



VILNIUS GEDIMINAS TECHNICAL UNIVERSITY
FACULTY OF ENVIRONMENTAL ENGINEERING
DEPARTMENT OF ENVIRONMENTAL PROTECTION

Tomas Astrauskas

**EVALUATION AND ANALYSIS OF TRAFFIC CALMING MEASURES
INFLUENCE TO VIBRATION SPREAD IN ENVIRONMENT
VERTIKALIŲJŲ TRANSPORTO GREIČIO MAŽINIMO PRIEMONIŲ
ĮTAKOS KELIAMAI VIBRACIJAI APLINKOJE TYRIMAI BEI VERTINIMAS**

Master's degree thesis

Environmental protection technology and management, state code 621H17003

Study field of General Engineering

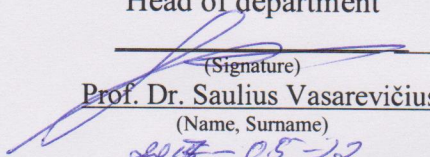
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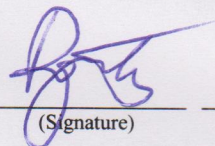
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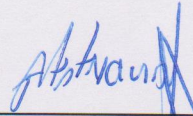
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Mano darbo vadovas doc. dr. Raimondas Grubliauskas.

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2015-09-30

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TASK FOR MASTER THESIS

17 03 2017 No.

Vilnius

For student Tomas Astrauskas
(Name, Surname)

Master Thesis title: EVALUATION AND ANALYSIS OF TRAFFIC CALMING MEASURES
INFLUENCE TO VIBRATION SPREAD IN ENVIRONMENT

Approved on 17 of March 2017 by Dean's decree No. 83ap.

The Final work has to be completed by 22 of May 2017

THE TASK OF MASTER THESIS:

Aim: Evaluate the impact to traffic induced vibrations when vehicles crossing traffic calming
measures using measurement data and modelling.

Tasks:

- Create the methodology of traffic induced vibrations crossing traffic calming measures evaluation.
- Evaluate soil freezing impact to the traffic induced ground borne vibrations
- Evaluate distance of vibration spreading induced by traffic crossing vertical calming measures.
- Evaluate the difference of vibration acceleration values depending on type of road transport

Academic Supervisor
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Task accepted as a guidance for my Master Thesis

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Master Degree Studies **Environmental Protection Technology and Management** study programme Master Graduation Thesis 4
(Environmental Management and Clean Production)

Title	Evaluation and Analysis of Traffic Calming Measures Influence to Vibration Spread in Environment
Author	Tomas Astrauskas
Academic supervisor	Raimondas Grubliauskas

Thesis language: English

Annotation

The final Master 's thesis analyses the vertical traffic calming measure impact to the traffic induced ground-borne vibration. Season change is taken into account. Aim of thesis is to evaluate the impact to traffic induced vibrations when vehicles crossing traffic calming measures using measurement data and modelling.

In the first chapter of thesis analysed spread properties of ground borne vibration, possible impacts of ground borne vibration to human and buildings. In the second chapter methodology of experimental research, equipment and measurement sites is described. In the third chapter of this master thesis results of experimental research, conclusions and recommendations are presented. In the fourth chapter of thesis modelling methodology and results are presented. In the end of the final Master's thesis conclusions, references and list of author's publications are presented.

Thesis consists of 8 main parts: introduction, literature review, description of experimental research, analysis of experimental research results, methodology of modelling and results analysis, conclusions, references, list of author's publications.

Volume of the thesis: 158 pages without appendices, 186 figures, 17 tables, 75 references

Keywords: Traffic calming measures, speed table, traffic induced vibration, ground-borne vibration

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Antrosios pakopos studijų **Aplinkos apsaugos technologijų ir vadybos** programos magistro baigiamasis darbas 4 (aplinkos apsaugos vadyba ir švarioji gamyba)

Pavadinimas **Vertikaliųjų transporto greičio mažinimo priemonių įtakos keliamai vibracijai aplinkoje tyrimai bei vertinimas**
Autorius **Tomas Astrauskas**
Vadovas **Raimondas Grubliauskas**

Kalba: anglų

Anotacija

Baigiamajame magistro darbe yra nagrinėjama trapecinių autotransporto greičio mažinimo priemonių įtaka automobilių transporto sukeliamoms žemės vibracijoms įvertinant sezoniskumą. Darbo tikslas – įvertinti automobilių transporto važiuojančių per iškiliąsias greičio mažinimo priemones įtaką automobilių sukeliamoms žemės vibracijoms remiantis tyrimų ir modeliavimo duomenimis.

Pirmajame skyriuje nagrinėjama automobilių transporto sukeliamos žemės vibracijos sklaidos įpatybės, galimi vibracijos padariniai žmogui ir statiniams. Taip pat apžvelgtos modeliavimo programos naudojamos šioje srityje. Antrame skyriuje pateikta automobilių sukeliamos žemės vibracijos tyrimų metodika, aprašyta naudojama įranga, pasirinktos tyrimų vietos. Trečiajame skyriuje pateikti automobilių sukeliamos žemės vibracijos tyrimų rezultatai, išvados, rekomendacijos. Ketvirtajame skyriuje pateikiama modeliavimo metodika ir rezultatai. Baigiamojo darbo pabaigoje pateikiamos išvados, naudotos literatūros sąrašas, bei autoriaus publikacijų sąrašas.

Darbą sudaro 8 pagrindinės dalys: įvadas, literatūros apžvalga, tyrimų metodikos aprašymas, tyrimų rezultatų analizė, modeliavimo metodikos ir rezultatų analizė, išvados, literatūros sąrašas, autoriaus publikacijų sąrašas.

Darbo apimtis: 158 p. be priedų, 186 pav., 17 lentelių, 75 lit. Šaltiniai

Prasminiai žodžiai: Greičio mažinimo priemonės, trapecinė iškilioji greičio mažinimo priemonė, transporto sukeliamą vibraciją, žemę sklindanti vibracija

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Introduction

Transportation is the means to carry people and goods from one place to another. This has become very important in each stage of human civilization. If the present means of transportation were not developed, situation of the world would be totally different. In today's world, we use car every day. Ground traffic causes ground-borne vibrations. This impact could cause annoyance of residents who lives near streets or roads.

To reduce accidents in roads traffic calming measures were developed. Traffic calming is the combination of mainly physical measures that reduce the negative effects of motor vehicle use, alter driver behaviour and improve conditions for non-motorized street users (I. M. Lockwood, 1997). It is indicated that traffic calming could mean anything from lowering speeds to an all-encompassing transportation policy. To decrease the speed of vehicles in urban conditions, various types of road bumps can be used.

Problem description. Vertical traffic calming measures is often used in urban territories. When traffic crosses these measures, it might induce vibrations which could be not acceptable for residents or harm their property. Exposure to whole body vibration causes motions and forces within the human body that may cause discomfort, adversely affect performance, cause health effect or aggravate pre-existing conditions.

Actuality of thesis. Traffic induces vibrations. Vertical traffic calming measures is mostly being used in highly populated urban areas. It is important to know if these measures could increase traffic induced vibration. The longer a human is exposed to whole body vibration, the greater the risk of health effects. The most commonly reported that traffic and railway vibration could cause annoyance or stress or other psychic diseases.

Vibrations emitted from roads or railway tracks are mainly dominated by surface waves that might damage the foundation of nearby buildings, resulting in structural vibrations that may cause malfunctioning of sensitive equipment, discomfort to people and structural damage. (S. Francois et. Al., 2007).

Object of this thesis. The object of this master thesis is vibration induced by road transport crossing vertical traffic calming measures (speed tables).

Aim of this thesis.

Evaluate the impact to traffic induced vibrations spread into environment and buildings when vehicles crossing traffic calming measures using measurement data and modelling.

Tasks of this thesis.

1. Evaluate season change impact to the traffic induced ground borne vibrations.
2. Evaluate distance of vibration spreading induced by traffic crossing vertical calming measures.
3. Evaluate the difference of vibration acceleration values depending on type of road transport.
4. Evaluate soil impact on spread of ground-borne vibration using numerical modelling.

Practical value of this thesis.

Traffic induced vibration in buildings is a common source of nuisance affecting residents and under certain circumstances degrading the performance of precision measuring equipment. Traffic induced vibration crossing speed bumps became important just recently. It is important to know if these vibrations could affect resident normal life or health. After this research knowledge could be used for further investigations.

Novelty of the thesis

Novelty of this thesis consists of the fact that this is a complex research of traffic induced vibration spread in environment and buildings. The season change between warm and cold seasons is taken into account. In this master thesis model designed to calculate railway ground - borne vibration is adapted for road transport ground borne vibration modelling.

1. Traffic induced ground borne vibrations in environment

In this chapter will be reviewed the fundamentals of seismic waves, traffic induced vibrations propagation. Also types of traffic calming measures is presented, how vibrations can affect the health. What measures can be used to reduce the ground borne vibrations induced by traffic. Vibration of the air that can be heard by people is called sound. Sound that annoys is called noise. Vibration of materials other than air is called simply vibration.

1.1. Fundamentals of vibrations

Ground-borne vibration can be a serious concern for nearby neighbors of a transit system route or maintenance facility, causing buildings to shake and rumbling sounds to be heard. In contrast to airborne noise, ground-borne vibration is not a common environmental problem. It is unusual for vibration from sources such as buses and trucks to be perceptible, even in locations close to major roads. Some common sources of ground-borne vibration are trains, buses on rough roads, and construction activities such as blasting, pile-driving and operating heavy earth-moving equipment.

Seismic waves are elastic waves. Earth material must behave elastically to transmit them. The degree of elasticity determines how well they are transmitted. By the pressure front expanding from an underground explosion, or by an earthquake shear rupture, the surrounding Earth material is subjected to stress (compression, tension and/or shearing). As a consequence, it undergoes strain, i.e., it changes volume and/or distorts shape. In an inelastic (plastic, ductile) material this deformation remains while elastic behavior means that the material returns to its original volume and shape when the stress load is over.(Borman P., et. Al. 2012, Kramer, 1996.)

Elastic material resists differently to stress depending on the type of deformation. It can be quantified by various elastic moduli:

- The bulk modulus κ is defined as the ratio of the hydrostatic (homogeneous all-sides) pressure change to the resulting relative volume change, i.e., $\kappa = \Delta P / (\Delta V/V)$, which is a measure of the incompressibility of the material (Fig. 1.1 top); (Borman P., et. Al. 2012)
- The shear modulus μ (or “rigidity”) is a measure of the resistance of the material to shearing, i.e., to changing the shape and not the volume of the material. Its value is given by half of the ratio between the applied shear stress τ_{xy} (or tangential force ΔF divided by the area A over which the force is applied) and the resulting shear strain e_{xy} (or the shear displacement ΔL divided by the length L of the area acted upon by ΔF), that is $\mu = \tau_{xy}/2 e_{xy}$ or $\mu = (\Delta F/A) / (\Delta L/L)$ (Fig. 2.2

middle). For fluids $\mu = 0$, and for material of very strong resistance (i.e. $\Delta L \rightarrow 0$) $\mu \rightarrow \infty$; (Borman P., et. Al. 2012)

- The Young's modulus E (or “stretch modulus”) describes the behavior of a cylinder of length L that is pulled on both ends. Its value is given by the ratio between the extensional stress to the resulting extensional strain of the cylinder, i.e., $E = (F/A) / (\Delta L/L)$ (Fig. 1.1 bottom);
- The Poisson's ratio σ is the ratio between the lateral contraction (relative change of width W) of a cylinder being pulled on its ends to its relative longitudinal extension, i.e., $\sigma = (\Delta W/W) / (\Delta L/L)$ (Fig. 1.1 bottom). (Borman P., et. Al. 2012; Mott P. H. and Roland C. M. 2012.)

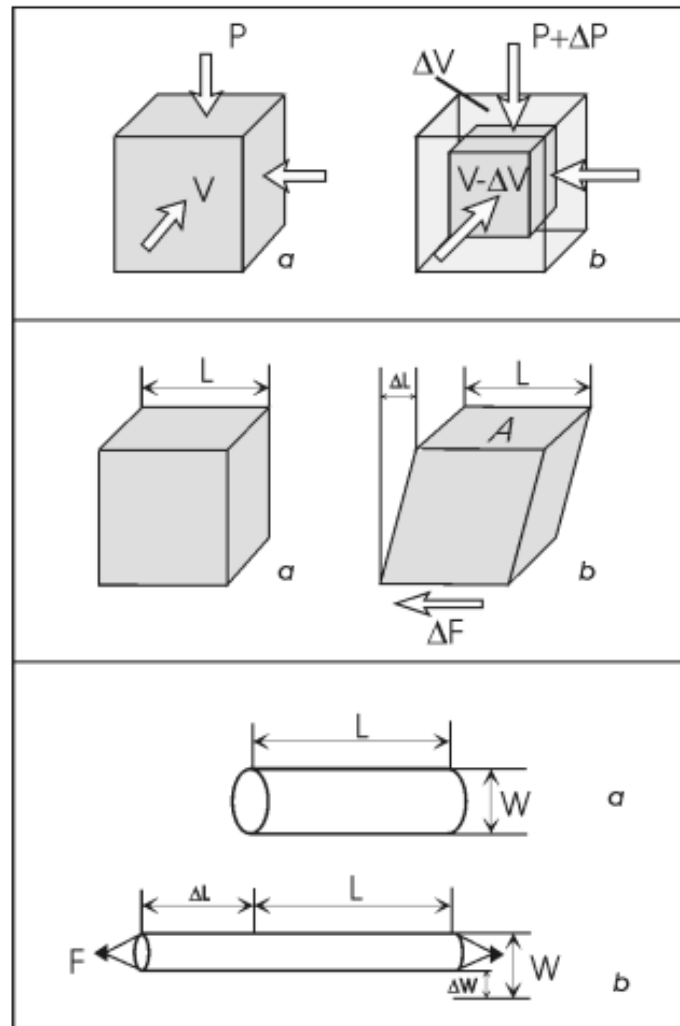


Fig. 1.1 Deformation of material samples for determining elastic moduli. Top: bulk modulus κ ; middle: shear modulus μ ; bottom: Young's modulus E and Poisson's ratio σ . A – original shape of the volume to be deformed; b – volume and/or shape after adding pressure ΔP to the volume V (top), shear force ΔF over the area A (middle) or stretching force F in the direction of the long axis of the bar (bottom). (Borman P., et. Al. 2012)

Shear waves (S waves) spread in the solid bodies and liquid bodies or gas bodies boundaries (for example on surface of ground) because of body shear deformations according the Hook Law. (Bogdanovičius A. 2006, Kramer, 1996., Massarsch, 2000):

$$C_s = \sqrt{\frac{G}{\rho}} = \sqrt{\frac{E}{2\rho(1-\sigma)}} \text{ (m/s)} \quad (1.1)$$

Here:

C – Wave velocity (m/s); G – Shear module (Pa); ρ – Density of body (kg/m³); E – elasticity module (MPa); ν – Poisson ratio (-).

Poisson ratio for different material is:

- Clay (0,35-0,45)
- Sand (0,2 – 0,45)
- Concrete (0,1 – 0,2)

Compressional waves (P waves) spread in gas, liquids and solid bodies because of compressions and dilatations towards the wave direction of propagation. (Bogdanovičius A. 2006) These waves are shown by the equation: (Möller *et al.*, 2000; Kramer, 1996.)

$$C_p = \sqrt{\frac{M}{\rho}} = \sqrt{\frac{G(2-2\nu)}{\rho(1-2\nu)}} = \sqrt{\frac{E(1-\nu)}{\rho(1-2\nu)(1+\sigma)}} \text{ (m/s)} \quad (1.2)$$

Here:

C – Wave velocity (m/s); M – deformation module or odometric deformation module (Pa); G – Shear module (Pa); ρ – Density of body (kg/m³); E – elasticity module (MPa); ν – Poisson ratio (-).

Vibration is an oscillatory rapidly fluctuating motion of a medium. The oscillatory motion causes particles to move in a retrograde ellipse. Because the motion is oscillatory, there is no net movement of the vibratory element. The oscillatory motion is propagated forward in a wave motion. The difference between the oscillatory particle motion and wave propagation is analogous to the difference between the bobbing of a cork on the surface of a body of water and spreading out of ripples on the water surface - the cork oscillates but does not move forward. These type of waves are called Rayleigh waves. (Hajek J.

J. et. Al. 2006). Rayleigh waves, also known as "ground roll", are the result of an incident P and SV plane waves interacting at the free surface and traveling parallel to that surface. Rayleigh waves travel along the surface with a retrograde elliptical particle motion and changing to prograde with depth passing through a node where there is no motion at all. (Murray T. W. et. Al. 1990)

$$\left(2 - \frac{c^2}{\beta^2}\right) = 4 \left(1 - \frac{c^2}{\alpha^2}\right)^{1/2} \left(1 - \frac{c^2}{\beta^2}\right)^{1/2} \quad (1.4)$$

Here:

C – phase velocity; α – P – wave velocity; β – S – wave velocity

The Love wave is a result of the interference of many shear waves (S–waves) guided by an elastic layer, which is welded to an elastic half space on one side while bordering a vacuum on the other side. In seismology, Love waves (also known as Q waves) are surface seismic waves that cause horizontal shifting of the Earth during an earthquake. (Aster R. 2011)

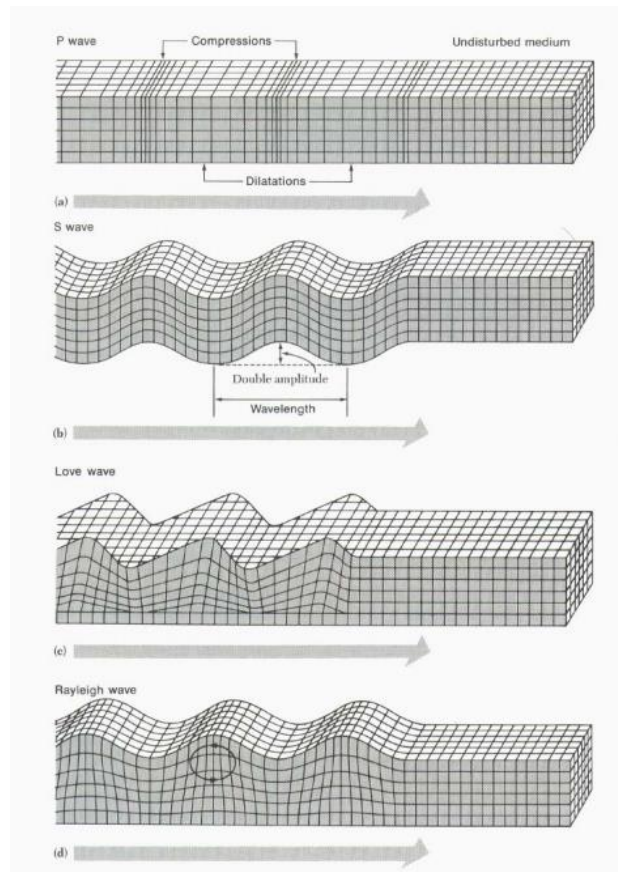


Fig. 1.2 Examples of the wave spread in the soil. (a) P – wave, (b) S –wave, (c) Love wave, (d) Rayleigh wave (Aster R. 2011)

A complete description of the vibratory motion at a point requires six variables corresponding to three directional components and three rotational components. Any of these six variables can be characterized by amplitude (maximum displacement), or by velocity (the instantaneous speed of the movement), or by acceleration (the rate at which the speed changes). For practical purposes for assessing traffic induced vibration, it is sufficient to use only one predominant component of the vibratory motion. The selected component is the directional vertical component which is typically characterized or measured in terms of the vibration velocity. The vibration velocity is defined as the peak particle velocity (PPV) of vibratory motion (corresponding to the maximum instantaneous positive or negative vibration velocity), or as a root mean square of the peak velocity. (Brown P. 2005)

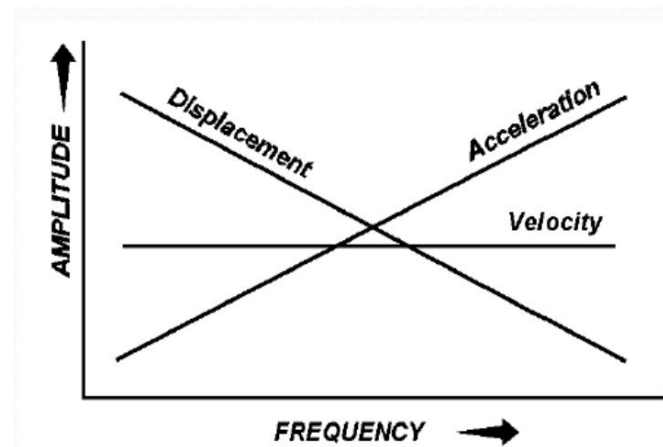


Fig. 1.3 Relation between vibration velocity, acceleration and displacement. (Brown P. 2005)

For sinusoidal signals, displacement, velocity and acceleration amplitudes are related mathematically by a function of frequency and time.

Table 1.1 Equations for Sinusoidal Motion Displacement (D), Velocity (V), Acceleration (A), and Frequency (f)

	A, f[Hz]	V, f[Hz]	D, f[Hz]
Acceleration, A =	—	$2\pi f V$	$(2\pi f)^2 D$
Velocity, V =	$1/(2\pi f) A$	—	$2\pi f D$
Displacement, X =	$1/(2\pi f)^2 A$	$1/(2\pi f) V$	—

If phase is neglected, as is always the case when making time-average measurements, then the velocity level can be obtained by dividing the acceleration signal by a factor proportional to frequency,

and the displacement can be obtained by dividing the acceleration signal by a factor proportional to the square of frequency.(Brüel & Kjær).

1.2. Traffic induced vibrations.

In accordance with functioning direction vibration is divided in three axis x,y and z. X axis is horizontal axis which should be directed parallel with vibration source (road). Y axis is horizontal axis which should be directed to cross linear vibration source. Z – vertical axis which is directed vertically. If whole body vibration is measured x axis should be from back to chest, y – from right shoulder to left shoulder, z- from foot to head. Axis direction while measuring whole body vibration is shown in figure 1.4.

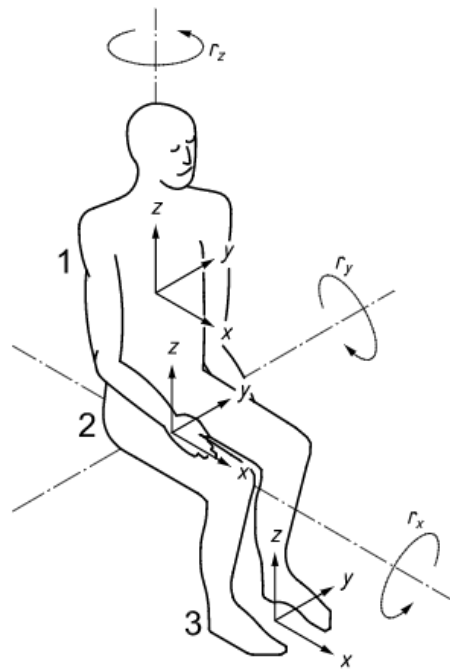


Fig. 1.4 Axis directions while measuring whole body vibration (HN 50:2003)

There are two ways in which road traffic can induce vibration in nearby buildings:

- Ground-borne vibration caused by the dynamic impact forces of tires on the pavement surface that can propagate and excite footings and foundation walls below ground.

Vibration of footings and foundation walls can induce vibration in other building components below or above ground.

- Air-borne vibration caused by low frequency sound that can excite building components above ground. Air-borne vibrations could be called sound.(Hajek J. J. et. Al. 2006)

These two types of vibrations can be caused by the passage of the same vehicle at the same time.

Ground-borne vibration is caused by the interaction between the dynamic forces produced by tires of highway vehicles and pavement surface irregularities. (Hunaidi O, Rainer J. H. 1995)

Pavement surface irregularities can be classified as random pavement surface irregularities or as specific pavement surface irregularities.

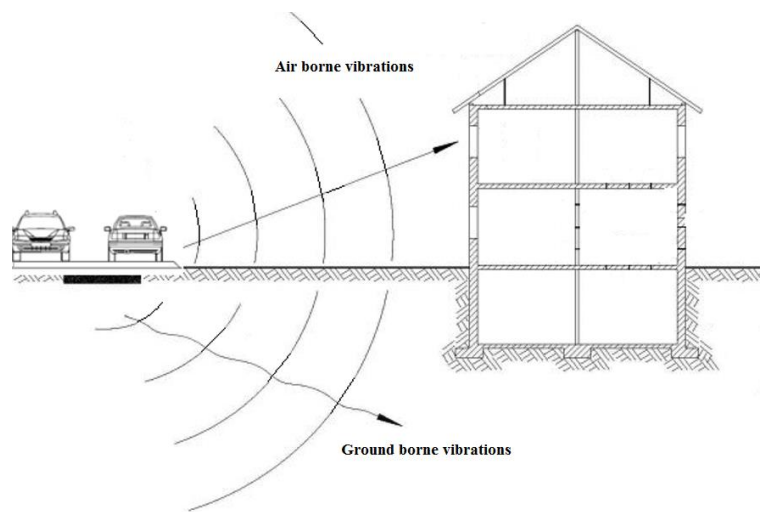


Fig. 1.5 Types of traffic induced vibrations

Random pavement surface irregularities exist on all pavements and are typically characterized by measures of pavement smoothness or roughness such as the International Roughness Index (IRI). Typically, random surface irregularities can result in randomly occurring dynamic forces that are up to 15 percent higher than the corresponding static forces. The impact of these dynamic forces on pavements results in randomly occurring ground-borne vibration. Although random ground-borne vibration is always present (the pavement is never completely smooth and highway vehicles are never completely dynamically inert), it is too low to be perceived even by observers very close to the source. (Hajek J. J. et. Al. 2006)

Specific pavement surface irregularities, such as potholes and stepped transverse cracks, can significantly increase the force of the tire striking the pavement. Compared to the static force, the dynamic force may be up to 50 to 80 percent higher. The higher dynamic forces result in proportionately

higher ground borne vibration. Consequently, main generators of highway traffic induced vibration are specific surface irregularities. (Hajek J. J. et. Al. 2006)

Air-borne vibration is caused by low frequency sound, produced by engines and exhaust systems of large diesel trucks, which can excite building components above ground. The fundamental frequency of truck exhaust systems (engine combustion and firing) is typically 50 to 200 Hz, and this frequency may correspond to the fundamental frequency of light building components. Consequently, the variation in sound pressure (or vibration of the air) that impinges on the building components can result in excitation or vibration of these components. The key to the generation of air-borne vibration is resonance – repeated excitation of building components and other elements at their fundamental frequency. Light flexible elements of a structure, such as window panes and door panels, may start to vibrate independently of other elements when resonance is achieved. The result may be, for example, an audible rattle of loose windows. (Lefebvre J.P., 1999)

The main factors influencing traffic induced vibration are shown in Figure 1.6. These factors include the source of vibration, transmission path, and the receiver.

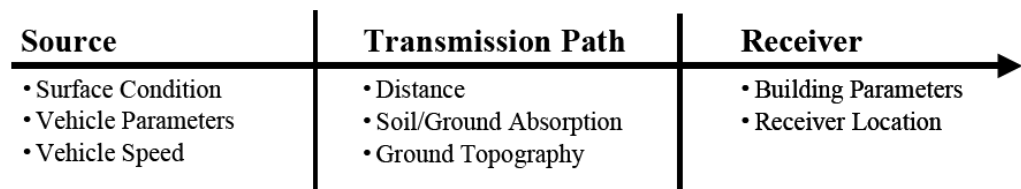


Fig. 1.6 Main variables influencing traffic induced vibration (Hajek J. J. et. Al. 2006)

The condition of the pavement surface is the decisive contributor to ground-borne vibration. It is also the most significant factor that can be controlled by highway agencies. Discrete pavement discontinuities, such as stepped transverse cracks exceeding about 4 mm, appear to be significant enough to overshadow the effect of random surface roughness and result in specific sources of vibration. Potholes or bumps, typically more than 25 mm in depth or height and about 150 mm long, are necessary to overshadow the effect of random pavement roughness. The different criteria for transverse cracks, compared to potholes, stem from the observation that transverse cracks are typically perpendicular to the direction of travel and affect all wheels of the axle simultaneously. Pavement discontinuities closest to the observer are of primary importance because ground-borne vibration decreases rapidly with distance from the source. (Hajek et. Al. 2006; Lak M.A. et. Al. 2001)

The propagation of traffic-induced vibration from the source depends on the distance from the receiver, frequency of vibration, topography between the source and the receiver, and on the soil and other geotechnical characteristics of the ground. Vibration propagates through the ground in the form of body waves (compression and shear waves), and in the form of surface or Rayleigh waves (Figure 1.7.).

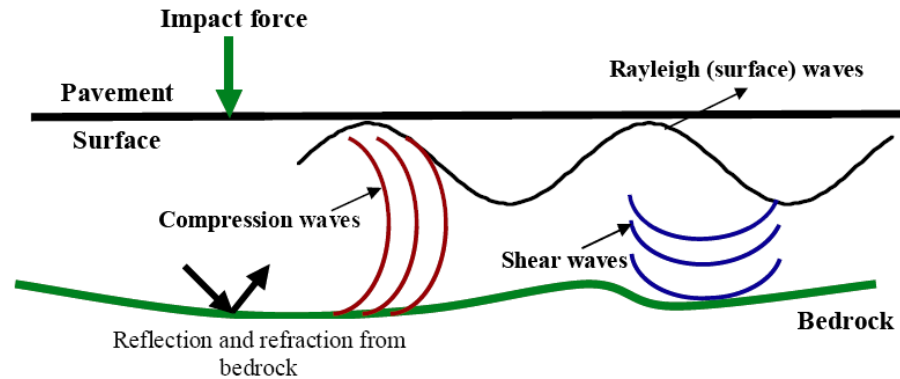


Fig. 1.7 Propagation of ground borne vibration (Hajek J. J. et. Al. 2006)

The Rayleigh waves are the most important form for the propagation of traffic induced vibration because at the ground level the amplitude of the Rayleigh waves decreases (due to geometric spreading) as the inverse of the square root of the distance from the source, while the amplitude of body waves decrease as the inverse of the square of the distance from the source (Hajek J. J. et. Al. 2006).

Vibrations induced by road traffic are a common concern in cities worldwide. House owners may complain about annoyance and building damage. There may be concern about the possibility of adverse long-term effects of vibrations on historic buildings, especially those in a weak condition. Vibrations may also interfere with sensitive processes, such as those in hospital operating theatres, scientific research laboratories and high-tech industries.

Like most vibration problems, traffic vibrations can be characterized by a source-path receiver scenario (Figure 1.9). Vehicle contact with irregularities in the road surface (e.g., potholes, cracks and uneven manhole covers) induces dynamic loads on the pavement (Hunaidi, 2000).

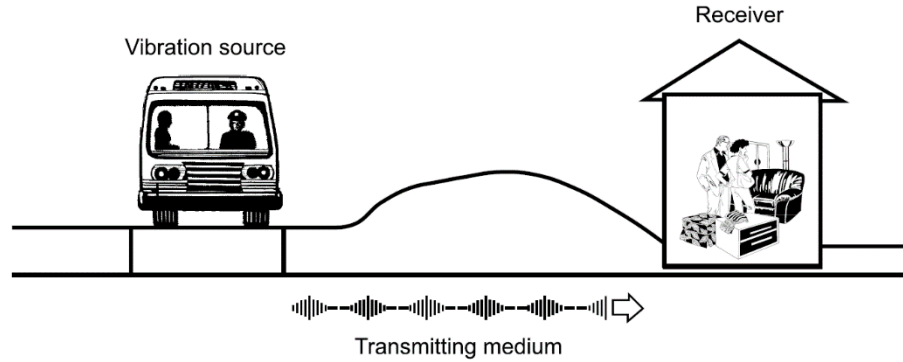


Fig. 1.8 Traffic vibrations can be characterized by a source path-receiver scenario.(Hunaidi, 2000)

These loads generate stress waves, which propagate in the soil, eventually reaching the foundations of adjacent buildings and causing them to vibrate. Traffic vibrations are mainly caused by heavy vehicles such as buses and trucks. Passenger cars and light trucks rarely induce vibrations that are perceptible in buildings.

Ground-borne vibration transmitted through the ground to foundation footings or foundation walls can spread to other parts of the building. The amount of vibration experienced by an observer depends on building parameters and on the location of the observer in the building. Typically, the vibration of floors or walls above ground is larger than vibration of basement walls. For example, the results of measurements reported indicate that vibration of floors can be significantly higher than the corresponding vertical vibration at foundations. Measurements carried out on one-and two-story buildings indicate that vibrations increase with height above ground. The increase of vibrations with building height may not apply above a certain building height above the ground. (Hunaidi, 2000)

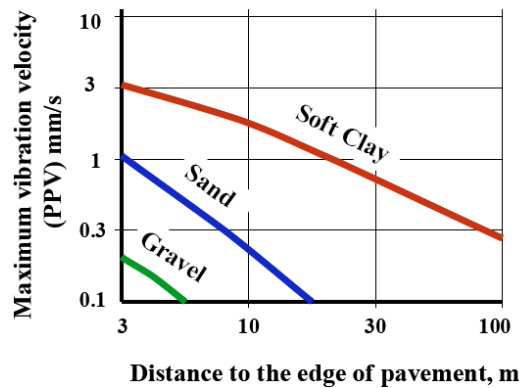


Fig. 1.9 Effect of soil type on the propagation of vibration (Hajek J. J. et. Al. 2006)

When a bus or a truck strikes an irregularity in the road surface, it generates an impact load and an oscillating load due to the subsequent “axle hop” of the vehicle. The impact load generates ground vibrations that are predominant at the natural vibration frequencies of the soil whereas the axle hop generates vibrations at the hop frequency (a characteristic of the vehicle’s suspension system). If the natural frequencies of the soil coincide with any of the natural frequencies of the building structure or its components, resonance occurs and vibrations will be amplified.

In contrast to irregularities such as manhole covers or potholes, normal road surface roughness induces continuous dynamic loads on the road. If the road surface roughness includes a harmonic component that, at the posted speed, leads to a forcing frequency that coincides with any of the natural frequencies of the vehicle and/or those of the soil, substantial vibration may be induced.

The effect of vehicle speed, for instance, depends on the roughness of the road. Generally, the rougher the road, the more speed affects the vibration amplitude. The effect of the suspension system type also depends on vehicle speed and road roughness (Hunaidi O. 2000).

1.3. Vibration legal regulations.

1.3.1. Vibrations regulation in Lithuania.

The vibration limits and main requirements for measuring it in Lithuania is stated in HN 50:2003 “The whole body affecting vibration: largest allowed values and measuring requirements in residential and public buildings”. In this Lithuanian hygiene norm is stated main notions what the vibration is, whole body vibration, steady vibration, a variable vibration, impulsive vibration and other. This hygiene norm is obligatory for all individuals and legal persons who is building, controlling and monitoring the residential or commercial buildings. In this hygiene norm are stated main parameters definitions of the whole body vibration. According the HN 50:2003 vibration is measures in 1/3 octave band, if measurements are taken during day time (from 7 AM to 11 PM) allowed vibrations are increased by 1.8 times (5 dB). If vibration is changeable (case of traffic vibration) allowed vibration is reduced by 3,15 times (10 dB). If vibrations are measured from building site nearby allowed vibration is increased by 3,15 times (10 dB)

In HN 50:2003 it is described how whole body vibration should be measured. Whole body should be measured in x, y, z axis (shown in 1.2. chapter). The vibration in measured on plate with 3 support point which is put on the ground.

Table 1.2 Maximum allowed whole body vibration values and levels according HN 50:2003

1/3 octave band average geometrical frequency, Hz	Maximum allowed vibration acceleration value a_{vkr} , m/s ²			Maximum allowed vibration acceleration level $L_{a,}$ dB		
	Z axis	X and Y axis	the axle resultant	Z axis	X and Y axis	the axle resultant
1,00	$1,00 \cdot 10^{-2}$	$3,60 \cdot 10^{-3}$	$3,60 \cdot 10^{-3}$	80	71	71
1,25	$8,90 \cdot 10^{-3}$	$3,60 \cdot 10^{-3}$	$3,60 \cdot 10^{-3}$	79	71	71
1,60	$8,00 \cdot 10^{-3}$	$3,60 \cdot 10^{-3}$	$3,60 \cdot 10^{-3}$	78	71	71
2,00	$7,00 \cdot 10^{-3}$	$3,60 \cdot 10^{-3}$	$3,60 \cdot 10^{-3}$	77	71	71
2,50	$6,30 \cdot 10^{-3}$	$4,51 \cdot 10^{-3}$	$3,72 \cdot 10^{-3}$	76	73	71
3,15	$5,70 \cdot 10^{-3}$	$5,68 \cdot 10^{-3}$	$3,87 \cdot 10^{-3}$	75	75	72
4,00	$5,00 \cdot 10^{-3}$	$7,21 \cdot 10^{-3}$	$4,07 \cdot 10^{-3}$	74	77	72
5,00	$5,00 \cdot 10^{-3}$	$9,02 \cdot 10^{-3}$	$4,30 \cdot 10^{-3}$	74	79	73
6,30	$5,00 \cdot 10^{-3}$	$1,14 \cdot 10^{-2}$	$4,60 \cdot 10^{-3}$	74	81	73
8,00	$5,00 \cdot 10^{-3}$	$1,44 \cdot 10^{-2}$	$5,00 \cdot 10^{-3}$	74	83	74
10,00	$6,30 \cdot 10^{-3}$	$1,80 \cdot 10^{-2}$	$6,30 \cdot 10^{-3}$	76	85	76
12,50	$7,81 \cdot 10^{-3}$	$2,25 \cdot 10^{-2}$	$7,80 \cdot 10^{-3}$	78	87	78
16,00	$1,00 \cdot 10^{-2}$	$2,89 \cdot 10^{-2}$	$1,00 \cdot 10^{-2}$	80	89	80
20,00	$1,25 \cdot 10^{-2}$	$3,61 \cdot 10^{-2}$	$1,25 \cdot 10^{-2}$	82	91	82
25,00	$1,56 \cdot 10^{-2}$	$4,51 \cdot 10^{-2}$	$1,56 \cdot 10^{-2}$	84	93	84
31,50	$1,97 \cdot 10^{-2}$	$5,68 \cdot 10^{-2}$	$1,97 \cdot 10^{-2}$	86	95	86
40,00	$2,50 \cdot 10^{-2}$	$7,21 \cdot 10^{-2}$	$2,50 \cdot 10^{-2}$	88	97	88
50,00	$3,13 \cdot 10^{-2}$	$9,02 \cdot 10^{-2}$	$3,13 \cdot 10^{-2}$	90	99	90
63,00	$3,94 \cdot 10^{-2}$	$1,14 \cdot 10^{-1}$	$3,94 \cdot 10^{-2}$	92	101	92
80,00	$5,00 \cdot 10^{-2}$	$1,44 \cdot 10^{-1}$	$5,00 \cdot 10^{-2}$	94	103	94
Corrected value and level	$5,00 \cdot 10^{-3}$	$3,60 \cdot 10^{-3}$	–	74	71	–

In this hygiene norm maximum allowed values is shown on 1/3 octave band average geometrical frequency from 1 Hz to 80 Hz. Lower frequency vibrations is more perceptible to human. Lowest value is allowed at 1 Hz frequency and maximum allowed vibration acceleration at frequency 80 Hz. Limit values of vibration acceleration is shown in the 1.2 table.

To protect workers from vibrations in Lithuania is another document prepared by Ministry of Social safety and work. This document called “Regulations of worker protection from vibration caused risks” regulated the hand – arm vibration and whole body vibration. In this document said that hand – arm vibration should be measured and calculated according LST EN ISO 5349-1:2002. The main parameter that is regulated in this document is vibration exposition within the work day. Per 8 hour work day exposition to the vibration must not exceed 5 m/s², whole body vibration must not exceed 1,15 m/s² per 8 hour workday.(Baltrėnas et. Al. 2008)

1.3.2. Vibration regulation in EU countries.

Protection against vibration nuisance in order to maintain satisfactory conditions during work, sleep, rest and recreation in buildings was specified in the European Directive on Construction Products and introduced in the Norwegian Building Regulations in 1997. As a qualified vibration measurement method was lacking, work with a new standard, NS 8176, was initiated (Klæboe et. Al. 2002). An empirical method for determination of statistical maximum velocity, $v_{w;95}$ or alternatively acceleration, $a_{w;95}$, was introduced. The vibration measure is obtained as the 95-percentile of maximum weighted vibration velocities (or acceleration) from a minimum number of representative road and rail traffic events. This Norwegian standard defines the statistical maximum weighted vibration velocity $v_{w;95}$ (or alternatively the statistical maximum weighted acceleration $a_{w;95}$) and describes the measurement procedure. (Turunen-Risea I.H. et. Al., 2003)

In Germany standard DIN 4150-3:1999 “Structural vibration - Effects of vibration on structures” threshold vibration levels are different in different purpose buildings. Commercial and industrial building are allowed to be exposed to higher vibrations. In this standard normative vibration parameter is Peak particle velocity (PPV). According this standard in Germany vibrations must be measured PPV of the foundation and floor of the highest storey of the building. This standard is concentrated on construction vibrations. The allowed vibrations of the foundation divided into 3 groups according the frequency:

- 1 – 10 Hz
- 10 – 50 Hz
- 50 – 100 Hz

Highest floor vibration norm is the same for all frequency bands. The maximum allowed vibrations for the different types of buildings is shown in table 1.3.

Table 1.3 Standard DIN 4150-3:1999 normative threshold levels.

Nr.	Type of building	Peak particle velocity (PPV) (mm/s)			
		Foundation			Highest storey floor
		1 – 10 Hz	10 – 50 Hz	50 – 100 Hz	1 – 100 Hz
1.	Commercial buildings, industrial buildings and other similar buildings	20	20 - 40	40 - 50	40
2.	Residential and other similar buildings	5	15 - 20	15 - 20	15
3.	Buildings which could not be chosen as 1 or 2 category because of sensitivity to	3	3 - 8	8 - 10	8

	vibration. (old, bad condition buildings)				
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In British standard BS7835-2: 1993 shown vibration threshold levels when it's possible cosmetic damage to the building. In this standard 2 types of building are considered:

- Industrial and large commercial buildings with reinforced framed structures
- Residential buildings and small commercial buildings with the light framed structures.

