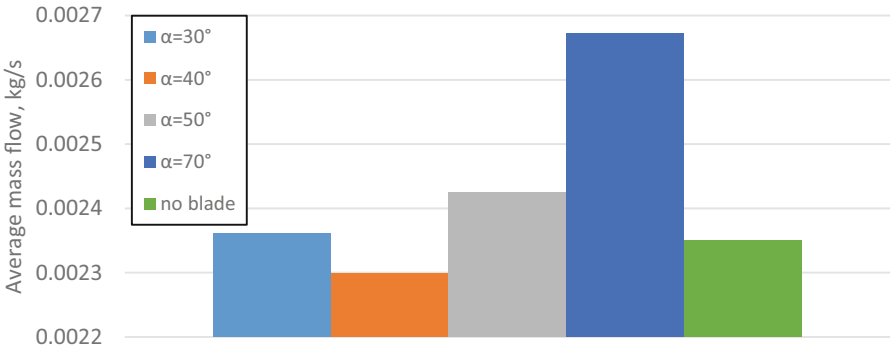


Fig. 7. Average airflow debit to blade angle inflow into engine inlet.

Computational analysis of a detail showed that additional blades added to the engine shaft work positively as they increase the inlet airflow velocity and mass by approximately 11% when the blade angle is 80° (Fig. 6 and Fig. 7). However, it also has drawbacks: added blades require more torque to rotate the shaft, increasing the value by 33% (Fig. 8) compare with shaft without blades. While these type of engine generating power exceed up to 0.8 – 0.95 kW. Therefore, this increase of require torque reality small compare with positive outcome and could be neglected.

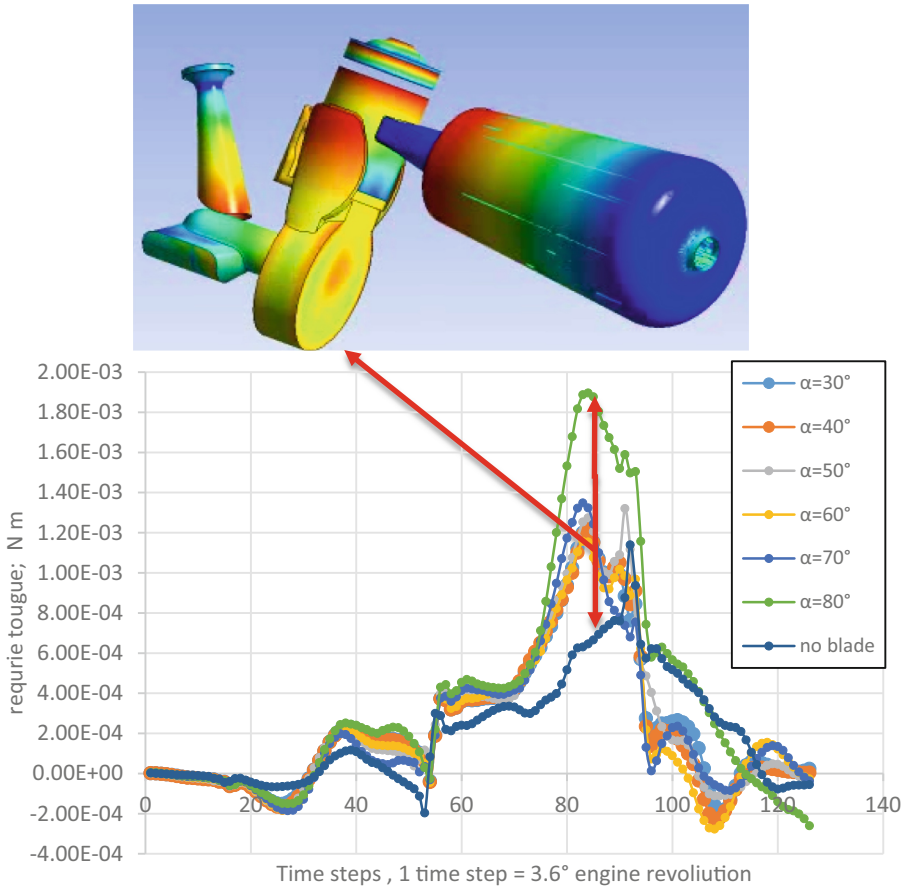


Fig. 8. Required momentum to rotate the shaft with respect to blade angle. Required momentum increased by 33%, and the maximum peak at the opposite side of the intake.

4 Conclusions

Numerical investigation of a two-stroke engine "Fora" shows similar results with [7] numerical error exceeding 6%. It indicates that this investigated engine with low volume and reality high speed compare with more traditional motorcycles engines are affected by similar scavenging process by use cold flow simulation approach. One of possible engine power increase opportunities is additional added blade elements positively contribute to the engine scavenging process, and the physical model could validate it. Due to high gas flow velocities inside engine the blade angle α must be quite big more than 70°… 80°. Physical testing of high complicity of investigation object is quite difficult to measure contribution of new added element to whole engine performance due to it CFD tool give useful role to investigation and optimization engine performance.

References

1. Tsai, J.S.: Characteristics of emissions from a portable two-stroke gasoline engine. Aerosol Air Qual. Res. (2020). https://doi.org/10.4209/aaqr.2019.12.0650
2. Pathak, Y.R., Deore, K.D., Patil, V.M.: In cylinder cold flow CFD simulation of IC engine using hybrid approach. Int. J. Renew Energy Technol. **3**(8), 16e21 (2014)
3. Kurniawan, W.H., Abdullah, S., Shamsudeen, A.: A computational fluid dynamics study of cold-flow analysis for mixture preparation in a motored four-stroke direct injection engine. J. Appl. Sci. **7**(19), 2710e24 (2007)
4. Illa´n, F., Alarco´n, M.: Numerical analysis of combustion and transient heat transfer processes in a two-stroke SI engine. Appl. Therm. Eng. **30**(16), 2469e75 (2010)
5. Varol, Y., Oztop, H.F., Firat, M., Koca, A.: CFD modeling of heat transfer and fluid flow inside a pent-roof type combustion chamber using dynamic model. Int. Commun. Heat Mass Transf. **37**(9), 1366e75 (2010)
6. Grabowski, K., Pietrykowski, and Karpiński, P.: The zero-dimensional model of the scavenging process in the opposed-piston two-stroke aircraft diesel engine. Propulsion Power Res. (2019). https://doi.org/10.1016/j.jppr.2019.11.003
7. Herrmann, S., Nora, M.D., Lanzanova, T.D.M.: Development of a two-stroke cycle engine for use in the agricultural aviation sector. J. Aerosp. Technol. Manag. (2020). https://doi.org/10.5028/jatm.cab.1155
8. Ciampolini, M., Bigalli, S., Balduzzi, F., Bianchini, A., Romani, L., Ferrara, G.: CFD analysis of the fuel-air mixture formation process in passive prechambers for use in a high- pressure direct injection (HPDI) two-stroke engine. Energies (2020). https://doi.org/10.3390/en13112846
9. Yum, Kevin Koosup, Bhushan Taskar, Eilif Pedersen, and Sverre Steen: "Simulation of a Two-Stroke Diesel Engine for Propulsion in Waves." International Journal of Naval Architecture and Ocean Engineering. (2017). https://doi.org/10.1016/j.ijnaoe.2016.08.004
10. Qiao, Y., Duan, X., Huang, K., Song, Y., Qian, J.: Scavenging ports' optimal design of a two-stroke small aeroengine based on the Benson/Bradham model. Energies (2018). https://doi.org/10.3390/en11102739
11. Gordon, P.: Blair Design and Simulation of Two-Stroke Engines SAE International, p. 647 (February 1 1996) ISBN-13: 978–1560916857
12. Retrieved May 22, 2022 http://www.f2d.dk/rules/f2d-rules-2018.htm

Optimization of the Special Cargo Delivery by UAV

Anna Ayrapetyan(✉) and Viktoriia Ivannikova

National Aviation University, Kyiv 03058, Ukraine
ayrapetyan1007@gmail.com

Abstract. During the pandemic, drones helped many FFCs access goods and services to the government and the general population. In response, many regulatory bodies worldwide have shown interest in helping the industry develop. Regulators are now looking for ways to support the development of drone technology by exploring ways to transport heavier goods and people. They are issuing more permits within existing frameworks and adopting more comprehensive frameworks to allow for more drone operations.

Overall, drones are expected to play an essential role in all applications. This makes them an excellent solution for transportation applications.

This study analyzes the role of unmanned aerial vehicles (UAVs) in delivering medical and emergency supplies to remote areas. It outlines potential considerations for operators wishing to use UAVs to provide medical and emergency supplies to remote locations.

The article also discusses some practical considerations regarding the organization wishing to conduct such operations, the operations themselves, and the technology used.

These considerations are primarily driven by the nature of the international regulatory framework for UAV operations and the specifics of using UAVs to deliver medical and emergency supplies.

Keywords: Unmanned Aerial Vehicle (UAV) · Supply chain · Transportation problem · Special cargo · COVID-19

1 Actually of the Subject Matter

As the entire world scrambles to react to the global health crisis caused by the spread of the new coronavirus and the COVID-19 illness, conversations about automation and the role of robotics in society have never been more relevant. In the face of the global COVID-19 pandemic, there have been reported attempts to utilize drone technology in different scenarios.

When organizing the shipment of thermal products, there are a lot of issues related to the delivery of shipments. First of all, it is necessary to choose the methods of organization of transportation and type of UAV.

When rationally selecting the type of UAV, the specialists pay attention to its suitability to the characteristics of the transported cargo. The main criterion is the preservation

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 790–796, 2023.
https://doi.org/10.1007/978-3-031-25863-3_77

of cargo, the best possible use of space and capacity, lower transportation costs if it is possible. Transportation of thermal luggage by drone is the most expeditious and reliable delivery. The broad geography of the flight, the ability to perform flights over long distances in a short time, and the most remote points of the region, as well as the innocuousness of the medium of transportation, make the use of drones very advantageous and handy, especially under conditions of pandemics [8].

Carriage of this type of cargo by UAV is carried out, in general, by chartered flights on established airlines, to places where regular flights are not carried out. Delivery of thermal cargo is carried out by the shortest route and, as a rule, direct flights.

Transportation of medicines is classified under the category of critical loads. That is why the service is luggage requirements, which relate to the complete preservation of relocation. Transportation and storage must be carried out in compliance with a unique "cold chain" system. The main components of the cold chain are:

- specially trained staff- agents, which ensures the maintenance of refrigeration equipment, proper storage of vaccines, and their delivery to the structural units;
- refrigeration equipment designed for the storage and transportation of vaccines in optimal temperature conditions;
- a control mechanism for compliance with the required temperature regime at all stages of cold storage [2].

The goal is to deliver drugs without losing primary characteristics, preserving their properties. It has controlled not only the state of the vaccines and fluids and the integrity of the packaging, quantity, and quality of products that are delivered to the party. Transportation of medicines is considered successful if the recipient receives the order and does not get a loss.

2 Problem Solution

The limitations must be considered to plan the routes of a group of UAVs connected with selected points. This, together with arranging the shortest path, requires the development of approaches considering this limitation in the calculation.

UAVs can transport special cargo from the point of origin to the point of delivery both at the point of collection, i.e., at the central warehouse of the air terminal and the main warehouse of the delivery point. It is impossible to say a priori which sections of the routes will be assigned to certain types of UAVs and which will be assigned to ground vehicles. The answer can only be obtained by solving an optimization problem. The solution will depend on UAVs' technical and economic parameters (payload weight, range, cruising speed, fares, charges, requirements for takeoff and landing characteristics, etc.), the number of UAVs of each type in the fleet, and the competing modes of transport.

Considering the above efficiency criteria, factors, and general notions of special cargo delivery using air transport, let us define the stages of FFC decision-making to optimize the process.

Methods can be extended to obtain a short path from longer routes to avoid obstacles or synchronize the arrival time of autonomous vehicles. Algorithms for designing the

fastest routes are conducted in various fields, such as computational geometry, analysis of operations, and logistics. One of the well-studied problems in computational geometry is that finding the shortest route was known back in 1987. This problem is known in the literature as the "transportation problem" [7].

Let's assume each center stores drugs in a warehouse; these district centers can serve each other on-demand. Considering the transport problem for the region on the profitability of the request. The main criterion is cost. The estimated cost per ton-km (USD) for the large fixed-wing roughly equals 6 USD/ton-km. The weight of one full container of Pfizer Softbox, where the vaccines and medicaments can be transported, is 36 kg. The *Pfizer Softbox thermal container can temporarily store the vaccine for up to 30 days from delivery (the container should be refilled every five days if the container is opened up to 2 times a day for less than 3 min at a time) [3].

DHL and other logistics companies were already transporting pharmaceutical products at minus 70 °C in boxes packed with dry ice before the coronavirus pandemic. They also use passive cooling systems for freezer and refrigerator temperatures for other products. The challenge for coronavirus vaccine logistics concerning these cooling systems is to adapt the known technology as quickly as possible to specific requirements such as package size as well as storage and transport times [1].

The commercial load of a UAV is 150 kg, so the maximum that 1 UAV Agroaircraft can carry is four containers (see Table 1). According to the distance between cities, we can calculate the delivery cost. As of May 25, 2022, 37% of Ukraine's population is fully vaccinated. According to this data and the number of people in the administrative center, we can roughly determine the needs for the 26th of May to meet demand and consumption.

Table 1. Agroaircraft flight characteristics.

Maximum takeoff weight, kg	300
Wing span, m	5.8
Empty weight, kg	150
Length, m	2.4
Height on ground, m	1.7
Capacity of caisson tanks, l	90
Flighing time, hours	6–12
Hourly fuel consumption, l/h	14–15
Commercial load, kg	150 (in containers)
Cruising speed, km/h	280 -300
Cost of production UAV, USAD	50–60 thousand
Gasoline engine, low-horsepower, hp	64 (Rotax-582)
Autopilot	1 ('Pixhawk')

Let's say there are supplies, six suppliers, and seven consumers. Certain medicines can be shipped both ways from where it is more expedient to send (see Table 2).

Table 2. The cost of shipping a container between cities in the Kyiv region.

Departures	Destinations							Supply (a_{ij})
	Obukhiv(B_1)	Vyshhorog(B_2)	Vasylkiv(B_3)	Skvyra(B_4)	Tarascha(B_5)	Slavutich(B_6)	Boguslav(B_7)	
Kyiv(A_1)	20	8	17	51	50	60	52	8
Bila Tserkva(A_2)	26	45	22	17	20	98	31	7
Boryspil(A_3)	18	21	25	58	47	66	58	6
Brovary(A_4)	23	14	25	59	54	56	54	5
Bucha(A_5)	29	10	21	50	31	57	61	4
Fastiv(A_6)	27	34	16	21	36	86	46	4
Demand(b_{ij})	3	4	2	3	1	2	1	

Table 3. Model of the transportation problem.

	B_1	B_2	B_3	B_4	B_5	B_6	B_7	B_8	Supply
A_1	20	8	17	51	50	60	52	0	8
A_2	26	45	22	17	20	98	31	0	7
A_3	18	21	25	58	47	66	58	0	6
A_4	23	14	25	59	54	56	54	0	5
A_5	29	10	21	50	31	57	61	0	4
A_6	27	34	16	21	36	86	46	0	4
Demand	3	4	2	3	1	2	1	18	34

The number of departure points m = 6, and the number of destination points n = 7. Therefore, the reference plan of the problem is determined by the numbers in m + n–1 = 6 + 7–1 = 12 filled cells of the table. The matrix gives the tariffs for transporting a cargo unit from each point of departure to all destination points.

Cargo availability at suppliers is equal:

$$\sum A_i = 8 + 7 + 6 + 5 + 4 + 4 = 34.$$

The total demand for cargo at the destinations is equal:

$$\sum B_i = 3 + 4 + 2 + 3 + 1 + 2 + 1 = 16.$$

Since $\sum A_i \geq \sum B_i$, the model of the transportation problem is open. To obtain a closed model, we enter an additional destination point B8 with requirements 34–16 = 18. We assume that transportation tariffs from the points of departure to B8 equal zero. As a result, we obtain a closed model of the transportation problem:

Table 4. Solved reference plan of the transportation problem.

	B_1	B_2	B_3	B_4 **1**	B_5	B_6	B_7	B_8	Supply
A_1	20	8 **4**	17	51	50	60	52	0 **4**	0 [8].
A_2	26	45	22	17 **3**	20 **1**	98	31 **1**	0 **2**	0 [7].
A_3	18 **3**	21	25	58	47	66	58	0 **3**	0 [6].
A_4	23	14	25	59	54	56 **2**	54	0 **3**	0 [5].
A_5	29	10	21	50	31	57	61	0 **4**	0 [4].
A_6	27	34	16 **2**	21	36	86	46	0 **2**	0 [4].
Demand	0 [3].	0 [4].	0 [2].	0 [3].	0 [1].	0 [2].	0 [1].	0 [18].	34
	B_1=18	*B_2=8*	*B_3=16*	*B_4=17*	*B_5=20*	*B_6=18*	*B_7=31*	*B_8=0*	

Δ 11=18-20-0=-2
Δ 13=16-17-0=-1
Δ 14=17-51-0=-34
Δ 15=20-50-0=-30
Δ 16=56-60-0=-4
Δ 17=31-52-0=-21
Δ 21=18-26-0=-8
Δ 22=8-45-0=-37
Δ 23=16-22-0=-6
Δ 26=56-98-0=-42
Δ 32=8-21-0=-13
Δ 33=16-25-0=-9
Δ 34=17-58-0=-41
Δ 35=20-47-0=-27
Δ 36=56-66-0=-10
Δ 37=31-58-0=-27
Δ 41=18-23-0=-5
Δ 42=8-14-0=-6
Δ 43=16-25-0=-9
Δ 44=17-59-0=-42
Δ 45=20-54-0=-34
Δ 47=31-54-0=-23
Δ 51=18-29-0=-11
Δ 52=8-10-0=-2
Δ 53=16-21-0=-5
Δ 54=17-50-0=-33
Δ 55=20-31-0=-11
Δ 56=56-57-0=-1
Δ 57=31-61-0=-30
Δ 61=18-27-0=-9
Δ 62=8-34-0=-26
Δ 64=17-21-0=-4
Δ 65=20-36-0=-16
Δ 66=56-86-0=-30
Δ 67=31-46-0=-1

Stage I. Finding the first reference plane. In this step, we find the reference plan of the problem by the minimum element method.

There are no positives among the α_{ij}. Consequently, this reference plan is optimal. Solution. In this plan, the cost of transportation is calculated as follows:

S = 8–4 + 17–3 + 20–1 + 31–1 + 18–3 + 56–2 + 16–2 = 332 USD.

Resource allocation:

- From warehouse Kyiv (A1), send container (4) to Vyshhorog (B2).
- From store Bila Tserkva (A2) ship container (3) to Skvyra (B4).
- From warehouse Bila Tserkva (A2) ship container (1) to Tarascha (B5).
- From warehouse Bila Tserkva (A2) ship container (1) to Boguslav (B7).
- From warehouse Boryspil (A3) ship container (3) to Obukhiv (B1).
- From warehouse Brovary (A4) ship container (2) to Slavutich (B6).
- From warehouse Fastiv (A6), send container (2) to Vasylkiv (B3).

3 Conclusions

In the global cold chain context, UAVs could change how medicines are delivered for undemanding care in remote areas.

It was suggested to transport medications using a UAV. From the regional center to the district – UAV "Agroaircraft"; from district centers to villages -VTOL. The minimum cost, the distance between cities of the region, the weight of the contains, the maximum payload of the drone, and the number of necessary resources depending on the population number were taken into account,

The introduction of this technology could be a significant step toward providing blood products or vaccines to a person infected with the disease, the time it saves in delivering could prove crucial to the end of their life. UAVs can change the way of delivering medicines to provide non-demanding assistance in remote areas. The time that this technology saves on delivering blood products or vaccines to a person who has been infected with the disease could be crucial for the end of his life.

As part of the design section, the functional structure of the system for organizing thermal cargo delivery using unmanned aerial vehicles is considered, and the mathematical structure of the formation of UAV routes is described in detail. Algorithms for the organization of the delivery of thermal cargoes using unmanned aerial vehicles with the justification of choice are given.

Principles, methods, and mathematical models are an integral part of the methodology of special cargo delivery cost-effectiveness management and provide flexibility in making FFC decisions on determining the optimal variant of special cargo delivery in case of changes in the competitive situation in the special cargo transportation markets. Using the developed model will increase the work of managers for the transportation of thermal luggage, thus reducing the amount of time spent on the route to calculate the cost of special cargo and improving the quality of managers in the enterprise.

References

1. DHL: Vaccine distribution, https://www.dhl.com/global-en/delivered/globalization/vaccine-distribution.html
2. Mbachan, F.: Design and implementation of a medical autonomous delivery drone. Thesis for Bachelor's Degree / Technology University Yaounde-Cameroon (July 2019)
3. COVID-19: Vaccine Storage and Handling Guidance, https://www.health.gov.on.ca/en/pro/programs/publichealth/coronavirus/docs/vaccine/vaccine_storage_handling_pfizer_moderna.pdf
4. Marintseva, K., Yun, G., Vasilenko, I.: Delivery of Special Cargoes Using the Unmanned Aerial Vehicles. Unmanned Aerial Vehicles in Civilian Logistics and Supply Chain Management (ALOMS) Book Series (January 2019)
5. Market Watch, "Growth of Medical Drones Market Report Till 2025," Market Watch, (January 2020). https://www.marketwatch.com/press-release/growth-of-medical-drones-market-report-till-2025-2020-01-29
6. Ayrapetyan, A.G., Ivannikova, V. Y.: Drones and the coronavirus: from crisis to opportunity. In: International Transport Technologies and Transport Systems, Kyiv, NAU, 6 May (2022)
7. Europe Commercial Drone Market Forecast 2027 By Application, https://www.graphicalresearch.com/industry-insights/1016/europe-commercial-drone-unmanned-aerial-vehicle-UAV-market
8. Murray, C.C., Chu, A.G.: The flying sidekick traveling salesman problem: Optimization of drone-assisted parcel delivery. Trans. Res. Part C, Emerging Technol. **54**, 86–109 (2015). https://doi.org/10.1016/j.trc.2015.03.005
9. Ivannikova, V.Y., Ayrapetyan, A.G.: Unmanned Aerial Vehicles(UAVs) operation in Ukraine: a regulations review. Scientific Notes V.I. Vernadsky Tavriyskii National Univ. Techn. Sci. Rev. **32**(71) 6, 209–215 (2021)
10. Ivannikova, V.Y., Ayrapetyan, A.G.: Analysis of modern approaches to improve the efficiency of logistics systems for the delivery of international goods. Integration of science, education and production - the basis for the implementation of the Plan of the Nation: International scientific-practical online conference dedicated to the 30th anniversary of the independence of the Republic of Kazakhstan, 17–18 June 2021: theses - Karaganda, p. 15 – 17 (2021)
11. What should you deliver by UAS? The role of geography, product, and UAS type in prioritizing deliveries. JSI Research & Training Institute, Inc., https://publications.jsi.com/JSIInternet/Inc/Common/downloadpub.cfm?id=19145&lid=3
12. FAA. UAV's operational risks and hazards. https://www.faa.gov/uas/resources/events_calendar/archive/2018_uas_symposium/media/Risk-Mitigation-in-UAS-Operations.pdf
13. How Drones Can Be Used to combat COVID-19. UNICEF Rapid Guidance. https://www.unicef.org/supply/media/5286 /file/%20Rapid-guidance-how-can-drones-help-in-COVID-19-response.pdf.pdf

Crack Open/Close Effect on Impedance Based System of Structural Health Monitoring

Vitalis Pavelko[2] and Pavithra Nagaraj[1(✉)]

[1] Riga Technical University, Kipsalas Lela 6A, Rīga 1048, Latvia
Pavithra.nagaraj@rtu.lv
[2] Riga Technical University, Lauvas Lela 8A, Rīga 1019, Latvia

Abstract. The purpose of this article is to investigate the fatigue crack open/close effect to electromechanical impedance (EMI) of the system 'host structure/ piezoelectric transducer' and to estimate of efficiency of effect application for structural health assessment of aircraft structures. The experimental study was performed using the PI Ceramic a piezoelectric transducer PIC151 of 0.5 × 10 × 50 mm (PZT). Two types of the 1.14 mm aluminum alloy thin-walled samples were used as the host structures for testing of different geometrical configurations. The PZT were glued at the surface of sample by the Epoxy Paste HYSOL EA 9309.3 NA. The sample was subjected to static load of different levels and at each of them EMI and electrical capacitance of the piezoelectric transducer were measured by the impedance analyzer C60 (Cypher Instrument). Combined effect of the load and the boundary conditions (partial detachment of the sample fixing zone) was also investigated. In all tests the significant effect of load to the different signatures of the EMI and the PZT capacitance was observed. For the analysis, designing and calculations software like Cypher Graph, Microsoft Excel were used. The obtained results make it possible to assess the main properties of the effect of the fatigue crack open/close and demonstrate the sensitivity of different parts of EMI to the action of external load.