In standard BS7835-2: 1993 normative parameter is peak particle velocity (PPV). In table is shown threshold levels when cosmetic damage of the building could occur.

Table 1.4 Threshold levels when cosmetic damage of the building could occur, according BS7835-2: 1993

No.	Type of building	Peak particle velocity (PPV) (mm/s)	
		4 - 15Hz	15Hz and above
1	Industrial and large commercial buildings.	50 mm/s at 4 Hz and above	
	reinforced framed structures		
2	Residential buildings and small commercial buildings	15 mm/s at 4Hz increasing to 20 mm/s at 15Hz	20 mm/s at 15Hz 50 mm/s at 40Hz and above
	light framed structures		

In figure 1.11 and in the table we can see that reinforced structures can tolerate same vibration in all frequencies but unreinforced structures cannot. Higher the frequency, building have higher tolerance to the vibration.

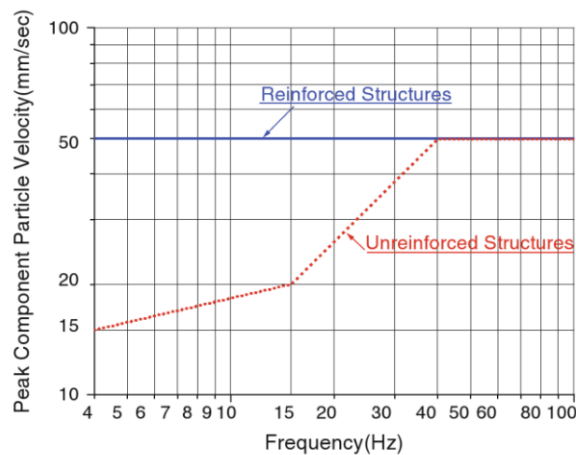


Fig. 1.10 Threshold levels according the standard BS7835-2: 1993

Other standards for evaluating human response to vibration levels:

- ISO 2631/2 (1989), International Organization for Standardization
- ISO 8041 (1990), International Organization for Standardization
- BS 6472 (1984), British Standards Institution

Other standards evaluating the potential for building damage:

- ISO 4866 (1990), Mechanical vibration and shock - Vibration of fixed structures - Guidelines for the measurement of vibrations and evaluation of their effects on structures.

1.4. Vertical traffic calming engineering measures

Traffic calming is the combination of mainly physical measures that reduce the negative effects of motor vehicle use, alter driver behaviour and improve conditions for non-motorized street users.(I. M. Lockwood, 1997)

It is indicated that traffic calming could mean anything from lowering speeds to an all-encompassing transportation policy.

To decrease the speed of vehicles in urban conditions, various types of road bumps can be used.

These measures require the vehicle to slow before the bump and usually its speed increases after the bump, adding an accelerating engine to the noise sources. (N. Elioy, et. Al.)

Vertical Speed Control Measures are vertical elevated segments of roadway that require a vehicle to slow. Typical vertical speed control measures include speed humps, speed tables, raised sidewalks and raised intersections.

The traffic calming measures normally is organized into six types: Non-Physical Measures, Volume Control Measures, Vertical Speed Control Measures, Horizontal Speed Control Measures, Narrowing Measures, and Combined Measures. In this master thesis only vertical speed control measures will be discussed.

Traffic calming measures can be implemented whenever the authority with jurisdiction over the road or street believes that they are necessary and appropriate to the situation. This can be on roads under municipal jurisdiction. However, the function and design of vertical traffic calming measures makes them more appropriate for relatively low speed roads than for roads with higher speed limits. Since the majority of state highways typically carry traffic moving at speeds over 50 kilometres per hour, they are not usually considered appropriate for highways. But municipalities have many more residential style streets for which they may be useful as way of further calming traffic. (Fazzalero J. J., 2006)

1.4.1. Speed Hump

A speed hump is a raised rounded device usually constructed from asphalt that is placed across a roadway. Speed humps are usually 76 to 101 millimetres in height and are parabolic in shape. They extend fully across the roadway but are tapered on each side to allow unimpeded water flow in curb and gutter system. The design speed for a speed hump is approximately 24-40 kMph. (Seidel W. 2007)



Fig. 1.11 Typical speed hump (City of Tshwane, <https://brentwood-tn.org>)

Table 1.5 Advantages and disadvantages of speed hump. (Seidel W., 2007)

Advantages	Disadvantages
Relatively inexpensive	Causes a rough ride for drivers
Relatively easy for bicyclists to cross at taper if designed properly	Slows and may damage emergency vehicles
Very effective at slowing travel speed	Increase noise and air pollution
	Poor aesthetics

In table 1.5. it is shown advantages and disadvantages of such traffic calming measure. Biggest advantage is effectiveness of speed reduction, but in the other hand it increases air and noise pollution created by cars.

1.4.2. Speed table

A speed table is a raised flat-topped device, which is placed across the roadway. Speed tables are usually 76 to 101 millimetres in height. The flat-top is approximately 3 metres in the direction of travel and each ramp is 1,8 metres. The flat-top is usually constructed of asphalt, concrete, brick, or other textured materials. The ramps are parabolic in shape and are usually made of asphalt. Speed tables extend fully across the roadway but are tapered on each side to allow unimpeded water flow in curb and gutter system. The design speed for a speed table is approximately 30 kMph, which is a safe and comfortable speed for passenger vehicles. (Seidel W. 2007)

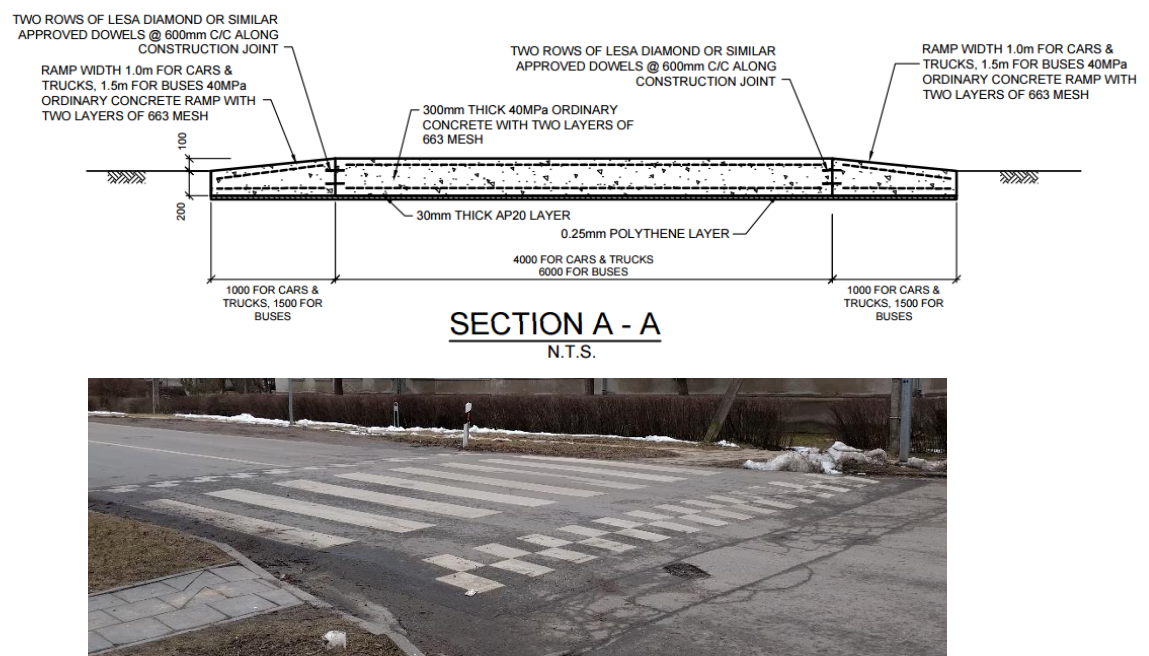


Fig. 1.12 speed table (author's picture)

Table 1.6 Advantages and disadvantages of speed table. (Seidel W. 2007)

Advantages	Disadvantages
Relatively inexpensive	Poor aesthetics if no textured material are used
Smoother on large vehicles than speed humps	Some textured materials can be expensive
Effective at slowing travel speed	Increase noise
	Slows and may damage emergency vehicles

In table 1.6 is shown advantages and disadvantages of such traffic calming measure. Biggest advantage is effectiveness of speed reduction, but in the other hand it increases noise pollution created by vehicles.

1.4.3. Speed bump

A speed bump is generally designed as a rounded, raised pavement structure usually from 0,05 to 0,15 m high. It usually is designed to be from 0,3 to 0,9 m “long” (from the front of the bump to the back). A speed bump may be as 0,3 m “wide” (from one side to the other) or as much as 3 m wide, depending on the intent of the measure and the nature of the road to which it is being applied. Their design generally dictates comfortable crossing speeds of 8 kilometres per hour or less so they are usually appropriate only for use where vehicle speeds are typically the lowest to begin with such as parking lots, private roads, and on some residential streets. The peak vertical acceleration, and thus the occupant discomfort associated with this, are greatest at relatively low speeds and decrease as the speed at which the vehicle encounters the bump increases.

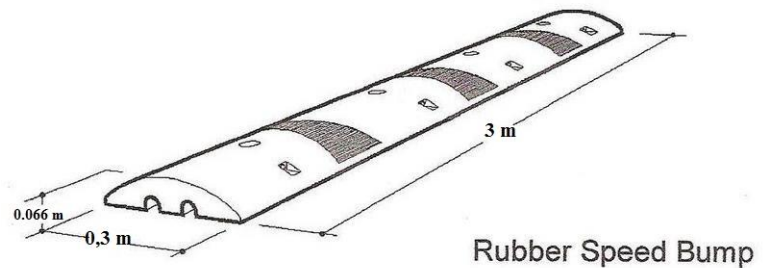


Fig. 1.13 Speed bump (<http://www.secure-lane.com/>)

This is because the vehicle's suspension tends to absorb the vertical forces before the vehicle body has time to react. This is why bumps are used where traffic is already going at a relatively slow speed. (J. J. Fazzalaro, 2006).

Table 1.7 Advantages and disadvantages of speed table. (Fazzalaro J. J., 2006)

Advantages	Disadvantages
Relatively inexpensive	Poor aesthetics
Effective at slowing travel speed	Increase noise
	Slows and may damage emergency vehicles
	Causes a rough ride for drivers

1.4.4. Speed cushion

Speed cushions have been used in Europe. A speed cushion is a raised area on a road, similar to a speed hump, but which does not cover the entire width of the road. Speed cushions are usually configured two or three across depending on the width of the road. The width of each cushion is designed intentionally so that the wider axle of emergency vehicles can pass unaffected but that smaller passenger vehicles must ride over the raised area. This configuration addresses one of the main concerns with speed humps: the fact that emergency vehicles are also forced to slow down.(Berthod C. 2011)

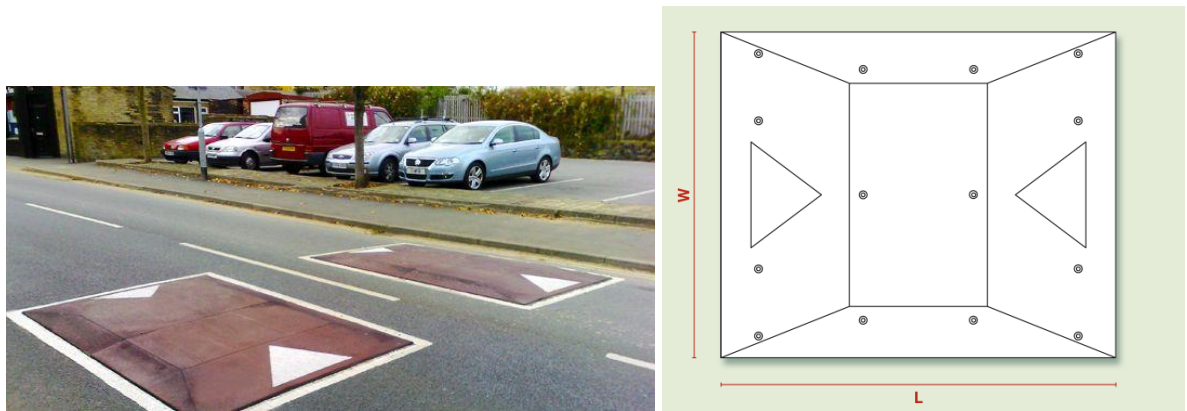


Fig. 1.14 Speed cushion (<http://www.rosehillhighways.com>)

Table 1.8 Advantages and disadvantages of speed table. (Berthod C. 2011)

Advantages	Disadvantages
Relatively inexpensive	Poor aesthetics if no textured material are used
Smoother on large vehicles than speed humps	Some textured materials can be expensive
Effective at slowing travel speed	Increase noise
Do not slow down emergency vehicles	

In the table 1.8 is shown advantages and disadvantages of speed cushion. The main advantage of this vertical traffic calming measure design that it do not slow down ambulances and fire trucks.

1.5. Traffic induced vibrations crossing vertical traffic calming engineering measures.

Ground-borne vibrations are produced when vehicles pass over these profiles and in some cases they can reach perceptible levels in adjacent buildings. G.R. Watts and V.V. Krylov took measurements of peak particle velocity alongside a selection of hump and cushion designs using a range of vehicles under controlled driving conditions. Ground-borne vibrations are generally perceptible in situations where the road surface is uneven and buildings are situated close to the road. Road humps and cushions

can therefore be a potential source of this type of vibration. The frequencies of these vibrations are generally in the range 8 ± 16 Hz and result from the "wheel hop" mode of vibration of the vehicle's suspension, i.e. the oscillation of the axle and wheel between the tire and suspension. Both compression and shear waves are produced in the ground and their amplitudes and attenuation with distance depend critically on the soil composition. These short duration or impulsive ground-borne vibrations, rather than those produced by airborne sound waves, often produce the highest peak particle velocities (PPVs) in the hard structure of the building (Watts G.R. et. Al., 2000)

Figure 1.16. Shows the layout of the test site. An array of three geophones was mounted firmly on the surface of the test track alongside the test profile to detect vibrations along three orthogonal axes (vertical, radial and transverse). The mounting position was in line with the centre of the profile at a distance of 6 m from the nearside wheel track. The geophones were connected to a multi-channel signal processor, which digitised the input signals at a sampling rate of 1 kHz. This device was connected to a portable computer, which scaled and recorded the digitised particle velocity signal.

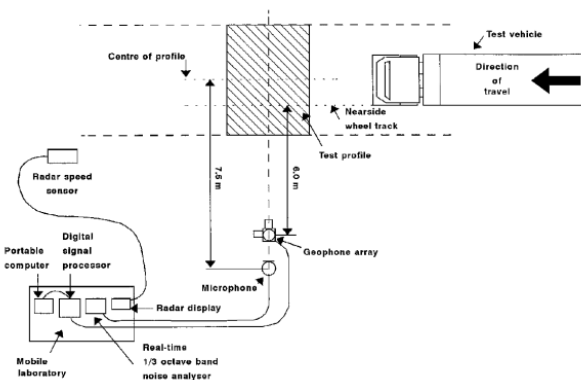


Fig. 1.15 Layout of test site and measurement equipment (Watts G.R. et. Al., 2000)

Following each drive-by, the maximum velocity amplitude (PPV) value in each axis was recorded. Vehicle road speed was monitored using a radar speed meter. At least two measurements were taken for each drive-by condition.

Generally the highest levels of vibration were produced by the heaviest vehicles. Considering all profiles the maximum and mean PPVs for vehicles over 7.5 tonne were 0.51 and 0.25 mm/s, respectively, while for vehicles less than 7.5 tonne the corresponding levels were 0.23 and 0.1 mm/s. (G.R. Watts et. Al., 2000).

Fig. 1.16. shows the trends for the heaviest articulated vehicle DAF95 350 ATI (Leyland), with their suspension system, its weight during tests was 32,2 tonnes.

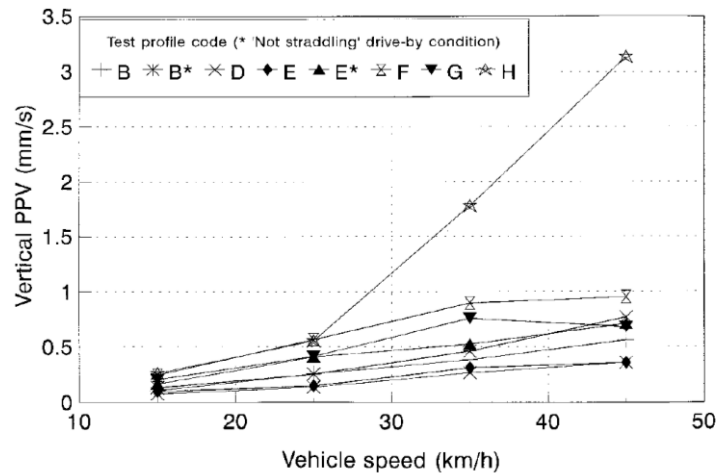


Fig. 1.16 Measured vertical peak particle velocity using DAF95 350 ATI (Leyland). Truck crossing different vertical traffic calming measures. B, C, D, E – speed cushions, F, G, H – speed humps(Watts G.R. et. Al., 2000)

The highest peak particle velocity noticed when truck was crossing speed cushion at speed 45 km/h. The results of this study show that speed control cushions and road humps can produce perceptible levels of ground-borne vibration. This can lead to complaints under the most severe conditions and anxieties concerning building damage. However, even under these worst case conditions it is very unlikely that the introduction of the profiles pose a significant risk of even minor damage to property(G.R. Watts et. Al., 2000).

It is not generally possible to find a strong correlation between the vibration level and the speed of transit of the vehicles in a real transport flow. This may be due to the fact that the dynamic overload does not always increase with vehicle speed as this modifies the way the road profile is “read” by the vehicle i.e. the frequency content of the vehicle base motion; in addition, the relationship is rather scattered since the inertial and mechanical parameters of the vehicles may vary, as well as the path followed by the wheels (Crispino M. and D'apuzzo M. 2000)

The transmission and reduction of vibrations in the far-field of the surface of the ground due to a surface load is investigated theoretically and validated with given field measurement data. In order to prevent exposures to vibration sources in the built-up area, several different countermeasures have been attempted for example: a row of concrete piles or steel sheet-piles; open trenches; in-fill trenches with concrete constructed along the track. Roughly speaking these wave barriers aim to protect structures and facilities by creating a shadow zone. Barriers are classified by the location of their installation; those measures nearby a source are referred to as “active” while those more in the proximity of the protected structures are termed “passive”. These barriers are very hard to design because in most cases barrier is

stiffer than soil and “let vibration through itself”. However measurement and modeling data show that lime–cement column barrier is good mitigating vibration levels at low frequencies to 30 Hz. This barrier could reduce ground- borne vibrations to 6 dB. According to Lithuanian hygiene norm low frequencies vibrations are most annoying to human.(Peplow A. T., Kaynia A. M. 2007). When designing an isolation paving, the dynamic characteristics of the input should first be studied and the object to be protected should be analysed both experimentally and numerically in order to identify its dynamic properties. (Clemente P. and Rinaldis D. 1998)

Hong Hao and two other scientists did traffic-induced ground vibrations measurements at four soil sites. Responses of five hypothetical reinforced concrete structures subjected to field measured ground motions caused by normal traffic conditions are analysed. Results were compared with various specifications of allowable vibration levels.

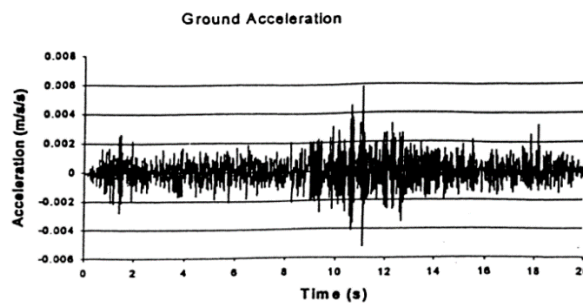


Fig. 1.17 Ground vibrations acceleration at measurement site 20 from center of the road, many cars and motorcycles passed at 50 km/h (Hao H. et. Al.,2001)

The measured vertical motions have similar characteristics to the horizontal motions, but their effects on structural responses are neglected owing to the relatively large weight and large vertical stiffness of the structure that the corresponding level of vertical motion is unlikely to excite the structure vertically. The nearest measurement point is 20 m from the road center, and the farthest point is about 120 m from the road center. The ‘road center’ indicates here the center of the traffic lane closest to the measurement site if there are more than one lane. To ensure proper contact, a small hole of about 20 cm deep was dug at each measurement point. All the accelerometers were mounted to their magnetic mounting base, and the magnetic mounting base was pushed into the soil at the bottom of the hole. (Hao H. et. Al.,2001)

1.6. Traffic induced vibrations in buildings

Traffic induced vibrations in buildings are caused by moving vehicles on an uneven road or track and have become an important environmental issue. Vibrations emitted from roads or railway tracks are mainly dominated by Rayleigh waves that impinge on the foundation of nearby buildings, resulting in structural vibrations that may cause malfunctioning of sensitive equipment, discomfort to people and structural damage.(S. Francois et. Al., 2007)

There are three major concerns on building vibrations, which are:

- damage building itself might suffer;
- disturbance to the occupants of the building; and
- effect on the normal operation of sensitive equipment.(Hao H. et. Al. 2001)

Whiffen and Leonard reviewed traffic - induced ground vibrations, which could be considered as continuous in nature, and concluded that architectural damage may occur if peak particle velocity exceeds 5 mm/s, and structural damage may take place if peak particle velocity exceeds 10 mm/s. (Whiffen A.C. and Leonard D.R., 1971)

Structural damage is usually correlated to ground vibration amplitudes and its principal vibration frequencies since structural response not only depends on excitation amplitudes, but also is frequency sensitive. However, many codes and researchers give allowable vibration limits of structures in terms of the peak particle velocity (PPV) of ground motion because PPV is by nature relatively frequency independent as compared to the peak acceleration and peak displacement. (Dowding C. H. 1996) For example, Whiffen and Leonard reviewed traffic induced ground vibrations, which could be considered as continuous in nature, and concluded that architectural damage may occur if PPV exceeds 5 mm/s, and structural damage may take place if PPV exceeds 10 mm/s.

Hao H. modelled responses of five hypothetical reinforced concrete structures subjected to field measured ground motions caused by normal traffic conditions were analysed. Results were compared with various specifications of allowable vibration levels.

After measurements at sites the scientists did a computer modeling how these vibrations could impact buildings. Commercial software ETABS is used to carry out the numerical simulation of dynamic responses of structures. In computer modeling, all the floors are assumed to be rigid in their own plane. Because the ground vibration frequency is relatively high, all the structural vibration modes are considered in the analysis. (Hao H. et. Al.,2001)

With modeling after measurements they could predict the vibration acceleration in building. In figure 1.19 shown acceleration response envelope to vibrations according to their measurements.

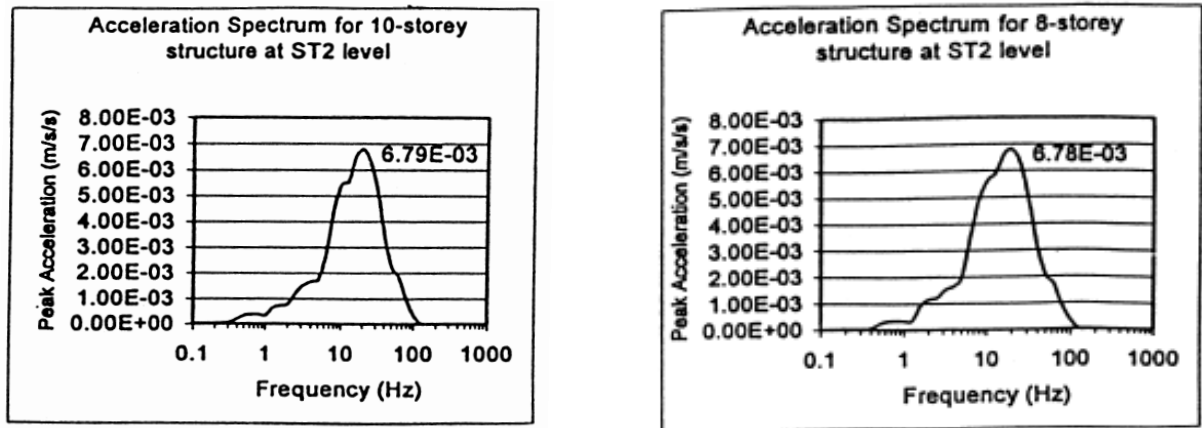


Fig. 1.18 Maximum modeled lateral acceleration response spectra of building. Left – 10 storey building at 2nd storey level, right 8 – storey building at 2nd storey level. (Hao H. et. Al.,2001)

The way people “feel” vibrations depends strongly on the vibration direction. One has to distinguish between vertical vibration and horizontal vibration, the latter often called lateral vibration. (Schindler 3300)

The largest acceleration responses of the model, occur at the second floor, but they remain almost unchanged along the building height. These observations indicate that the dynamic responses are dominated by the low vibration modes of structures although the dominant ground motion frequencies are much higher than the fundamental vibration frequencies of structures. (Hao H. et. Al.,2001)

However, it should be noted that resonance at the fundamental vibration modes of the structural models does not occur as the dominant ground motion frequencies are much higher than the structural fundamental vibration frequencies. (Hao H. et. Al.,2001)

1.7. Vibrations effect on health

Traffic induced vibration causes whole body vibrations to human. Whole-body vibration is vibration transmitted to the whole body by the surface supporting it (i.e. via a seat or floor). It is commonly experienced by drivers, operators and passengers in vehicles and machines when travelling over uneven surfaces. . (Government of...)

The transmission of vibration to the body is dependent on body posture. The effects of vibration are complex. Exposure to whole body vibration causes motions and forces within the human body that may:

- cause discomfort
- adversely affect performance
- cause health effect or aggravate pre-existing conditions
- present a health and safety risk.

The longer a human is exposed to whole body vibration, the greater the risk of health effects and musculoskeletal disorders. The most commonly reported disorder from exposure to whole body vibrations is low-back pain. (Grubliauskas et. Al. 2006)

Epidemiological studies of long-term exposure to whole body vibration have shown evidence for risk to the lumbar spine and the neck and shoulder. Results of epidemiological studies also show a higher prevalence rate of low-back pain, herniated disc and early degeneration of the spine in excessive whole body vibrations- exposed humans. (Bogaerts A. et. Al. 2007)

Exposure to whole body vibrations may also cause or exacerbate other health or safety effects such as:

- cardiovascular, respiratory, endocrine and metabolic changes
- digestive problems
- reproductive organ damage
- impairment of vision, balance or both
- interference with activities and discomfort that could lead to accidents.(Government of...)

Passengers of the cars crossing vertical speed calming measures might be harmed by vibration also. The amount of shock that might harm the health of vehicle occupants depends on the vehicle speed, measure geometry, vehicle type, position of occupants in the vehicles, and evaluation method. The whole-body vibration of the driver's seat for three vehicle categories is affected greatly by speed calming measure geometry, especially it's height. As the height increases, the health risk increases. The rear-seated passenger is also at high health risk, compared to the front-seated driver. Vehicles with good suspension-seat systems can reduce possible health risks when crossing speed calming measures. (Khorshid E. et. Al. 2007)

Evaluation of whole body vibration effect on human described in International standard ISO 5349-1:2001 "Evaluation of human exposure to whole-body vibration -- Part 1: General requirements".

Instructions of evaluating effect on human of whole body vibration are written in this standard. According this standard effect on human of whole body vibration depends on intensity of vibration and time of exposure. According this standard there is not enough data to tell that certain amount of vibration will cause risk to the health.

1.8. Vibration modeling software

1.8.1. Etabs

Etabs and Revit structure is the most popular structure vibrations modeling software in buildings. Revit Structure's, structural analysis programs are able to extract the relevant structural elements and properties. Within Revit Structure, beam, column, wall, and slab sizes are automatically defined and exported to ETABS based on the building model. Grid lines and floor levels are also automatically transferred into ETABS, though some further adjustment may be necessary (either in Revit Structure or ETABS) to ensure that columns, beams, walls, and slabs all lie on the same analytical plane, so they connect at single nodes. Loads can be defined within the building model, but there is currently no distinct advantage to applying loads within Revit Structure, especially since during analysis most programs including ETABS offers several code-based tools for applying seismic and wind loads (Senescu R., et. Al.).

ETABS is a stand-alone finite-element-based structural analysis program with special purpose features for structural design and analysis of building systems. Embedded beneath the simple, intuitive user interface are very powerful numerical methods, design procedures and international design codes that allow you to be versatile and productive, whether what is designing a simple dimensional frame or performing a dynamic base isolation analysis of a complex high-rise.

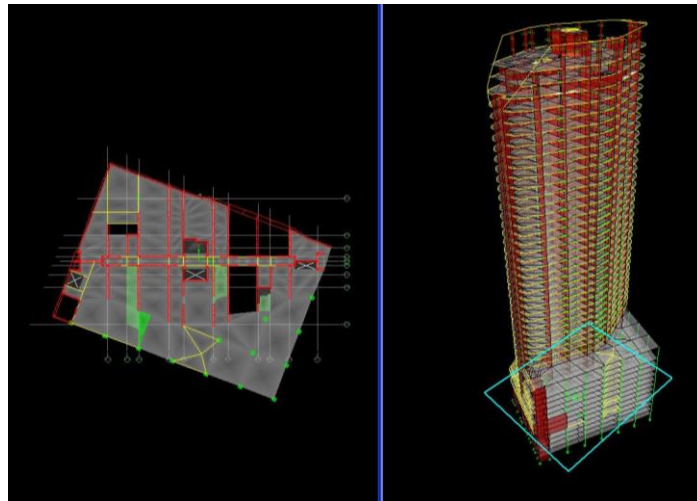


Fig. 1.19 Etabs model of Tameer tower (Abu-Dhabi) (<https://rommelds.files.wordpress.com/2011/09/etabs-model-tameer-tower-4.jpg>)

ETABS works off of an integrated database. The basic concept is that designer creates only one model consisting of the floor systems and the vertical and lateral framing systems to analyze and design the whole building. Everything is integrated into one versatile analysis and design system with one user interface. There are no external modules to maintain. The effects on one part of the structure from changes in another part are instantaneous and automatic.

The numerical methods used to analyze the building allow modeling of steel deck floors and concrete floor systems that can automatically transfer their loads to main girders. The automated finite element meshing of complex floor systems with automated displacement interpolation at mismatched mesh transitions, coupled with Ritz analysis for dynamics, makes inclusion of diaphragm flexibility effects in the analysis very practical. (An introduction..., 2002)

1.8.2. Meffisto

MEFISSTO is a software dedicated to the study of wave propagation in soils and structures. It is based on FEM (Finite Elements Method) and BEM (Boundary Element Method) techniques. The FEM approach is well adapted to the modelling of bounded domains and structures (foundations, buildings, portions of soil). The BEM models domains by discretizing only its boundaries; BEM is therefore well adapted for unbounded soils.

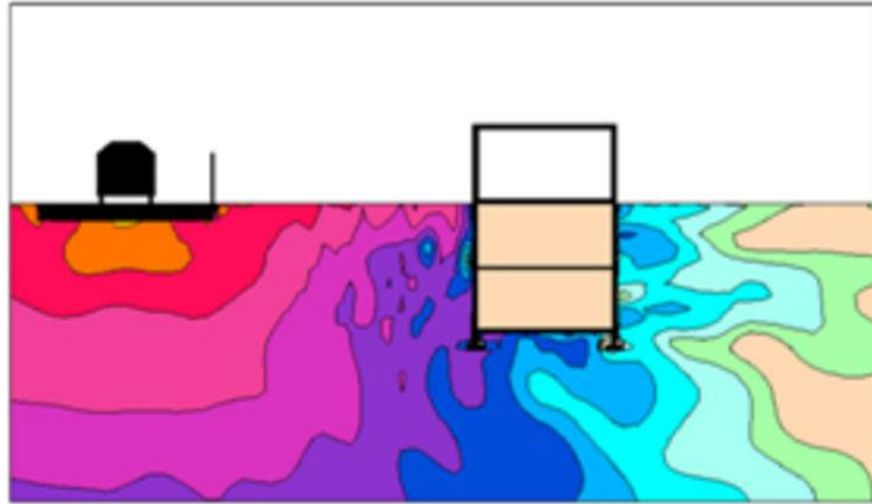


Fig. 1.20 Ground – borne Vibration simulation with Mefisto software. Vibration field at 100 Hz (<http://www.cstb.fr>)

The study of an underground with foundations, carried in 2.5D, can be interfaced with 3D computations of buildings carried with other software by using an adaptation of the mobility technique applied at the foundation/upper structure level.

1.8.3. Solidworks vibration analysis

Solid works gives opportunity to evaluate different vibration sources: static and dynamic. Static studies assume that loads are constant or applied very slowly until they reach their full values, thereafter remaining constant with time. Because of this assumption, all inertial effects must be considered negligible, including the velocity and acceleration of the excited system. Static studies therefore produce stresses and displacements that are constant.

For many practical cases, however, loads either are not applied slowly or they change with time or frequency. Inertia and damping become relevant, and meaningful simulation demands the use of a dynamic study. An often misused practice is the application of a static force to simulate the deflection that a structure might experience in a seismic or impact event. These events involve accelerations or decelerations that act on all the mass in the system everywhere, not just at a point or at the center of gravity of each component. Additionally, in the case of seismic or shaker-table loading, if the applied loading is reversed as a system is responding from the initial application, induced accelerations in

components can be very difficult to predict without a dynamic simulation. Consequently, a static simplification can be very misleading. Because there is no consistency as to whether it will be conservative or nonconservative, a static simplification is inappropriate for most cases (Solidworks, 2010).

1.9. Mitigation of ground borne vibration

Techniques to mitigate vibration propagation can be divided into two categories: active and passive isolation. Active isolation refers to the isolation of vibration within locations either close to or inside the track structure such as floating slab track, resilient wheels. Passive isolation refers to screening vibration through measures placed at locations in close proximity to vibration sensitive sites rather than in close proximity to the track. (Connolly D. et. Al. 2013, Tayabji S. et. Al. 2001, Kouroussis G. 2011.)

In-ground barriers. Wave barriers or trenches are a form of passive vibration isolation. They offer an attractive option because they offer high isolation performance and do not require direct access to the railway line. To maximize performance, trench properties such as size, shape and infill material must be selected relative to the excitation frequency(s). Despite this, few researches have investigated the effect of trench properties and their ability to mitigate moving excitations, which emit a broad band of frequencies, as is the case of a high speed train.(Connolly D. et. Al. 2013)

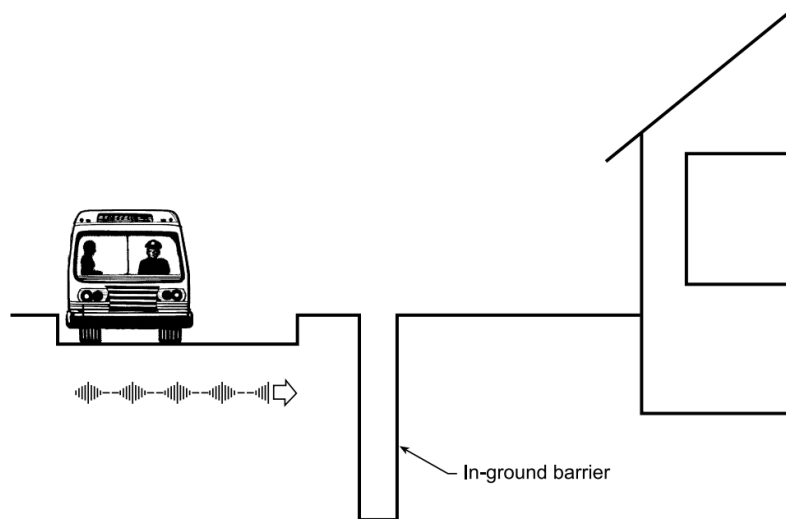


Fig. 1.21 Scheme of trench used to reduce ground – borne vibrations.(Hunaidi, 2000)

Trenches are usually filled with cushions filled with low density gases or polyurethane. Trench effectiveness depends on three parameters of the trench: (Connolly D. et. Al. 2013)

- Width;
- Depth
- Length.
- Distance from the road to the trench.

Width of the vibration barrier is not the main factor to reduce ground borne vibrations. Connolly during research changed width of trench from 0,1 to 0,6 m and didn't found the difference enough for consideration.

Depth of the trench is one most important parameter when we look for the trench effectiveness to reduce vibration. As I wrote in other chapters mainly traffic induce surface vibration (z – axis), this parameter is most important in trench effectiveness. Rayleigh waves has 67 % energy of whole induced vibration energy. (Connolly D. et. Al. 2013)

The length of the trench shall be as long as possible to protect buildings or people from vibrations in this case waves could only go through under the trench. (Connolly D. et. Al. 2013).

Distance from the road to the trench should be smaller or equal to the Rayleigh wavelength that is induced by traffic. Rayleigh wavelength is calculated by formula (Foti S. 2000):

$$\lambda_R = \frac{V_R}{f}, (m) \quad (1.5)$$

Here:

λ_R – Rayleigh wavelength, m

V_R – Rayleigh wave velocity, m/s

f – frequency, Hz

Trenches can be ineffective if the induced wavelengths are very long. (Yang Y. B. 1997)

Modification of the road. To preserve an ancient building in Rome against traffic-induced vibrations, an anti vibration system was introduced under the paving of the near Lungotevere road. Modification of the road, with the construction of an isolation structure able to intercept both direct and reflected waves, seemed more suitable. A new structure for the road, made of a concrete grid supported by rubber pads. Two grids, one for each half of the road, of 6452 m length were built. Each had a weight of about 4000 kN and was supported on 1000 rubber bearings. The rubber was protected from the sun's radiation, so its life could be supposed to be infinite. Two typical bridge joints were arranged at the ends of the structure. (Clemente P., Rinaldis D. 1998)

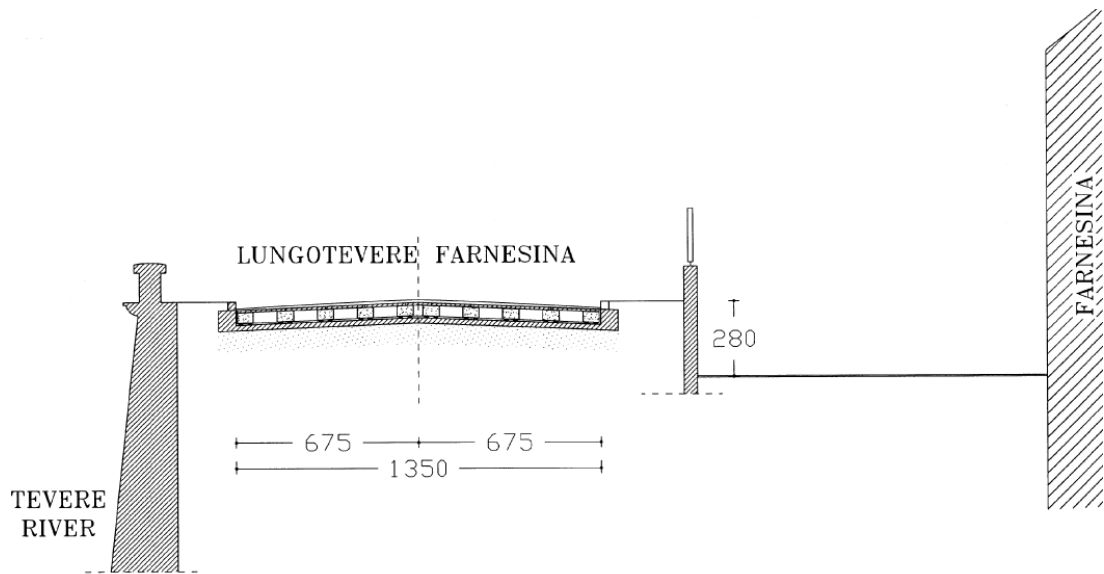


Fig. 1.22 Cross section of road near villa Farnesina

Today, new roads are normally of good quality and the amplitude of vibration due to the traffic is low. In fact, the amplitudes of the vibrations recorded on the old anti-vibration paving are much higher than those recorded on the new normal paving, while there is no significant difference between those recorded on the ground at different distances from the road. The influence of the anti-vibration paving is apparent also in power spectral densities, where the amplification of the frequency content between 10 and 13 Hz due to the paving is evident. The anti-vibration intervention do not affect dangerously the frequency content of the traffic induced vibrations. (Clemente P. and Rinaldis D. 1998)

Sleepers could be used also to reduce ground vibrations. The sleepers, the resilient railpads and the ballast are modelled by smeared mass, springs and dashpots. The sleepers' dimensions are 2,5 x 0,24 x 0,21 m, the sleeper distance is 0,6m, and the smeared sleeper mass is 525 kg/m. The pad stiffness is $235,6 * 10^6 \text{ N/m}^2$ and the railpad damping is $25,1 * 10^3 \text{ Ns/m}^2$. (Fiala P. et. al. 2007)

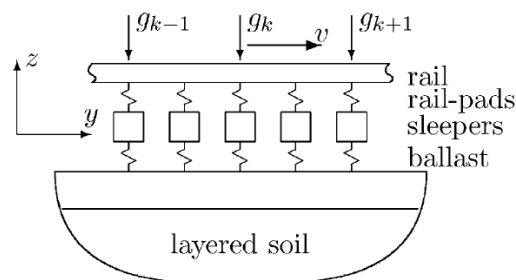


Fig. 1.23 Cross section of the track, longitudinal section in the y-z plane

The base isolation technique is recognized as an effective measure for reducing seismic response of a building. This technique is tried by scientists Xu Y. L. and team to see if it is effective for microvibration control of high tech facilities. The structural properties of the three-storey building remain unchanged.