Keywords: Crack opening/closing · Electromechanical impedance · Fatigue crack

1 Introduction

In ultrasound non-destructive inspection the concept of electromechanical impedance was used primary in [1–3]. Since this time the electromechanical impedance (EMI) several authors used the EMI method for structural health monitoring, by comparing the impedance method was used efficiently for damage detecting in different kinds of structure [4–10 and other]. Many examples of application of EMI method can find in fundamental monographs [11, 12]. The effect of structural damage is associated with the changes of dynamic properties of a structure and can be effectively defined at ultrasonic frequencies by identification of EMI of system 'sensor-structural element'. Many ways of the EMI interpretation were proposed. One of the most perspectives is mathematical

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 797–805, 2023.
https://doi.org/10.1007/978-3-031-25863-3_78

simulation of mechanical impedance of structural element. The simple models of the EMI were developed and used for some applications [11–14].

The key problem of increase of efficiency of EMI inspection is development of acceptable methods of prediction of effect of damage to the impedance. Many ways of the EMI interpretation were proposed. One of the most perspectives of them to which was focused this investigation is mathematical simulation of EMI of a system 'structural element-ultrasonic transducer'.

The theoretical electromechanical impedance Z can be estimated by formula

$$Z(\omega) = \frac{1}{i\omega C}\left[1 - k_{31}^2\left(1 - \frac{w_1(l) - w_1(0)}{d_{31}E_3}\right)\right], \tag{1}$$

where k_{31} and d_{31} is the electromechanical coupling factor and coefficient, transverse to electric field E_3, C is the capacitance of the piezoceramics transducer, ω is the cyclic frequency.

Main effect of global or local stiffness degradation is associated with a range $w_1(l) - w_1(0)$ of relative displacement of tips of ultrasound transducer. It defines the change of natural frequencies and can be estimated by modal analysis of non-damaged and damaged systems. The imaginary part of the electromechanical coupling parameters defines the effect of damping.

The conventional principle of damage detection using EMI technology is comparison of a current state of system 'host structure/ultrasound sensor' with its intact state (baseline). But the mechanical load and environmental exposure leads to degradation both the monitored structural element, and the sensor of SHM system, embedded into the structure. It is known that the static and fatigue tensile strength of piezoceramics is low, and if the transducer is loaded in parallel to monitored structure, then it can be partly or fully damaged.

The alternative principle of damage detection using the effect of fatigue crack open/close (FCOC) was considered in [15] in respect to Lamb wave technology. As a principle, similar approach can be realized using EMI technology. In this case, the current information of the piezoelectric transducers can be sufficient for damage detection. This can be derived from comparing the contrasting behavior of structure under 2 different states [15]: it can be done by comparing the characteristics of ultrasonic waves at closed crack (unloaded state) with an open crack (loaded state).

The principal advantage of this approach is the use current information on the structure and monitoring system technical conditions. The EMI evolution is caused by the structure and the sensor degradation (fatigue, corrosion, layered composite delamination) or environmental effects (temperature and humidity variation, mechanical loading). Mentioned approach allows full excluding or sufficient weakening the negative effects of aging to monitoring results.

The present paper is focused to some practical aspects of mentioned innovative approach of a fatigue crack detection using EMI technology: general procedure of measurement, data processing and EMI integrated parameters, types of the damage signature, their properties and efficiency comparison. Mainly the study is based to test results. The example of hypothetic system of SHM for aeronautical application is discussed also.

2 Experimental Study

2.1 On the Electromechanical Impedance

EMI is a complex variable $Z(\omega)$ which is a function of the frequency ω of harmonic excitation.

$$Z(\omega) = Re(\omega) + iIm(\omega), \tag{2}$$

where $i = \sqrt{-1}$, $Re(\omega)$ the real part, which is called resistance, $Im(\omega)$ the imaginary part, which is called reactance, $|Z(\omega)| = \sqrt{[Re(\omega)]^2 + [Im(\omega)]^2}$ absolute value of EMI, which is called magnitude.

EMI magnitude, resistance and reactance are basic information which should be obtained in test below and should be used for extraction of properties of relation 'EMI/load'.

The admittance is the inverse of impedance and it's the real part (conductance) and the imaginary part (susceptance) partly should be used also.

2.2 Measurement Procedures

The experimental study was performed using the PI Ceramic a piezoelectric transducer PIC151 of 0.5×10×50 mm (PZT). Two types of the 1.14 mm aluminum alloy thin-walled samples were used as the host structures for testing of different versions of load. The PZT were glued at the surface of sample by the Epoxy Paste HYSOL EA 9309.3 NA. The sample was subjected to static load of different levels and at each of them EMI and electrical capacitance of the piezoelectric transducer were measured by the impedance analyzer C60 (Cypher Instrument). Combined effect of the load and the boundary conditions (partial detachment of the sample fixing zone) was also investigated. In all tests the significant effect of load to the different signatures of the EMI and the PZT capacitance was observed. The sample were equipped by two Piezoceramic transducers PIC151 0.5×10×50 mm (T1 and T2) (Fig. 1). Results of two samples test were used. Sample No. 1 had a central hole with a diameter of 4 mm in center only. The EMI measurement and results of this sample testing was performed earlier. Similar sample No. 2 with 4 mm central hole for fatigue crack initiation was subjected by cyclic load 12/4 kN and at frequency 10 Hz using 100 kN hydraulic test machine Instron 8801. The corresponding maximal tensile stress was equal to 150 MPa, and minimal 50 MPa. After fatigue test this sample had a central fatigue crack of 40 mm length (including a 4 mm central hole) [15].

For EMI measurement each of samples was loaded by tensile static load from zero to 5 kN with 0.5 kN increment and was performed at each level of load in the frequency range of 20–100 kHz. Static loading was done by the Rel Vi-5 electrodynamics test machine. The C60 device (Cypher Instrument) was used for EMI measurement. This device also allows to measure the electric capacity of the transducer at the frequency of about 20 kHz.

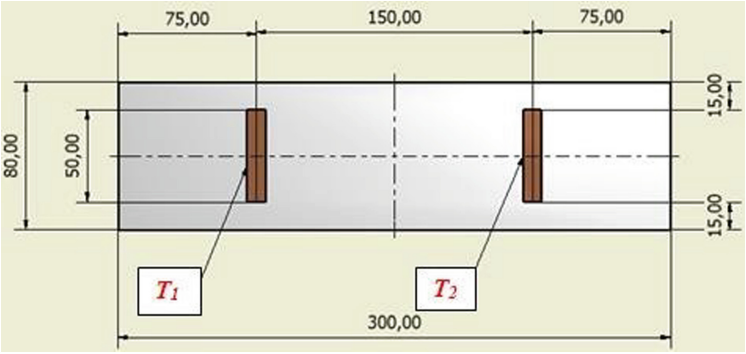


Fig. 1. Test sample of Al2024-T3 with two piezo electric sensors.

2.3 Processing of the Test Data

For this purpose, three type of damage indices were used. The most widely used indices are the root mean square deviation (RMSD) and the correlation coefficient deviation (CCDM) [4, 5]. Third one is the mean value of EMI in the frequency range of 20–40 kHz was used.

At conventional monitoring all indices have the same basis: comparison of some signature of EMI (the magnitude, the resistance, or the reactance) with corresponding one of some initial EMI that is usually called the baseline [5]. In contrast, at alternative approach the comparison should be done with signature which is measured for the unloaded state of monitored structure (current baseline).

The RMSD index is defined by follow equation.

$$RMSD = \sqrt{\frac{\Sigma_{k=1}^{N}\left[y(\omega_k) - y_0(\omega_k)\right]^2}{\Sigma_{k=1}^{N}\left[y_0(\omega_k)\right]^2}}, \tag{3}$$

where $y(\omega_k)$ is realizing of some signature of EMI that changing should be estimated, $y_0(\omega_k)$ signifies EMI for the initial (unloaded) state, N is the number of sample points in the impedance signature spectrum.

The CCD index is defined by follow equation.

$$CCD = 1 - CC = 1 - \frac{Cove(y(\omega), y(\omega))}{\sigma_y \sigma_{y0}}, \tag{4}$$

where CC is the correlation coefficient that indicates the linear relationship between two impedance signals $y(\omega)$ and $y_0(\omega)$.

There are other indices of EMI in impedance-based system of SHM. Only one of them is used here as average or mean value of the EMI signature in selected frequency band. This index is effective for estimation of vertical shift of EMI curve in the frequency domain.

2.4 Test Analysis

The data's derived from Cypher Graph is used for the calculations. The effect of load on electromechanical impedance is determined by plotting different graphs between loads and Root mean square deviation (RMSD) of EMI. In each graph RMSD values of different signatures are plotted against load. The graphs are obtained for different iterations. The test sample was subjected to periodic loading and unloading. RMSD values always begin from zero.

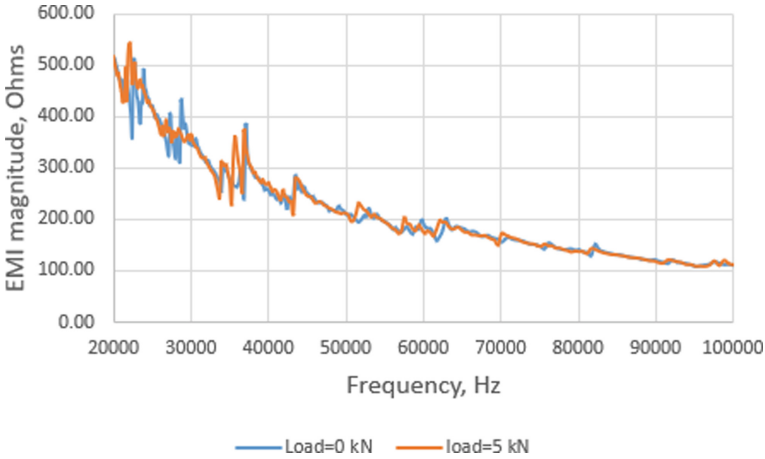


Fig. 2. The effect of loading to the spectrogram of EMI magnitude.

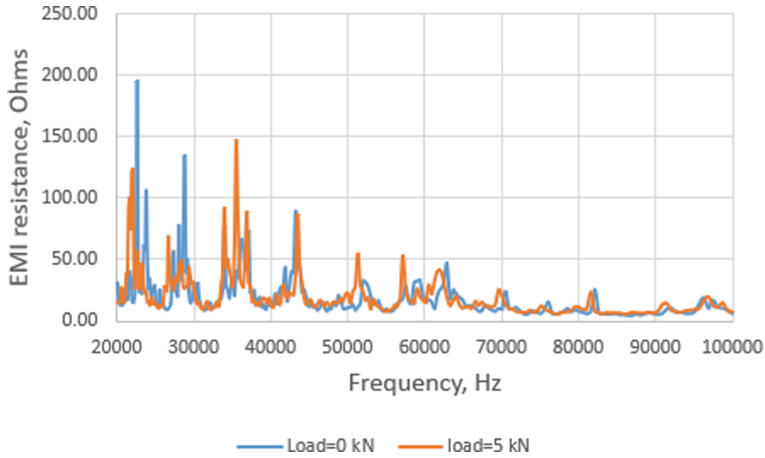


Fig. 3. The effect of loading to the spectrogram of EMI resistance.

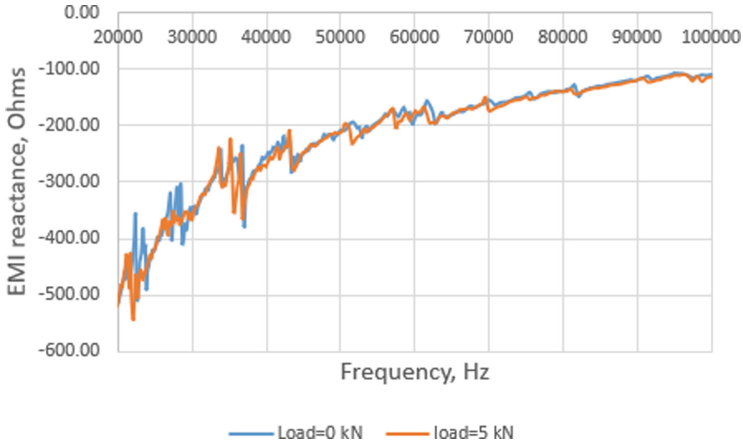


Fig. 4. The effect of loading to the spectrogram of EMI reactance.

In (Fig. 2, 3, 4) plot the graph has been obtained between root mean square deviations of resistance against load. It is subjected to 6 different iterations, and it shows considerable deviation in resistance signature. All these readings are obtained from the sensors attached to the sample plate.

3 Demonstration of Impedance-Based SHM of the Hermetic Fuselage Skin

A small part of typical aeronautical panel of the Al-alloy (2024-T3) hermetic fuselage is taken for demonstration of previous structural analysis and definition of basic architecture of its SHM system. Structure.

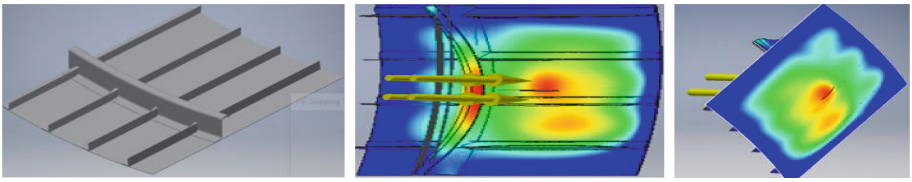


Fig. 5. Aeronautical panel and some results of stress state analysis in presence of possible fatigue crack.

The geometry modeling is carried out in Autodesk Inventor. First a panel (Fig. 5, left fragment) is designed and satisfied to Airworthiness Requirements. The direct and shear stresses in the skin of fuselage caused by bending and torsion were neglected. It is assumed that in the skin of the panel circumferential direct stress is two times more than meridional direct stress and those stresses are caused by air pressure of 100 mPa inside

cabin. So, in the mentioned stress field the fatigue crack propagates to the longitudinal direction (Fig. 5, middle and right fragments). The stress state analysis is carried out using the Autodesk Inventor module Environments (option Static Analysis). Two views of full displacements are represented at the same Fig. 5.

Critical length of the fatigue crack is defined by condition of crack start of growth:

$$K_I = K_{Ic} \tag{5}$$

where K_I is the Stress Intensity Factor (SIF) that is a crack size function, and K_{Ic} is a constant of material which called by the fracture toughness. It is accepted that

$$K_I = \sigma\sqrt{\pi l}Y(l) \tag{6}$$

where l is a crack half-length, σ is circumferential direct stress in the skin of panel, $Y(l)$ is correction multiplier. It can be exactly calculated by using results of FEA, and approximately is equal to 1. Material of a skin mechanical properties defined its crack resistance at static and cyclic loading is given in Table 1. The C and m are constants of Paris' law which describes the crack grow rate at cyclic loading (Eq. 7).

Using Eqs.5 and 6 the critical length of the fatigue crack corresponding to the remaining strength of skin 34.6 MPa (circumferential direct stress at maximum pressure in a passenger cabin) is equal 265 mm.

Table 1. Mechanical properties of Al alloy 2024-T3.

Materials	K_{Ic}, MPa·m$^{0.5}$	m	C
2024-T3	26	4.2	$8.8 \cdot 10^{-11}$

Prediction of the fatigue crack propagation is done using the Paris' law for the rate of fatigue crack growth

$$\frac{dl}{dN} = C(\Delta K_I)^m \tag{7}$$

It is a simple first order differential equation. Solution is obtained by numerical integration at the initial condition: the length of the initial crack is equal to 20 mm. It is a size that can be detected reliably by method of EMI.

Result of prediction is showed in the picture. It is seen that the predicted lifetime of crack propagation to the critical length is equal about 50,000 of flights (Fig. 6).

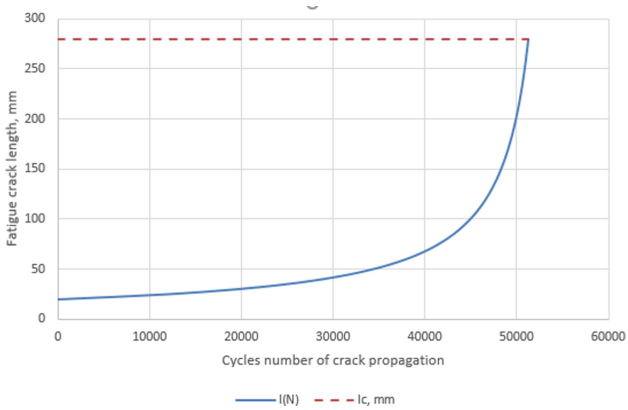


Fig. 6. Prediction of the fatigue crack growth and estimation of lifetime.

4 Conclusions

The effect of structural damage is associated with the changes of dynamic properties of a structure and can be effectively defined at ultrasonic frequencies by identification of EMI of system 'sensor-structural element'. The developed 1-D model of constrained PZT can be used for analysis of the elastic and geometrical parameters effect to properties of piezoceramics transducer, and for structural health monitoring of element with possible damage.

The key problem of increase of efficiency of EMI inspection is development of acceptable methods of prediction of effect of damage to the impedance. The simple method of estimation was developed. This method uses the effect of natural frequency changing as a result of PZT and structural element coupling. The effect of a crack is approximately estimated as a function of elastic compliance of a plate using the energetic approach of fracture mechanics. The model of constrained piezoceramics transducer can be also used for creation of a type of pre-stressed one protected from effect of mechanical fatigue and environmental degradation.

Acknowledgement. This study was funded by European Regional Development Fund (ERDF), Measure 1.1.1.5 "Support to international cooperation projects in research and innovation of RTU". Project No. 1.1.1.5/18/I/008. The author is very grateful for this help and support.

References

1. Liang, C., Sun, F.P., Rogers, C.A.: Coupled electro-mechanical analysis of adaptive material system-determination of the actuator power consumption and system energy transfer. J. Intell. Mater. Syst. Struct. **5**, 12–20 (1994)
2. Sun, F.P., Liang, C., Rogers, C.A.: Experimental modal testing using piezoceramic patches as collocated sensors-actuators. In: Proceeding of the 1994 SEM Spring Conference and Exhibits, Baltimore, MI, 6–8 June (1994)

3. Sun, F.P., Chaudhry, Z., Rogers, C.A., Majmundar, M.: Automated real-time structure health monitoring via signature pattern recognition. In: Proceedings, SPIE North American Conference on Smart Structures and Materials, vol. 2443. San Diego, CA, 26 Feb.–3 March, pp. 236–247 (1995)
4. Chaudhry, Z., Sun, F.P., Rogers, C.A.: Health monitoring of space structures using impedance measurements. In: Fifth International Conference on Adaptive Structures, Sendai, Japan, 5–7 December, pp. 584–591 (1994)
5. Chaudhry, Z., Joseph, T., Sun, F., Rogers, C.: Local-area health monitoring of aircraft via piezoelectric actuator/sensor patches. In: Proceedings, SPIE North American Conference on Smart Structures and Materials, Vol. 2443. San Diego, CA, 26 Feb.–3 March, pp. 268–276 (1995)
6. Ayres, T., Chaudhry, Z., Rogers, C.: Localized health monitoring of civil infrastructure via piezoelectric actuator/sensor patches. In: Proceedings, SPIE's 1996 Symposium on Smart Structures and Integrated Systems, SPIE, Vol. 2719, pp. 123–131 (1996)
7. Giurgiutiu, V., Rogers, C.A.: Electro-mechanical (E/M) impedance method for structural health monitoring a non-destructive evaluation. In: Int. Workshop on Structural Health Monitoring Stanford University, CA, September 18–20, pp. 433–444 (1997)
8. Giurgiutiu, V., Zagrai, A.: Characterization of piezoelectric wafer active sensors. J. Intell. Mater. Syst. Struct. **11**(12), 959–976 (2000)
9. Giurgiutiu, V., Zagrai, A., Bao, J.: Piezoelectric wafer active sensors (PWAS), USC IPMO Invention Disclosure #00330/2002 (2002)
10. Giurgiutiu, V., Zagrai, A., Jing Bao, J.: Piezoelectric Wafer Embedded Active Sensors for Aging Aircraft Structural Health Monitoring. SHM **1**(1), 0041–0061 (2002)
11. Giurgiutiu, V.: Structural Health Monitoring with Piezoelectric Wafer Active Sensors, p. 760. Elsevier Academic Press (2008)
12. Adams, D.E.: Health Monitoring of Structural Materials and Components: Methods with Application, pp. 60. John Wiley & Sons, Ltd. (2007)
13. Pavelko, I.: Research on the Protection of piezoceramics transducers from the destruction by mechanical loading. Int. Virtual J. for Science, Technics and Innovations for the Industry, Issue 7, pp. 17–21 (2010)
14. Pavelko, I. et al.: Problems of structural health monitoring of aircraft component. In: The proceeding of 27th Congress of the International Council of the Aeronautical Sciences, Nice, France, 19–24 September (Section 10, ICAS 2010–10.6.1) (2010)
15. Pavelko, V.: Application of the fatigue crack opening/closing effect for SHM using electromechanical impedance technology. Appli. Mech. Mater **811**, 228–235. Crossref, (2015). :https://doi.org/10.4028/www.scientific.net/amm.811.228

Improvement of Methodology of Calculation and Assessment of Transport and Operational Condition of Airfield Pavement (on the Example of Airport Pavements of Kyiv and Mykolaiv International Airports)

Viktor Karpov[1], Oleksandr Stepanchuk[1], Oleksandr Dubyk[1](✉), Oleksandr Rodchenko[1], and Olegas Prentkovskis[2]

[1] Faculty of Architecture, Civil Engineering and Design, National Aviation University, Kyiv, Ukraine
saschadubik@ukr.net

[2] Faculty of Transport Engineering, Vilnius Gediminas Technical University, Vilnius, Lithuania

Abstract. The article presents the results of assessment and forecasting of transport and operational condition of airfield pavements on the example of airfield pavements of Kyiv and Mykolaiv International Airports. Domestic and foreign methods of assessment of transport and operational condition and calculation of airfield pavements have been analyzed. One of the most common methods of qualitative assessment of the transport and operational condition of airfield pavements is the method, the essence of which is to compare the classification numbers of aircraft and the bearing capacity of the pavement at the same strength of the subgrade. The results of calculation and design of airfield pavements were performed on the example of Kyiv and Mykolaiv International Airports using the FAARFIELD program. An alternative design of flexible airfield pavement of Kyiv International Airport is proposed. The engineering and geological conditions of Kyiv International Airport were analyzed in detail. Visual investigation of the surface of the pavements of all elements of the airfield of Kyiv International Airport showed that they have satisfactory transport and operational condition. The classification numbers PCN of rigid airfield pavements of Kyiv and Mykolaiv International Airports and flexible airfield pavement of Kyiv International Airport have been calculated with the help of the FAARFIELD program. PCN of the offered design of a rigid airfield pavement of the «Mykolaiv» International Airport is PCN 70/R/C/W/T. This means that the aircraft of this element of the airfield can perform take-off and landing operations without restrictions. Likewise, aircraft can perform take-off and landing operations without restrictions on rigid and flexible airfield pavements of «Kyiv» International Airport

Keywords: Runway · Transport and operational condition · Airfield pavement · Method of signal estimation · *ACN - PCN* method · Reliability · Pavement slabs

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 806–823, 2023.
https://doi.org/10.1007/978-3-031-25863-3_79

1 Introduction

The choice of optimal solutions in the design of airfield pavement structures, both rigid and flexible, technologies for their manufacture, construction and operational control necessitates the widespread use of methods of mathematical analysis [7, 8, 19, 21]. Ensuring the reliability and durability of rigid types of airfield pavement is becoming increasingly important in connection with the mass construction and reconstruction of airports in Ukraine and the development of modern aircraft [9, 19]. Premature destruction of concrete and reinforced concrete structures of airfield pavements requires significant investment to strengthen them. The reasons for the premature destruction of rigid airfield pavements are the imperfection of the theory of calculation, which does not allow to fully take into account the real working conditions during operation, as well as, to some extent, the low culture of construction work performance [7, 8, 15, 19, 21–23]. Variety of soil and climatic conditions, differences in the work of individual structural layers of pavement, and a significant number of factors (temperature and humidity, statistical, acoustic and dynamic loads, vibration) require a very complex analysis in the selection and substantiation of the design of the airfield pavement [7, 8, 15, 16, 19, 21].

To determine the quantitative characteristics of the durability of rigid airfield pavements it is necessary to know the regularity of changing a complex of external and internal factors that determine the behavior of the structure over time. These factors include power factors – the load from the weight of the aircraft, the thermodynamic effects of gas flows, the effects of ambient temperature and other climatic factors. It is also necessary to take into account the elements of geometric schematization and the corresponding deflection of structures, anisotropy of physical and mechanical properties of materials used in the construction of airfield pavements. The actual construction parameters of airfield pavement structures are of great importance – these are the objective characteristics that are obtained during the construction of pavements.

During operation, airfield pavements are affected by repeated application of force loads. This change in time is significant not only for fast processes that are associated with dynamic loading but also for quasi-static loading processes, i.e., periodic changes in ambient temperature.