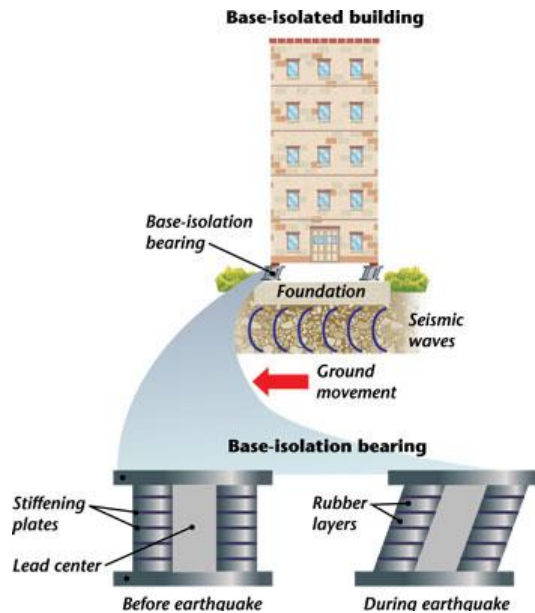


Fig. 1.24 Principal scheme of base isolated building.(<http://www.phschool.com/>)

Their simulation results show that passive building base isolation can reduce the microvibration of all types of high tech equipment to the allowable level in their country only when the frequency of the base isolator storey is less than 0.6 Hz.(Xu Y. L. et. Al. 2003)

Tunnels can be effective way to reduce ground borne vibrations according scientists Lakušič S. and Ahac M. if tunnel is deep enough vibrations will be less felt on the surface. According their research vibrations using tunnels vibrations could be reduced by 10 to 40 dB. (Lakušič S. and Ahac M. 2012)

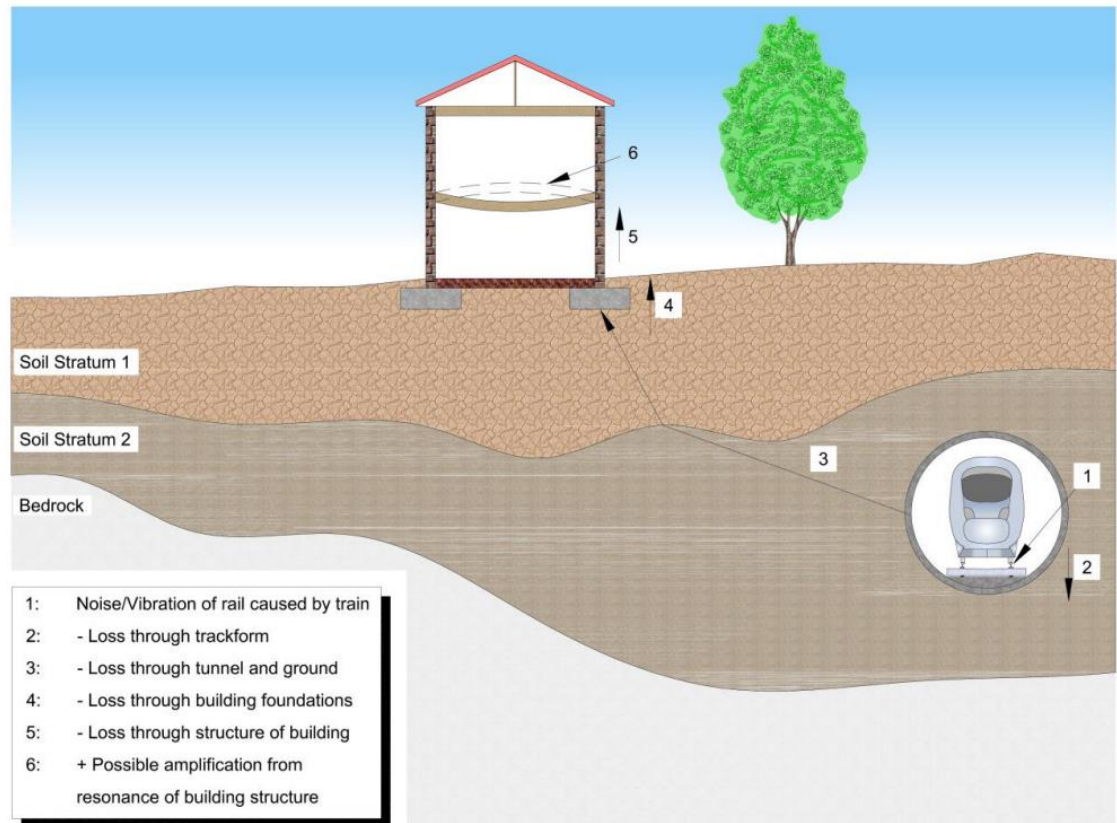


Fig. 1.25 Transmission of noise and vibration from source to receptor (ARUP, 2015)

Once a railway or road is in operation, the passage of trains or cars will generate vibration in the ground. The level of noise and vibration in neighboring buildings is dependent on the forces applied by the vehicles and the attenuation between the source and the buildings. This attenuation can be calculated and the level of mitigation can be designed to achieve acceptable levels of noise and vibration inside buildings.

Conclusions of the 1st chapter

1. Road traffic induces shear, compression and Rayleigh waves in soil. Highest energy contains Rayleigh waves.
2. The best vertical traffic calming measure is the speed cushions. These engineering measures designed only to reduce light vehicles speed. These traffic calming measures designed not reduce speed of emergency vehicles such as ambulances and fire trucks.
3. The main engineering measure to reduce ground borne vibrations spreading in the environment is trenches. These measures are used to reduce rail transport induced ground borne vibrations.
4. Road traffic induce ground borne vibrations due to road surface irregularities. When wheels strikes into irregularity force creates vibrations. If road surface is even (without cracks) ground borne vibrations induced by road traffic should be lower.

2. Methodology of the research

In this chapter and vibration research method is presented. Vibration measurements inside the building was being held and evaluated according Lithuanian hygiene norm HN 50: 2003. Modified method is used to evaluate the vibrations in the environment.

Ground-borne vibrations was measured during two different seasons, winter and summer. According other researches soil freezing mainly effects dynamic modulus and damping ratio of soil which are most important physical soil parameters in ground borne vibration spread. (Wang T. et. Al. 2013)

Transport were divided into three categories:

1. Light vehicles (Light passenger vehicles)
2. Moderate weight vehicles (Light cargo or light passenger vehicle with trailer)
3. Heavy weight vehicles (Buses or heavy cargo vehicles)

2.1. Research points.

In order to evaluate vertical traffic calming measures induced vibrations four traffic calming measures were selected in streets of Vilnius, Lithuania. In Lithuania the use of speed tables is most common, in account of that, selected traffic calming measures are speed tables. General information about measurements is provided in 2.1. table.

Table 2.1 Research points and general information.

No.	Research point	Type of traffic calming measure	Distance to nearest façade wall of building, m.	Length, m	Width, m	Height, m
1.	Crossroad of Kęstučio and D. Poškos streets;	Speed table	8 m	7,5	11	0,1
2.	L. Asanavičiūtės st. 5	Speed table	10 m	7,5	11	0,1
3.	Crossroad of Verkių and Apkasų streets.	Speed table	10,1 m	7,5	11	0,1
4.	Gurių st. 51	Speed table	15 m	7,5	11	0,1

Research point no. 1. Crossroad of Kęstučio and D. Poškos streets, Vilnius

Speed table is 8 meter distance to three storey commercial building (Kęstučio St. 41A , Vilnius). Traffic induced ground-borne vibrations were measured in 5 places: 1 meter near the speed table, in the first and third floor of the commercial building and two reference point where speed table has no influence on traffic induced vibrations. Speed table place in the map and the view of the site is shown in figure 2.1. In this site different categories of transport were measured.



Fig. 2.1 Research point No. 1. Crossroad of Kęstučio and D. Poškos streets.

Research point no. 2. L. Asanavičiūtės St. 5, Vilnius.

Speed table is 10 meter distance to five storey residential apartment building (L. Asanavičiūtės St. 5, Vilnius). Traffic induced vibrations were measured inside the building (first, third and fifth floor stairway) and on sidewalk, 1 m distance to the speed table, and near the foundation of the apartment building. Speed table place in the map and the view of the site is shown in figure 2.2 In this site different categories of transport were measured.



Fig. 2.2 Research point No. 2. L. Asanavičiūtės st. 5, Vilnius.

Research point no. 3. Crossroad of Verkių and Apkasų streets, Vilnius

Speed table is 10,1 m distance to five storey residential apartment building (Apkasų St. 5, Vilnius).. Traffic induced vibrations were measured inside the building (first, third and fifth floor stairway) and on sidewalk, 1 m distance to the speed table, and near the foundation of the apartment building. No special irregularities were noticed in this research point. Speed table place in the map and the view of the site is shown in figure 2.3. In this site different categories of transport were measured..

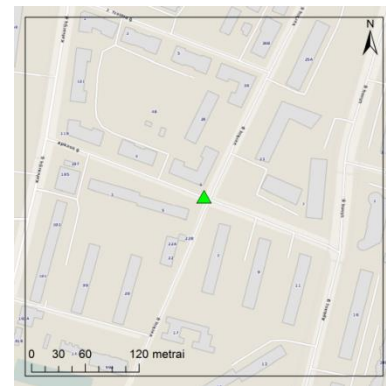


Fig. 2.3 Research point No. 3. Crossroad of Verkių and Apkasų streets, Vilnius

Research point No. 4. Gurių 51 St., Vilnius

Speed table is 15 m distance to 3 storey residential apartment building (Gurių 51 St., Vilnius). Vibration measurement site and situation plan is shown in Fig. 2.4.



Fig. 2.4 Research point no. 4. Gurių 51 st., Vilnius

2.2. Methodology of ground-borne vibration research

Vibration measurements were being held and evaluated according to Lithuanian hygiene norm HN 50: 2003 in the apartment residential and commercial buildings and in their environment. Traffic is divided into three categories: light, moderate weight and heavy vehicles..

Measurements were taken in two seasons: winter and summer season. According to the same methodology to evaluate the influence of freezing on the traffic vibrations.

Distance from buildings to vertical traffic calming measure, relief, pavement ground structure, area building environment is being taken into account when selecting measuring points.

The values of vibration acceleration are being evaluated according to the threshold values of Lithuanian hygiene norm HN 50:2003 (check 1.3 table).

To measure traffic induced vibration, a sound level and vibration meter Bruel&Kjaer Mediator 2260. In the set of equipment, a 3-axis accelerometer Delta Tron 4506 and amplifier 3-channel Human Vibration Front-end — Type 1700 is also used. Set of equipment used for vibration measurement is shown in figure 2.5.

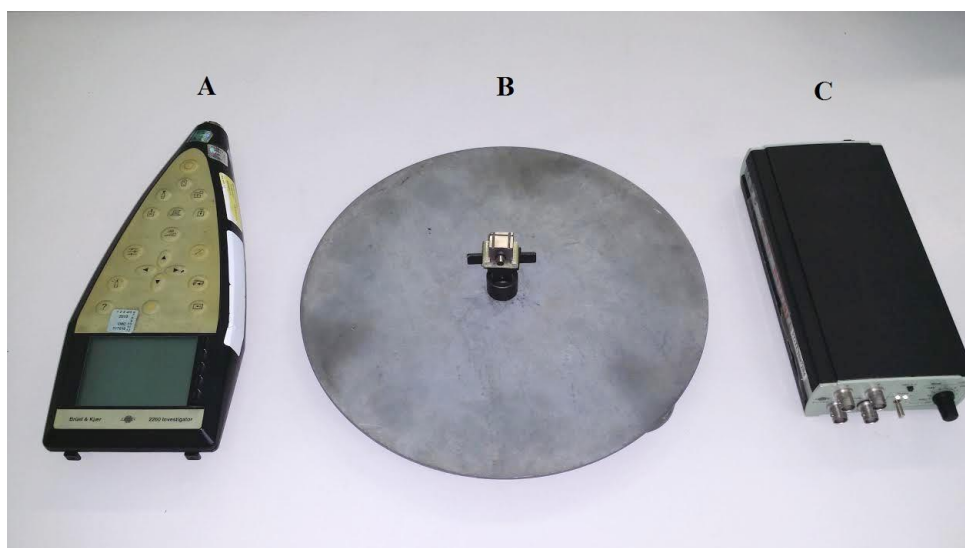


Fig. 2.5 Set of equipment used for vibration measurement A – Sound level and vibration meter Bruel&Kjaer Mediator 2260; B – Steel plate with 3-axis accelerometer Delta Tron 4506; C – amplifier 3-channel Human Vibration Front-end — Type 1700

Acceleration of the vibration is being measured in all three axis (X, Y, Z). After the check measurements are taken in that axis in which acceleration of the vibration is highest. Z axis is vertical axis, X axis parallel to the road, y axis crossing the road. Measuring parameter is acceleration of vibrations (mm/s^2).



Fig. 2.6 Steel plate and accelerometer use in field measurements

Every vehicle crossing the vertical traffic calming measure was measured separately. Measuring parameters are:

- Acceleration of the vibration in 1/3 octave band. Measurement units (mm/s^2). Measuring in frequencies from 6,3 Hz to 3150 Hz

2.3. Method to evaluate traffic induced ground-borne vibration

With this methodology is measured 3 of 7 research point (research points No. 1 – 3). With this method I tried to find out is traffic crossing vertical traffic calming measures induced vibrations acceptable according the hygiene norm HN 50:2003.

Measurement points in building should be selected in the rooms where residents or workers stay the longest time. Measurement are taken on the ground in every second storey of building, 2 meters distance to the wall which is nearest to the source of the vibration. Flooring (linoleum, parquet and etc.) must be tight-fitted in measuring point. Principal scheme of measuring points is shown in figure 2.7.



Fig. 2.7 Principal scheme of vibration measurement points (method A)

Measuring equipment is being calibrated before and after measurements. If calibration results differs more than 1,1 times vibration measurement must be repeated.

Accelerometer with magnet fitted to steel plate, which has 3 support points. Steel plate with accelerometer is fitted on the ground. Human whose weight is 60–80 kg is required to stand on the plate with mounted accelerometer.

2.3. Vibration measurement data processing

Huge amount of data was received after measurements. In every octave band trimean is being calculated. This characteristic is not “sensitive” to extreme values, trimean is used in asymmetric value distribution. (Čekanavičius V. and Murauskas G. 2000)

$$Trimean = \frac{Q_1 + 2Md + Q_3}{4} \quad (2.1.)$$

Here:

Md – median

Q₁ – First quartile

Q₃ – Third quartile

In descriptive statistics, the quartiles of a ranked set of data values are the three points that divide the data set into four equal groups, each group comprising a quarter of the data. A quartile is a type of quantile. The first quartile (Q₁) is defined as the middle number between the smallest number and the median of the data set. The second quartile (Q₂) is the median of the data. Median is the number separating the higher half of a data sample, a population, or a probability distribution, from the lower half. The third quartile (Q₃) is the middle value between the median and the highest value of the data set.

Observational error (or measurement error) is the difference between a measured value of quantity and its true value. In statistics, an error is not a "mistake". Variability is an inherent part of things being measured and of the measurement process.

Root mean square error (RMSE) is a frequently used measure of the differences between values (sample and population values) predicted by a model or an estimator and the values actually observed.

$$S_x = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n(n-1)}}; \quad (2.2)$$

Here:

S_x – root mean square error

X_i – measured value

$\bar{x}$ – Arithmetic mean

n – Number of observations

In mathematics and statistics, the arithmetic mean, or simply the mean or average when the context is clear, is the sum of a collection of numbers divided by the number of numbers in the collection.

$$\overline{x_n} = \frac{1}{n} \sum_{i=1}^n x_i , \quad (2.3)$$

Here:

$\overline{X_n}$ – Arithmetic mean

n – Number of observations

X_i – measurement value.

All ground borne vibration measurement data and error is presented using this methodology.

3. Results of the research

In this chapter results of the measurements is presented. All measurements is done according the methodology that is described in chapter 2.

3.1. Research results during winter time.

Winter time in Lithuania is starts when average temperature three days lower than 10⁰C. In this chapter measurement results are shown that are taken during summer season.

3.1.1. Research point No. 1. Kęstučio and D. Poškos st. crossroad

Measurements of the ground borne vibration was done in 2016 – 01 – 04 d. During measurements air temperature was – 5,6 °C, wind speed 1,2 m/s, humidity 78,4, atmosphere pressure 99,8 kPa. The vibration measurements was done to the axis z, because in this axis was found biggest vibration.

Table 3.1 Number of vehicles measured.

Measurement point	Light vehicles	Moderate weight vehicles	Heavy weight vehicle
1 m from traffic calming measure	15	10	15
1st storey in commercial building hall	16	14	15
3rd storey in commercial building staircase	15	12	12
Reference point 1m distance to street	15	13	11
Reference point 10 m distance to street	15	14	12

At measurement point in first storey of commercial building maximum vibration acceleration was found when heavyweight transport was passing, maximum vibration was found at 2000 Hz frequency and acceleration was 5,4 mm/s².

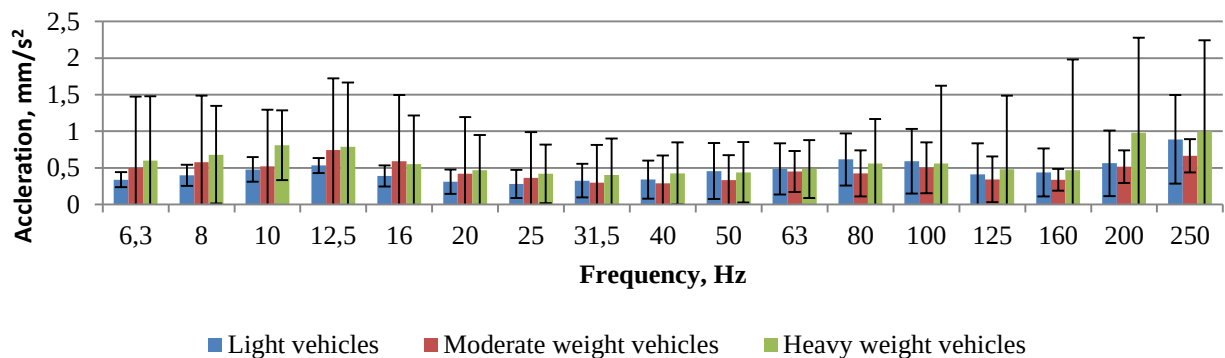


Fig. 3.1 Acceleration of the vibrations in first storey hall in frequencies from 6,3 to 250 Hz

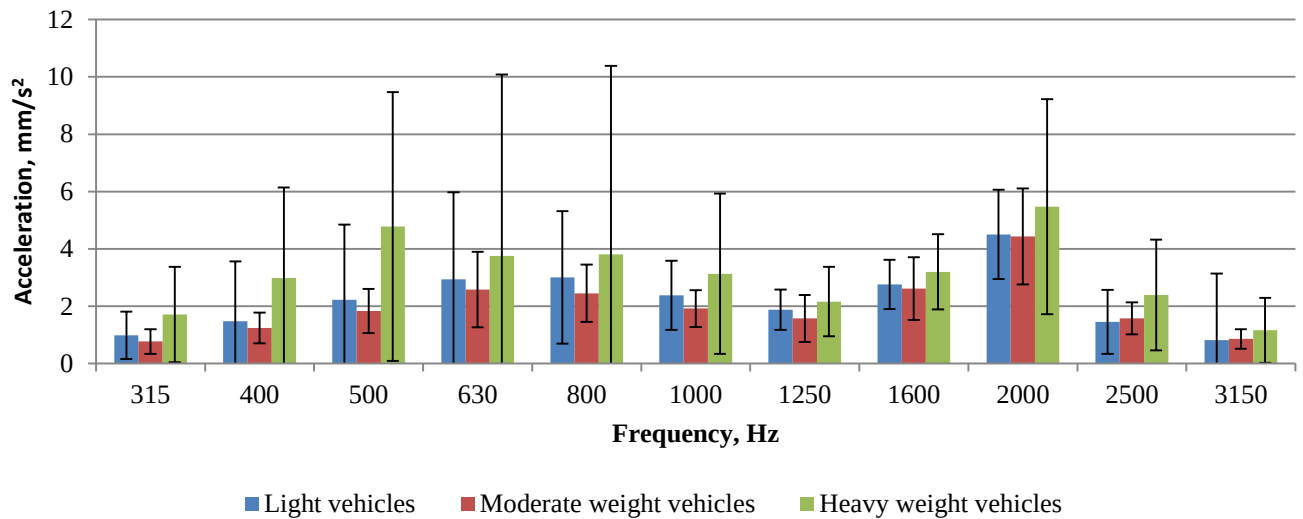


Fig. 3.2 Acceleration of the vibrations in first storey hall in frequencies from 315 to 3150 Hz

Light vehicles induced maximum vibrations was $4,4 \text{ mm/s}^2$ at 2000 Hz frequency and moderate weight vehicles induced vibrations was the same $4,4 \text{ mm/s}^2$ at the same frequency. During measurements were noticed that light weight vehicles reduce speed less than other category transport. Graphs of measurement results shown in 3.1. and 3.2 figures.

Measurement results was compared with HN 50: 2003 threshold levels. At frequencies from 6,3 to 80 Hz vibration acceleration level, when light vehicles was passing was from $0,28 \text{ mm/s}^2$ to $0,61 \text{ mm/s}^2$ it is from 1,2 to 8 % of the threshold level. When moderate weight vehicles was passing it reached from 0,85 to 11,6 % of the threshold level. When heavy weight transport was passing vibrations in first storey of the building reached from 1,1 to 13,6 % of the threshold level. No exceeding of threshold level was found.

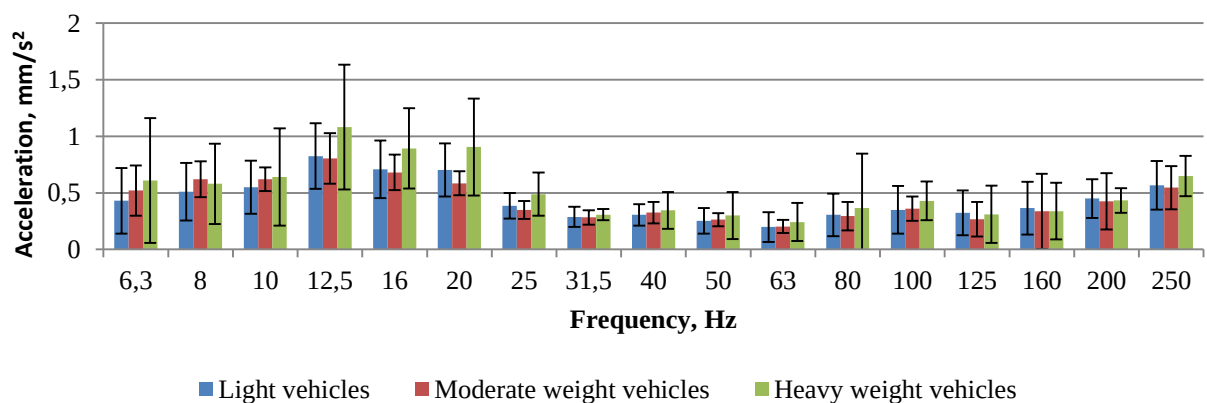


Fig. 3.3 Acceleration of the vibrations in third storey staircase in frequencies from 6,3 to 250 Hz

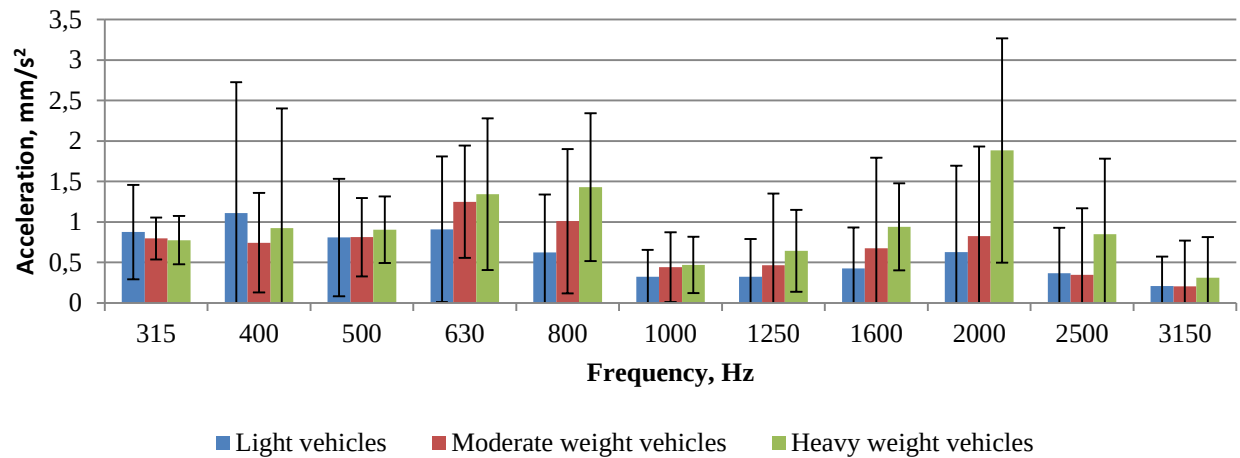


Fig. 3.4 Acceleration of the vibrations in third storey staircase in frequencies from 315 to 3150 Hz

At measurement point in first storey of commercial building maximum vibration acceleration was found when heavyweight transport was passing, maximum vibration was found at 2000 Hz frequency and acceleration was 1,8 mm/s². Light vehicles induced maximum vibrations was 1,1 mm/s² at 400 Hz frequency and moderate weight vehicles induced vibrations was the same 1,3 mm/s² at the frequency of 630 Hz. Graphs of measurement results shown in 3.3. And 3.4. Figures.

Measurement results at the third storey was also compared with HN 50: 2003 threshold levels. At frequencies from 6,3 to 80 Hz vibration acceleration level, when light vehicles was passing was from 0,20 mm/s² to 0,83 mm/s² it is from 0,50 to 12,4 % of the threshold level. When moderate weight vehicles was passing vibration reached from 0,51 to 12,4 % of the threshold level. When heavy weight transport was passing vibrations in first storey of the building acceleration of the vibration reached from 0,62 to 13,8 % of the threshold level. No exceeding of threshold level was found.

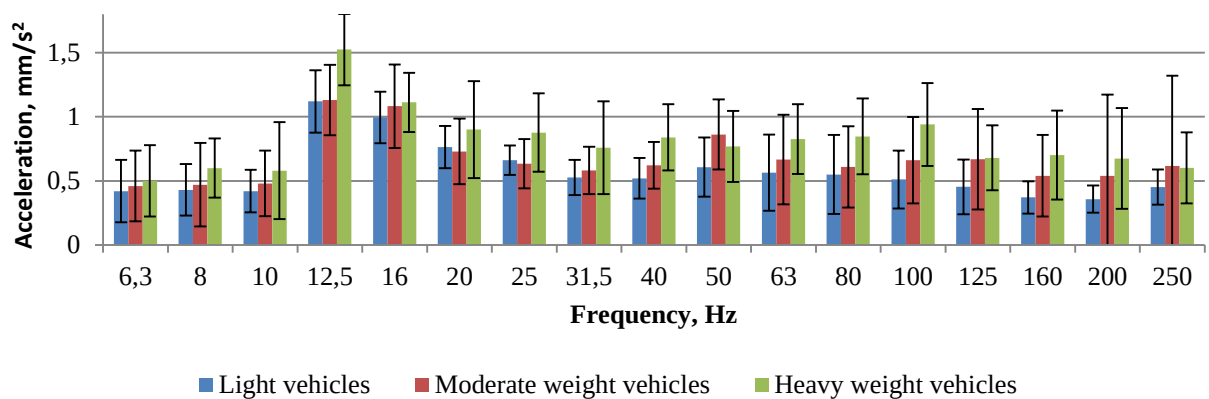


Fig. 3.5 Acceleration of the vibrations in 1m distance to traffic calming measure in frequencies from 6,3 to 250 Hz

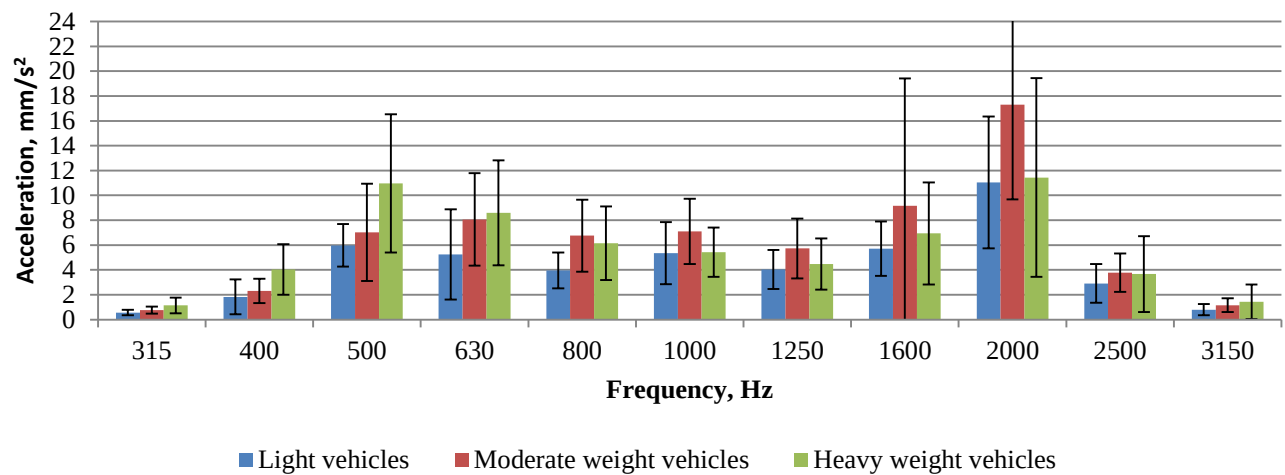


Fig. 3.6 Acceleration of the vibrations in 1m distance to traffic calming measure in frequencies from 315 to 3150 Hz

In measurement one meter distance to the traffic calming measure, highest vibrations acceleration was found in 2000 Hz frequencies (light vehicles 5,7 mm/s², moderate weight vehicles 17,3 mm/s², heavyweight vehicles 11,4 mm/s²). During measurement was noticed that light and moderate weight vehicles when passing speed table reduced their speed less than heavyweight vehicles. Moderate weight vehicles induces highest vibrations at this measurement point.

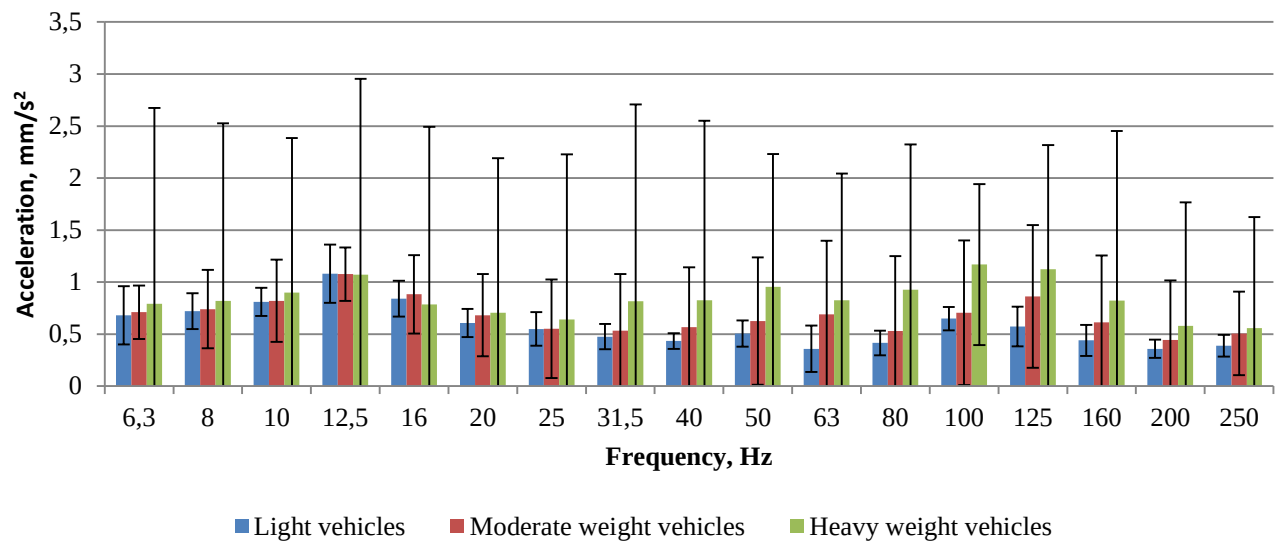


Fig. 3.7 Acceleration of the vibrations in reference point 1m from road infrequencies from 6,3 to 250 Hz

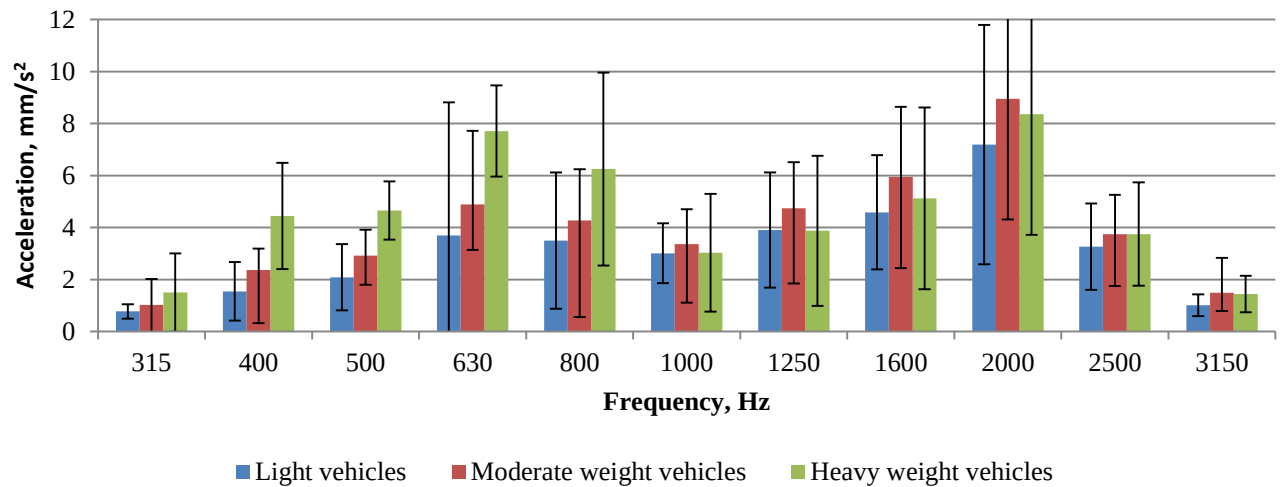


Fig. 3.8 Acceleration of the vibrations in reference point 1m from road infrequencies from 315 to 3150 Hz

Acceleration of the vibration was measured in reference point 1m from Kęstučio street where vertical traffic calming measure has no impact on the traffic induced vibrations. highest vibrations acceleration was found at 2000 Hz frequencies (light vehicles 7,1 mm/s², moderate weight vehicles 8,9 mm/s², heavyweight vehicles 8,3 mm/s²). In comparison with measurement with 1 m distance to traffic calming measure was found that at frequencies 12,5 – 31,5 Hz is similar, but at frequencies 400 – 2500 Hz acceleration of the vibration was higher near the speed table. Results is shown in 3.7 and 3.8 figures.

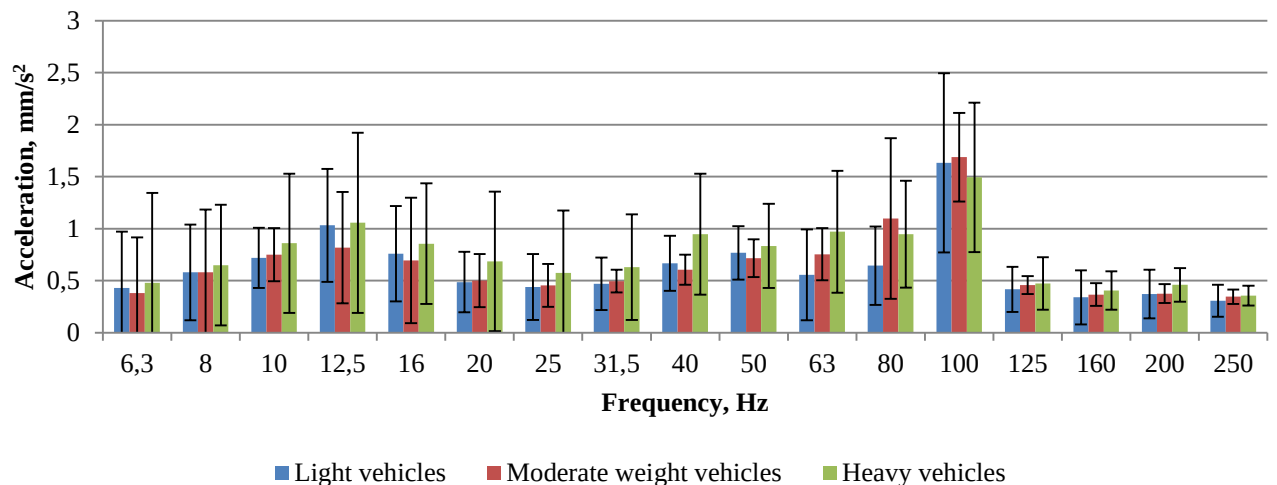


Fig. 3.9 Acceleration of the vibrations in reference point 10 m from road infrequencies from 6,3 to 250 Hz

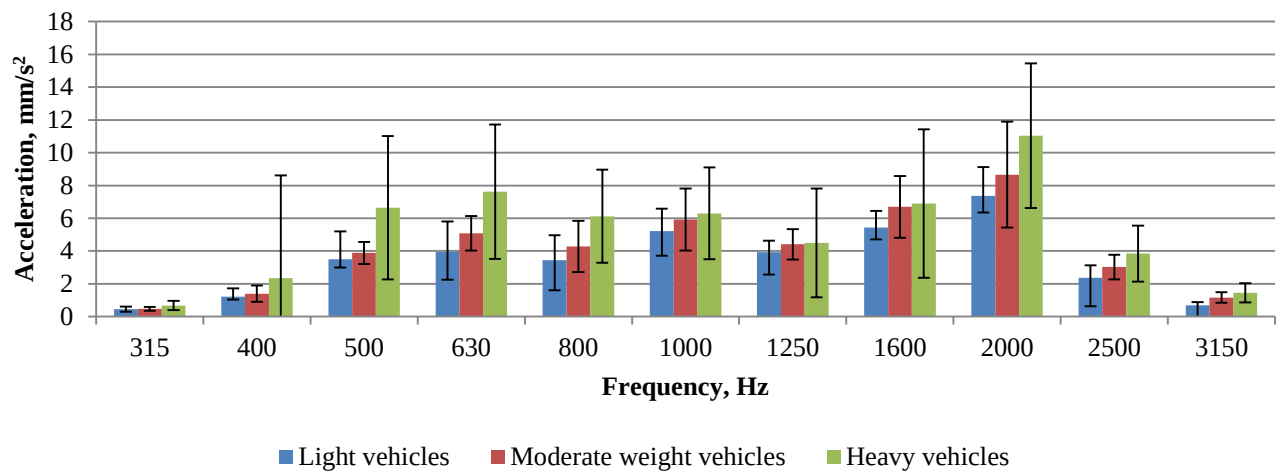


Fig. 3.10 Acceleration of the vibrations in reference point 10 m from road infrequencies from 315 to 3150 Hz

Acceleration of the vibration was measured in reference point 10 m from Kęstučio Street. Highest vibrations acceleration was found at 2000 Hz frequencies (light vehicles 7,4 mm/s², moderate weight vehicles 8,6 mm/s², heavyweight vehicles 11 mm/s²). In this measurement point was found that, acceleration of the vibrations is slightly bigger than in 1 m reference point. It might be because of building not far from this reference point, buildings near this street is close to road.

Summary of the results in measurement site

After the results analysis was found that highest acceleration of the vibrations was in measurement point 1 m distance to the speed table. Highest vibration values was induced by the moderate weight transport. Inside the commercial building traffic induced vibrations was significantly smaller than in measurement points outside the building, it was found that vibration acceleration gain highest values at frequencies 500 – 2000 Hz.

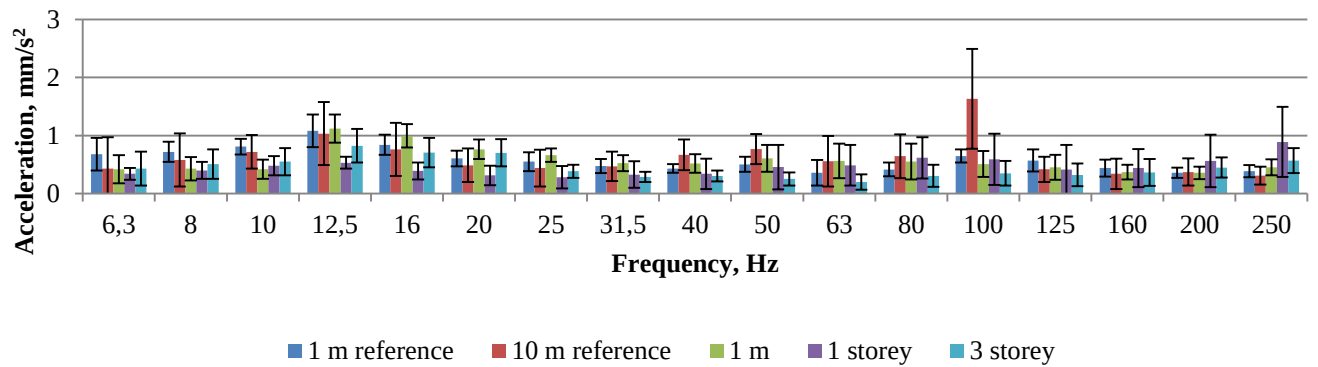


Fig. 3.11 Comparison of acceleration of the vibration when light vehicles is passing in different measurement points at frequencies 315 – 3150 Hz.