To determine the durability of the pavement structure, along with the above data, it is necessary to operate on the reliability characteristics that make up the pavement elements, the types of connections of these elements, and data on the impact of element failures on the reliability of the structure as a whole. Real constructions can be represented by analogues in the form of appropriate mathematical models [7–9, 15, 19, 21–23].

Ensuring long-term unfailing operation of rigid airfield pavements is associated with certain material costs, so when selecting and substantiating the design of airfield pavements taking into account the specified durability it is necessary to consider not only the cost of the designed pavement but also the cost-effectiveness of extension of service life of the corresponding design. Therefore, taking into account the above-mentioned, it is offered the experience of designing airfield pavements in the modern conditions of Ukraine on the example of the «Kyiv (Zhulyany)» International Airport and the «Mykolaiv» International Airport. Reasonable choice of design and airfield planning solutions will ensure the safety and comfort of takeoff and landing of aircraft [7–9, 15, 16, 19, 21].

2 Assessment Methods of the Transport and Operational Condition and Calculation of Airfield Pavement

Successful operation of airfield pavements depends on the condition of structural elements, proper organization of maintenance work, and design of airfield pavements. During operation, under the influence of aircraft loads and natural factors, there is physical deterioration of the surface of the pavement and internal force damage of the airfield structure, which reduces its load-bearing capacity and surface quality [7–9, 15, 16, 19, 21]. Preservation of the suitability of pavement is the main task of the airport. The rate of accumulation of damage in the pavement during operation is highly dependent on the rate of its overload. Reliability of airfield pavements is the probability of their unfailing work in a given period of operation. The realization of the reliability of the structure laid down in the design of airfield pavements is ensured by the concerted work of the main bearing layer, base course, and subgrade. The concept of durability is closely related to the reliability of the system. Durability is the time of operation of the system from the beginning of the operation to its failure. The relationship between reliability $p(\tau)$ and density distribution probability for durability $P(\tau)$ is determined by the formula:

$$p(\tau) = -\frac{P(\tau)}{d(\tau)}. \tag{1}$$

The main function of the «airfield pavement» system is to ensure the safe operation of aircraft. Impairment or loss of coverage of the ability to provide take-off and landing operations of aircraft is a failure. The reliability scheme of the «airfield pavement» system is determined by a group of interconnected elements «plate», «joint», «base», and «soil», each of which has its own probabilistic characteristics of unfailing operation. The probability of unfailing work of any element of the pavement is a function of failure rate and operating time. The main calculated indicators that make up the quality of the pavement are: strength and durability of raw materials; characteristics of design loads; working conditions of the structure. Each of the calculated indicators is characterized by a complex functional relationship of different characteristics that reflect the design, technological and operational properties.

As a mathematical basis for the analysis of reliability and durability of airfield rigid pavements, it is necessary to use statistical methods in building mechanics which have found practical application in the estimation of reliability of some engineering structures [7–9, 15, 16, 18, 19, 21].

The theory of reliability allows estimating statistical stress fields which arise in structures of airfield pavements at various combinations of loads and influences [9]. If the structure is loaded with a random load, then the movement of the structure is a random process. This motion can be described by the methods of correlation and spectral theories or by the theory of random processes of the Markov type. Using these methods, it will be possible to calculate the statistical characteristics of stresses that occur in the structure. Further growth comes to the determination of the reliability and durability of the structure. Thus, if the change in stress in the structure is a narrow stationary random

process and the reason for failure – the accumulation of fatigue damage, the average durability can be determined by the formula:

$$\overline{T} = -\frac{T_{eф.}}{\int_0^\infty \frac{\rho(S)dS}{N(S)}}, \tag{2}$$

where $\rho(S)$ – is the distribution density of probability for stress maxima; $N(S)$ – the equation of the fatigue curve, which connects the limit number of cycles with stress; $T_{eф}$– effective period of stress change.

The application of methods of reliability theory in structural mechanics requires the accumulation of statistical data for external loads and properties of applied materials of structures [9]. The application of these data requires advanced experimental research using the methods of mathematical statistics to process the results. Necessary statistical experimental data on the reliability of elements and structures of pavements can be obtained as follows: the results of operation; according to the results of tests; by modeling the operation processes of airfield pavements.

The greatest importance for the reliable operation of rigid airfield pavements is to consider the force factors of the effects of moving load and ambient temperature [16].

The system "man-made surface" on the runway, taxiway or parking position in its simplest form is a certain representation of the elements – plates, the failure of which is the loss of load-bearing capacity installed during operation or as a result of specially organized tests. The butt joint is "included" in the "paving slab" element, since failure (failure of butt joints) in all cases causes the paving slab failure. In the case where the failure of the pavement occurs in the condition of failure of any individual plate, there is a so-called serial connection of elements for reliability, which is defined by a well-known expression:

$$P = \prod_{i=1}^{n} P_{en}^{i}, \tag{3}$$

where n – the number of plates in the airfield pavement.

Since the purpose of calculating the design of the airfield pavement is to obtain a guarantee that during the period of operation will not occur any of the unacceptable limit states, the strength condition will be written as follows:

$$S \leq R, \tag{4}$$

where S – load, effort or stress in the plate from external forces; R – bearing capacity of the plate.

For today, airfield pavements continue to be in operation after a sufficient number of slabs were damaged.

One of the most common methods of qualitative assessment of the transport and operational condition of airfield pavements is the *ACN - PCN* method, the essence of which is to compare the classification numbers of aircraft and the bearing capacity of the pavement at the same strength of the subgrade. The classification number of airfield

pavement shall not be lower than the classification number of the aircraft operated on the pavement:

$$K \cdot ACN \leq PCN, \tag{5}$$

where K – is the coefficient that takes into account the intensity of aircraft movement; ACN – aircraft classification number; PCN – pavement classification number [4–6, 10–14, 17, 24].

In practice, the following methods of estimation the transport and operational condition of airfield pavements are also widely used: methods of signal estimation; determination of the airfield pavement condition index; standard method for determining the pavement condition index PCI.

3 Assessment Methods of the Transport and Operational Condition and Calculation of Airfield Pavement

Assessment of the suitability for further operation of rigid airfield pavement was performed on the example of «Kyiv (Zhulyany)» and «Mykolaiv» International Airports.

3.1 Results of Calculation and Design of Airfield Pavements on the Example of «Kyiv (Zhulyany)» International Airport

During the research of physical and mechanical characteristics of the subgrades of the airfield pavements, natural and soil-geological conditions of the Kyiv (Zhulyany) airport location area were studied and taken into account. It was stated that the climate of the territory, as well as the entire Kyiv region, belongs to the temperate-continental. The average air temperature for the year ranges from 6.6 to 7.2 °C. The maximum temperature in summer is 37–39 °C, the minimum in the coldest winters −36 °C. The average long-term amount of precipitation is 550 mm with fluctuations over the years from 392 to 925 mm. The main number of which (about 75%) falls on the period from April to October.

The relative humidity is high and on average is 84% per year, decreasing to 73–60% in summer and rising to 91% in winter. This causes the evaporation of a relatively small amount of moisture from the soil surface, which with a significant amount of precipitation creates a positive balance of moisture in the soil. In general, the area belongs to the zone with moderate humidity and moderate warm climate.

The main source of soil moistening is rainwater. Due to insufficient surface water runoff and close location from the daily surface of groundwater (1.7 – 2.0 m), the airfield area, according to the existing road-climatic classification, should be classified as 2nd type of hydrogeological conditions (wet places with excessive moisture in certain periods of the year), the second road-climatic zone [20], or U-1 for the territory of Ukraine. The upper part of the engineering geological cross-section consists of bulk soils, represented by sand with insignificant content of organic matter (humus 0.5–1.0%), as well as supra-moraine thickness of fine-grained and dusty sands of water-glacial origin of the Middle Quaternary period.

1. In the upper part of the engineering-geological cross-sections (up to a maximum depth of 5.2 m) on the entire area of the airfield there are only two engineering-geological elements (EGE):

   – EGE-1 (upper layer of soil)—sandy loam with layers of coarse sandy loam, from gray to dark color and from hard to plastic consistency. Index of dry soil density:
   – $\rho_d = 1.58 – 1.62$ g/cm3, porosity coefficient e = 0.65 – 0.70, natural soil humidity
   – W = 12 – 24%. Such soils can be singled out at the end section of taxiway-2, where they are well compacted at the subgrade of the pavements (ρ_d = 1.68 – 1.78 g / cm3, e = 0.50 – 0.60) and have mostly semi-solid and even solid consistency with natural humidity W = 17%;
   – EGE-2 (lower, under EGE-1, soil layer) - fine-grained sand with layers of dusty sand, from light gray to yellow, water-saturated, high density with layers of medium density. Index of water saturation coefficient Sr = 0.8 – 1.0 and porosity coefficient e = 0.55.

2. Analysis of engineering geological research data shows that for these two types of soils (sandy loam and fine-grained sand) at the airfield of the «Kyiv (Zhulyany)» airport in the calculation of PCN classification numbers for all elements of the airfield it is possible to accept with sufficient justification the normative values of the coefficient of subgrade resistance Ks = 50 MN/m3 and Ks = 70 MN/m3 and the modulus of elasticity E = 37 MPa and E = 100 MPa respectively.

   The geological structure of the site is composed of loams, sandy loams, sands and clays, which are covered with bulk soil and soil-vegetation layer [15].

   According to engineering geological researches and laboratory analyzes at the site, the following engineering geological elements (EGE) have been identified:

   – EGE - 1. Bulk layer - brownish-gray loam, in places with content of construction debris up to 10%. With layers of sand, in places rubble with loamy aggregate (tH).
   – EGE - 2. Soil-vegetative layer – dark gray sandy loam, humus-rich, with grass roots, has solid consistency (bH).
   – EGE - 3. Dark gray sandy loam, humus-rich, with a solid consistency (bH).
   – EGE - 4. Yellowish-gray, pale yellow sandy loam, loess-like, non-sedimentary, consistency range from solid to plastic (vd PII-III).
   – EGE - 5. Grayish-yellow sand, fine, low-moisture, with medium density (vd PII-III).
   – EGE - 6. Brownish-yellow, light gray, light brown sandy loam, sandy, has from solid to plastic consistency (fPIIdn).
   – EGE - 7. Dark yellow, grayish-yellow sand, dusty, with layers of loam, with the inclusion of gravel and fine pebbles up to 10%, low moisture, dense (fPIIdn).
   – EGE - 8. Dark yellow, brownish-yellow sand, fine, loamy, with layers of sandy loam to the bottom, low-moisture, dense (fPIIdn).
   – EGE - 9. Light gray sand, fine, with thin layers of sandy loam, saturated with water, dense (fPIIdn).

– EGE - 10. Brownish-gray, light brown loam, with the inclusion of gravel and carbonate concretions up to 10%, consistency range from semi-solid to low-plastic (fPIIdn).
– EGE - 11. Brownish-gray, dark brown clay, with inclusions of carbonate concretions up to 5%, has semi-solid consistency (N2).

The master plan of «Kyiv (Zhulyany)» International Airport is shown in Fig. 1.

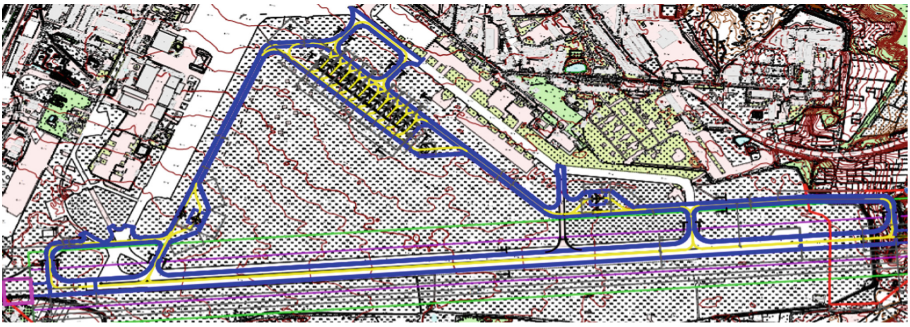


Fig. 1. The master plan of «Kyiv (Zhulyany)» International Airport.

The power, boundaries and conditions of engineering-geological elements are shown in the engineering-geological cross-section (see Fig. 2).

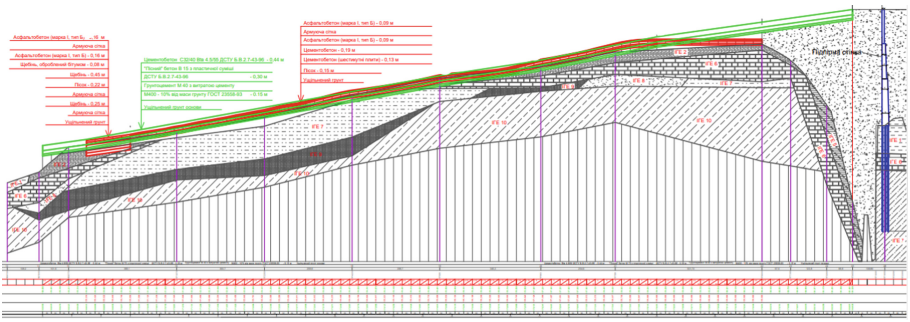


Fig. 2. Longitudinal profile along the axis of the runway of “Kyiv (Zhulyany)" International Airport.