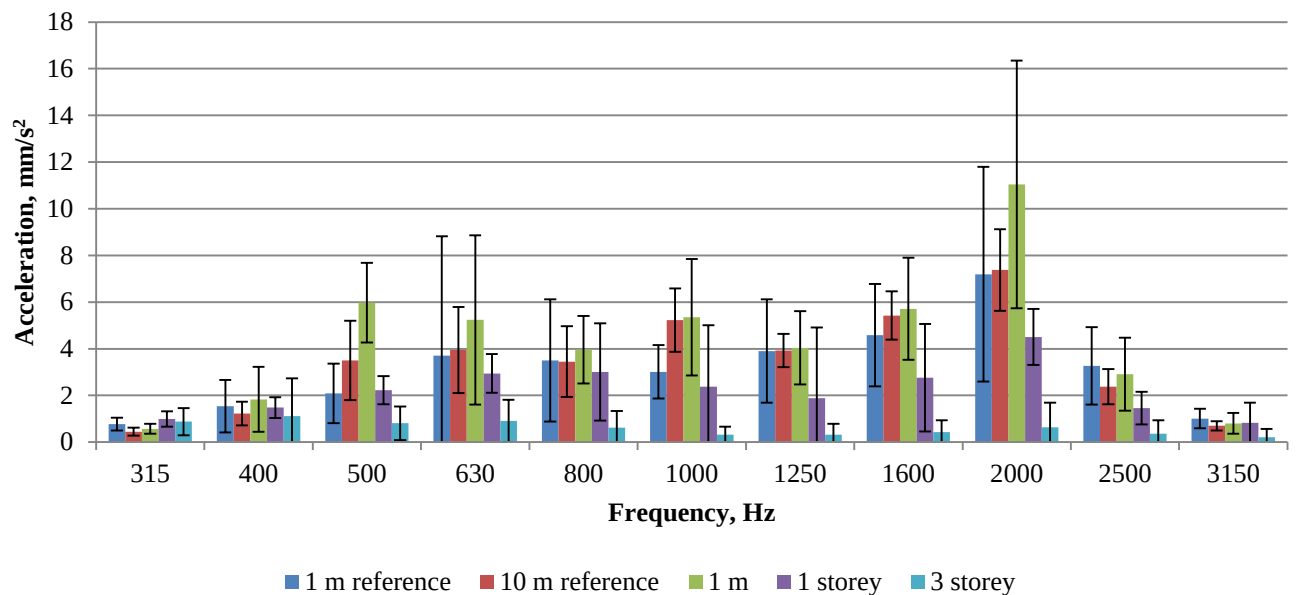


Fig. 3.12 Comparison of acceleration of the vibration when light vehicles is passing in different measurement points at frequencies 315 – 3150 Hz.

When light vehicles was passing in different measurements points (Fig. 3.11.) was found that values of acceleration of the vibration differ from 0,20 to 1,63 mm/s² at frequencies 6,3 – 250 Hz. Lowest value of the acceleration was found in third storey staircase, and the highest value was found in 10 m reference point. At frequencies from 315 to 3150 Hz (Fig. 3.12.) acceleration of the vibrations differ from 0,21 to 11,04. Lowest value of the acceleration was found in third storey staircase, and the highest value was found in 1 m distance to the vertical traffic calming measure.

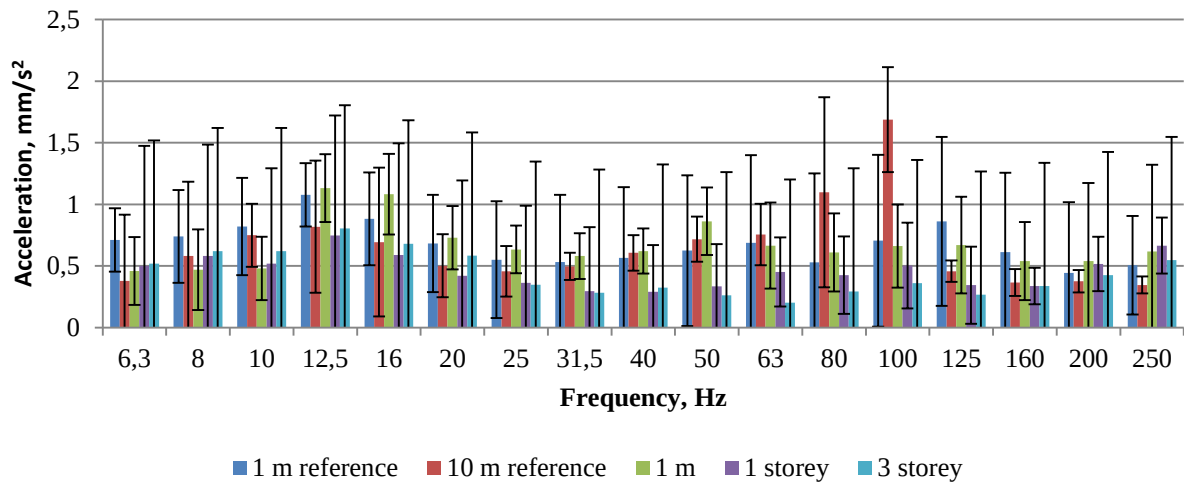


Fig. 3.13 Comparison of acceleration of the vibration when moderate weight vehicles is passing in different measurement points at frequencies 6,3 – 250 Hz.

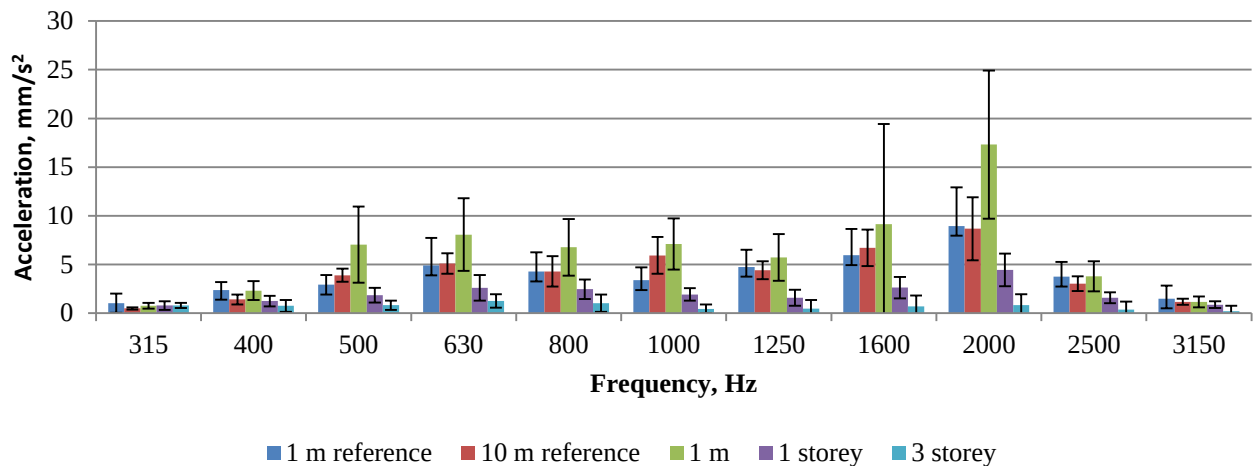


Fig. 3.14 Comparison of acceleration of the vibration when moderate weight vehicles is passing in different measurement points at frequencies 315 – 3150 Hz

When moderate weight vehicles was passing in different measurements points (Fig. 3.13.) was found that values of acceleration of the vibration differ from 0,20 to 1,68 mm/s² at frequencies 6,3 – 250 Hz. Lowest value of the acceleration was found in third storey staircase, and the highest value was found in 10 m reference point. At frequencies from 315 to 3150 Hz (Fig. 3.14.) acceleration of the vibrations differ from 0,20 to 17,30. Lowest value of the acceleration was found in third storey staircase, and the highest value was found in 1 m distance to the vertical traffic calming measure.

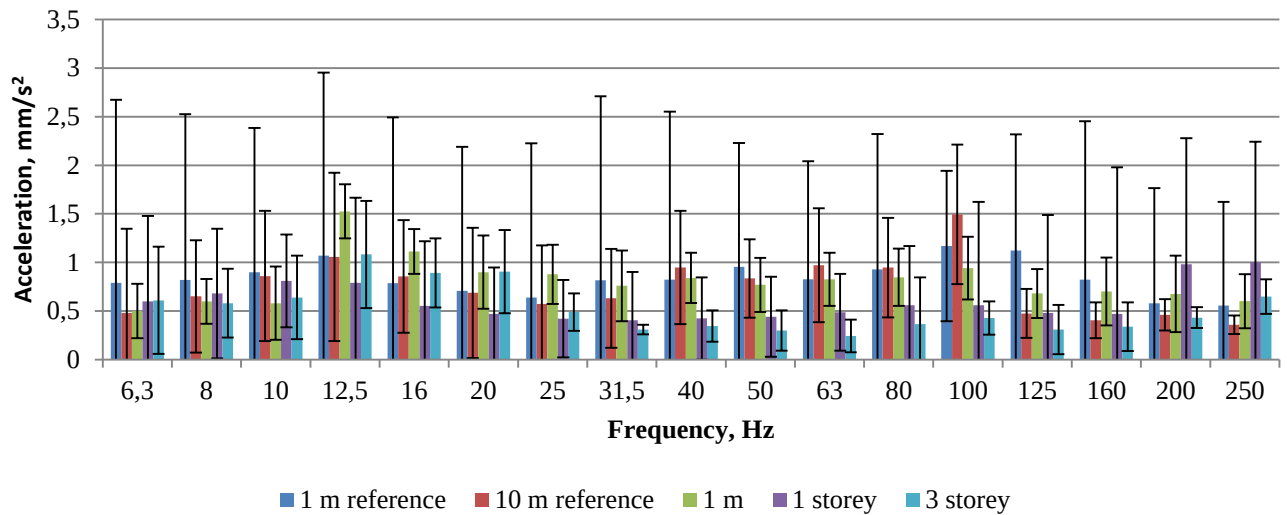


Fig. 3.15 Comparison of acceleration of the vibration when heavyweight vehicles is passing in different measurement points at frequencies 6,3 – 250 Hz.

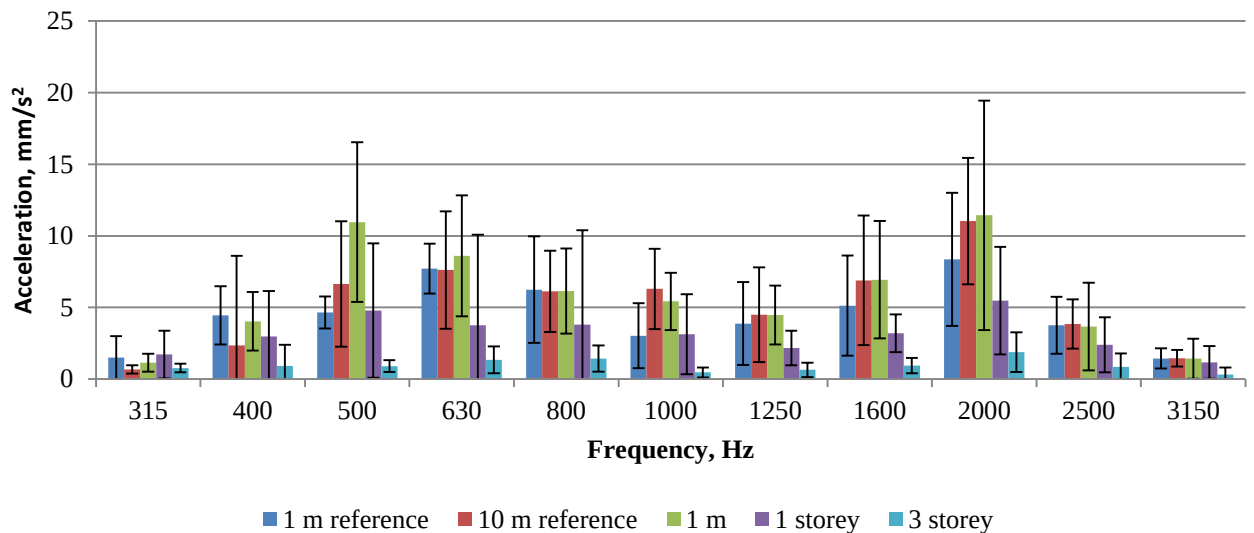


Fig. 3.16 Comparison of acceleration of the vibration when heavyweight vehicles is passing in different measurement points at frequencies 315 – 3150 Hz.

When heavyweight vehicles was passing in different measurements points (Fig. 3.15.) was found that values of acceleration of the vibration differ from 0,24 to 1,53 mm/s² at frequencies 6,3 – 250 Hz. Lowest value of the acceleration was found in third storey staircase, and the highest value was found in measurement point 1 m distance to the speed table. At frequencies from 315 to 3150 Hz (Fig. 3.16.) acceleration of the vibrations differ from 0,31 to 11,44. Lowest value of the acceleration was found in

third storey staircase, and the highest value was found in 1 m distance to the vertical traffic calming measure.

3.1.2. Research point No. 1. L. Asanavičiūtės st. 5, Vilnius

Measurements of the ground borne vibration was done in 2016 – 01 – 07 d. During measurements air temperature was – 7,0 °C, wind speed 0,8 m/s, humidity 75,3, atmosphere pressure 98,9 kPa. The vibration measurements was done to the axis z, because in this axis was found biggest vibration.

In this measurement site vibration was measured in first, third and fifth storey of apartment building and in its environment. Near the speed table, on the road manhole was noticed which could increase traffic induced vibrations.



Fig. 3.17 Manhole near the speed table (Author's picture)

In this measurement site vibration was measured in first, third and fifth storey of apartment building and in its environment. Near the speed table, on the road manhole was noticed which could increase traffic induced vibrations.

Table 3.2 Number of vehicles measured.

Measurement point	Light vehicles	Moderate weight vehicles	Heavy weight vehicle
1 m from traffic calming measure	15	9	4
10 m away from speed table, near the testing apartment building	15	10	6
1st storey in apartment building hall	17	6	7
3rd storey in apartment building staircase	15	5	3
5th storey in apartment building staircase	28	5	4
Reference point 1m distance to street	15	9	4
Reference point 10 m distance to street	15	7	3

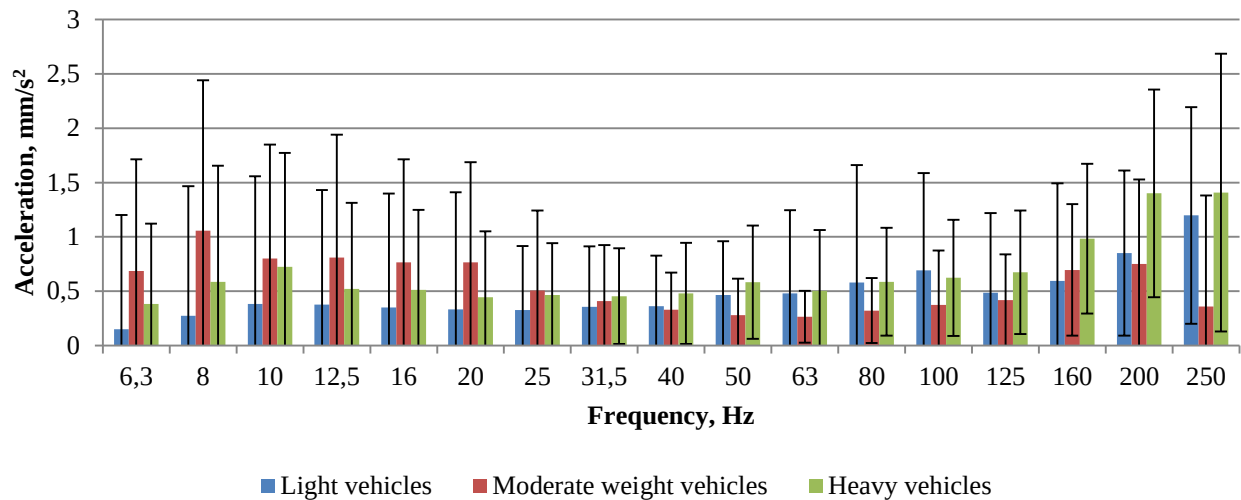


Fig. 3.18 Acceleration of the vibrations in first storey staircase in frequencies from 6,3 to 250 Hz

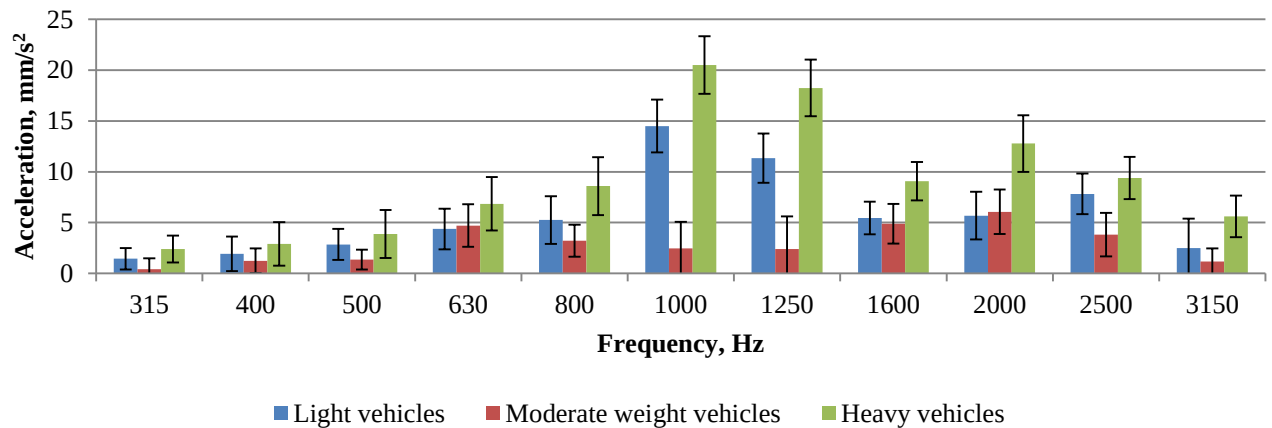


Fig. 3.19 Acceleration of the vibrations in first storey staircase in frequencies from 315 to 3150 Hz

At measurement point in first storey of apartment building maximum vibration acceleration was found when heavyweight transport was passing, maximum vibration was found at 1000 Hz frequency and acceleration was 21 mm/s². Light vehicles induced maximum vibrations was 14,5 mm/s² at 1000 Hz frequency and moderate weight vehicles induced vibrations 6,1 mm/s² at the frequency of 2000 Hz. Graphs of measurement results shown in 3.18. And 3.19. Figures.

Measurement results was compared with HN 50: 2003 threshold levels. At frequencies from 6,3 to 80 Hz vibration acceleration level, when light vehicles was passing was 1,2 to 6,1 % of the threshold level. When moderate weight vehicles was passing it reached from 0,6 to 21,1 % of the threshold level. When heavy weight transport was passing vibrations in first storey of the building reached from 1,2 to 11,8 % of the threshold level. No exceeding of threshold level was found.

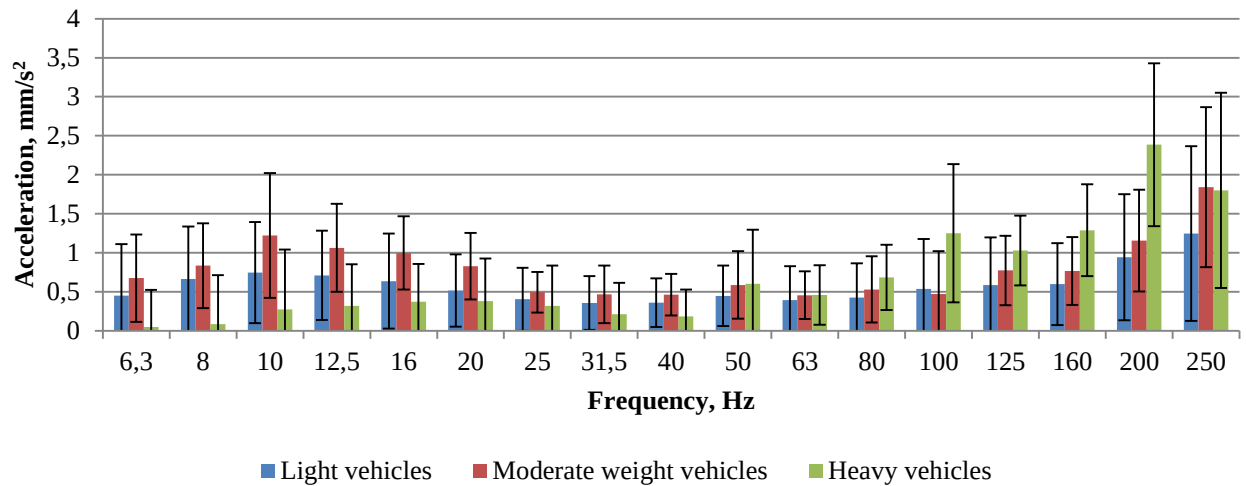


Fig. 3.20 Acceleration of the vibrations in third storey staircase in frequencies from 6,3 to 250

Hz

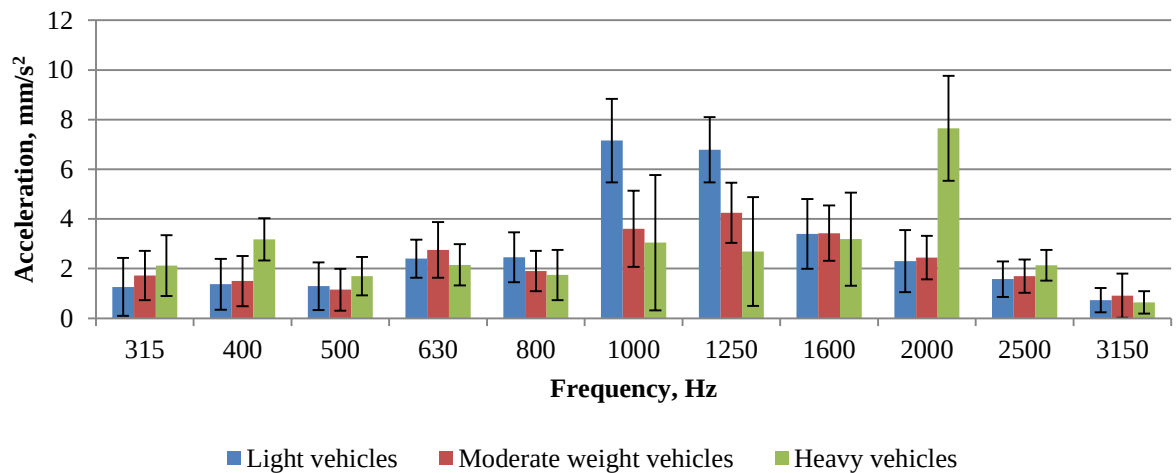


Fig. 3.21 Acceleration of the vibrations in third storey staircase in frequencies from 6,3 to 250

Hz

At measurement point in third storey of apartment building maximum vibration acceleration was found when heavyweight vehicles was passing, maximum vibration was found at 2000 Hz frequency and acceleration was 7,7 mm/s². Light vehicles induced maximum vibrations was 7,2 mm/s² at 1000 Hz frequency and moderate weight vehicles induced vibrations 4,3 mm/s² at the frequency of 1250 Hz. Graphs of measurement results shown in 3.20. and 3.21. Figures.

Measurement results was compared with HN 50: 2003 threshold levels. At frequencies from 6,3 to 80 Hz vibration acceleration level, when light vehicles was passing was from 0,9 to 13,2 % of the threshold level. When moderate weight vehicles was passing it reached from 1,1 to 19,4 % of the threshold level. When heavy weight transport was passing vibrations in third storey of the building reached from 0,7 to 4,3 % of the threshold level. No exceeding of threshold level was found.

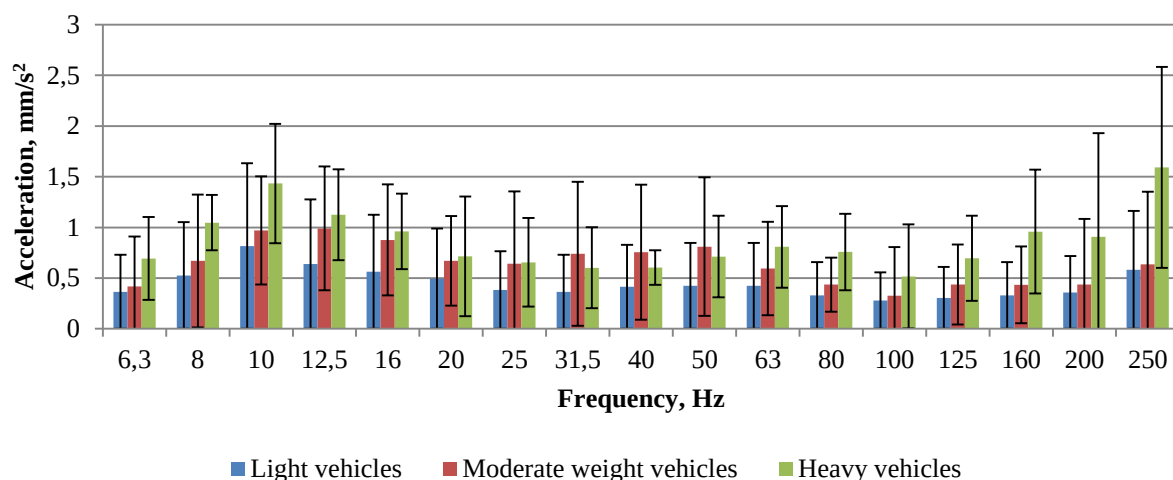


Fig. 3.22 Acceleration of the vibrations in fifth storey staircase in frequencies from 6,3 to 250

Hz

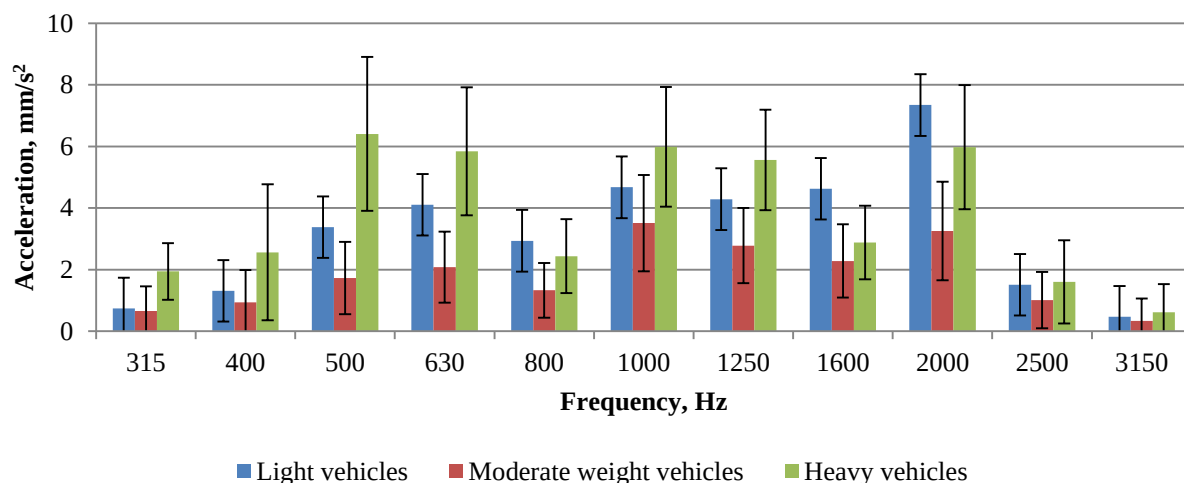


Fig. 3.23 Acceleration of the vibrations in fifth storey staircase in frequencies from 6,3 to 250

Hz

At measurement point in fifth storey of apartment building maximum vibration acceleration was found when light vehicles was passing, maximum vibration was found at 2000 Hz frequency and acceleration was $7,2 \text{ mm/s}^2$. Heavyweight vehicles induced maximum vibrations was $6,5 \text{ mm/s}^2$ at 500 Hz frequency and moderate weight vehicles induced vibrations $3,6 \text{ mm/s}^2$ at the frequency of 1000 Hz. Graphs of measurement results shown in 3.22. and 3.23. Figures.

Measurement results was compared with HN 50: 2003 threshold levels. At frequencies from 6,3 to 80 Hz vibration acceleration level, when light vehicles was passing was from 0,7 to 13,2 % of the threshold level. When moderate weight vehicles was passing it reached from 0,9 to 15,4 % of the threshold level. When heavy weight transport was passing vibrations in third storey of the building reached from 1,5 to 22,7 % of the threshold level. No exceeding of threshold level was found.

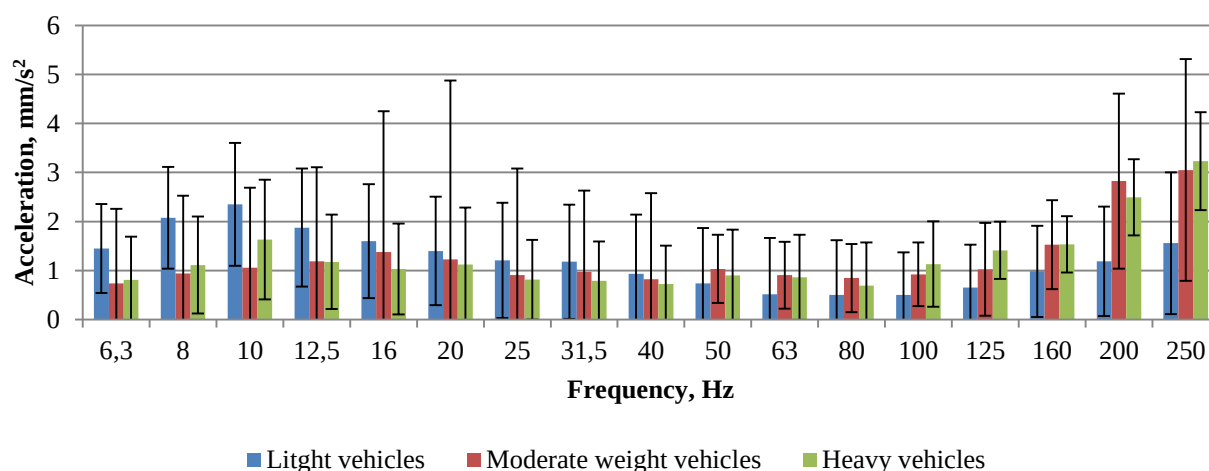


Fig. 3.24 Acceleration of the vibrations 1 m away from speed table in frequencies from 6,3 to 250 Hz

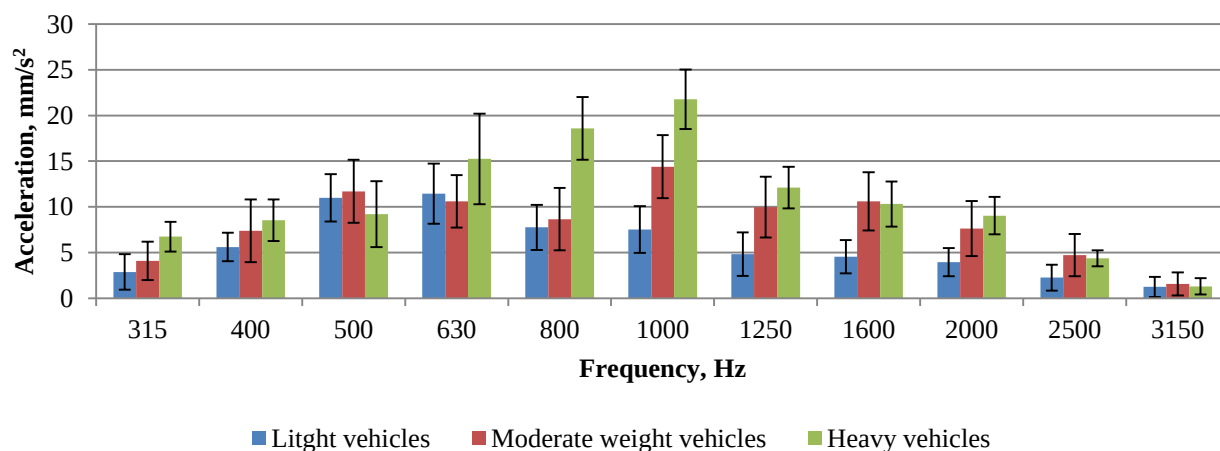


Fig. 3.25 Acceleration of the vibrations 1 m away from speed table in frequencies from 315 to 3150 Hz

In measurement one meter distance to the traffic calming measure, highest vibrations acceleration was found in 1000 Hz and 630 Hz frequencies (light vehicles 11,5 mm/s² at 630 Hz, moderate weight vehicles 14,4 mm/s² at 1000 Hz, heavyweight vehicles 21,8 mm/s² at 1000 Hz). During measurement was noticed that light and moderate weight vehicles when passing speed table reduced their speed less than heavyweight vehicles. But still heavy weight vehicles induces highest vibrations at this measurement point.

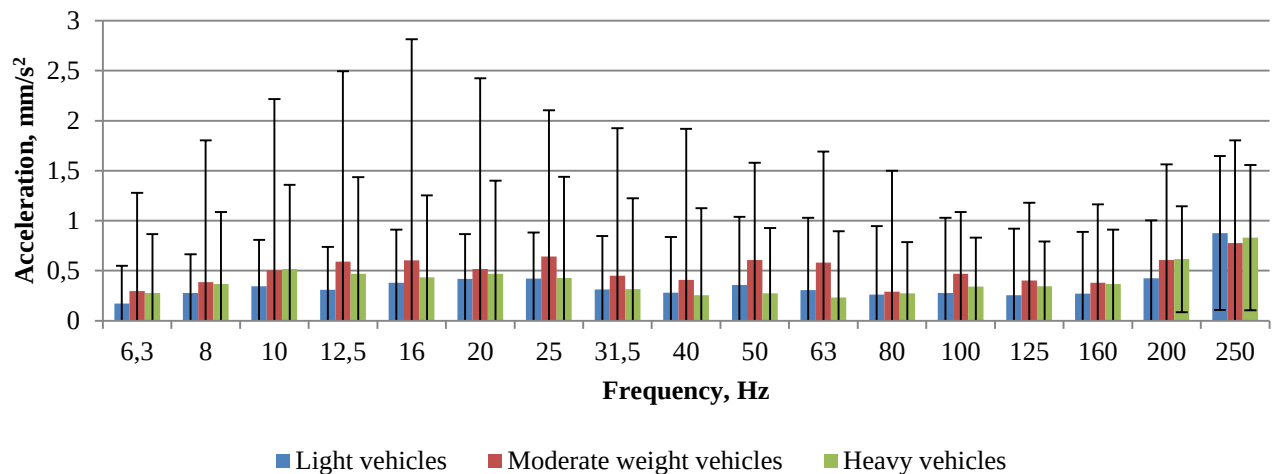


Fig. 3.26 Acceleration of the vibrations 10 m away from speed table near the test apartment building in frequencies from 6,3 to 250 Hz

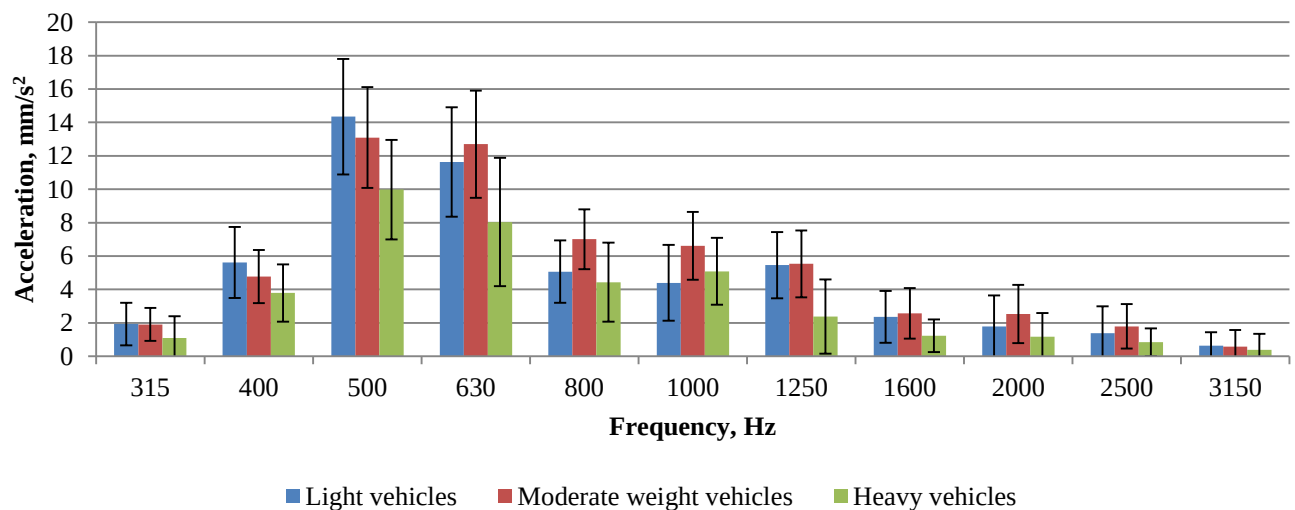


Fig. 3.27 Acceleration of the vibrations 10 m away from speed table near the test apartment building in frequencies from 315 to 3150 Hz

Acceleration of the vibration was measured 10 m away from speed table near the test apartment. Highest vibrations acceleration was found at 500 Hz frequencies (light vehicles 14,3 mm/s², moderate

weight vehicles $13,0 \text{ mm/s}^2$, heavyweight vehicles $9,9 \text{ mm/s}^2$). In this measurement point was found light weight vehicles induced higher vibration values than other categories vehicles, during measurements visually noticed that light and moderate weight vehicles passed speed table faster than heavy vehicles.

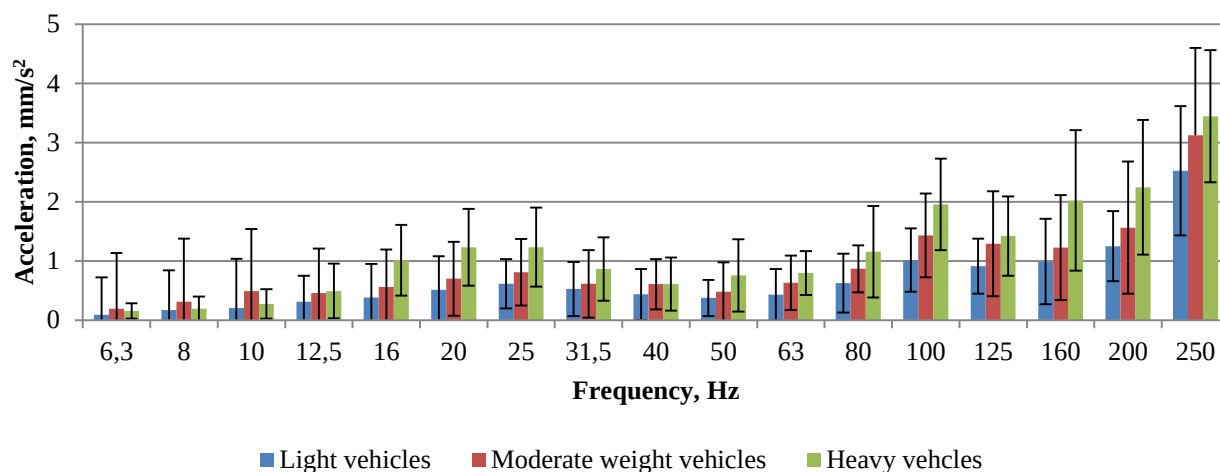


Fig. 3.28 Acceleration of the vibrations in reference point 1 m away from Asanavičiūtė street in frequencies from 6,3 to 250 Hz

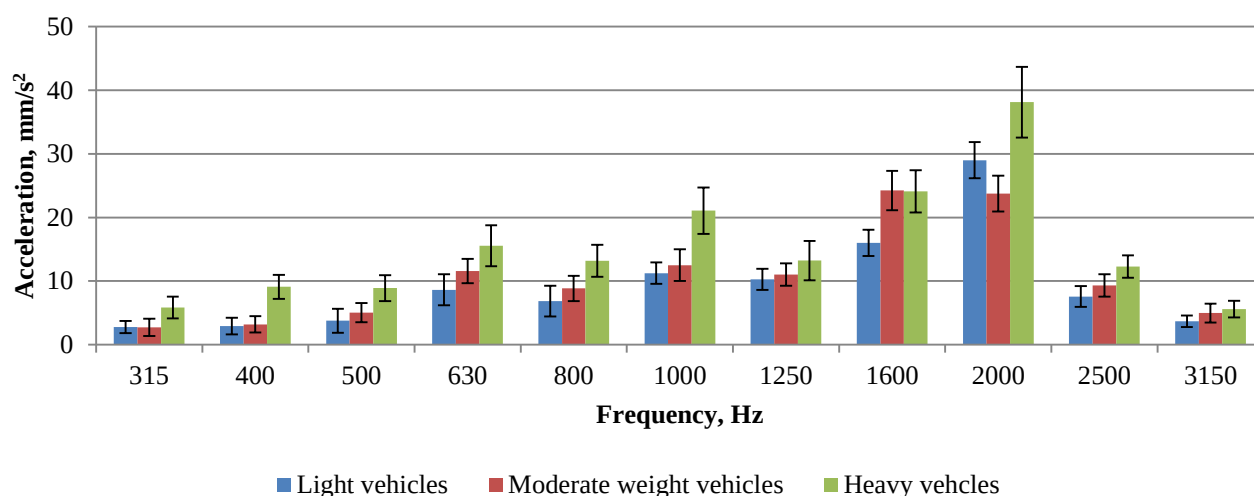


Fig. 3.29 Acceleration of the vibrations in reference point 1 m away from Asanavičiūtė street in frequencies from 315 to 3150 Hz

Acceleration of the vibration was measured in reference point 1 m from L. Asanavičiūtė Street where vertical traffic calming measure has no impact on the traffic induced vibrations. Highest vibrations acceleration was found at 2000 and 1600 Hz frequencies (light vehicles $29,0 \text{ mm/s}^2$ at 2000 Hz, moderate weight vehicles $24,8 \text{ mm/s}^2$ at 1600 Hz, heavyweight vehicles $38,1 \text{ mm/s}^2$ at 2000 Hz). Results is shown in 3.28 and 3.29 figures.