According to the inspection materials and in accordance with the information at the airfield are located:

– rectangular runway: 2,310 × 45.0 m;
– airfield class - B (4C);
– pavement - monolithic concrete, reinforced with asphalt concrete;

- the runway has a planned section of 75 m wide on both sides of the man-made runway surface and has a length of 2,890 m;
- FATO (final approach and take-off area) is 90 m wide and long.

The width of the runway is 280 m (140 m from the axis in each direction).

It is planned to operate B737–9/BBJ MAX9 and A321/neo aircraft at the aerodrome.

It is foreseen that the size and configuration of the apron and long-term parking positions should provide:

- placement of the estimated number of operated types of aircraft, taking into account the designed intensity of their movement and cost-effectiveness of planning decisions;
- safe maneuvering of aircraft and the minimum length of their routes between the runway and the parking positions on the apron and long-term parking positions;
- safe and convenient passage, placement and maneuvering of special vehicles and mechanization means;
- safe passage of passengers on the shortest routes between the air passenger terminal and aircraft parking positions;
- placement of stationary equipment for aircraft maintenance at the parking positions;
- processability of construction of pavements of apron and long-term parking positions of aircraft;
- the possibility of mechanized cleaning of the apron surface and long-term parking positions of aircraft from snow and ice, as well as mechanized collection of garbage and foreign objects;
- the possibility of expanding the area, taking into account the prospects of increasing traffic;
- appropriate sanitary and hygienic conditions and convenience in the location of the service and technical area of the airport.

Visual inspection of the surface of the pavements of all elements of the aerodrome showed that they have a satisfactory transport and operational condition. This is due to the fact that in 2008 and 2009 almost all pavements of «Kyiv (Zhulyany)» airfield were reinforced with structural layers of asphalt concrete. In addition, the existing runway was extended by 150 m by building a new flexible asphalt concrete pavement on this section, as well as on the part of taxiway-1 adjacent to the runway.

The designs of pavements and layer thicknesses were accepted according to the data carried out by the method of drilling test wells. The layer composition of the airfield pavement structures of Kyiv (Zhulyany) International Airport is shown in Table 1.

The actual thicknesses of the pavement layers were determined by means of averaging the thicknesses measured after bore core cutting-out and wake pitting of the pavements.

These thicknesses of artificial bases of coatings are accepted according to documentary data because determining the actual thickness of the layer of sand and gravel does not provide the accepted accuracy (these materials have the ability to partially displace the underlying soil during long-term operation of the coating).

On the coatings that were subject to amplification, the special alignment layers with asphalt concrete with a minimum thickness of 2 cm were laid.

Therefore, considering the above mentioned, 2 variants of the design of the artificial runway coating (Fig. 3, 4) are offered. The artificial pavement constructions are defined based on: climatic, hydrogeological, and soil conditions; features of the influence of the code C aircraft coverage, which are operated in these areas; availability and possibility of using local building materials.

The designed runway pavement construction is designed for loading from aircrafts B737–9/BBJ MAX9 and A321/neo and consists of: compressed soil; stabilized soil that is stabilized by cement to M40, h = 0,15 m; lightweight concrete B15, h = 0,30 m; cement concrete C32/40 Btb 4,5/55, h = 0.45 m.

The dimensions of cement-concrete slabs are 7.5×7.5.

The stabilized roadsides have a construction: compressed soil; sand-cement M40, h = 0.20 m; cement concrete C32/40 Btb 4,5/55, h = 0.26 m.

The coating is designed for loading from aircrafts B737–9/BBJ MAX9 and A321/neo, the technical characteristics of which are shown in Table 2 and Fig. 5 and 6.

Table 1. International airport «Kyiv (Zhulyany)» pavement constructions.

Airfield Element	Pavement Construction	Actual Pavement Thickness, cm
Runway (PK0–PK1+50)	Asphalt Concrete (brand I, type B)	16
	Reinforcing Mesh	
	Asphalt Concrete (brand I, type B)	16
	Gravel Processed by Bitumen	8
	Gravel	45
	Sand	22
	Reinforcing Mesh	
	Gravel	25
	Reinforcing Mesh	
	Compressed Soil	
Runway (PK1+50–PK19+50)	Asphalt Concrete (brand I, type B)	9
	Reinforcing Mesh	
	Asphalt Concrete (brand I, type B)	9
	Cement Concrete	19
	Cement Concrete (hexagonal slabs)	13
	Sand	
	Compressed Soil	15
Runway (PK19+50–PK23+10)	Asphalt Concrete (brand I, type B)	9
	Reinforcing Mesh	
	Asphalt Concrete (brand I, type B)	9
	Slabs ASP-18	18
	Sand-Cement	15
	Compressed Soil	

Thus: **for aircraft B737–9/BBJ MAX9:** basic load on the main gear $F_n = 408,3758$ kN; the number of wheels on the main gear $n_k = 2$; distance between the centers of tires footprints of the main gear $a = 0.86$ m; the number of the axis on the main gear $n_a = 1$; the inflation pressure into the main gear tires $p_a = 1.59$ P.

For aircraft A321/neo: basic load on the main gear $F_n = 453,544$ kN; the number of wheels on the main gear $n_k = 2$; distance between the centers of tires footprints of the main gear $a = 0.927$ m; the number of the axis on the main gear $n_a = 1$; the inflation pressure into the main gear tires $p_a = 1.57$ P.

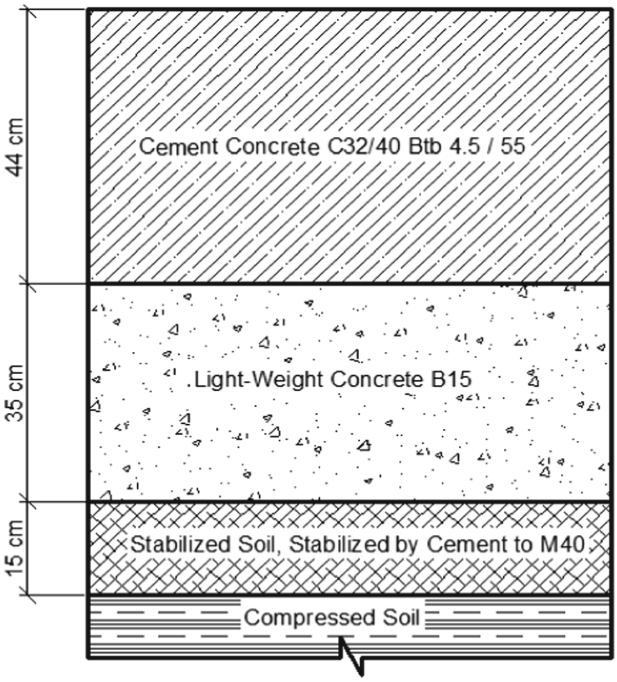


Fig. 3. Variant 2 of international airport «Kyiv (Zhulyany)» artificial pavement construction.

Mid-year number of take offs for B737–9/BBJ MAX9 $N_1 = 5000$; for A321/neo $N_1 = 5000$. The calculation of the runway strength was also performed in accordance with US regulations [1–3].

The results of the calculations in the FAARFIELD program are shown in Fig. 7. The alternative variant of the structural integrity with a flexible airfield pavement is considered and calculated in solutions and offers: asphalt concrete A40 (brand I, type A) – 16 cm; asphalt concrete A40 (brand I, type A) – 16 cm; gravel processed by bitumen – 8 cm; gravel – 45 cm; sand – 22 cm; reinforcing mesh; gravel – 25 cm; reinforcing mesh; compressed soil.

The results of the calculations of the alternative variant of the runway construction with a flexible pavement with the modulus of the subgrade elasticity E = 24 MPa and E = 28 are shown in Fig. 8. For the flexible airfield pavement, the aircraft classification number is PCN 70/F/D/W/T, which is more than the ACN of B737–9/BBJ MAX9 and A321/neo. This means that the flexible airfield pavement can take different take-off and landing operations without mass and intensity restrictions.

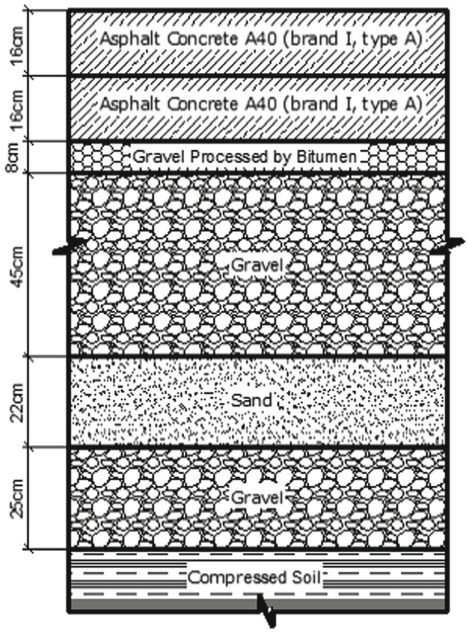


Fig. 4. Variant 2 of international airport «Kyiv (Zhulyany)» artificial pavement construction.

Table 2. Technical characteristics of aircrafts B737–9/BBJ MAX9 and A321/neo.

Aircraft	B737–9/BBJ MAX9	A321/neo
Maximum mass	88,541 kg	97,400 kg
Maximum load on main gear	41,671 × 9.8 = 408,375.8 kN	46,280 × 9.8 = 453,544 kN
Main gear tire pressure	1.59 MPa	1.57 MPa

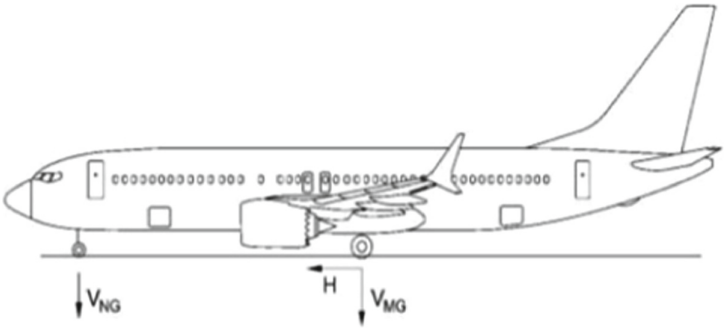


Fig. 5. Characteristics of aircraft B737–9/BBJ MAX9.

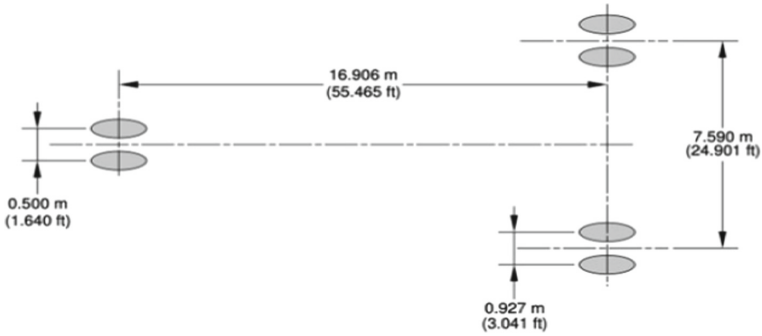


Fig. 6. Characteristics of aircraft A321/neo.

3.2 The Results of Calculating and Designing the Airfield Pavements by the Example of Mykolaiv International Airport

According to the survey, materials at the airport are: Rectangular shape runway: 2,555 × 43.8 m; Airfield class – B (4C); Pavement – monolithic cement concrete reinforced by asphalt concrete; Runway has a planned area of 65 m wide on both sides from the artificial runway; Runway and apron are connected by taxiway-A 112 m length. The width of taxiway-A is 21 m. Pavement – cement concrete reinforced by asphalt concrete. With a total area of 65,500 m^2, the apron is designed to service aircrafts on AP1 – AP9. The AP7H is equipped with a heliport deck. Apron pavement is cement concrete partially (on AP 7H-9) reinforced by asphalt concrete. The absolute minimum temperature (in January) is −30 °C. The absolute maximum temperature (in July) is + 39 °C.