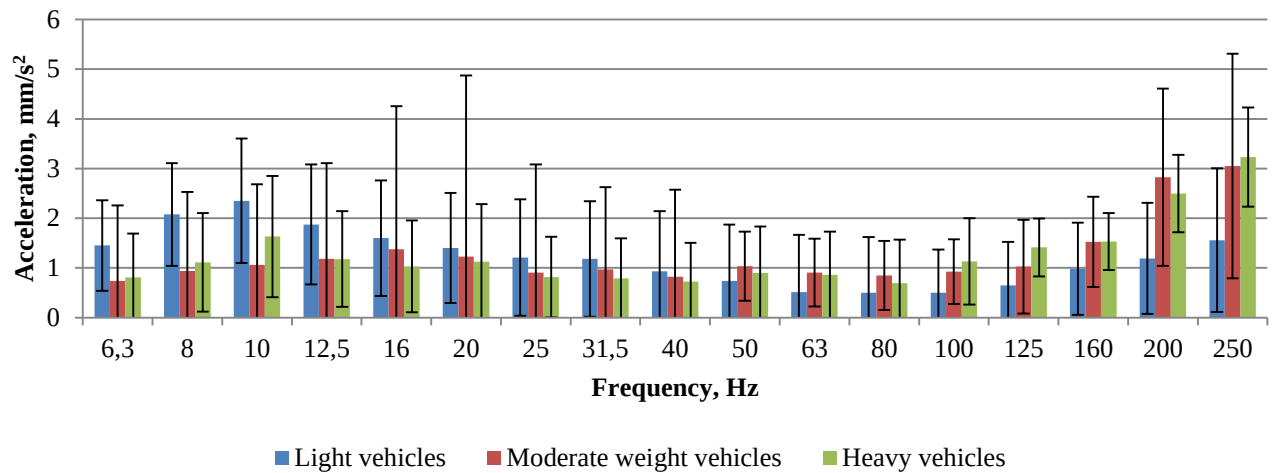


Fig. 3.30 Acceleration of the vibrations in reference point 10 m away from Asanavičiūtė street in frequencies from 6,3 to 250 Hz

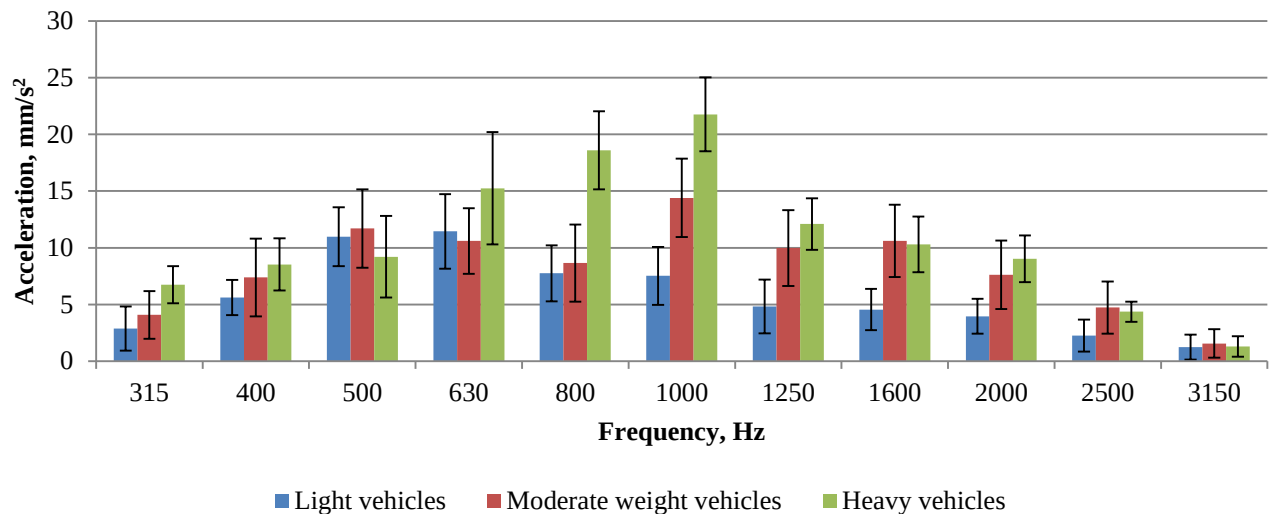


Fig. 3.31 Acceleration of the vibrations in reference point 10 m away from Asanavičiūtė Street in frequencies from 315 to 3150 Hz

Acceleration of the vibration was measured in reference point 10 m from L. Asanavičiūtė Street. Highest vibrations acceleration was found at 1000 Hz frequency (light vehicles 11,5 mm/s² at 630 Hz, moderate weight vehicles 14,4 mm/s² at 1000 Hz, heavyweight vehicles 21,8 mm/s² at 1000 Hz).

Summary of the results in measurement site

After the results analysis was found that highest acceleration of the vibrations was in reference measurement point 1 m distance to the street. Highest vibration values was induced by the heavy weight

vehicles. Inside the apartment building traffic induced vibrations was significantly smaller than in measurement points outside the building, it was found that vibration acceleration gain highest values at frequencies 500 – 2000 Hz.

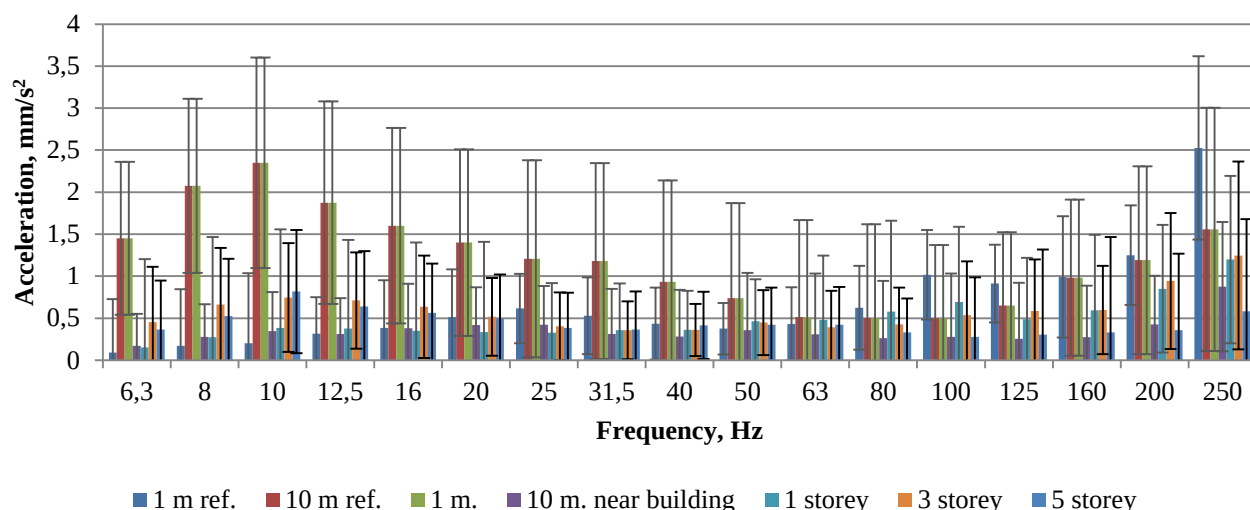


Fig. 3.32 Comparison of acceleration of the vibration when light vehicles is passing in different measurement points at frequencies 6,3 – 250 Hz.

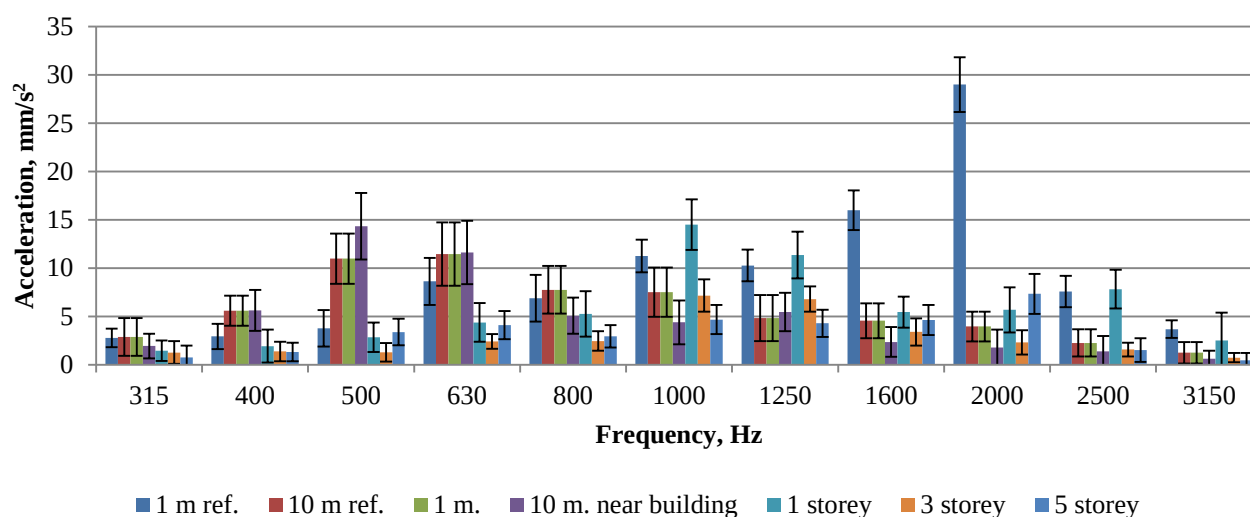


Fig. 3.33 Comparison of acceleration of the vibration when light vehicles is passing in different measurement points at frequencies 315 – 3150 Hz.

When light vehicles was passing in different measurements points (Fig. 3.32.) was found that values of acceleration of the vibration differ from 0,1 to 2,5 mm/s² at frequencies 6,3 – 250 Hz. Lowest value of the acceleration was found in 1m reference point, and the highest value was found in 1 m reference point. At frequencies from 315 to 3150 Hz (Fig. 3.33.) acceleration of the vibrations differ

from 0,7 to 29,0 mm/s². Lowest value of the acceleration was found in fifth storey staircase, and the highest value was found in 1 m reference point.

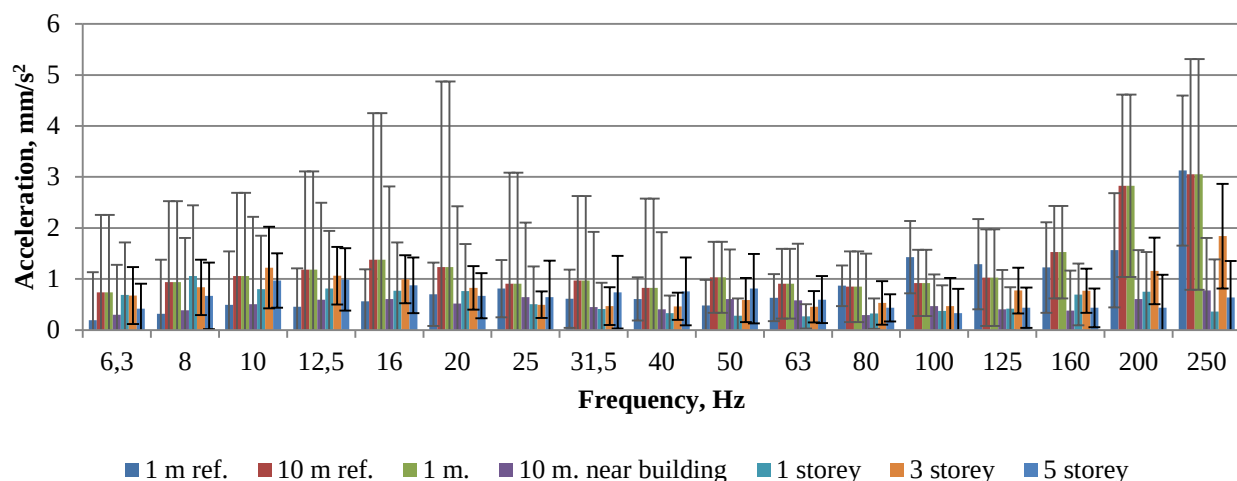


Fig. 3.34 Comparison of acceleration of the vibration when moderate weight vehicles is passing in different measurement points at frequencies 6,3 – 250 Hz.

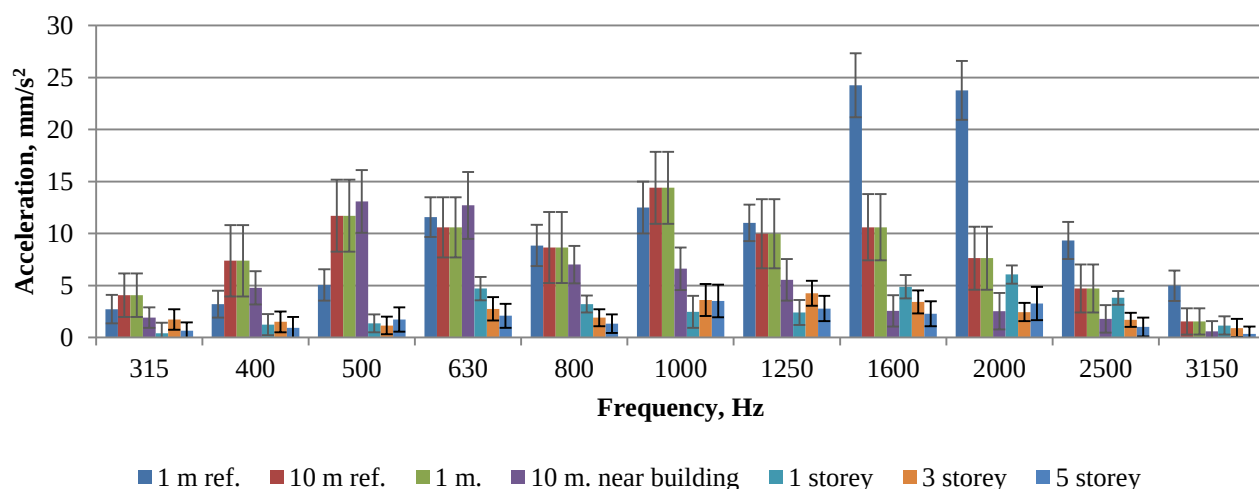


Fig. 3.35 Comparison of acceleration of the vibration when moderate weight vehicles is passing in different measurement points at frequencies 315 – 3150 Hz.

When moderate weight vehicles was passing in different measurements points (Fig. 3.34.) was found that values of acceleration of the vibration differ from 0,20 to 3,1 mm/s² at frequencies 6,3 – 250 Hz. Highest and lowest value of the acceleration was found in 1 m reference point. At frequencies from 315 to 3150 Hz (Fig. 3.35.) acceleration of the vibrations differ from 0,4 to 24,2 mm/s². Lowest value of the acceleration was found in first storey staircase, and the highest value was found in 1 m reference point.

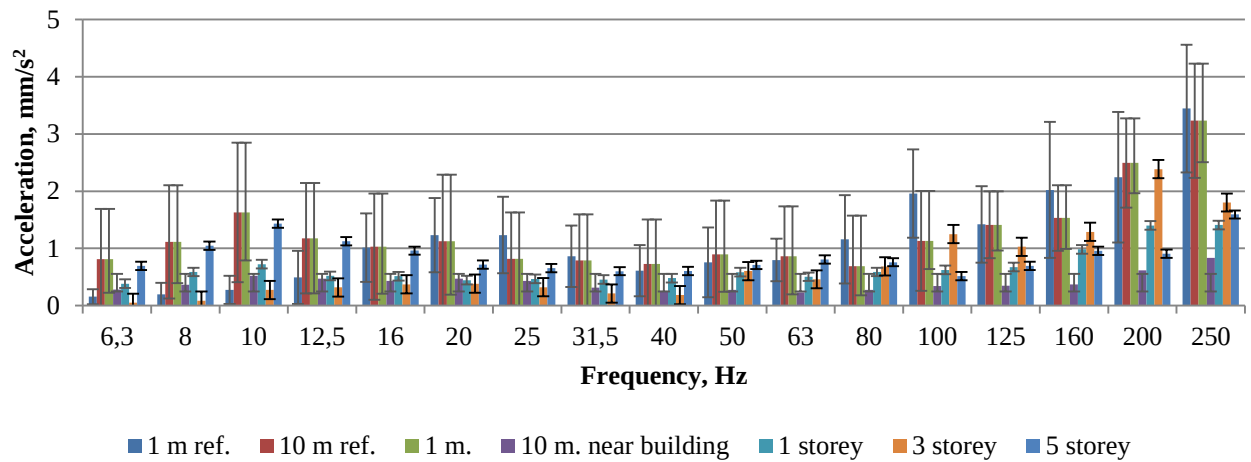


Fig. 3.36 Comparison of acceleration of the vibration when heavyweight vehicles is passing in different measurement points at frequencies 6,3 – 250 Hz.

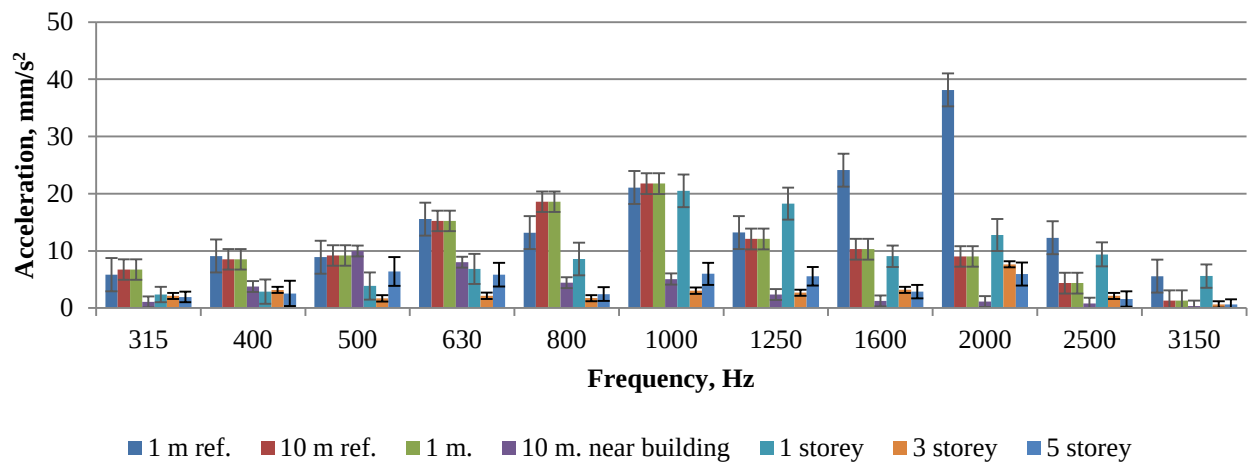


Fig. 3.37 Comparison of acceleration of the vibration when heavyweight vehicles is passing in different measurement points at frequencies 315 – 3150 Hz.

When heavyweight vehicles was passing in different measurements points (Fig. 3.36.) was found that values of acceleration of the vibration differ from 0,20 to 3,4 mm/s² at frequencies 6,3 – 250 Hz. Highest and lowest value of the acceleration was found in 1 m reference point. At frequencies from 315 to 3150 Hz (Fig. 3.37.) acceleration of the vibrations differ from 1,1 to 38,1 mm/s². Lowest value of the acceleration was found near the apartment building, and the highest value was found in 1 m reference point.

3.1.3. Research point No. 3. Verkių and Apkasų St. crossroad

Measurements of the ground borne vibration was done in 2016 – 01 – 11 d. During measurements air temperature was – 5,4 °C, wind speed 1,2 m/s, humidity 85,4% , atmosphere pressure 99,7 kPa. The vibration measurements was done to the axis z, because in this axis was found biggest vibration. Apartment building (Apkasų St. 5, Vilnius) is built 10,1 m distance to the speed table.

Table 3.3 Number of vehicles measured.

Measurement point	Light vehicles	Moderate weight vehicles	Heavy weight vehicle
1 m from traffic calming measure	18	17	6
10 m away from speed table, near the testing apartment building	15	16	5
1st storey in apartment building staircase	15	11	5
3rd storey in apartment building staircase	15	12	5
5th storey in apartment building staircase	15	10	4
Reference point 1m distance to street	15	15	5
Reference point 10 m distance to street	15	16	4

At measurement point in first storey of apartment building maximum vibration acceleration was found when heavyweight transport was passing, maximum vibration was found at 1250 Hz frequency and the acceleration was 6,3 mm/s².

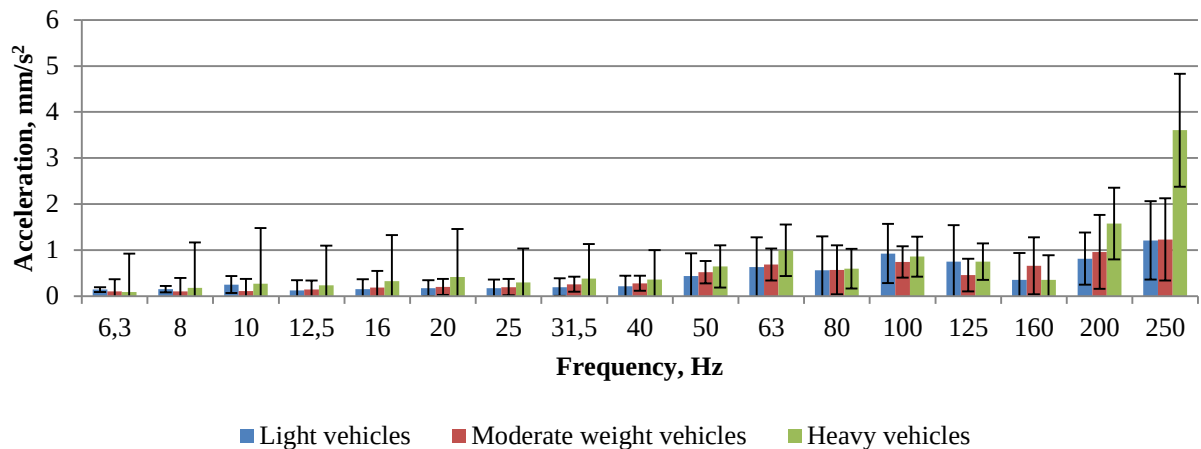


Fig. 3.38 Acceleration of the vibrations in first storey staircase in frequencies from 6,3 to 250 Hz

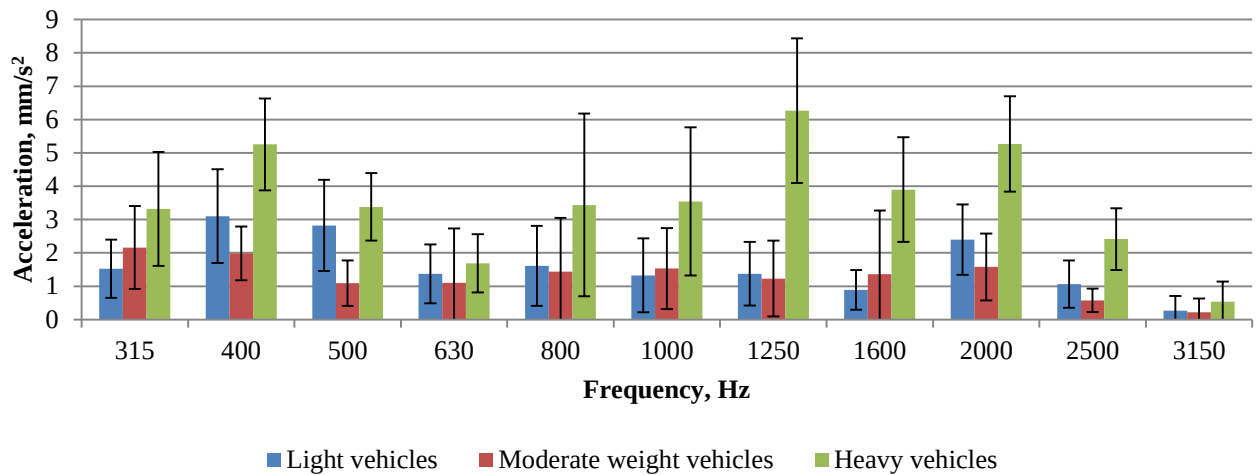


Fig. 3.39 Acceleration of the vibrations in first storey staircase in frequencies from 315 to 3150 Hz

Light vehicles induced maximum vibrations was 3,1 mm/s² at 400 Hz frequency and moderate weight vehicles induced vibrations 2,1 mm/s² at the frequency of 315 Hz. Graphs of measurement results shown in 3.38. And 3.39. Figures.

Measurement results was compared with HN 50: 2003 threshold levels. At frequencies from 6,3 to 80 Hz vibration acceleration level, when light vehicles was passing was up to 12 % of the threshold level. When moderate weight vehicles was passing it reached up to 17 % of the threshold level. When heavy weight transport was passing vibrations in first storey of the building also reached up to 17 % of the threshold level. No exceeding of threshold level was found.

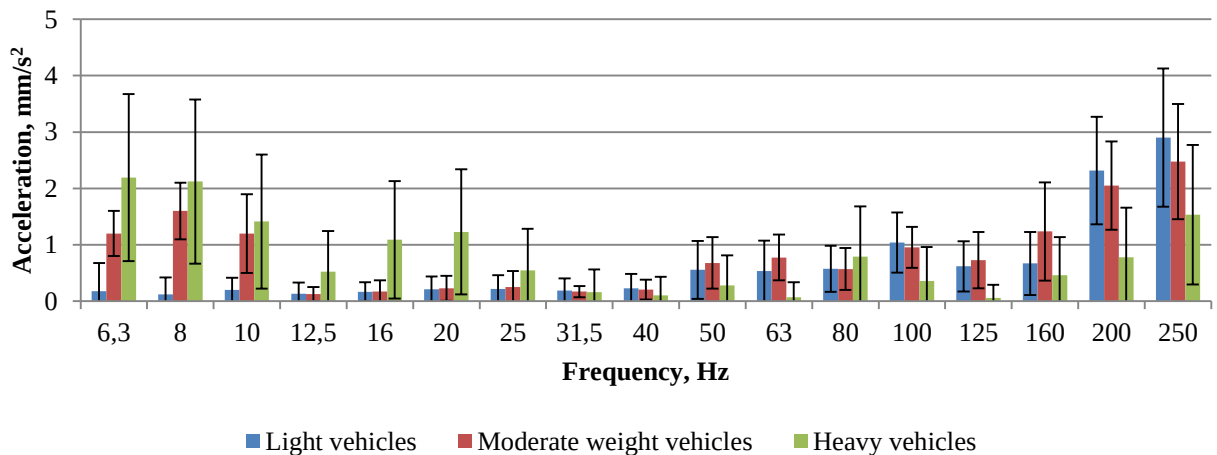


Fig. 3.40 Acceleration of the vibrations in third storey staircase in frequencies from 6,3 to 250 Hz

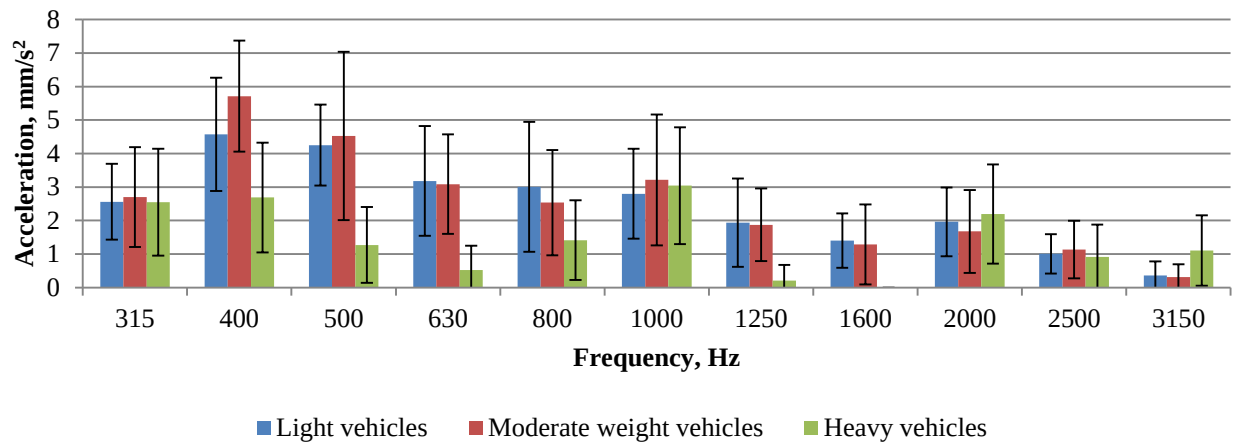


Fig. 3.41 Acceleration of the vibrations in third storey staircase in frequencies from 315 to 3150 Hz

At measurement point in third storey of apartment building maximum vibration acceleration was found when moderate weight transport was passing, maximum vibration was found at 400 Hz frequency and the acceleration was 5,7 mm/s². Light vehicles induced maximum vibrations was 4,5 mm/s² at 400 Hz frequency and heavyweight vehicles induced vibrations 2,7 mm/s² at the frequency of 315 Hz. Graphs of measurement results shown in 3.40. And 3.41. Figures. Heavyweight vehicles was mainly the public transport buses, these vehicles passed traffic calming measure very slowly.

Measurement results was compared with HN 50: 2003 threshold levels. At frequencies from 6,3 to 80 Hz vibration acceleration level, when light vehicles was passing was from 0,9 to 3,6 % of the threshold level. When moderate weight vehicles was passing it reached up to 32 % of the threshold level. When heavy weight transport was passing vibrations in third storey of the building also reached up to 44 % of the threshold level. No exceeding of threshold level was found.

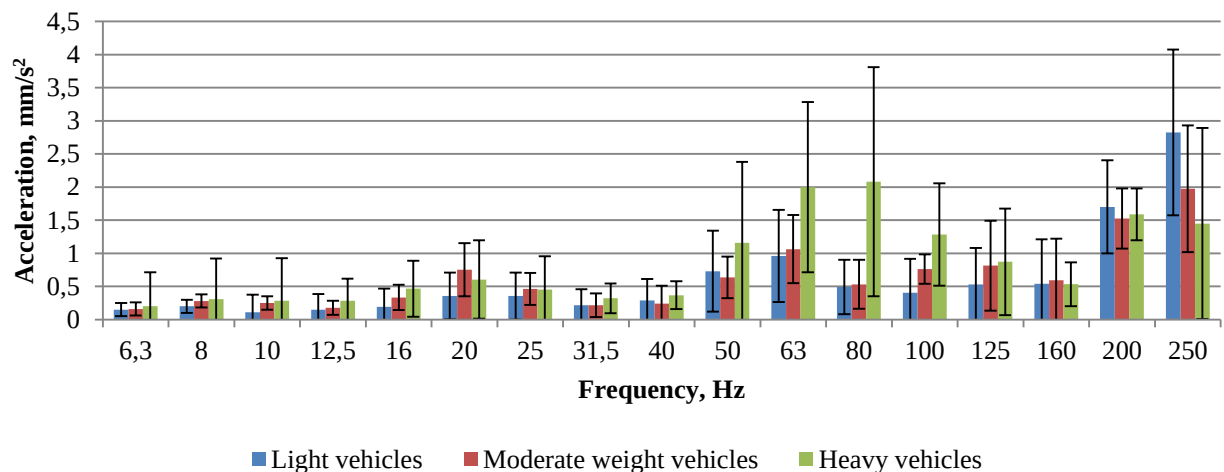


Fig. 3.42 Acceleration of the vibrations in fifth storey staircase in frequencies from 6,3 to 250 Hz

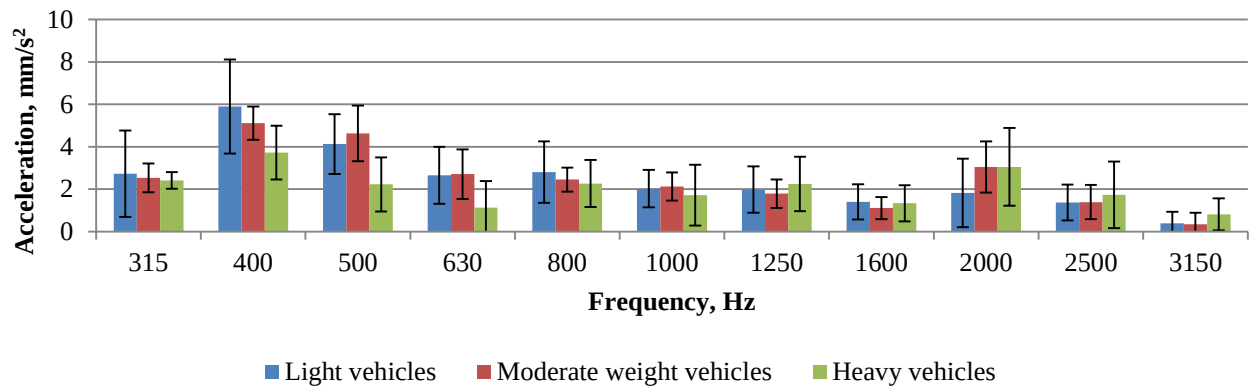


Fig. 3.43 Acceleration of the vibrations in fifth storey staircase in frequencies from 315 to 3150 Hz

At measurement point in fifth storey of apartment building maximum vibration acceleration was found when light vehicles was passing, maximum vibration was found at 400 Hz frequency and the acceleration was 5,9 mm/s². Moderate weight vehicles induced maximum vibrations was 5,1 mm/s² at 400 Hz frequency and heavyweight vehicles induced vibrations 3,7 mm/s² at the frequency of 400 Hz. Graphs of measurement results shown in 3.42. And 3.43. Figures. Heavyweight vehicles was mainly the public transport buses, these vehicles passed traffic calming measure very slowly.

Measurement results was compared with HN 50: 2003 threshold levels. At frequencies from 6,3 to 80 Hz vibration acceleration level, when light vehicles was passing was from 1 to 4 % of the threshold level. When moderate weight vehicles was passing it reached up to 6 % of the threshold level. When heavy weight transport was passing, vibrations in fifth storey of the building reached up to 6,2 % of the threshold level. No exceeding of threshold level was found.

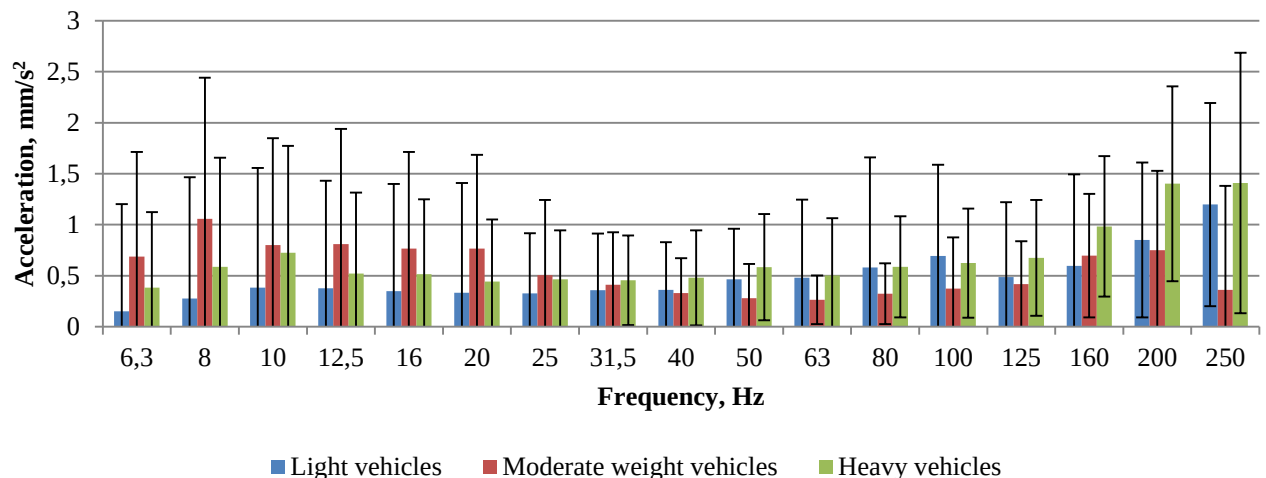


Fig. 3.44 Acceleration of the vibrations 1 m away from speed table in frequencies from 6,3 to 250 Hz

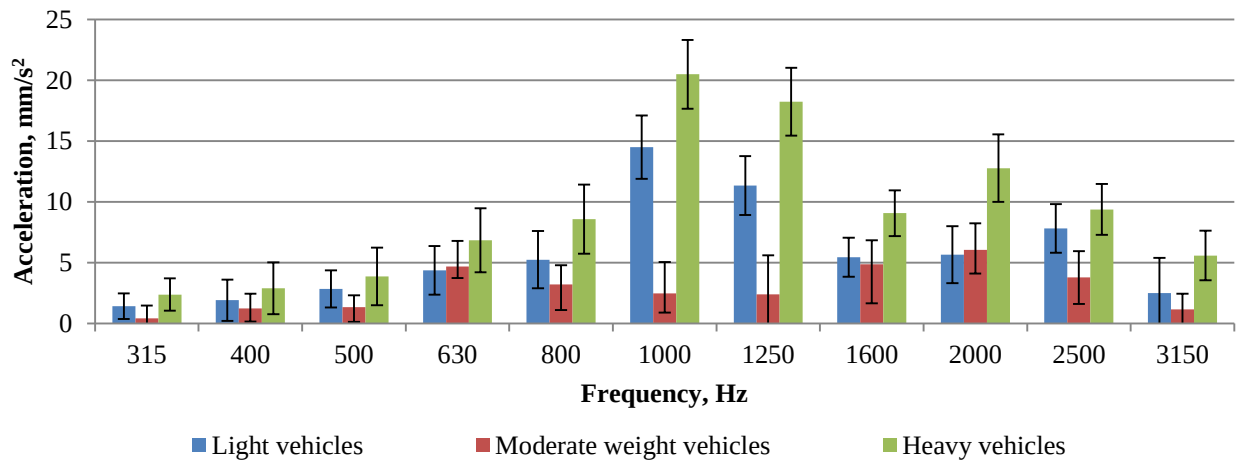


Fig. 3.45 Acceleration of the vibrations 1 m away from speed table in frequencies from 315 to 3150 Hz

In measurement one meter distance to the traffic calming measure, highest vibrations acceleration was found in 1000 Hz and 2000 Hz frequencies (light vehicles 14,5 mm/s² at 1000 Hz, moderate weight vehicles 6,0 mm/s² at 2000 Hz, heavyweight vehicles 20,5 mm/s² at 1000 Hz). During measurement was noticed that light and moderate weight vehicles when passing speed table reduced their speed less than heavyweight vehicles. But still heavy weight vehicles induces highest vibrations at this measurement point.

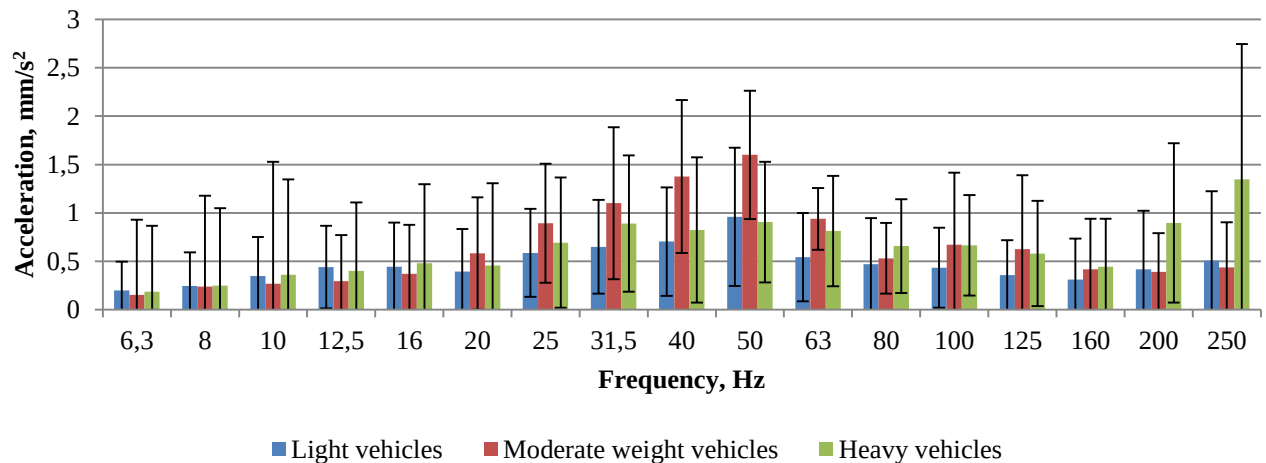


Fig. 3.46 Acceleration of the vibrations 10,1 m away from speed table, near the testing apartment building in frequencies from 6,3 to 250 Hz

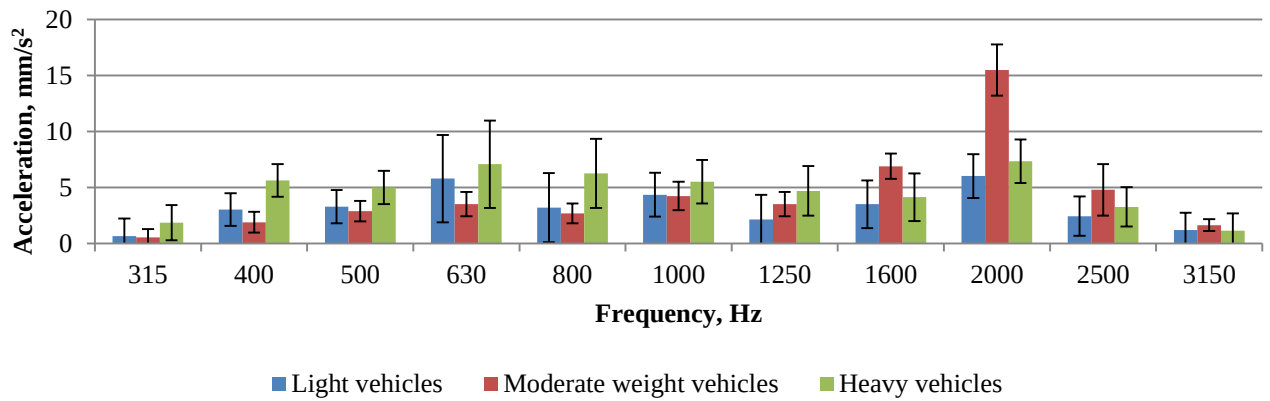


Fig. 3.47 Acceleration of the vibrations 10,1 m away from speed table, near the testing apartment building in frequencies from 315 to 3150 Hz

In measurement one meter distance to the traffic calming measure, highest vibrations acceleration was found in 2000 Hz frequency (light vehicles 6,0 mm/s² at 2000 Hz, moderate weight vehicles 15,5 mm/s² at 2000 Hz, heavyweight vehicles 7,4 mm/s² at 2000 Hz). During measurement was noticed that light and moderate weight vehicles when passing speed table reduced their speed less than heavyweight vehicles.

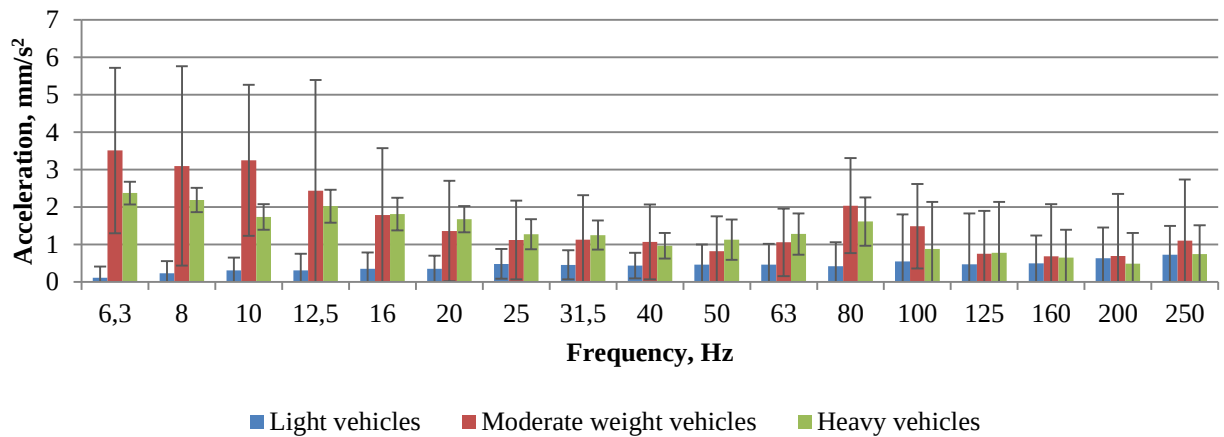


Fig. 3.48 Acceleration of the vibrations 1 m reference point in frequencies from 6,3 to 250 Hz

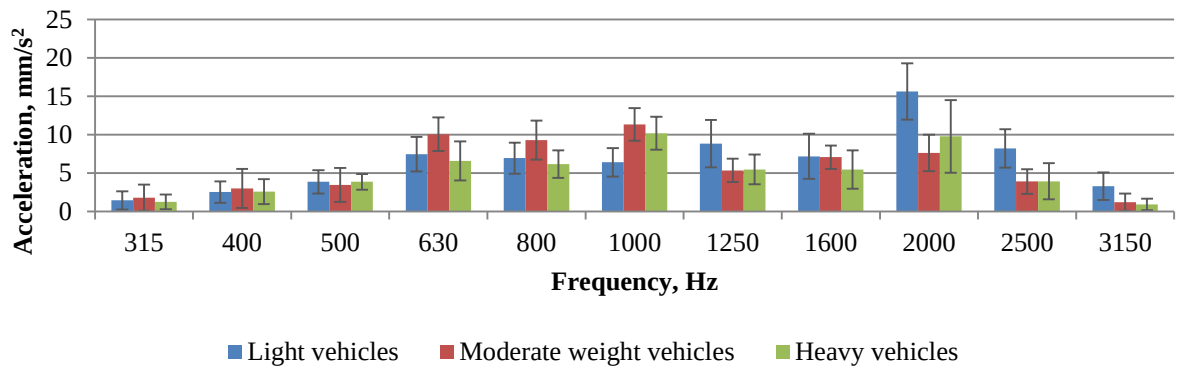


Fig. 3.49 Acceleration of the vibrations 1 m reference point in frequencies from 315 to 3150 Hz

In 1 m reference measurement point, highest vibrations acceleration was found in 2000 Hz and 1000 Hz frequencies (light vehicles 15,6 mm/s² at 2000 Hz, moderate weight vehicles 10,2 mm/s² at 1000 Hz, heavyweight vehicles 10,1 mm/s² at 1000 Hz). Moderate weight and light vehicles gains speed faster than heavy vehicles after passing speed table.

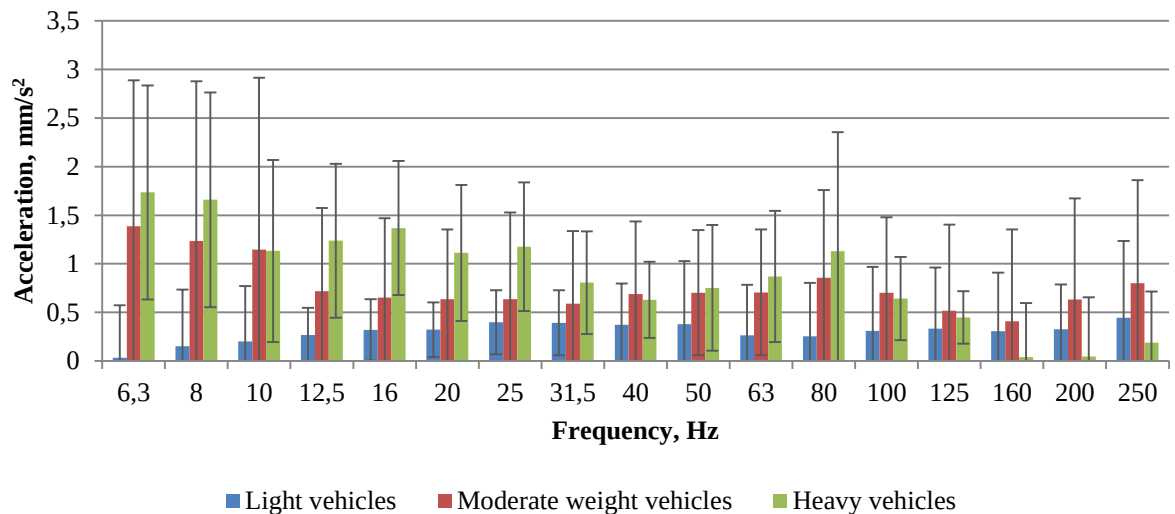


Fig. 3.50 Acceleration of the vibrations 1 m reference point in frequencies from 6,3 to 250 Hz

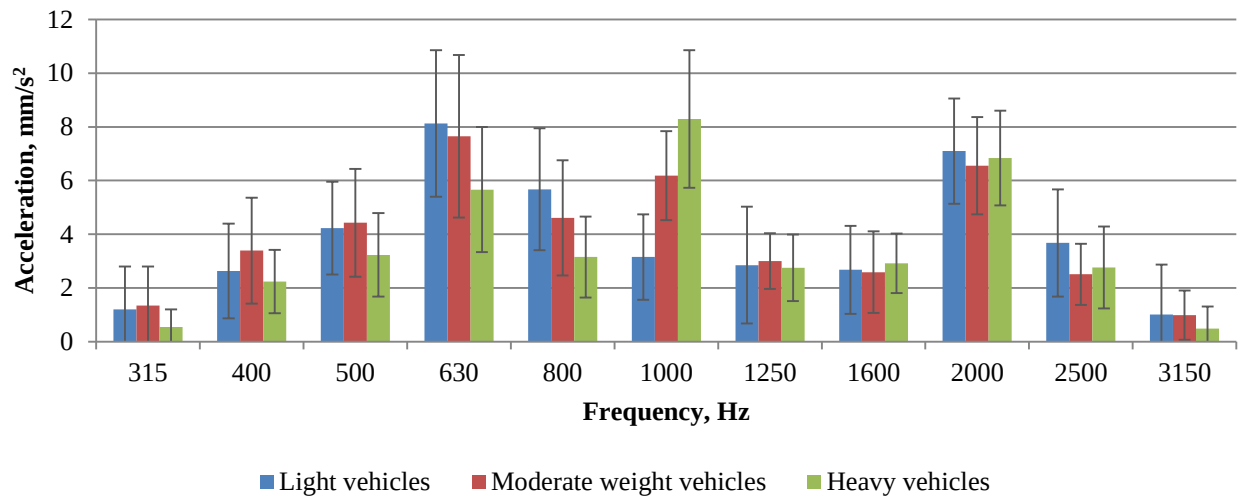


Fig. 3.51 Acceleration of the vibrations 1 m reference point in frequencies from 6,3 to 250 Hz

In 10 m reference measurement point, highest vibrations acceleration was found in 2000 Hz and 630 Hz frequencies (light vehicles 8,1 mm/s² at 630 Hz, moderate weight vehicles 7,7 mm/s² at 630 Hz, heavyweight vehicles 8,3 mm/s² at 1000 Hz). Moderate weight and light vehicles gains speed faster than heavy vehicles after passing speed table.

Summary of the results in measurement site

To sum up the results of measurement comparison between the different measurement points is done. Transport categories is separated.

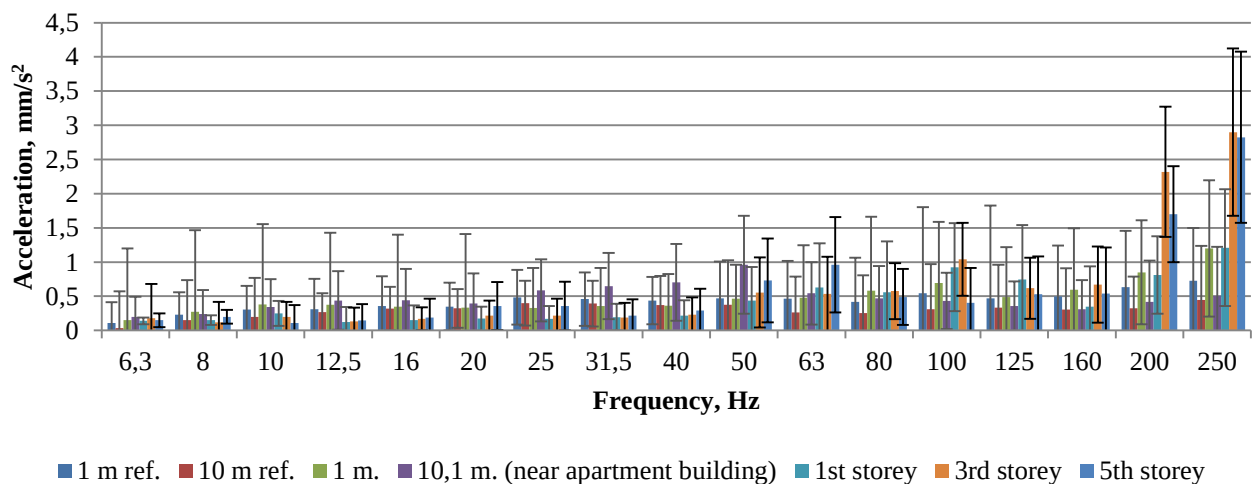


Fig. 3.52 Comparison of acceleration of the vibration when light vehicles is passing in different measurement points at frequencies 6,3 – 250 Hz.

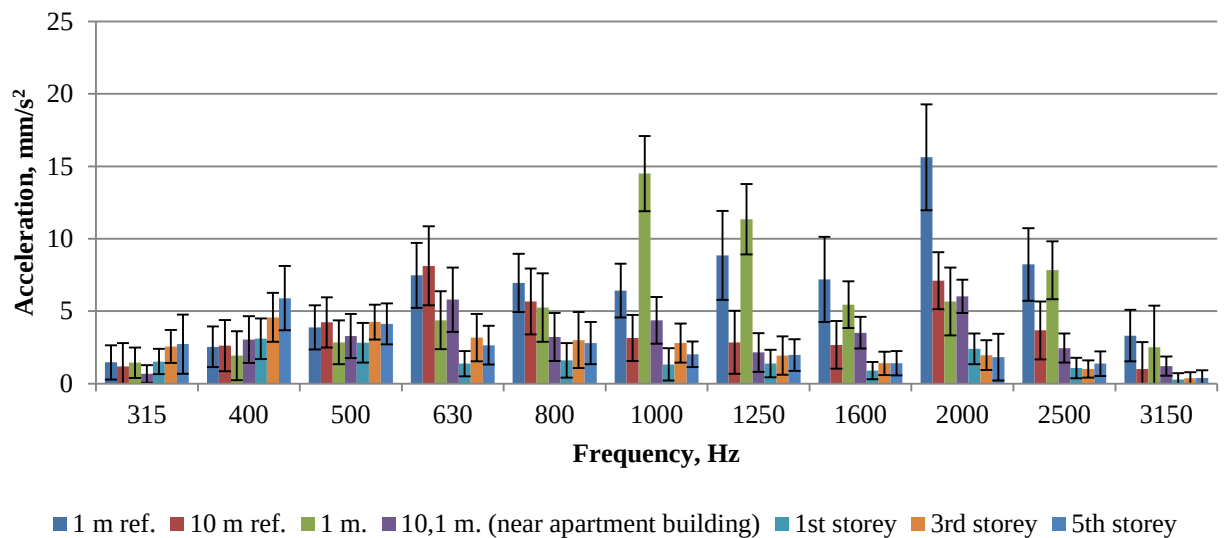


Fig. 3.53 Comparison of acceleration of the vibration when light vehicles is passing in different measurement points at frequencies 315 – 3150 Hz.

When light vehicles was passing in different measurements points (Fig. 3.52.) was found that values of acceleration of the vibration differ from 0,1 to 1,2 mm/s^2 at frequencies 6,3 – 250 Hz. Lowest value of the acceleration was found in 10 m reference point, and the highest value was found in 1 m near the speed table. At frequencies from 315 to 3150 Hz (Fig. 3.53.) acceleration of the vibrations differ from 0,3 to 15,6 mm/s^2 . Lowest value of the acceleration was found in first storey staircase, and the highest value was found in 1 m reference point.

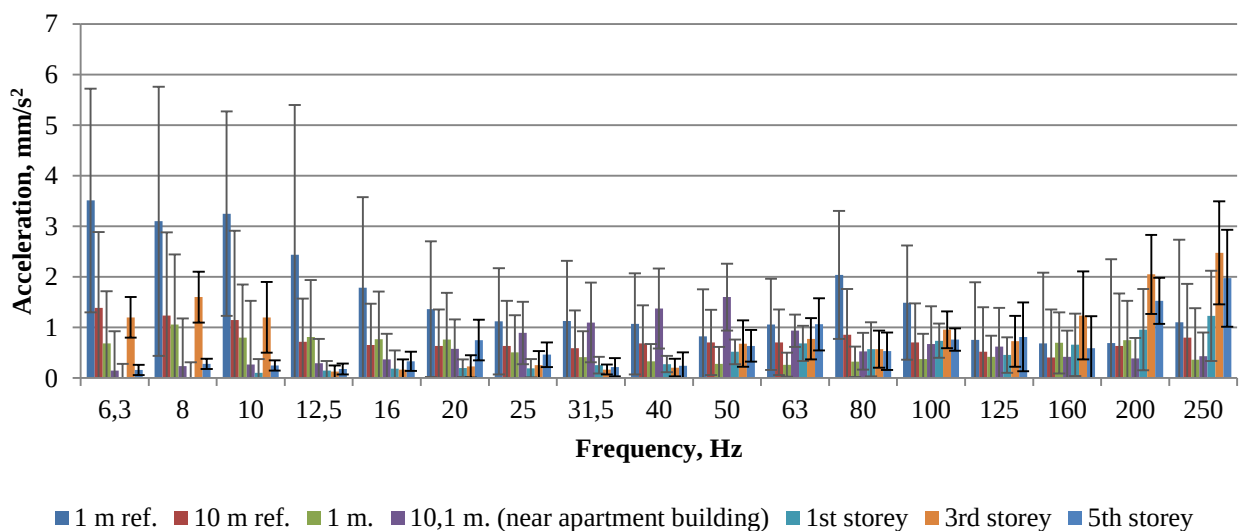


Fig. 3.54 Comparison of acceleration of the vibration when moderate weight vehicles is passing in different measurement points at frequencies 6,3 – 250 Hz.

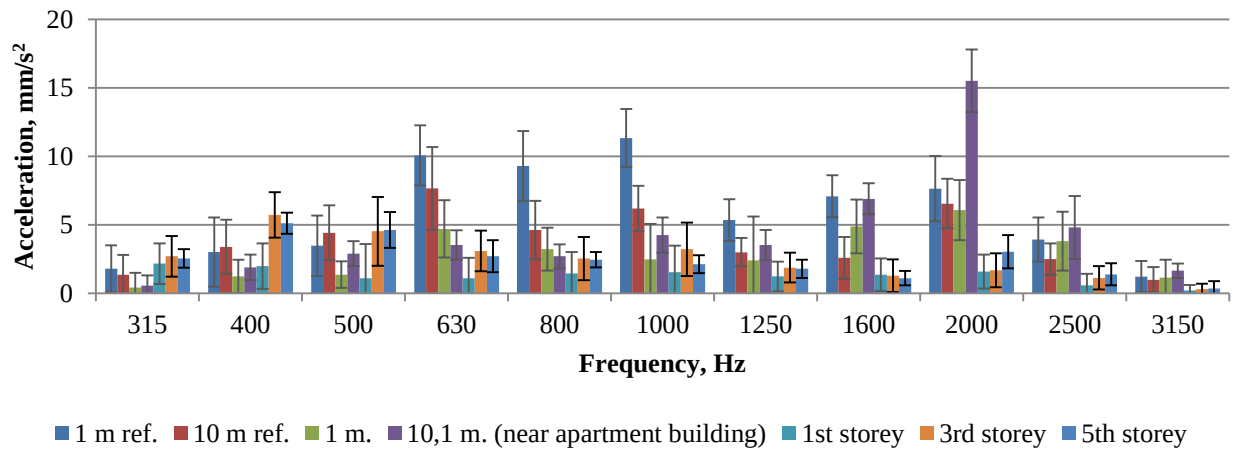


Fig. 3.55 Comparison of acceleration of the vibration when moderate weight vehicles is passing in different measurement points at frequencies 315 – 3150 Hz.

When moderate weight vehicles was passing in different measurements points (Fig. 3.54.) was found that values of acceleration of the vibration differ from 0,02 to 3,5 mm/s² at frequencies 6,3 – 250 Hz. Lowest value of the acceleration was found in 10 m reference point, and the highest value was found in 1 m near the speed table. At frequencies from 315 to 3150 Hz (Fig. 3.55.) acceleration of the vibrations differ from 0,2 to 15,5 mm/s². Lowest value of the acceleration was found in first storey staircase, and the highest value was found in near the apartment building.

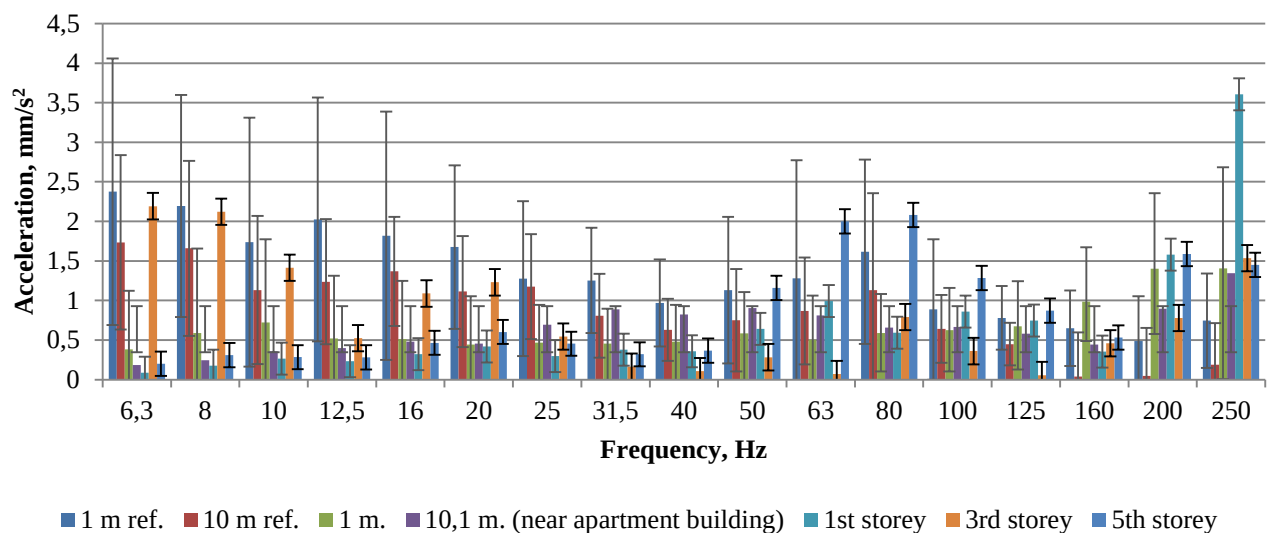


Fig. 3.56 Comparison of acceleration of the vibration when heavyweight vehicles is passing in different measurement points at frequencies 6,3 – 250 Hz.

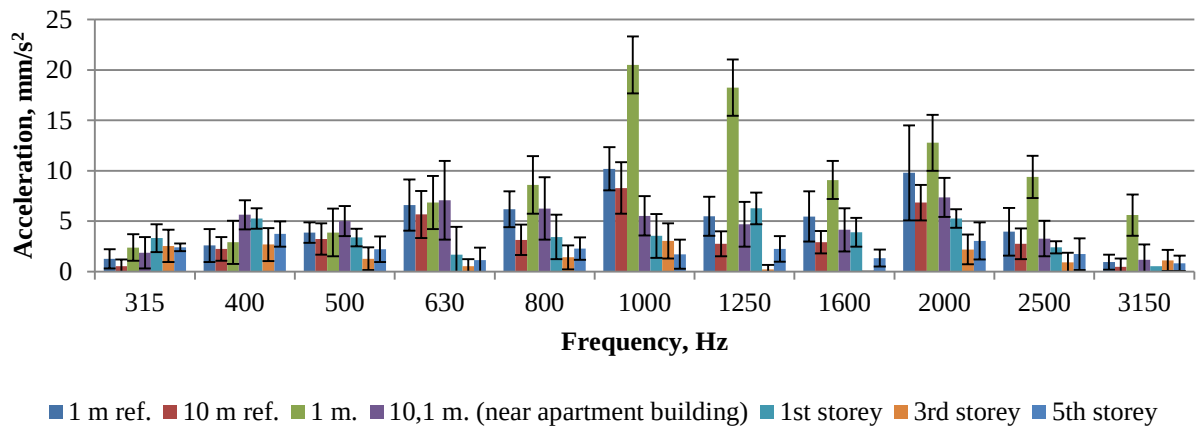


Fig. 3.57 Comparison of acceleration of the vibration when heavyweight vehicles is passing in different measurement points at frequencies 315 – 3150 Hz.

When heavyweight vehicles was passing in different measurements points (Fig. 3.56.) was found that values of acceleration of the vibration reach up to 3,5 mm/s² at frequencies 6,3 – 250 Hz. Highest lowest value of the acceleration was found in the first storey of the apartment building. At frequencies from 315 to 3150 Hz (Fig. 3.57.) acceleration of the vibrations differ from 0,2 to 15,5 mm/s². Lowest value of the acceleration was found in first storey staircase, and the highest value was found in near the apartment building.

3.1.4. Research point No. 4. Gurių 51 St., Vilnius

Measurements of the ground borne vibration was done in 2016 – 01 – 19 d. During measurements air temperature was – 6,1 °C, wind speed 0,3 m/s, humidity 68,7 % , atmosphere pressure 100,1 kPa. The vibration measurements was done to the axis z, because in this axis was found biggest vibration. Apartment building (Gurių St. 51, Vilnius) is built 15 m distance to the speed table. In this measurement site heavy weight transportation is forbidden, in this measurement site heavy weight vehicles was not measured.

Table 3.4 Number of vehicles measured.

Measurement point	Light vehicles	Moderate weight vehicles	Heavy weight vehicle
1 m from traffic calming measure	15	22	0
15 m away from speed table, near the testing apartment building	15	23	0
Reference point 1m distance to street	16	14	0
Reference point 10 m distance to street	19	14	0
1st storey in apartment building corridor	15	15	0
3rd storey in apartment building corridor	15	15	0

At measurement point in first storey of apartment building maximum vibration acceleration was found that acceleration was similar, maximum vibration was found at 2000 Hz frequency and the acceleration was 4,9 mm/s² (light vehicles).

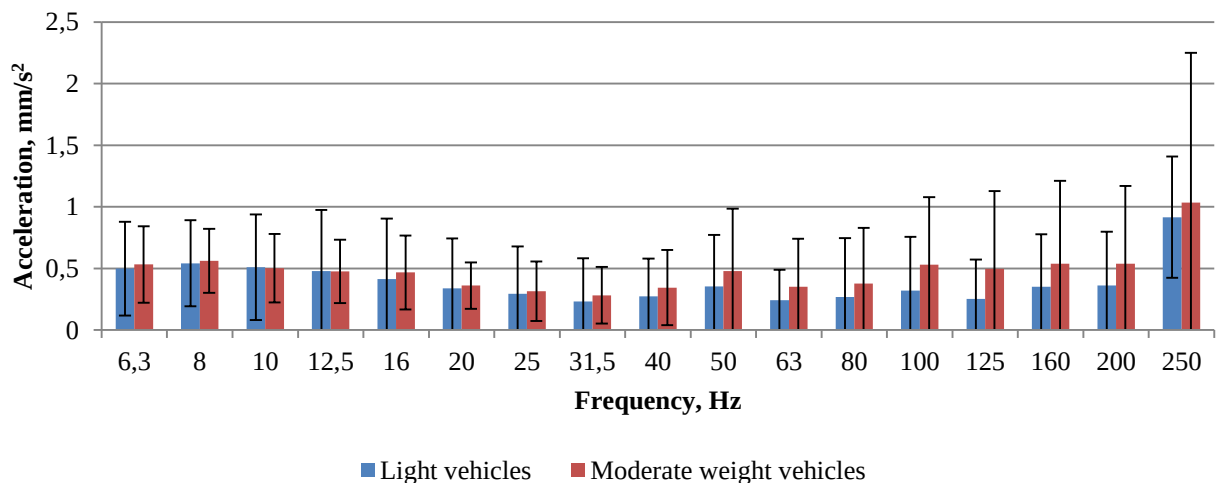


Fig. 3.58 Acceleration of the vibrations in first storey corridor in frequencies from 6,3 to 250 Hz

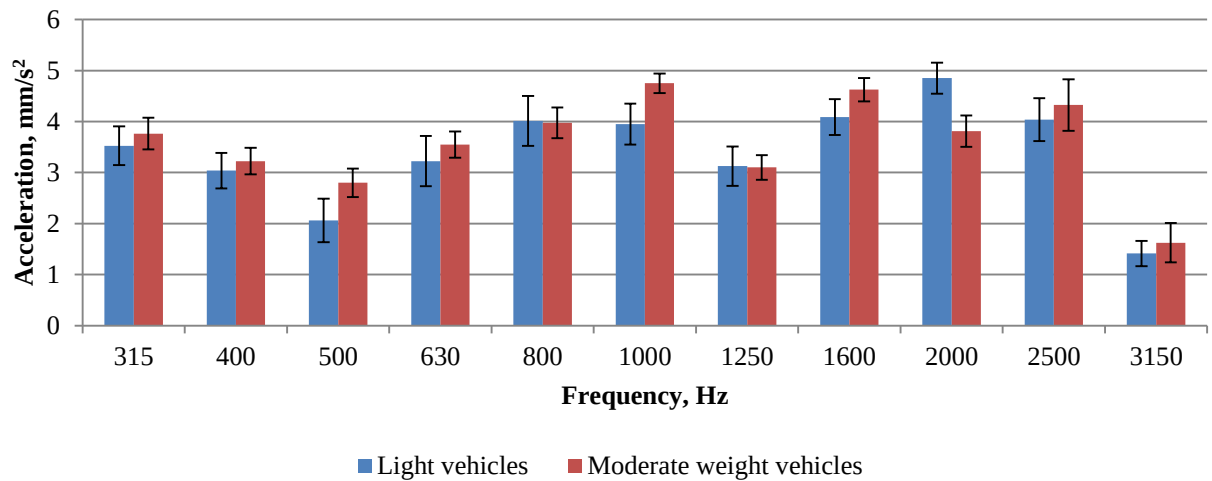


Fig. 3.59 Acceleration of the vibrations in first storey corridor in frequencies from 315 to 3150 Hz

Moderate weight vehicles maximum induced vibration was $4,8 \text{ mm/s}^2$ at 1000 Hz frequency. Graphs of measurement results shown in 3.58. And 3.59. Figures.

Measurement results was compared with HN 50: 2003 threshold levels. At frequencies from 6,3 to 80 Hz vibration acceleration level, when light vehicles was passing was up to 11 % of the threshold level. When moderate weight vehicles was passing it also reached up to 11 % of the threshold level.

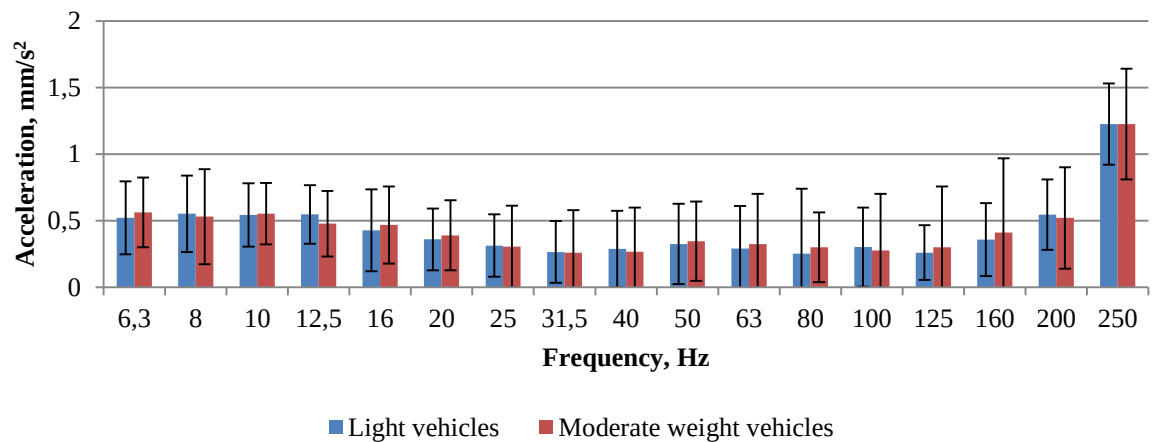


Fig. 3.60 Acceleration of the vibrations in third storey corridor in frequencies from 6,3 to 250 Hz

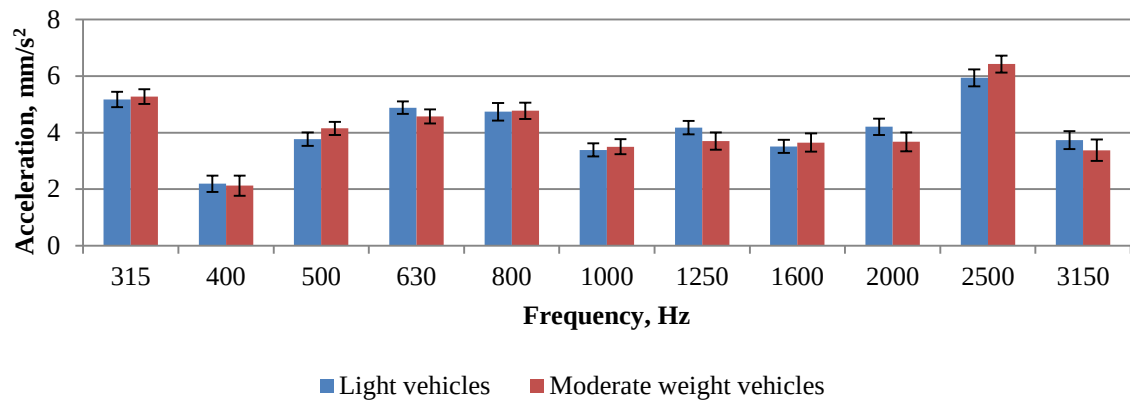


Fig. 3.61 Acceleration of the vibrations in third storey corridor in frequencies from 315 to 3150 Hz

At measurement point in first storey of apartment building maximum vibration acceleration was found that acceleration was similar, maximum vibration was found at 2500 Hz frequency and the acceleration was 6,4 mm/s² (moderate weight vehicles). Light vehicles maximum induced vibration was 5,9 mm/s² at 2500 Hz frequency. Graphs of measurement results shown in 3.60. And 3.61. Figures.

Measurement results was compared with HN 50: 2003 threshold levels. At frequencies from 6,3 to 80 Hz vibration acceleration level, when light vehicles was passing was up to 11 % of the threshold level. When moderate weight vehicles was passing it also reached up to 11 % of the threshold level.

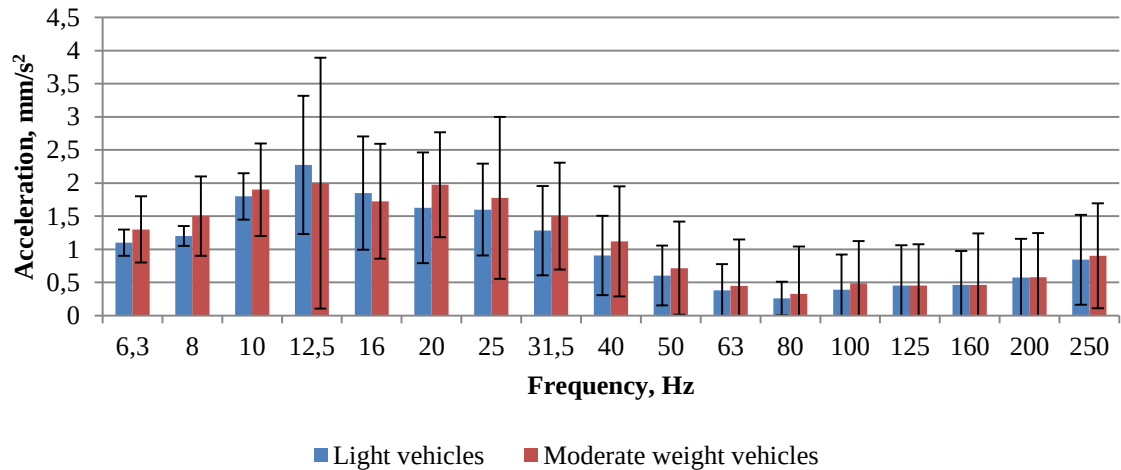


Fig. 3.62 Acceleration of the vibrations 1 m away from speed table in frequencies from 6,3 to 250 Hz

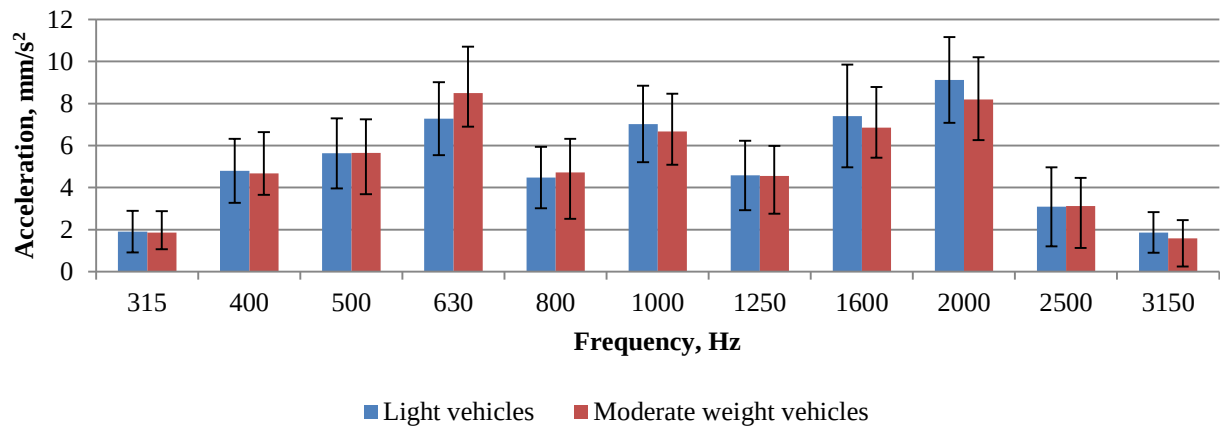


Fig. 3.63 Acceleration of the vibrations 1 m away from speed table in frequencies from 315 to 3150 Hz

In measurement one meter distance to the traffic calming measure, highest vibrations acceleration was found in 630 Hz and 2000 Hz frequencies (light vehicles 9,1 mm/s² at 2000 Hz, moderate weight vehicles 8,5 mm/s² at 630 Hz). Results are shown in Fig. 62. And Fig. 63. Usually light vehicles passed speed table faster than moderate weight vehicles.

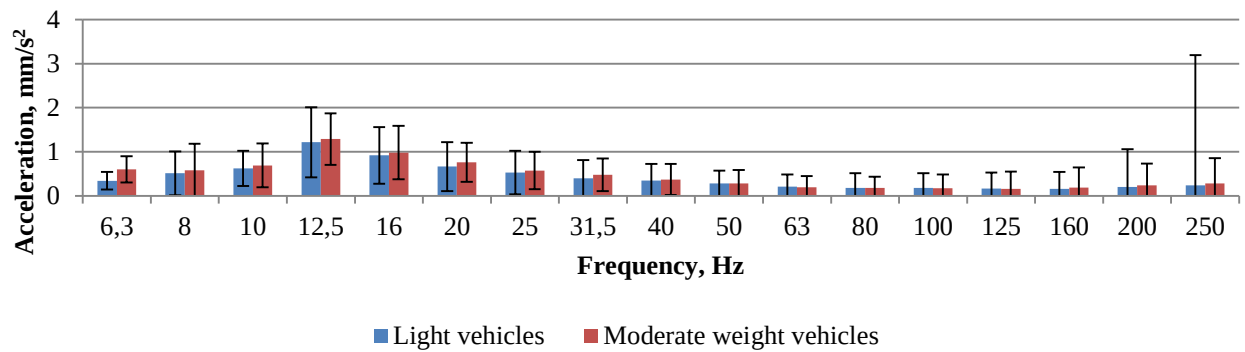


Fig. 3.64 Acceleration of the vibrations 15 m away from speed table, near the apartment building in frequencies from 6,3 to 250 Hz

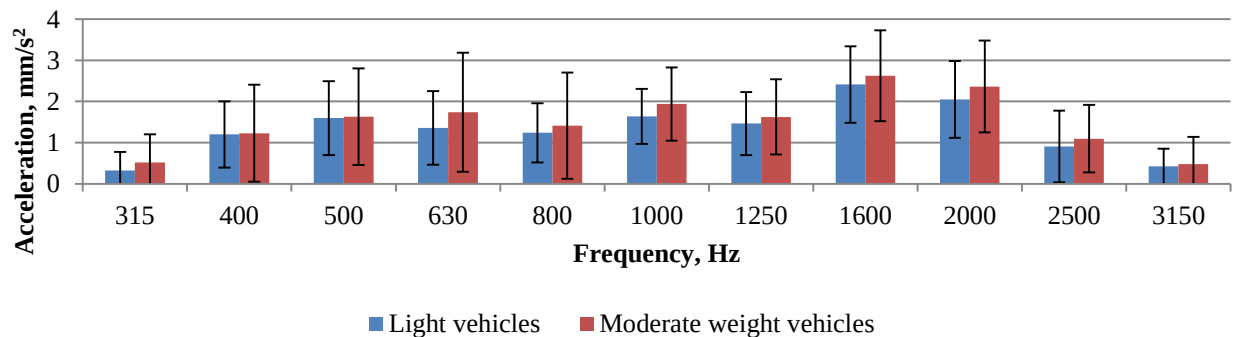


Fig. 3.65 Acceleration of the vibrations 15 m away from speed table, near the apartment building in frequencies from 6,3 to 250 Hz

In measurement one meter distance to the traffic calming measure, highest vibrations acceleration was found in 1600 Hz frequency (light vehicles 2,4 mm/s², moderate weight vehicles 2,6 mm/s²). Results are shown in Fig. 64. and Fig. 65.

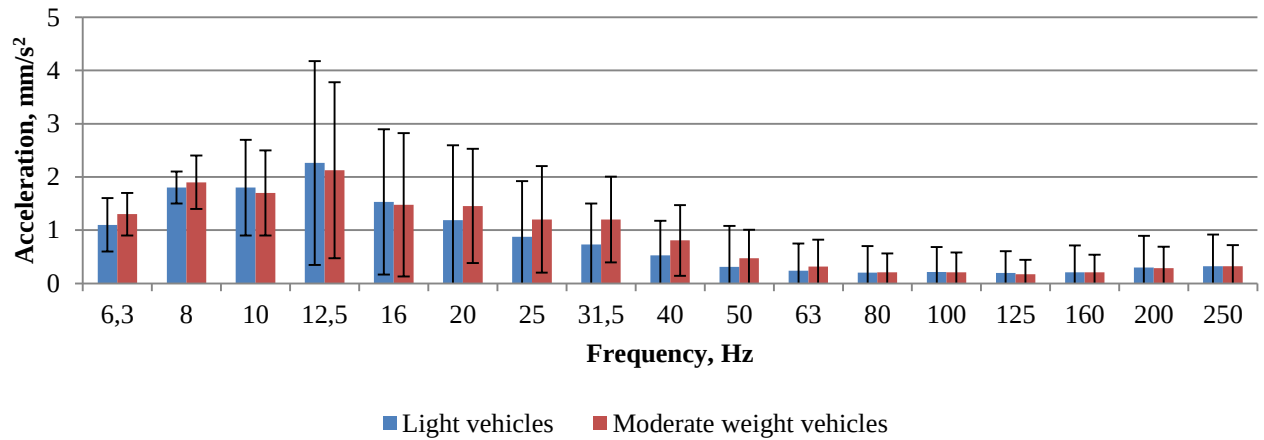


Fig. 3.66 Acceleration of the vibrations 1 m reference point in frequencies from 6,3 to 250 Hz

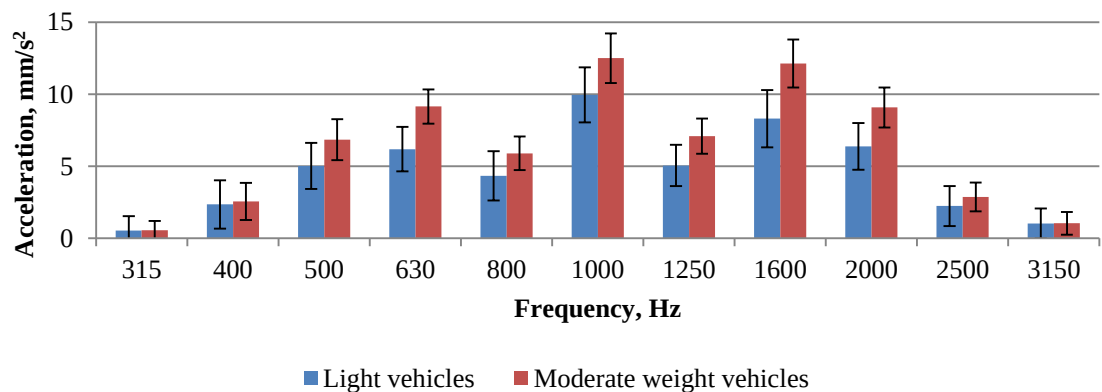


Fig. 3.67 Acceleration of the vibrations 1 m reference point in frequencies from 315 to 3150 Hz

In 1 m reference measurement point, highest vibrations acceleration was found in 1000 Hz and 1600 Hz frequencies (light vehicles 10,0 mm/s² at 1000 Hz, moderate weight vehicles 12,1 mm/s² at 1600 Hz). Moderate weight and light vehicles ran in similar speed through this measurement point.