Thus, the shoulders are located symmetrically on both sides of the runway so that the total width of the runway and its shoulders is 60 m for the airfield code letter D. The existing design of artificial runway surfaces, AP, and the apron of the Mykolaiv International airport is shown in Fig. 9a, b. For a long time of existence, airfield coverings have worked their calendar endurance. Operational inspection and monitoring of coatings are carried out regularly. As the project envisages the reconstruction of the artificial

runways with a change in geometric dimensions, the air approaches are also changing. The runway is planned to be expanded from 43.8 to 45 m. On both sides of the runway edge, there are shoulders 7.5 m wide each. The calculation of the runway strength was also performed in accordance with U.S regulations [1–3].

Two brands of the upper (designed) layer of cement concrete pavement were considered: Btb4.8 / 60 and Btb4.4. The calculation was performed for 3 takeoffs per hour of the aircraft B767-300F and 3 take offs per hour of the aircraft A321–200. The results of the calculations are shown below in Fig. 10. For the thickness of the cement concrete upper layer with a thickness of 450 mm, it is necessary to make restrictions on the weight with the cement concrete class Btb4.4.

For the cement concrete class Btb4.8, the classification number of airfield pavement is PCN 51/R/A/W/T, for Btb4.4 - PCN 44/R/A/W/T with the thickness of upper layer pavement of 450 mm.

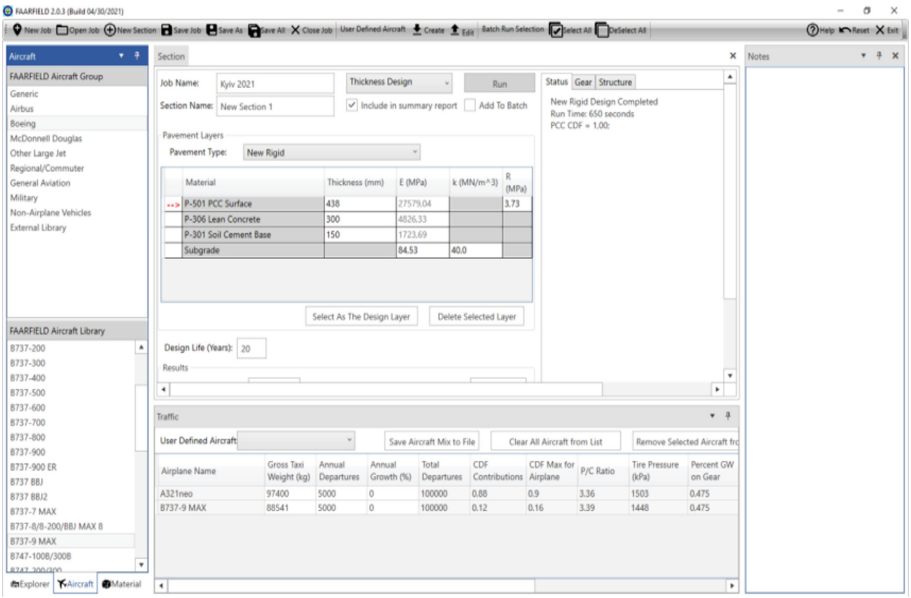


Fig. 7. The Results of the calculations of the rigid cement-concrete runway pavement of international airport «Kyiv (Zhulyany)» (PCN 70/R/C/W/T WITH A COATING THICKNESS OF 44 CM).

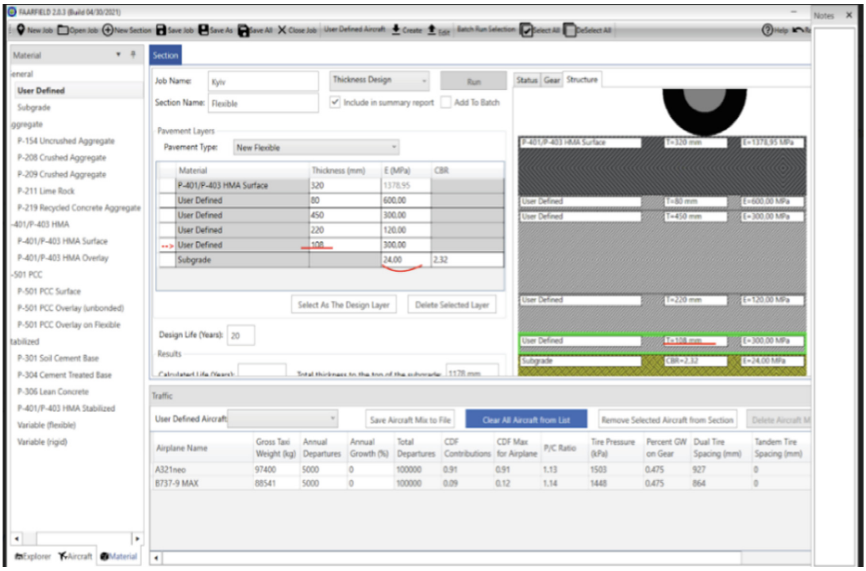


Fig. 8. The Results of the calculations of the alternative variant of the runway construction with a flexible pavement with the modulus of the subgrade elasticity E = 24 MPa and E = 28 MPa.

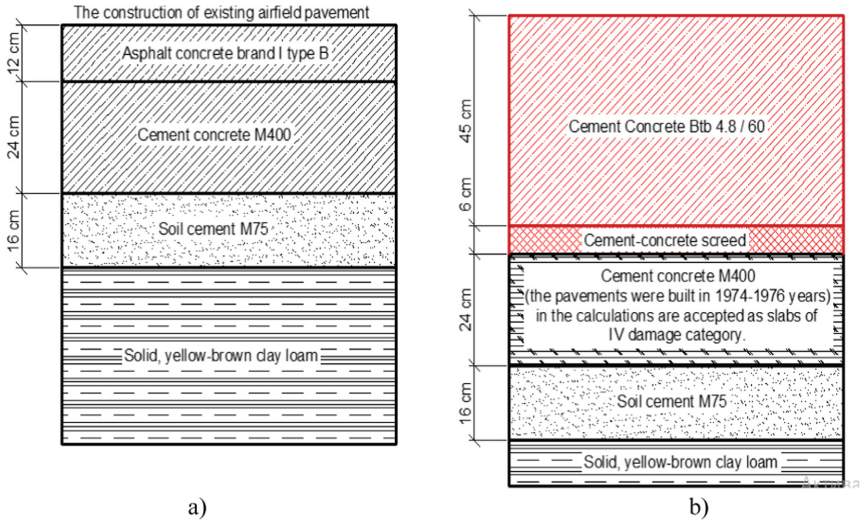


Fig. 9. Airfield pavement constructions of international airport «Mykolaiv»: a) Existed construction; b) Proposed construction.

This is more than the value of the ACN, which allows accepting aircrafts B767-300F and A321–200 without restrictions on weight and intensity.

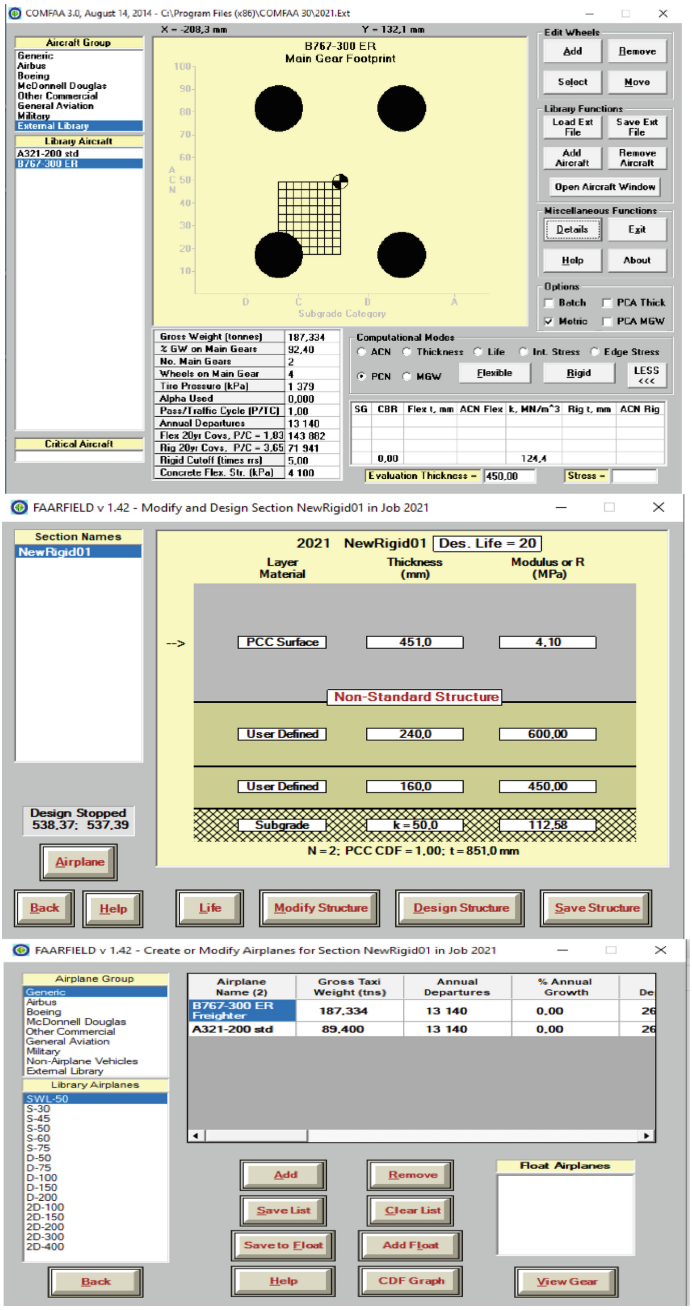


Fig. 10. The Results of classification numbers calculation of PCN airfield pavement of the Mykolaiv international airport for the cement concrete classes Btb4.4 and Btb4.8.

4 Discussion and Interpretation of the Results

Aircraft with an ACN number that is equal to or less than the PCN pavement of an airfield element may perform take-off and landing operations without restrictions, as shown by the calculations of rigid and non-rigid airfield pavements of International Airports «Mykolaiv» and «Kyiv». Given the probability of increasing the intensity of the load on the pavement and the number of take-off and landing operations by aircraft with ACN > PCN, it is possible that the airfield may need to operate in excess of bearing capacity.

According to the «International Standards and Recommended Practices» (ICAO, Doc 9157-AN/901 Sect. 2), it is allowed (in certain circumstances) to fly by aircraft even with the maximum ACN. For example, from the practice of Canada, such take-off and landing operations are possible provided the readiness of the authorized body of the airport to make financial operations for pre-schedule repairs. Also, according to the practice of French, there is a minimum danger for an aircraft landing on the runway with insufficient bearing capacity. Even landing an excessively heavy aircraft (loads significantly exceed the bearing capacity of the runway) will undoubtedly cause some damage to the pavement, but without any damage to the aircraft itself, and the owner of the aircraft will in no way be liable for such damage. However, the load from the aircraft must not, in any case, exceed the permissible one (for this aircraft) for all pavements more than 50%, except for aprons, where such exceedances are limited to 20%.

In the future, after performing take-off and landing operations of the aircraft with overload, it is necessary to make additional inspections of the pavement with the fixation of any deterioration of their condition. In the case of new defects (through cracks, chips, and chips at the edges and corners of slabs, subsidence, etc.), which can lead to unacceptable pavement damage and pose a danger to flight safety, it is necessary to stop take-off and landing operations and perform necessary repairs.

In case of a significant load increase on pavement and numbers of take-off and landing operations by aircraft, formation of new destructions or significant development of existing ones, overhaul or reconstruction, it is necessary to inspect and evaluate the technical condition of artificial airfield pavements, analyze flight intensity, aircraft types and perform a new calculation of PCNs.

5 Conclusion

To solve the problem of evaluating the transport and operational condition of aerodrome pavements of International Airports «Mykolaiv» and «Kyiv», the article provides theoretical research, which included the development of calculation schemes and models of airfield pavements based on world experience in design and calculation. In the FAARFIELD program was performed computer modeling and calculation of PCNs of rigid pavements of International Airports «Mykolaiv» and «Kyiv» and non-rigid airfield pavement of International Airport «Kyiv». According to the results of calculations, the PCNs of the airfield pavements are higher than the classification numbers of the ACN aircraft.

The calculation of rigid and non-rigid airfield pavement of International Airport «Kyiv» was performed under the action of loads from aircraft B737–9/BBJ MAX9 and A321/neo. For the rigid airfield pavement, the classification number is PCN 70/R/C/W/T, for the non-rigid one is PCN 70/F/D/W/T, which is more than ACN of B737–9/BBJ MAX9 and A321/neo aircrafts. This means that the rigid and non-rigid airfield pavement can take different take-off and landing operations without mass and intensity restrictions.