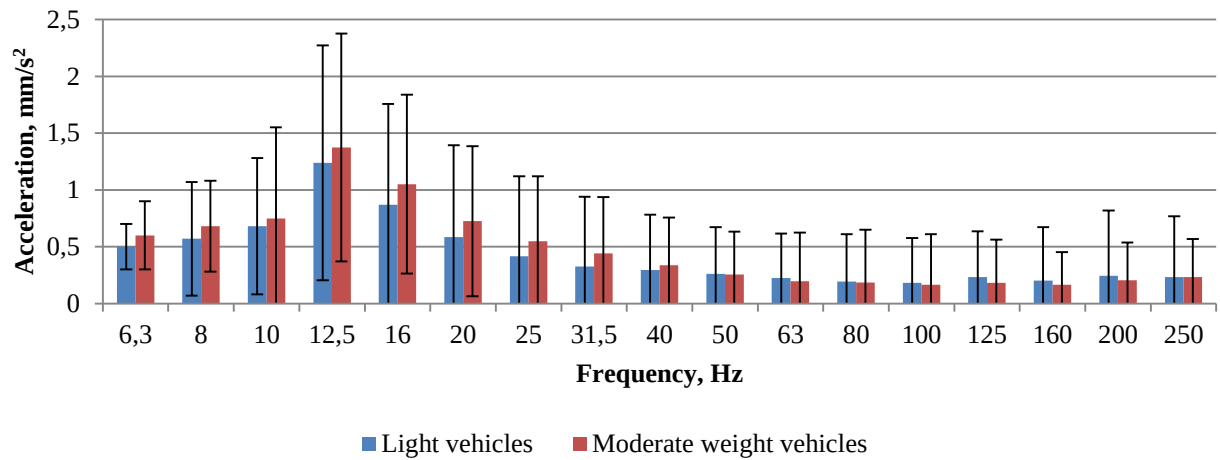


Fig. 3.68 Acceleration of the vibrations 10 m reference point in frequencies from 6,3 to 250 Hz

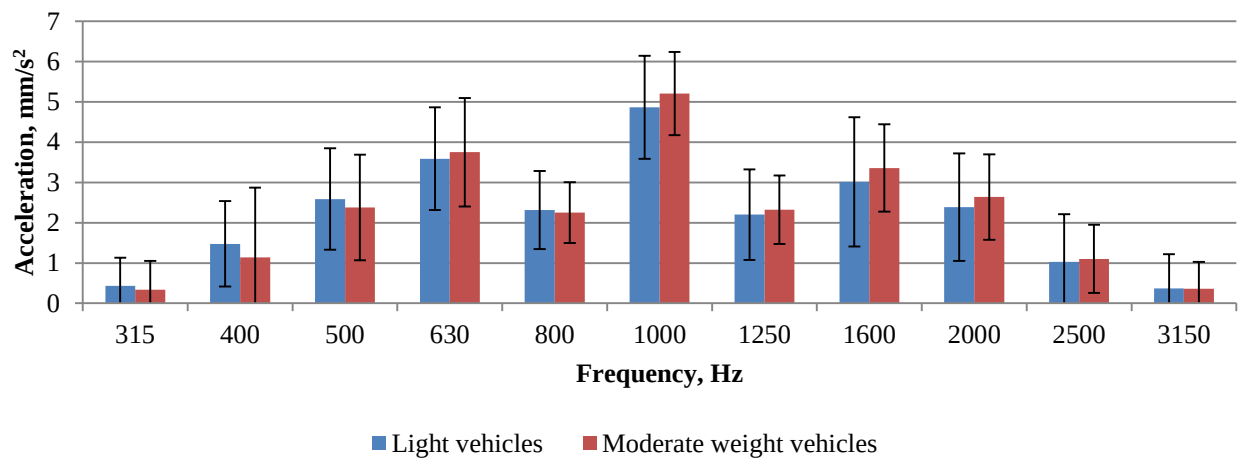


Fig. 3.69 Acceleration of the vibrations 10 m reference point in frequencies from 315 to 3150 Hz

In 10 m reference measurement point, highest vibrations acceleration was found in 1000 Hz frequencies (light vehicles 4,8 mm/s², moderate weight vehicles 5,2 mm/s²). Moderate weight and light vehicles ran in similar speed through this measurement point.

Summary of the results in measurement site

To sum up the results of measurement comparison between the different measurement points is done. Transport categories is separated.

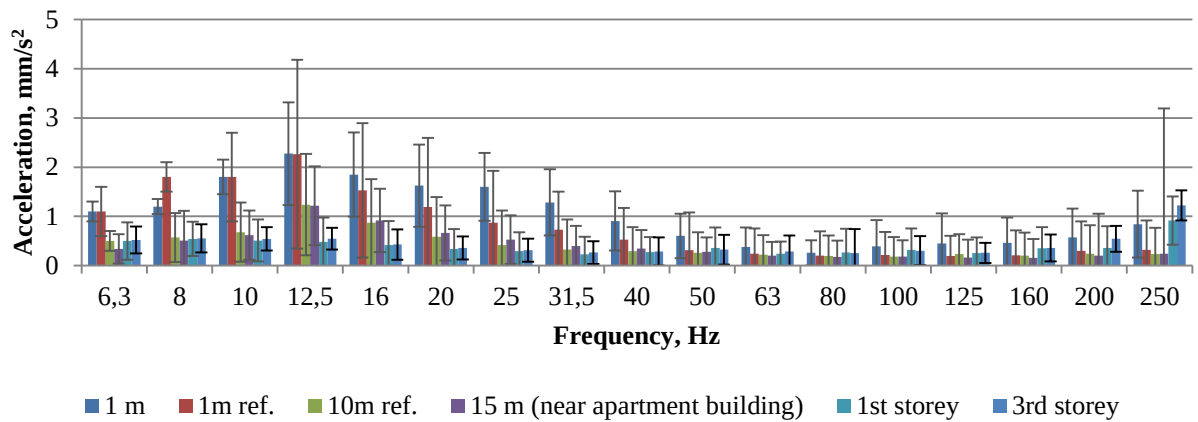


Fig. 3.70 Comparison of acceleration of the vibration when light vehicles is passing in different measurement points at frequencies 6,3 – 250 Hz.

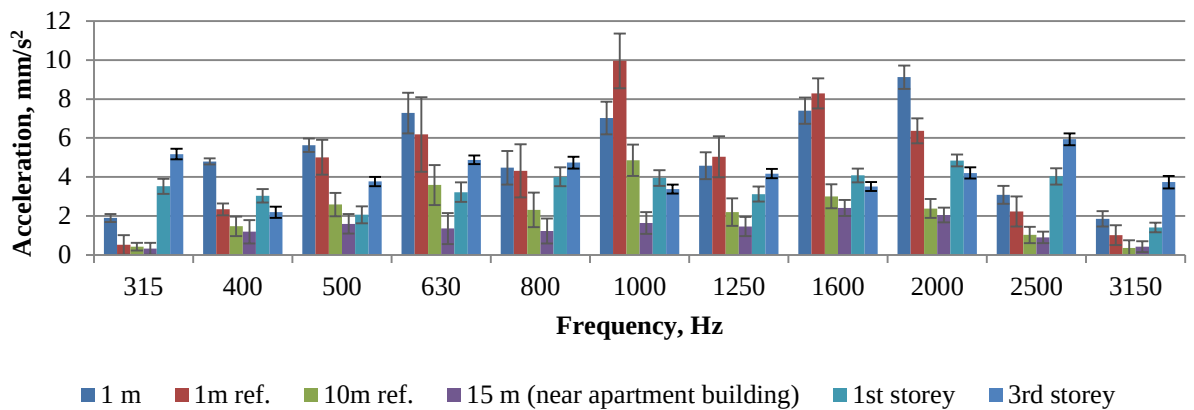


Fig. 3.71 Comparison of acceleration of the vibration when light vehicles is passing in different measurement points at frequencies 315 – 3150 Hz.

When light vehicles was passing in different measurements points (Fig. 3.70.) was found that values of acceleration of the vibration differ from 0,2 to 2,3 mm/s² at frequencies 6,3 – 250 Hz. Lowest value of the acceleration was found in 15 m distance to speed table near the apartment building , and the highest value was found in 1 m near the speed table. At frequencies from 315 to 3150 Hz (Fig. 3.71.) acceleration of the vibrations differ from 0,2 to 10,0 mm/s². Lowest value of the acceleration was found in 10 m reference point, and the highest value was found in 1 m reference point.

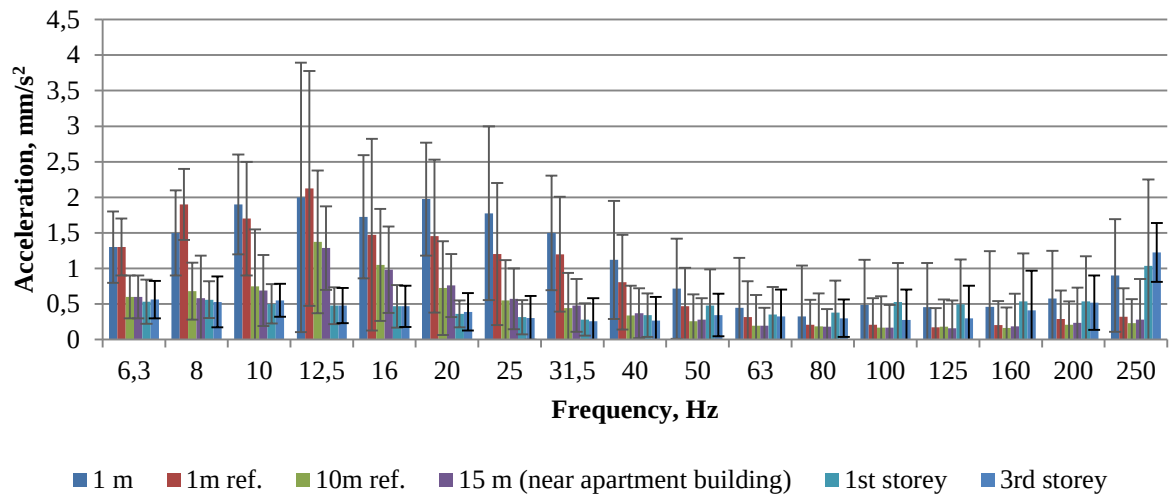


Fig. 3.72 Comparison of acceleration of the vibration when moderate weight vehicles is passing in different measurement points at frequencies 6,3 – 250 Hz.

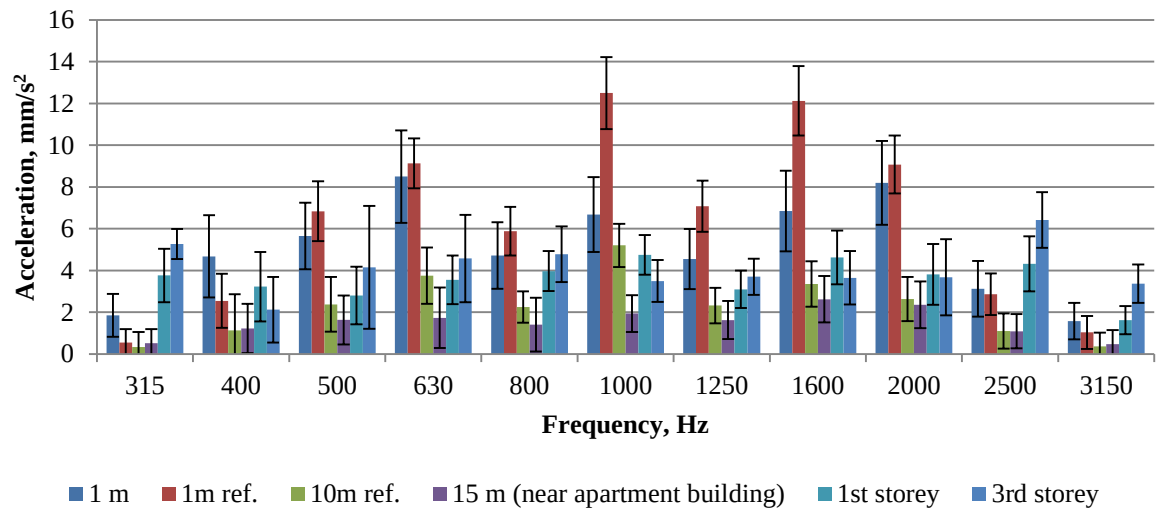


Fig. 3.73 Comparison of acceleration of the vibration when moderate weight vehicles is passing in different measurement points at frequencies 315 – 3150 Hz.

When moderate weight vehicles was passing in different measurements points (Fig. 3.72.) was found that values of acceleration of the vibration differ from 0,2 to 2,1 mm/s² at frequencies 6,3 – 250 Hz. Lowest value of the acceleration was found in 15 m distance to speed table near the apartment building , and the highest value was found in 3rd storey of the apartment building. At frequencies from 315 to 3150 Hz (Fig. 3.73.) acceleration of the vibrations differ from 0,2 to 12,5 mm/s². Lowest value of the acceleration was found in 10 m reference point, and the highest value was found in 1 m reference point.

3.2. Research results during summer time.

Winter time in Lithuania is starts when average temperature three days higher than 10⁰C. In this chapter measurement results are shown that are taken during summer season.

3.2.1 Research point no. 1. Crossroad of Kęstučio and D. Poškos streets, Vilnius

Measurements of the ground borne vibration was started in 2016 – 06 – 02 d. and finished 2016 – 08-03 During measurements air temperature was 17-19 °C, wind speed 0,2-0,4 m/s, humidity 66,2-78,4 %, atmosphere pressure 99,5-99,8 kPa. The vibration measurements was done to the axis z, because in this axis was found biggest vibration.

Table 3.5 Number of vehicles measured.

Measurement point	Light vehicles	Moderate weight vehicles	Heavy weight vehicle
1 m from traffic calming measure	15	17	10
1st storey in commercial building hall	18	10	13
3rd storey in commercial building staircase	17	10	5
Reference point 1m distance to street	16	11	11
Reference point 10 m distance to street	15	13	7

At measurement point in first storey of commercial building maximum vibration acceleration was found when heavyweight transport was passing, maximum vibration was found at 630 Hz frequency and acceleration was 4,7 mm/s².

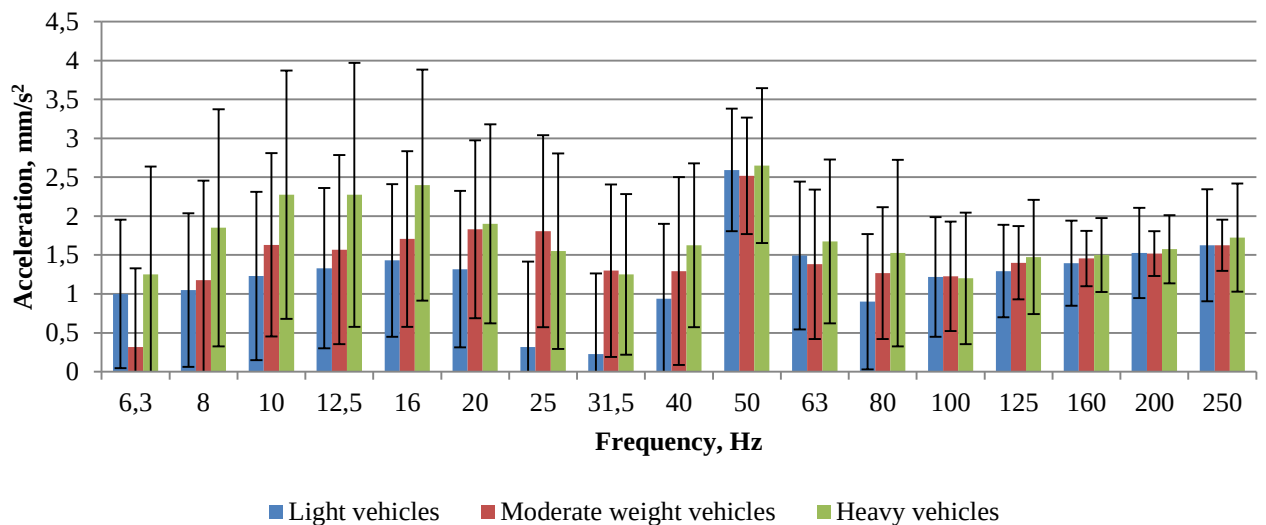


Fig. 3.74 Acceleration of the vibrations in first storey hall in frequencies from 6,3 to 250 Hz

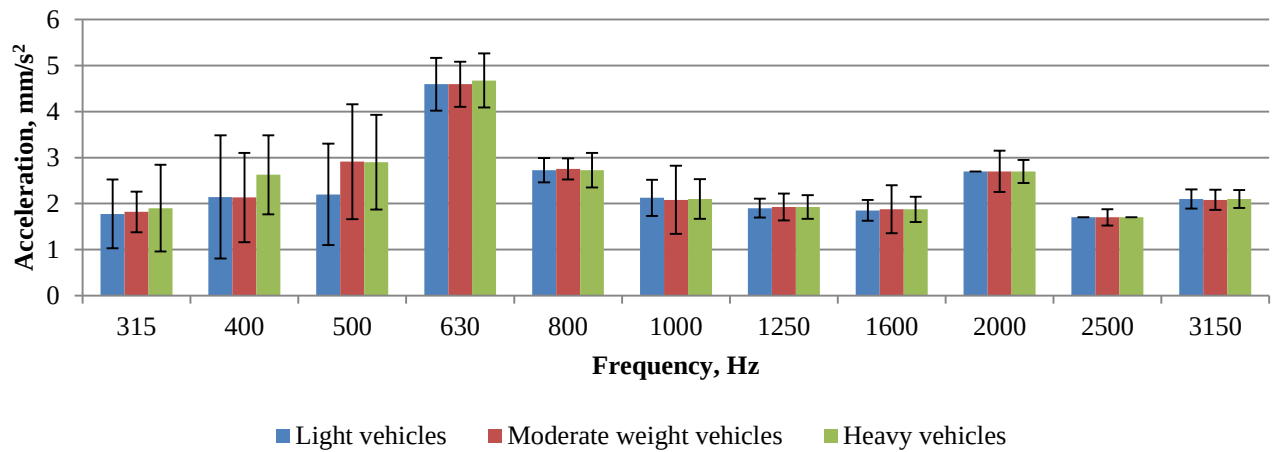


Fig. 3.75 Acceleration of the vibrations in first storey hall in frequencies from 315 to 3150 Hz

Light vehicles induced maximum vibrations was $4,6 \text{ mm/s}^2$ at 630 Hz frequency and moderate weight vehicles induced vibrations was the $4,6 \text{ mm/s}^2$ at the same frequency. During measurements were noticed that light weight vehicles reduce speed less than other category transport. Graphs of measurement results shown in 3.74. and 3.75. figures.

Measurement results was compared with HN 50: 2003 threshold levels. At frequencies from 6,3 to 80 Hz vibration acceleration level, when light vehicles was passing was from 1,8 to 21 % of the threshold level. When moderate weight vehicles was passing it reached from 5 to 26 % of the threshold level. When heavy weight transport was passing vibrations in first storey of the building reached from 3,5 to 37,0 % of the threshold level. No exceeding of threshold level was found.

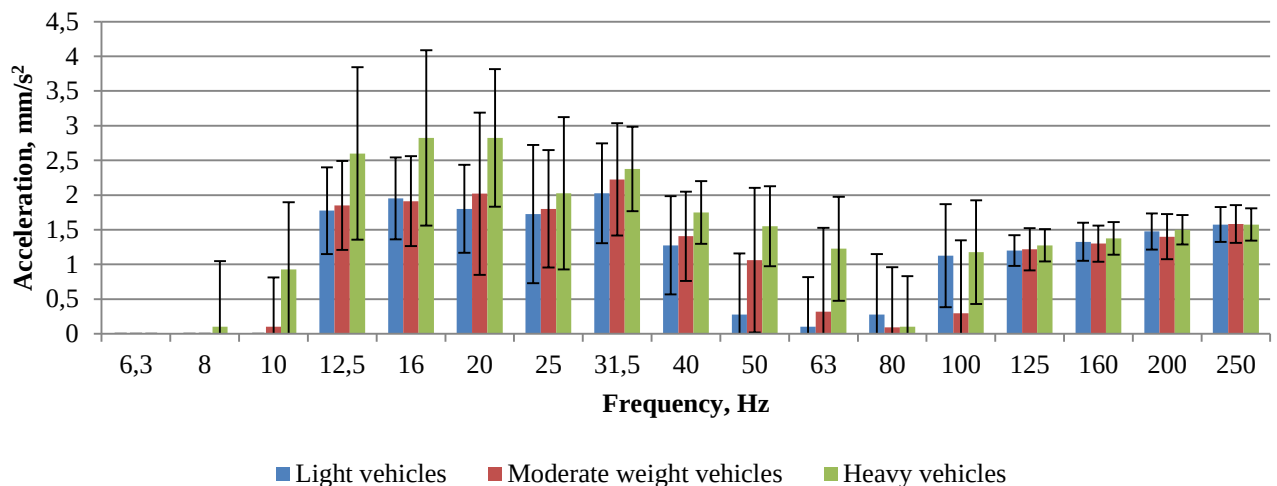


Fig. 3.76 Acceleration of the vibrations in third storey staircase in frequencies from 6,3 to 250 Hz

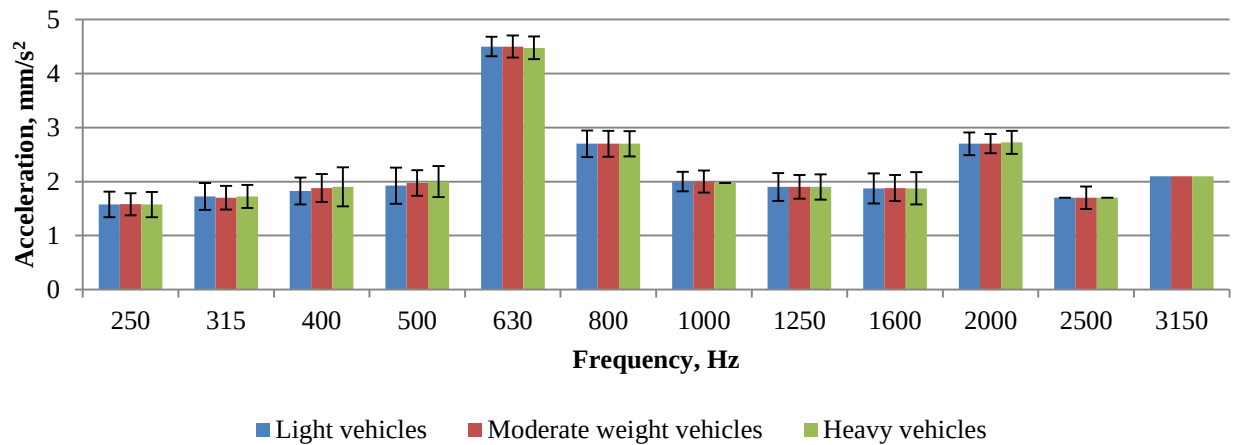


Fig. 3.77 Acceleration of the vibrations in third storey staircase in frequencies from 315 to 3150 Hz

At measurement point in third storey of commercial building maximum vibration acceleration was found similar when different transport was passing, maximum vibration was found at 630 Hz frequency and acceleration was 4,5 mm/s². Graphs of measurement results shown in 3.76. And 3.77. Figures.

Measurement results at the third storey was also compared with HN 50: 2003 threshold levels. At frequencies from 6,3 to 80 Hz vibration acceleration level, when light vehicles was passing was from up to 23 % of the threshold level. When moderate weight vehicles was passing vibration reached up to 24 % of the threshold level. When heavy weight transport was passing vibrations in first storey of the building acceleration of the vibration reached up to 33 % of the threshold level. No exceeding of threshold level was found.

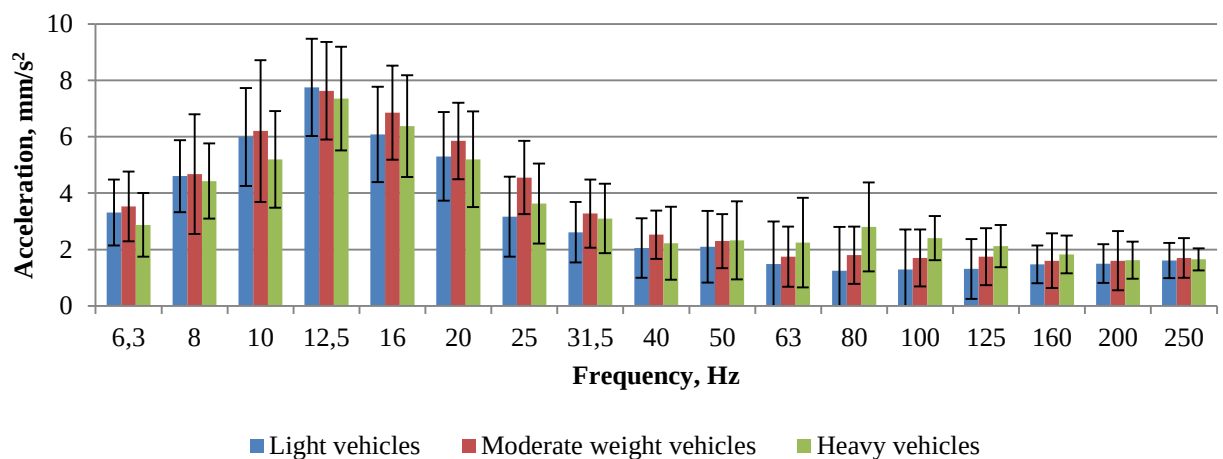


Fig. 3.78 Acceleration of the vibrations in 1m distance to traffic calming measure in frequencies from 6,3 to 250 Hz

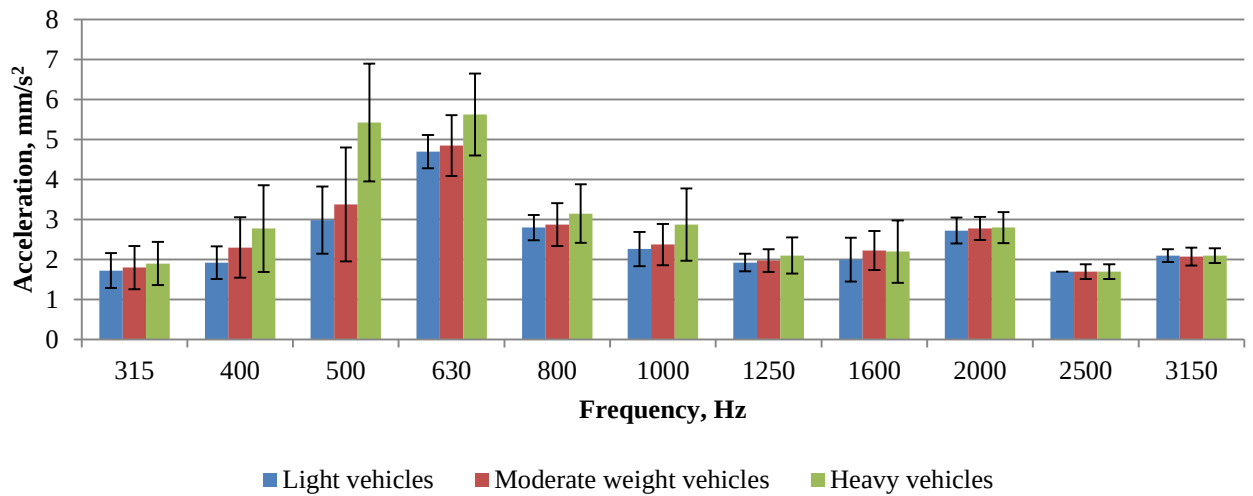


Fig. 3.79 Acceleration of the vibrations in 1m distance to traffic calming measure in frequencies from 315 to 3150 Hz

In measurement one meter distance to the traffic calming measure, highest vibrations acceleration was found in 12,5 Hz frequency (light vehicles 7,8 mm/s², moderate weight vehicles 7,6 mm/s², heavyweight vehicles 7,4 mm/s²). During measurement was noticed that light and moderate weight vehicles when passing speed table reduced their speed less than heavyweight vehicles. Heavyweight vehicles mainly was trolley buses which is moving extremely slow compared to other categories of transport.

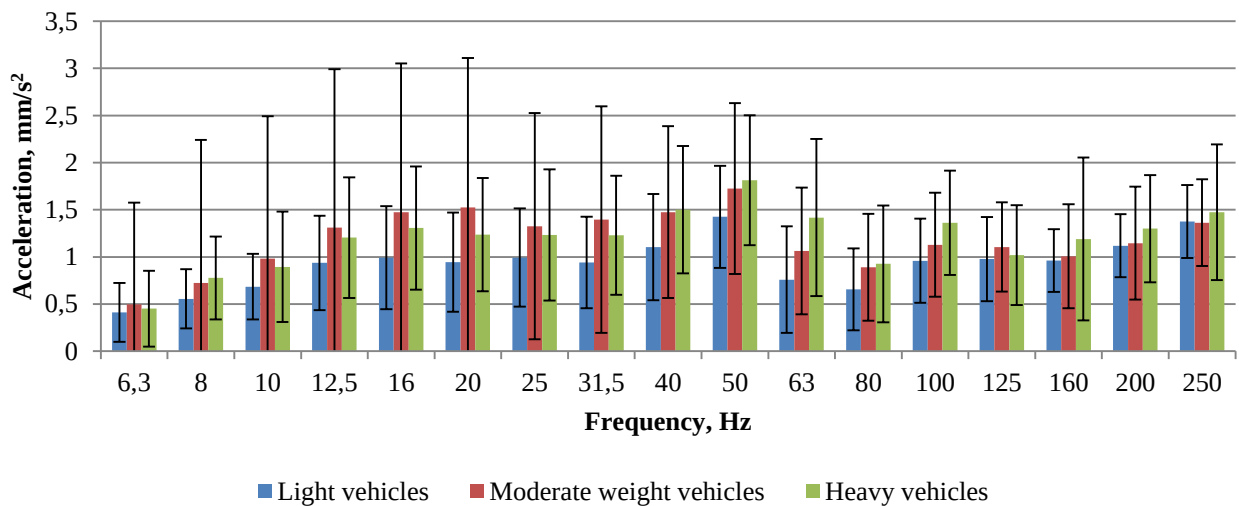


Fig. 3.80 Acceleration of the vibrations in reference point 1m from road in frequencies from 6,3 to 250 Hz

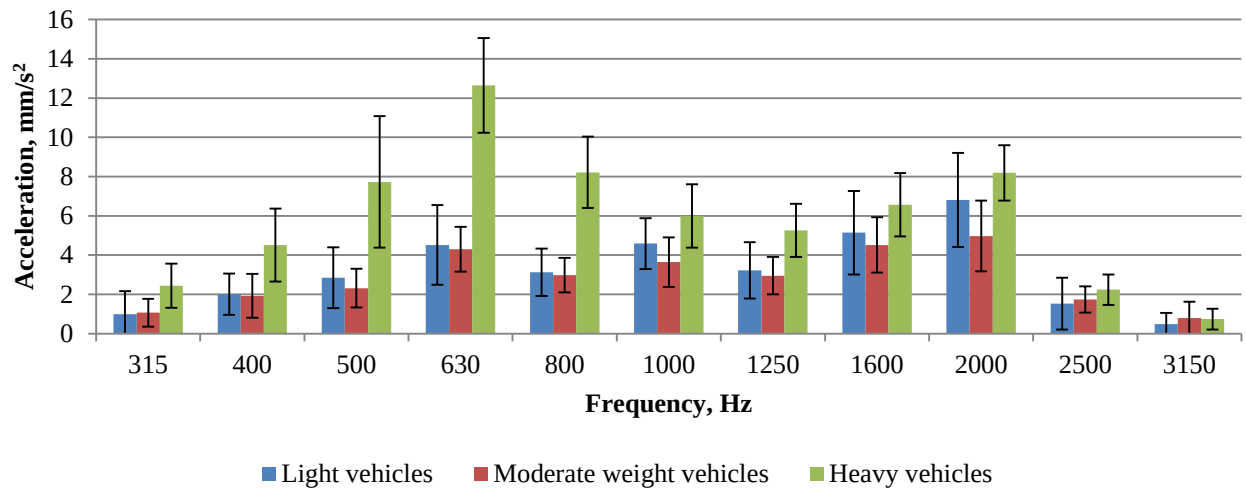


Fig. 3.81 Acceleration of the vibrations in reference point 1m from road in frequencies from 315 to 3150 Hz

Acceleration of the vibration was measured in reference point 1m from Kęstučio street where vertical traffic calming measure has no impact on the traffic induced vibrations. highest vibrations acceleration was found at 630 Hz frequency (light vehicles 4,5 mm/s², moderate weight vehicles 4,5 mm/s², heavyweight vehicles 12,65 mm/s²). Results is shown in 3.80 and 3.81 figures.

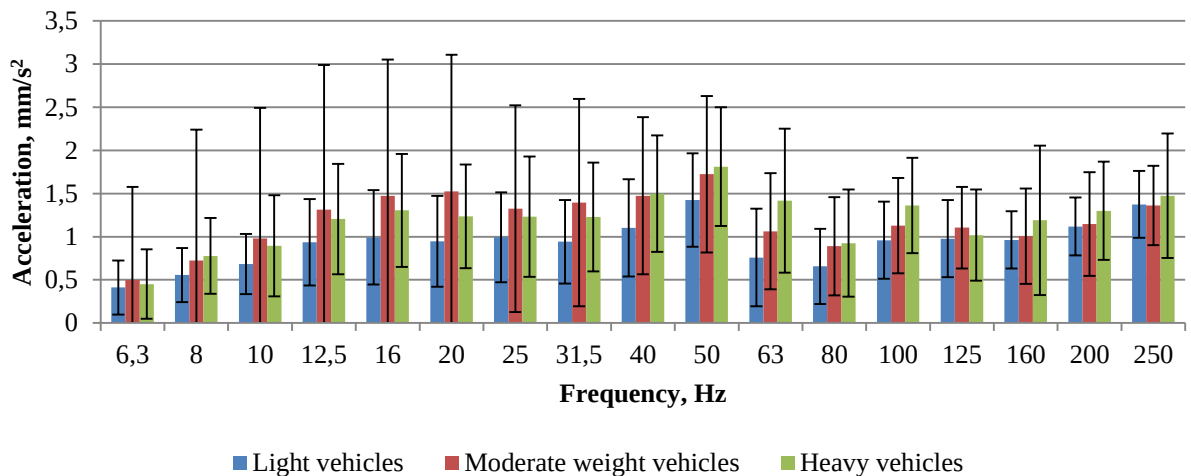


Fig. 3.82 Acceleration of the vibrations in reference point 10 m from road infrequencies from 6,3 to 250 Hz

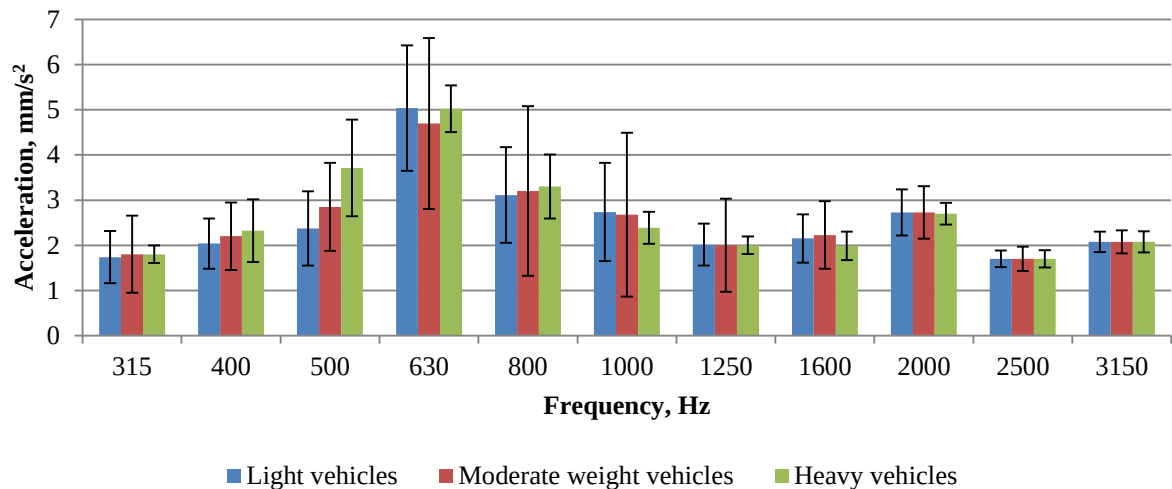


Fig. 3.83 Acceleration of the vibrations in reference point 10 m from road infrequencies from 315 to 3150 Hz

Acceleration of the vibration was measured in reference point 10 m from Kęstućio Street. Highest vibrations acceleration was found at 630 Hz frequency (light vehicles 4,7 mm/s², moderate weight vehicles 5,0 mm/s², heavyweight vehicles 5,0 mm/s²). Results is shown in 3.82 and 3.83 figures.

Summary of the results in measurement site

To sum up the results of measurement comparison between the different measurement points is done. Transport categories is separated.

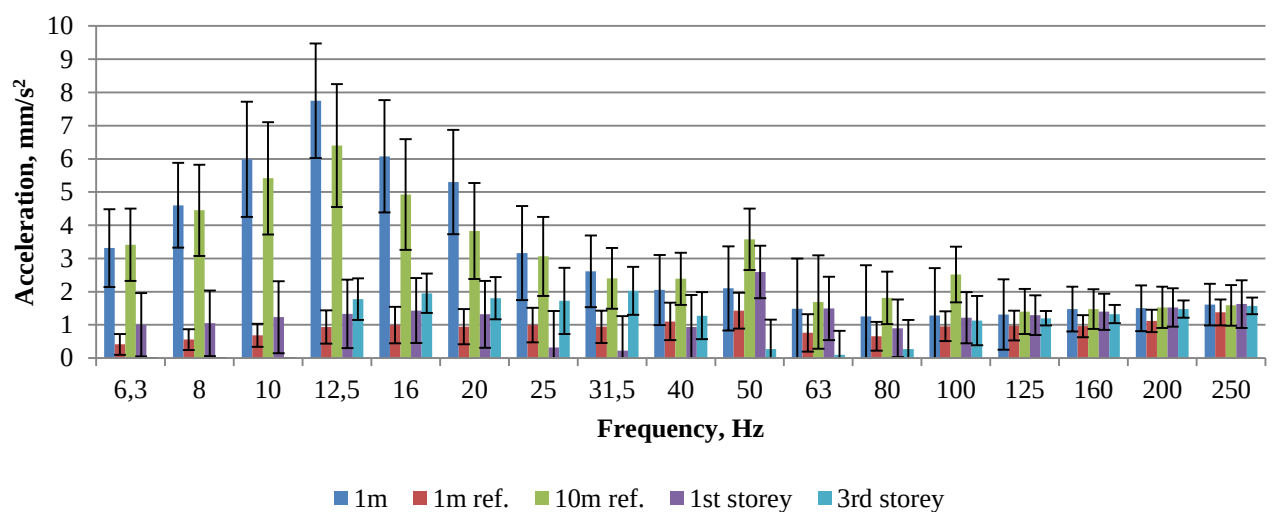


Fig. 3.84 Comparison of acceleration of the vibration when light vehicles is passing in different measurement points at frequencies 315 – 3150 Hz.

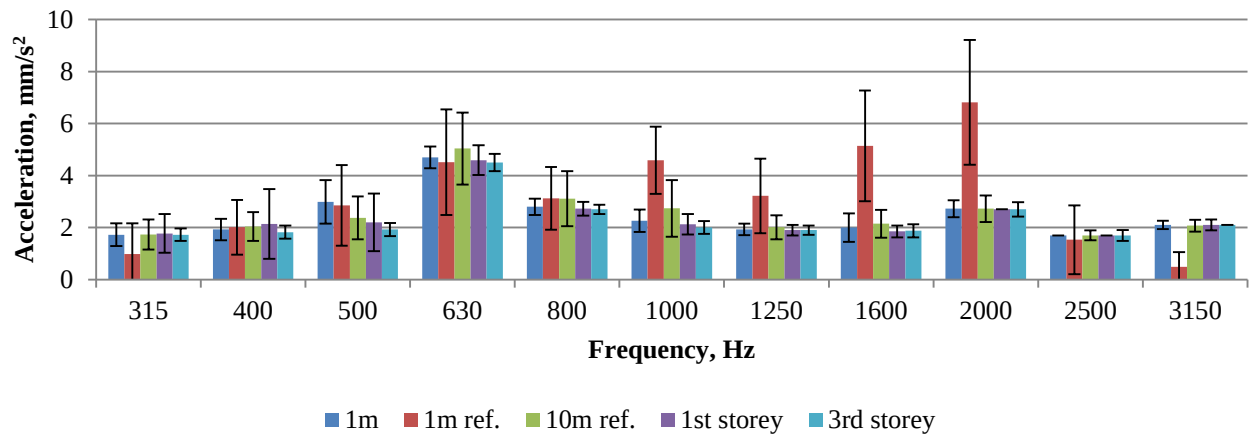


Fig. 3.85 Comparison of acceleration of the vibration when light vehicles is passing in different measurement points at frequencies 315 – 3150 Hz.