The calculation of the rigid airfield pavement of International Airport «Mykolaiv» was performed for the action of the load from the cargo aircraft B767-300F and the passenger aircraft A321/neo. For the thickness of the cement concrete upper layer with a thickness of 450 mm, it is necessary to make restrictions on the weight with the cement concrete class Btb4.4.

For the cement concrete class Btb4.8, the classification number of airfield pavement is PCN 51/R/A/W/T, for Btb4.4 - PCN 44/R/A/W/T with the thickness of upper layer pavement of 450 mm. This is more than the value of the ACN, which allows accepting aircrafts B767-300F and A321–200 without restrictions on weight and intensity. For the thickness of the cement concrete upper layer with a thickness of 450 mm, it is necessary to make restrictions on the weight with the cement concrete class Btb4.4.

References

1. Advisory Circular U.S. Department of Transportation Federal Aviation Administration. AC 150/5335 – 5C (2014)
2. Advisory Circular U.S. Department of Transportation Federal Aviation Administration. AC 150/5320 – 6F (2016)
3. Advisory Circular U.S. Department of Transportation Federal Aviation Administration. AC 150/53020 – 6G (2020)
4. ASTM D5340–12, Standard Test Method for Airport Pavement Condition Index Surveys (2018)
5. Brill, D.R.: Faarfield 1.4. updates, improvements and new capabilities. In: XI ALACPA Seminar on Airport Pavements and IX FAA Workshop, 3 September 2014, Santiago, Chile, p. 24 (2014)
6. Doug, J.: Airport pavement design and evaluation. Draft AC 150/5320–6F. Faarfield Ssoftware. In: ACC Summer Workshop, 10 August 2016, Washington, USA, p. 24 (2016)
7. Dubyk, O.M., Selenkov, V.N., Talakh, S.M.: Strength calculation of airfield pavements with weak soil foundations. In: Proceeding of the 16h Conference for Junior Researchers Science – Future of Lithuania. Transport engineering and management, pp. 55 – 59 (2013)
8. Dubyk, O.M.: Determination of the stress-strain state of rigid airfield pavements from multi-wheel loading of a super-heavy aircraft, Kharkiv, Khnahu, vol. 89, pp. 59–66 (2020)
9. Gamelyak, I.: Fundamentals of ensuring the reliability of pavement structures (dis ... Ph.D.: 05.22.11). National Transport University, Kyiv, Ukraine (2005)
10. Grošek, J.: Analysis of concrete pavement deformations on the road test section. In: 18th International Multidisciplinary Scientific Geoconference SGEM (2018)
11. Guo, E.: Critical gear configurations and positions for rigid airport pavements – observations and analysis. In: Pavement Mechanics and Performance, GeoShanghai International Conference, Shanghai, China, pp. 7–14 (2006)
12. Guo, E.: PCC pavement models in Faarfield today and tomorrow. In: Federal Aviation Administration Airport Pavement Working Group Meeting, 15–17 April 2013, Atlantic City, USA (Accessed 30 November 2015)

13. Hodáková, D.: Impact of climate characteristics on cement concrete Pavements. In: SGEM 2017. 17th International Multidisciplinary Scientific GeoConference,. Energy and Clean Technologies: Conference Proceedings. Albena, Bulgaria, vol. 17, pp. 467—472, 29 June - 5 July 2017. Sofia: STEF 92 Technology (2017)
14. International Civil Aviation Organization. Annex 14 to the Convention on International Civil Aviation. Aerodromes. Volume 1. Aerodrome Design and Operations (2018)
15. Karpov, V.V.: Design and construction of airifield complexes: monography, In: Karpova V.V. (ed.) For general, Kherson: Oldi +, 2022, p. 340 (2022)
16. Kulchitsky, V.A.: Airfield pavements. Modern look (2002)
17. Ministry of Transport of Ukraine. Decree of the Ministry of Transport of Ukraine dated 01.07.2013 № 441 "On approval of the Instruction on the airfields operation of state aviation of Ukraine", registered with the Ministry of Justice of Ukraine on 22.07.2013 on № 1229/23761 (2013)
18. Prusov, D.E.: Features of research of interaction of airfield pavements with soil bases with weak layers. Bull. National Aviation Univ. **2**, 129–133 (2009)
19. Rodchenko, O.V.: Computer technologies for concrete airfield pavement design. Aviation **21**(3), 111–117 (2017)
20. State building standards SBS B.2.3–4: 2015 Highways. Part 1. Design. Part 2. Construction (2015)
21. Talakh, S.: Some technical solutions for the use of aerodrome pavements in the soft soil conditions. In: International Conference Building Innovations, pp. 303–311 (2019)
22. Tsyhanivskyi, V.K.: Calculation of thin slabs on an elastic foundation by the finite element method, Kyiv, p. 234 (2008)
23. Tsyhanivskyi, V.K., Prusov, D.E.: The refined numerical calculation of rigid airfield pavements on weak soil bases with taking into account the inhomogeneity of material and features of joint elements of slabs. Resis. Mater. Theory Struct. Scient. Tech. Collect. **78**, 92–100 (2007)
24. U.S. Department of Transportation Federal Aviation. AC 150/5320–6F, Airport Pavement Design and Evaluations, 10 November 2016 (2016)

Author Index

A
Abramović, Borna 627
Akmaldinova, Oleksandra 175
Alnusairat, Zaid 459
Alqasem, Qasem 459
Alsarayreh, Duha 459
Aydin, Metin Mutlu 59
Ayrapetyan, Anna 790

B
Babatunde, Olufemi Olaulava 85
Bąk, Marcin 287, 365, 383, 393
Ballay, Michal 162, 415
Barta, Dalibor 258, 518
Batarlienė, Nijolė 566
Batory, Damian 236, 344
Bazaras, Darius 655
Blatnický, Miroslav 208, 247
Blumbergs, Ilmars 645
Bogdevičius, Marijonas 189
Boichenko, Sergii 85
Bondar, Boris 726
Brezani, Milos 518
Bručas, Domantas 767
Brzozowski, Michał 12
Buhrov, Anatolii 33
Bureika, Gintautas 756
Burinskienė, Liudmila 655

C
Çelik, Yasin 59
Čepaitis, Tomas 104
Čerškus, Edgaras 548
Cherednichenko, Kostiantyn 773
Činčikaitė, Renata 528, 539
Čižiūnienė, Kristina 479
Čulík, Kristián 125, 627
Czarnuch, Arkadiusz 236, 344

D
Danchuk, Viktor 43
Danilevičienė, Irena 427
Danilevičius, Algimantas 427
Delembovskyi, Maksym 3
Demchenko, Oksana 354
Deptuła, Adam 268
Dižo, Ján 208, 247
Dologa, Jindřich 491
Drazdauskas, Martynas 116
Dubovas, Andrius 767
Dubyk, Oleksandr 806

E
Elsakty, Khaled 645

F
Fedorenko, Kyrylo 175
Filina-Dawidowicz, Ludmiła 556
Flynnova, Lucie 737

G
Gecejova, Natalia 85
Gerlici, Juraj 258
Goolak, Sergiy 677
Grencik, Juraj 518
Gritsuk, Igor 23
Gryshchuk, Oleksandr 449
Gutarevych, Yurii 144

H
Hanáková, Natálie 491
Hasenko, Lina 576
Holub, Halyna 696
Hrudkay, Karol 125

I
Ilchenko, Volodymyr 336, 354
Išoraitė, Margarita 618

© The Editor(s) (if applicable) and The Author(s), under exclusive license
to Springer Nature Switzerland AG 2023
O. Prentkovskis et al. (Eds.): TRANSBALTICA 2022, LNITI, pp. 825–827, 2023.
https://doi.org/10.1007/978-3-031-25863-3

Iurchenko, Valentina 327
Ivannikova, Viktoriia 773, 790

J
Jadaan, Khair 459
Jančo, Ján 470
Jarašūnienė, Aldona 502
Juknelevičius, Romualdas 309
Junevičius, Raimundas 375

K
Kariuk, Alla 336
Karpenko, Mykola 189, 277, 383, 393
Karpov, Viktor 806
Kasanický, Gustáv 415
Kohút, Pavol 415
Kolla, Eduard 404
Kompan, Jaroslav 470
Kondratieva, Liliia 677
Kotenko, Viktoriia 606
Kravchenko, Kateryna 258
Kravchenko, Oleksandr 258
Krayushkina, Kateryna 175
Kubás, Jozef 162
Kuberskyi, Ihor 85
Kulbovskyi, Ivan 696
Kuranovič, Veslav 510

L
Lebedevas, Sergejus 104, 116, 152
Leśniewski, Tadeusz 268
Lytvynenko, Tetyana 576

M
Macurová, Ľudmila 404, 415
Macutkevičius, Andrius 375
Malekjafarian, Abdollah 737
Malūkas, Audrius 152
Martishevskij, Michail 726
Matijošius, Jonas 95, 144
Mazurenko, Roman 33
Medany, Aya 645
Meidutė-Kavaliauskienė, Ieva 528, 539, 548
Mejeras, Vilius 277
Melnikova, Oksana 327
Michalcova, Lenka 667
Mikalkėnas, Gediminas 135
Mishchenko, Roman 336
Molnár, Denis 208, 247, 518
Możdrzeń, Daria 556
Mykhalevych, Mykola 327
Myronenko, Viktor 438

N
Nagaraj, Pavithra 797
Navickienė, Olga 598
Nesterenko, Svitlana 586
Norkūnaitė, Dominyka 277

O
Ockasov, Oleksandr 726
Oliskevych, Myroslav 43
Ondruš, Ján 404
Overianova, Liliia 677

P
Pálková, Adriana 627
Parczewski, Krzysztof 12
Pasaulis, Tomas 300
Patrosz, Piotr 287, 365, 383, 393
Paulauskiene, Tatjana 556
Pavelko, Vitalis 797
Pečeliūnas, Robertas 300
Petraška, Artūras 479
Petrenko, Viačeslav 726
Petri, Ioan 59
Petryk, Anatoliy 449
Podhorský, Ján 404
Polishchuk, Leonid 200
Pomykala, Agata 716
Potoglou, Dimitris 59
Pozdniakov, Andrii 438
Prentkovskis, Olegas 806
Pronin, Sergii 23
Pukalskas, Saugirdas 135

R
Radvilaitė, Urtė 144
Rapalis, Paulius 77
Rayapureddy, Sai Manoj 95
Rehak, David 737
Riabov, Ievgen 677
Rimkus, Alfredas 135, 144
Rimša, Vytautas 782
Rodchenko, Oleksandr 806

Rolenec, Ota 491
Rybicka, Iwona 258

S
Saiapina, Inna 696
Samsonkin, Valery 438
Selivanova, Alla 556
Shariy, Grygoriy 586
Shchepak, Vira 586
Shevchenko, Anna 336
Shkilniuk, Iryna 85
Shuba, Yevhenii 144
Shulhin, Volodymyr 354
Šilas, Giedrius 77
Skačkauskas, Paulius 277
Skrypchenko, Oleksandra 175
Šlajus, Šarūnas 566
Slivkova, Simona 667
Śliwiński, Paweł 268, 287, 383, 393
Šmídová, Pavla 746
Smolskas, Tomas 309
Šohajek, Petr 746
Sokolova, Olena 773
Sorochuk, Nataliia 576
Soušek, Radovan 746
Stankiewicz, Sara 556
Staputis, Airidas 224
Štefancová, Vladimíra 125, 627
Steišūnas, Stasys 689
Stembalski, Marek 236, 344
Stepanchuk, Oleksandr 806
Stetsyk, Oleksii 33
Stosiak, Michał 189, 268, 287
Šukevičius, Šarūnas 287
Šustr, Martin 746
Syrota, Oleksandr 144
Szydłowski, Tomasz 236, 344

T
Terenchuk, Svitlana 3
Tetiana, Litus 449
Tkachenko, Iryna 576
Towarnicki, Krzysztof 189, 268
Trifonov, Dmitrij 144
Tsyrulnyk, Oleksandr 200

U
Ugnenko, Evgeniya 586
Urbanowicz, Kamil 189, 268, 287
Uzhviieva, Elena 354

V
Vaičiūnas, Gediminas 689, 706
Vaičius, Ernestas 655
Vaičiūtė, Kristina 634, 655
Vasiliauskas, Aidas Vasilis 548, 598
Volodarets, Mykyta 23

Y
Yakovlieva, Anna 85
Yatskiv, Irina 634
Yeremenko, Bohdan 33
Yerko, Yaroslav 449
Yurchenko, Oksana 438
Yurzhenko, Alona 23

Z
Zábovská, Katarína 162
Załuski, Paweł 365, 383, 393
Žemaitytė, Gabrielė 479, 502
Zigo, Andrej 258
Žuraulis, Vidas 224
Zvirko, Olha 200