When light vehicles was passing in different measurements points (Fig. 3.84) was found that values of acceleration of the vibration reach up to $7,8 \text{ mm/s}^2$ at frequencies $6,3 - 250 \text{ Hz}$. Lowest value of the acceleration was found in third storey staircase, and the highest value was found in 1 m near the speed table. At frequencies from 315 to 3150 Hz (Fig. 3.85) acceleration of the vibrations differ from $0,9$ to $6,8 \text{ mm/s}^2$. Lowest and highest value of the acceleration was found in 1m reference point.

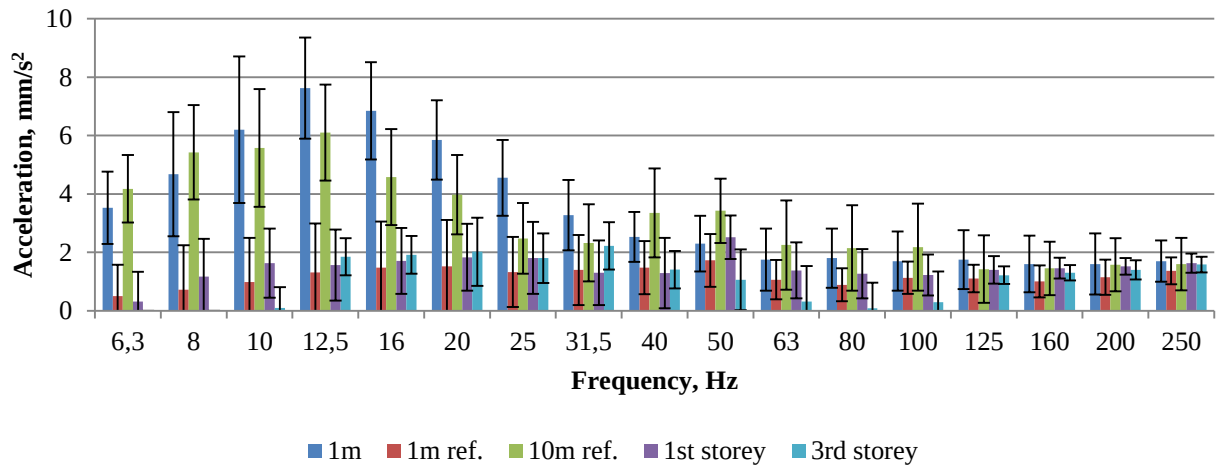


Fig. 3.86 Comparison of acceleration of the vibration when moderate weight vehicles is passing in different measurement points at frequencies $6,3 - 250 \text{ Hz}$.

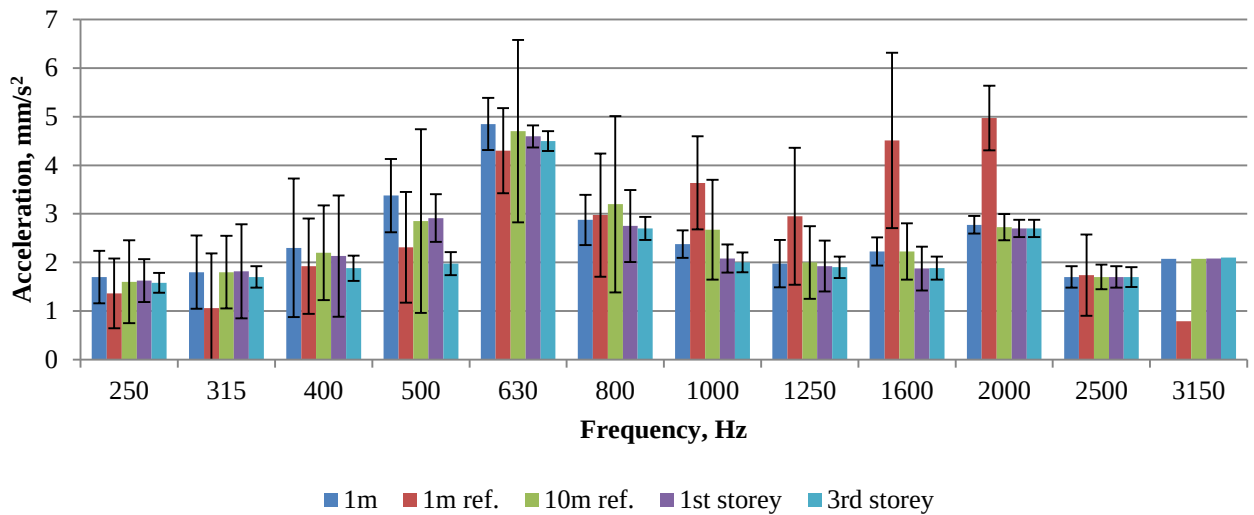


Fig. 3.87 Comparison of acceleration of the vibration when moderate weight vehicles is passing in different measurement points at frequencies 315 – 3150 Hz.

When moderate weight vehicles was passing in different measurements points (Fig. 3.86) was found that values of acceleration of the vibration reached up to 7,6 mm/s² at frequencies 6,3 – 250 Hz. Lowest value of the acceleration was found in third storey staircase, and the highest value was found in 1m distance to the speed table. At frequencies from 315 to 3150 Hz (Fig. 3.87) acceleration of the vibrations differ from 1,4 to 5,0 mm/s². Lowest and highest value of the acceleration was found in 1m reference point.

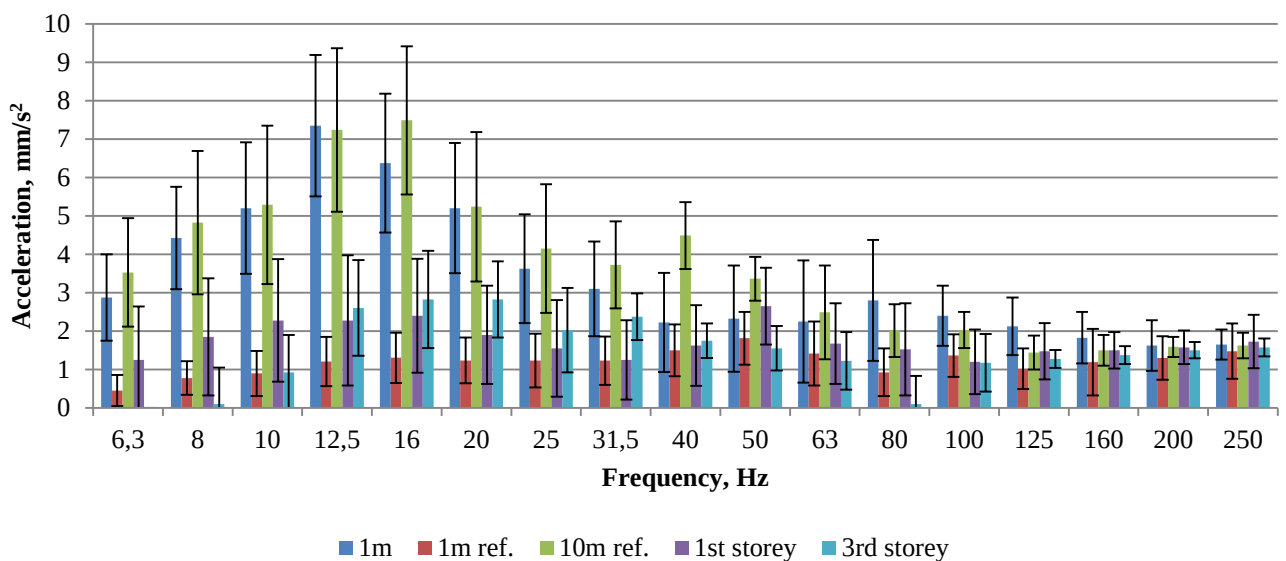


Fig. 3.88 Comparison of acceleration of the vibration when heavyweight vehicles is passing in different measurement points at frequencies 6,3 – 250 Hz.

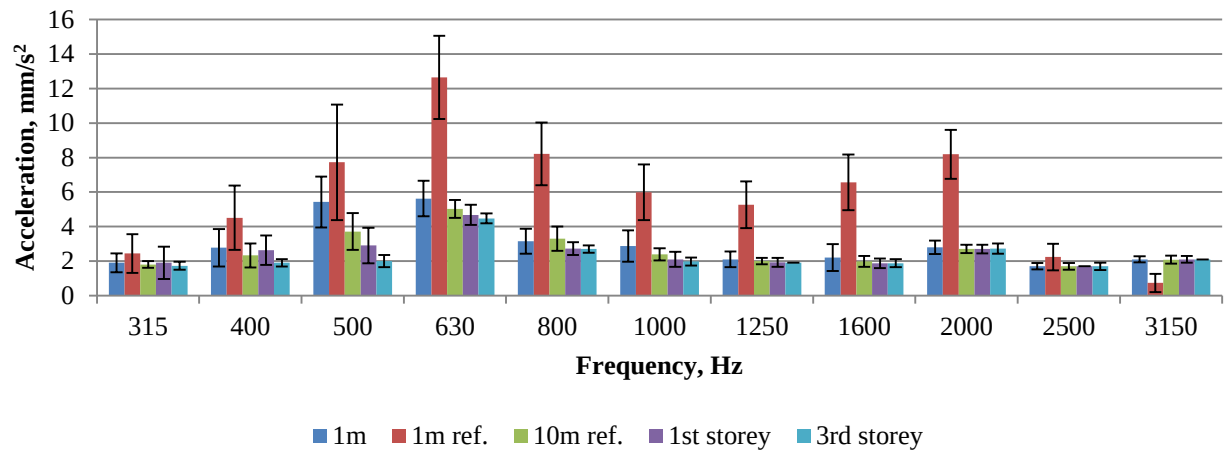


Fig. 3.89 Comparison of acceleration of the vibration when heavyweight vehicles is passing in different measurement points at frequencies 315 – 3150 Hz.

When heavyweight vehicles was passing in different measurements points (Fig. 3.88) was found that values of acceleration of the vibration reached up to 7,5 mm/s² at frequencies 6,3 – 250 Hz. Lowest value of the acceleration was found in third storey staircase, and the highest value was found in measurement point 10 m reference point. At frequencies from 315 to 3150 Hz (Fig. 3.89) acceleration of the vibrations differ from 1,7 to 12,7 mm/s². Lowest value of the acceleration was found in third storey staircase, and the highest value was found in 1 m reference point.

3.2.2. Research point No. 1. L. Asanavičiūtės st. 5, Vilnius

Measurements of the ground borne vibration was started in 2016 – 05 – 13 d. and finished in 2016 – 08 – 09 d. During measurements air temperature was 13,0 – 18 °C, wind speed 1,1-3,9 m/s, humidity 52-61 %, atmosphere pressure 100,4-101,1 kPa. The vibration measurements was done to the axis z, because in this axis was found biggest vibration.

In this measurement site vibration was measured in first, third and fifth storey of apartment building and in its environment. Near the speed table, on the road manhole was noticed which could increase traffic induced vibrations.

In this measurement site vibration was measured in first, third and fifth storey of apartment building and in its environment. Near the speed table, on the road manhole was noticed which could increase traffic induced vibrations.

Table 3.6 Number of vehicles measured.

Measurement point	Light vehicles	Moderate weight vehicles	Heavy weight vehicle
1 m from traffic calming measure	20	14	6
10 m away from speed table, near the testing apartment building	15	11	5
1st storey in apartment building hall	17	10	3
3rd storey in apartment building staircase	15	10	4
5th storey in apartment building staircase	15	10	3
Reference point 1m distance to street	16	11	5
Reference point 10 m distance to street	15	10	7

At measurement point in first storey of apartment building maximum vibration acceleration was found when heavyweight transport was passing, maximum vibration was found at 630 Hz frequency and acceleration was 4,7 mm/s².

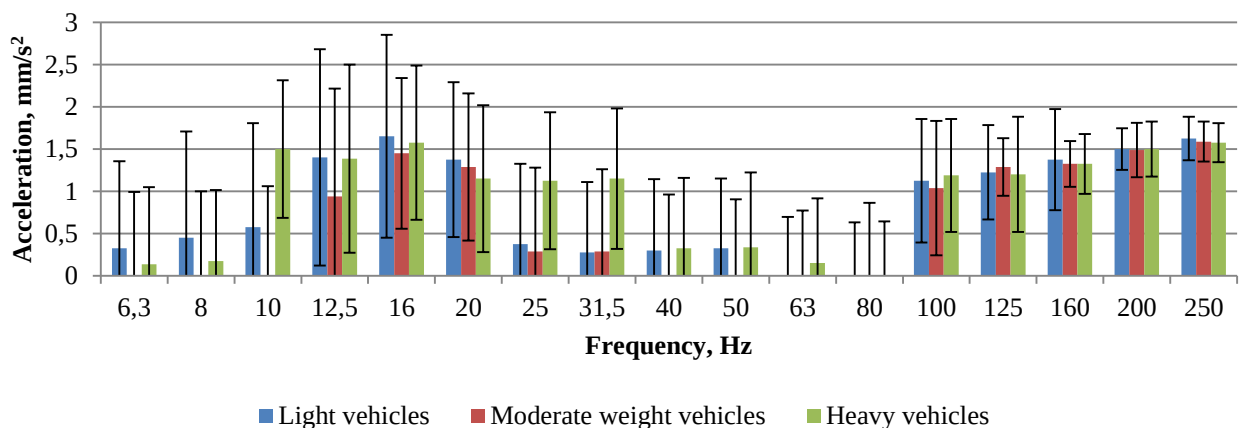


Fig. 3.90 Acceleration of the vibrations in first storey staircase in frequencies from 6,3 to 250 Hz

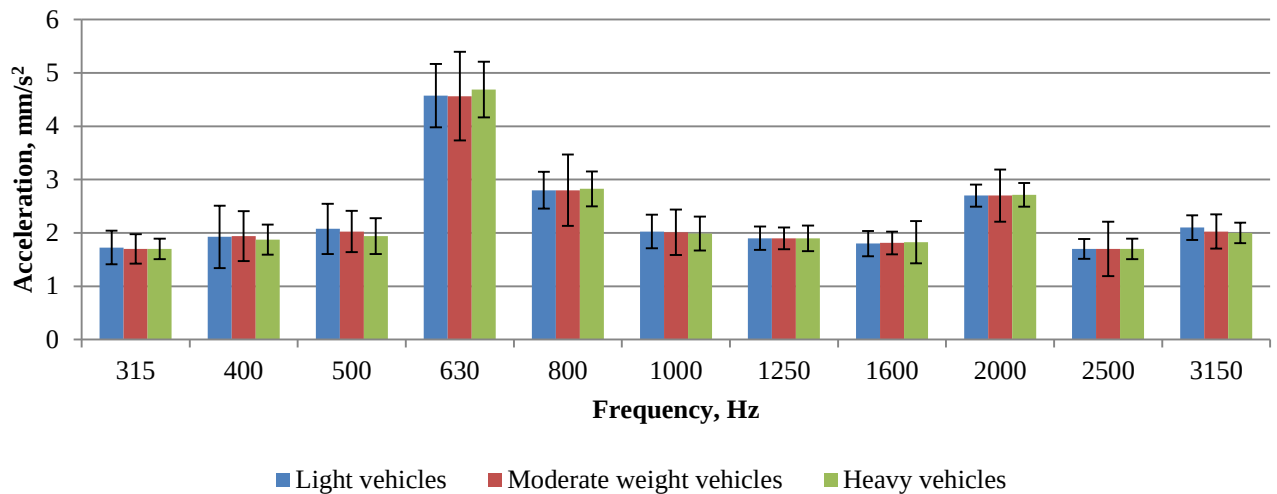


Fig. 3.91 Acceleration of the vibrations in first storey staircase in frequencies from 315 to 3150 Hz

Light vehicles induced maximum vibrations was 4,5 mm/s² at 630 Hz frequency and moderate weight vehicles induced vibrations 4,6 mm/s² at the frequency of 630 Hz. Graphs of measurement results shown in 3.90 And 3.91 Figures.

Measurement results was compared with HN 50: 2003 threshold levels. At frequencies from 6,3 to 80 Hz vibration acceleration level, when light vehicles was passing reached up to 18 % of the threshold level. When moderate weight vehicles was passing it reached to 15 % of the threshold level. When heavy weight transport was passing vibrations in first storey of the building reached to 18 % of the threshold level. No exceeding of threshold level was found.

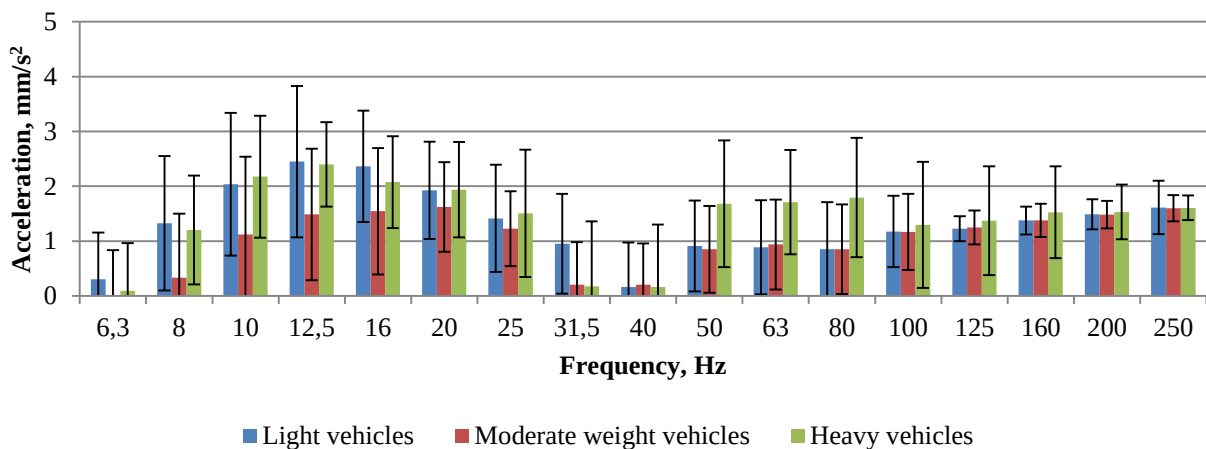


Fig. 3.92 Acceleration of the vibrations in third storey staircase in frequencies from 6,3 to 250 Hz

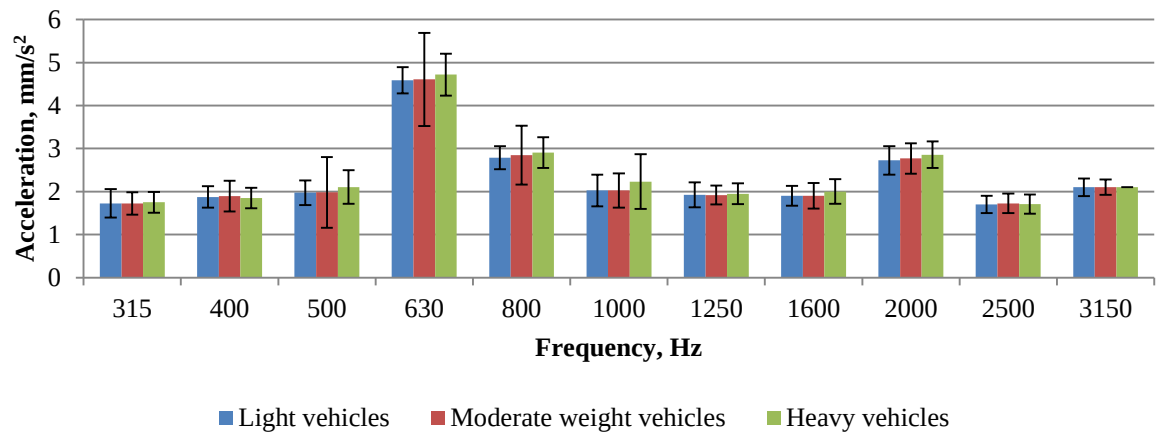


Fig. 3.93 Acceleration of the vibrations in third storey staircase in frequencies from 6,3 to 250 Hz

At measurement point in third storey of apartment building maximum vibration acceleration was found when heavyweight vehicles was passing, maximum vibration was found at 630 Hz frequency and acceleration was $4,7 \text{ mm/s}^2$. Light vehicles induced maximum vibrations was $4,6 \text{ mm/s}^2$ at 630 Hz frequency and moderate weight vehicles induced vibrations $4,6 \text{ mm/s}^2$ at the frequency of 630 Hz. Graphs of measurement results shown in 3.92 and 3.93 Figures.

Measurement results was compared with HN 50: 2003 threshold levels. At frequencies from 6,3 to 80 Hz vibration acceleration level, when light vehicles was passing was from 1 to 32 % of the threshold level. When moderate weight vehicles was passing it reached to 19 % of the threshold level. When heavy weight transport was passing vibrations in third storey of the building reached from 0,7 to 35 % of the threshold level. No exceeding of threshold level was found.

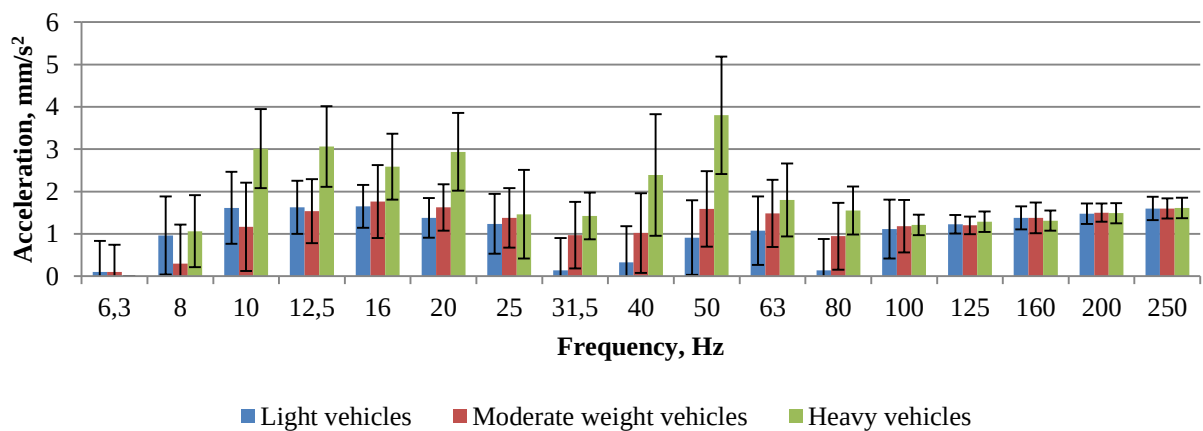


Fig. 3.94 Acceleration of the vibrations in fifth storey staircase in frequencies from 6,3 to 250 Hz

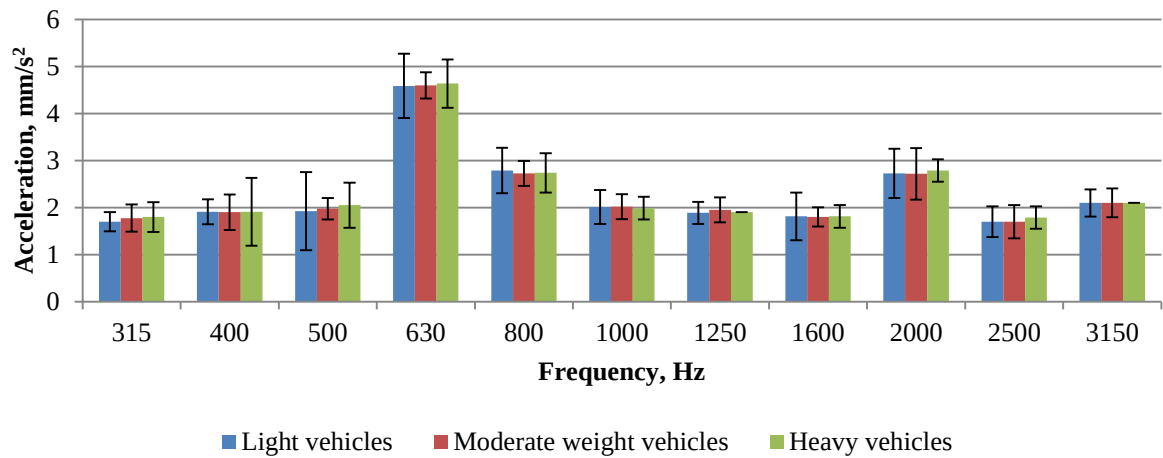


Fig. 3.95 Acceleration of the vibrations in fifth storey staircase in frequencies from 6,3 to 250 Hz

At measurement point in fifth storey of apartment building maximum vibration acceleration was found when light vehicles was passing, maximum vibration was found at 630 Hz frequency and acceleration was 4,6 mm/s². Heavyweight vehicles induced maximum vibrations was 4,6 mm/s² at 630 Hz frequency and moderate weight vehicles induced vibrations 4,6 mm/s² at the frequency of 630 Hz. Graphs of measurement results shown in 3.94 and 3.95 Figures.

Measurement results was compared with HN 50: 2003 threshold levels. At frequencies from 6,3 to 80 Hz vibration acceleration level, when light vehicles was passing was reached to 26 % of the threshold level. When moderate weight vehicles was passing it reached to 20 % of the threshold level. When heavy weight transport was passing vibrations in third storey of the building reached to 48 % of the threshold level. No exceeding of threshold level was found.

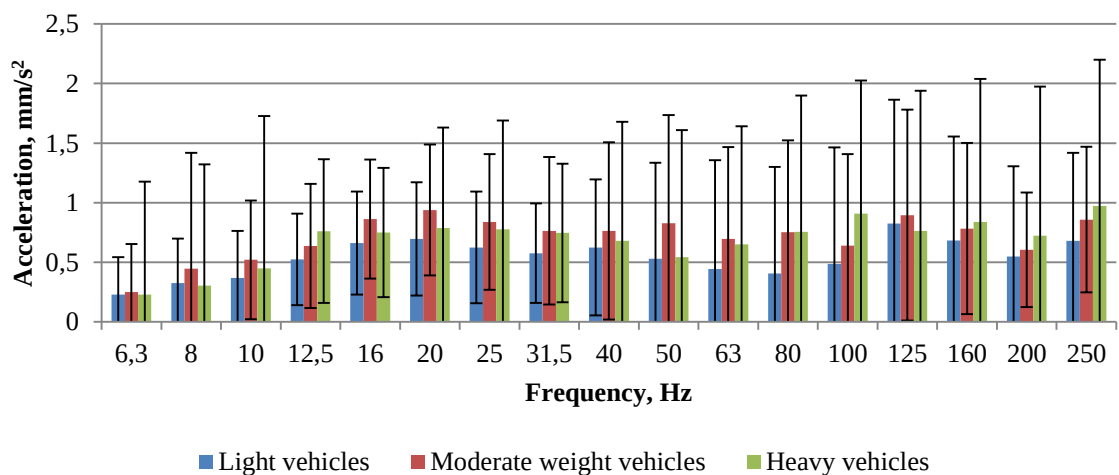


Fig. 3.96 Acceleration of the vibrations 1 m away from speed table in frequencies from 6,3 to 250 Hz

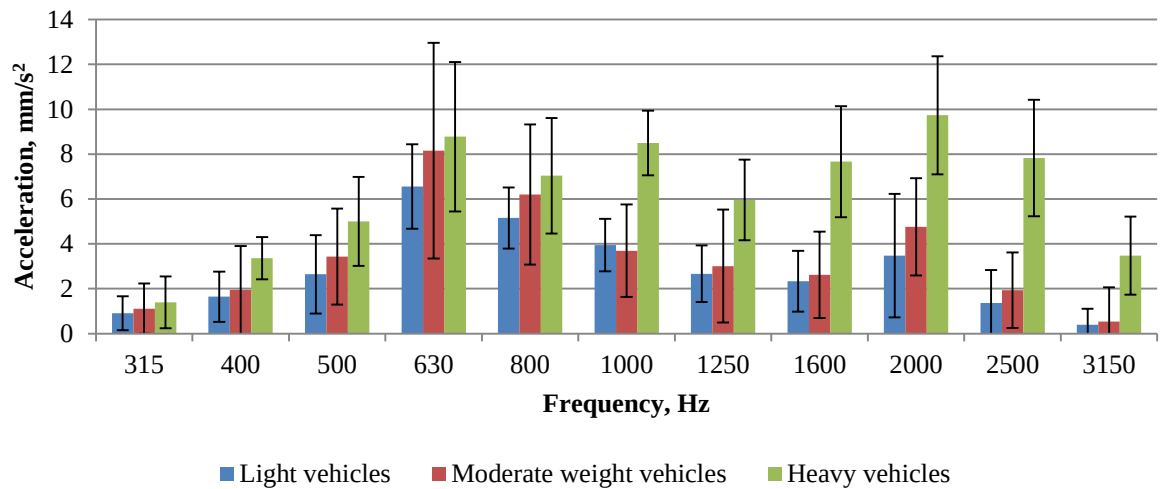


Fig. 3.97 Acceleration of the vibrations 1 m away from speed table in frequencies from 315 to 315 Hz

In measurement one meter distance to the traffic calming measure, highest vibrations acceleration was found in 630 Hz frequency (light vehicles 6,5 mm/s² at 630 Hz, moderate weight vehicles 8,2 mm/s² at 630 Hz, heavyweight vehicles 8,2 mm/s² at 630 Hz). During measurement was noticed that light and moderate weight vehicles when passing speed table reduced their speed less than heavyweight vehicles. But still heavy weight vehicles induces highest vibrations at this measurement point.

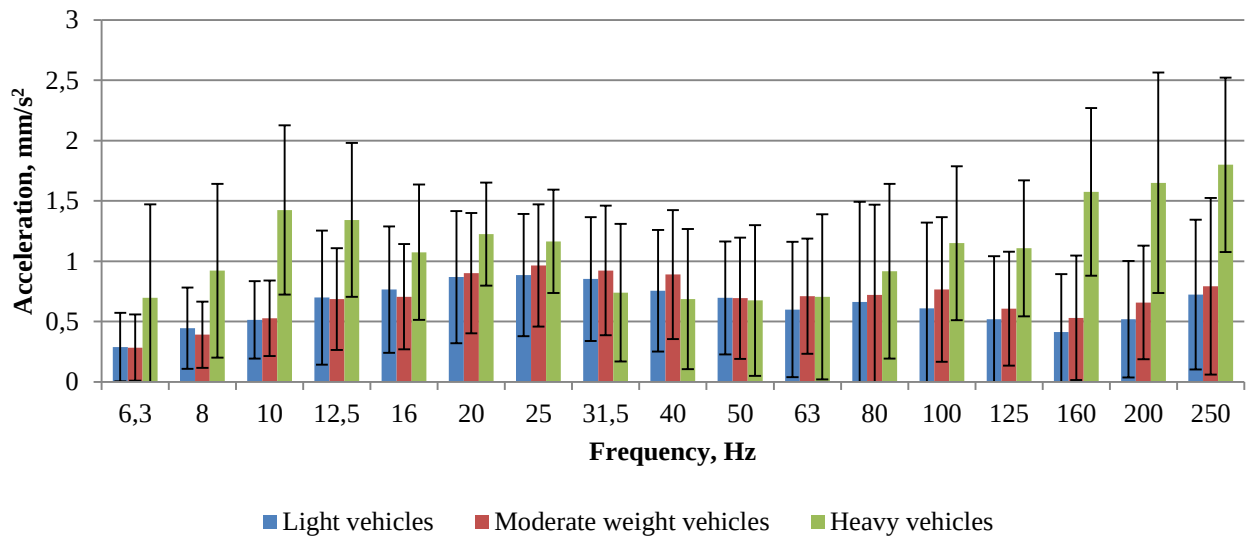


Fig. 3.98 Acceleration of the vibrations 10 m away from speed table near the test apartment building in frequencies from 6,3 to 250 Hz

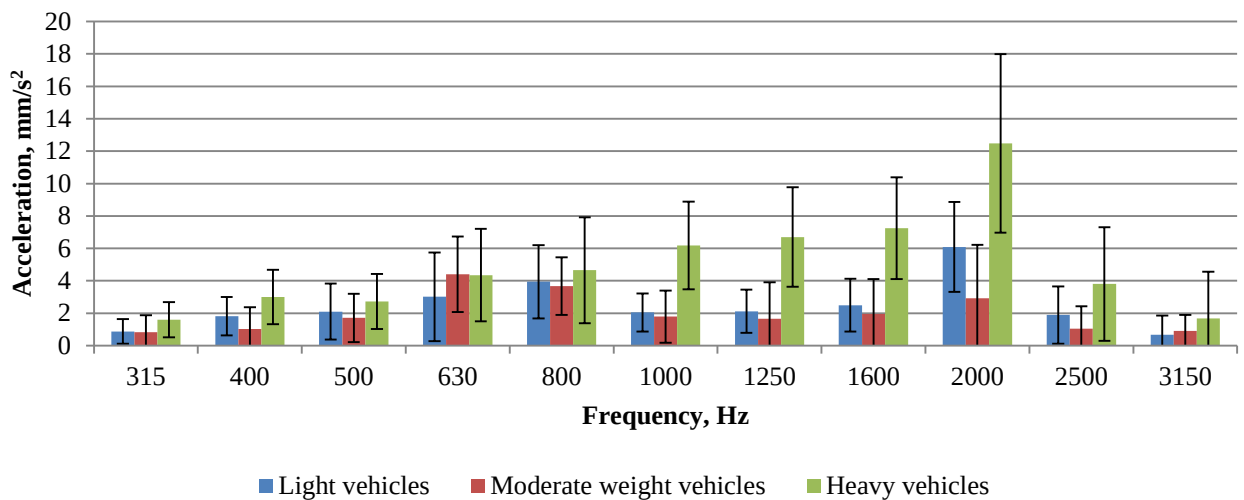


Fig. 3.99 Acceleration of the vibrations 10 m away from speed table near the test apartment building in frequencies from 315 to 3150 Hz

Acceleration of the vibration was measured 10 m away from speed table near the test apartment. Highest vibrations acceleration was found at 2000 and 630 Hz frequencies (light vehicles 6,0 mm/s², moderate weight vehicles 4,4 mm/s² at 630 Hz, heavyweight vehicles 12,5 mm/s²). In this measurement point was found light weight vehicles induced higher vibration values than other categories vehicles, during measurements visually noticed that light and moderate weight vehicles passed speed table faster than heavy vehicles.

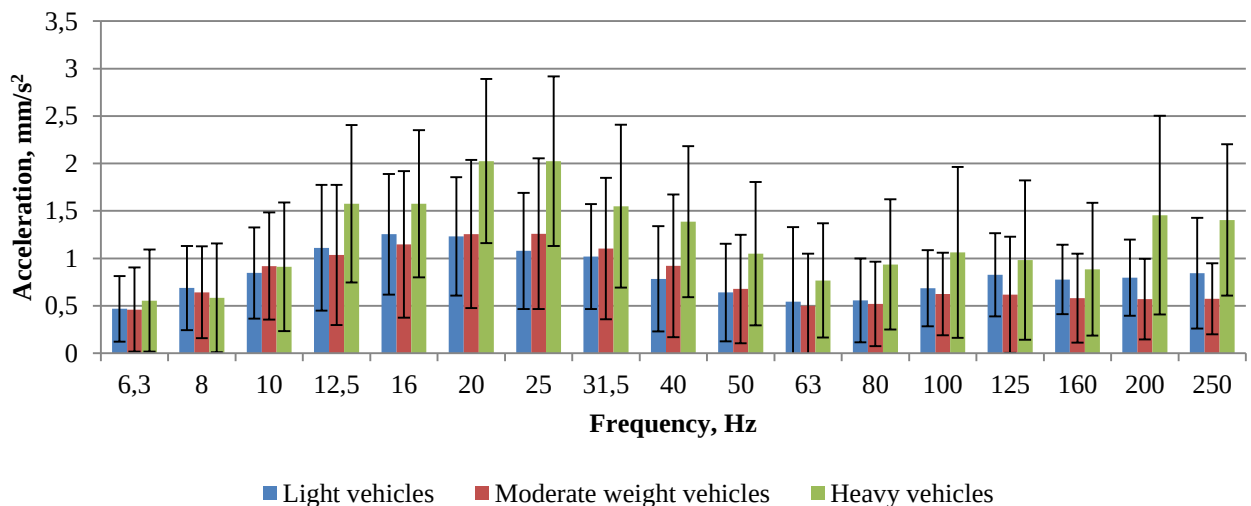


Fig. 3.100 Acceleration of the vibrations in reference point 1 m away from Asanavičiūtė street in frequencies from 6,3 to 250 Hz

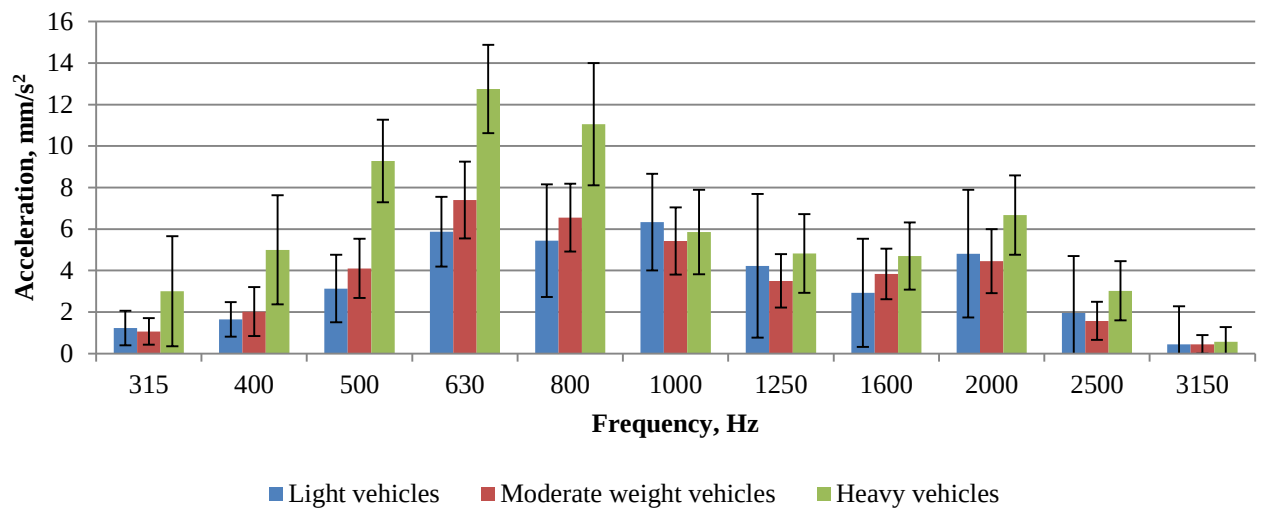


Fig. 3.101 Acceleration of the vibrations in reference point 1 m away from Asanavičiūtė street in frequencies from 315 to 3150 Hz

Acceleration of the vibration was measured in reference point 1 m from L. Asanavičiūtė Street where vertical traffic calming measure has no impact on the traffic induced vibrations. Highest vibrations acceleration was found at 630 Hz frequency (light vehicles 5,9 mm/s², moderate weight vehicles 7,4 mm/s², heavyweight vehicles 12,8 mm/s²). Results is shown in 3.100 and 3.101 figures.

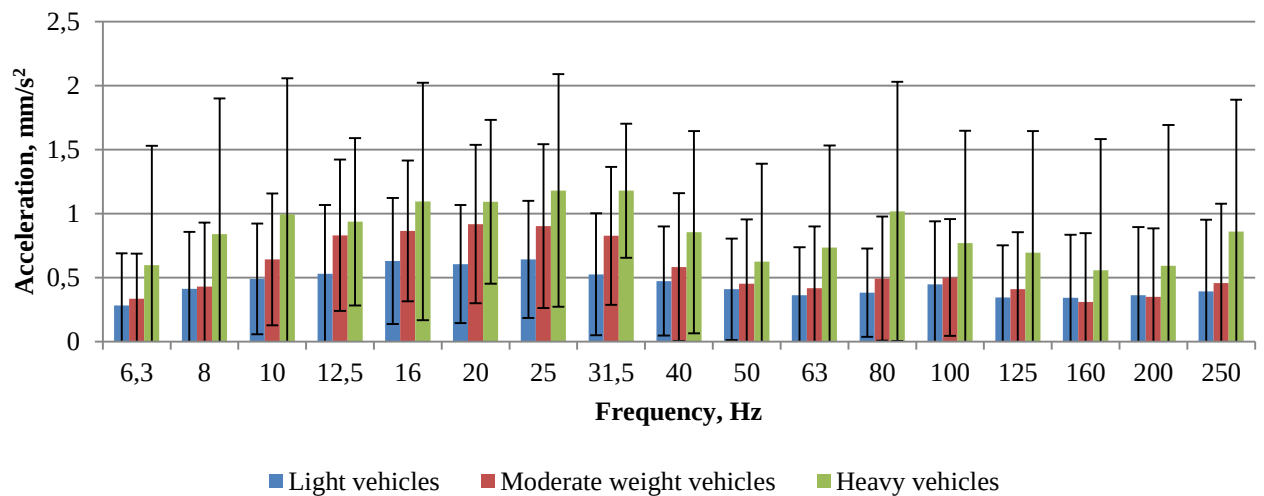


Fig. 3.102 Acceleration of the vibrations in reference point 10 m away from Asanavičiūtė street in frequencies from 6,3 to 250 Hz

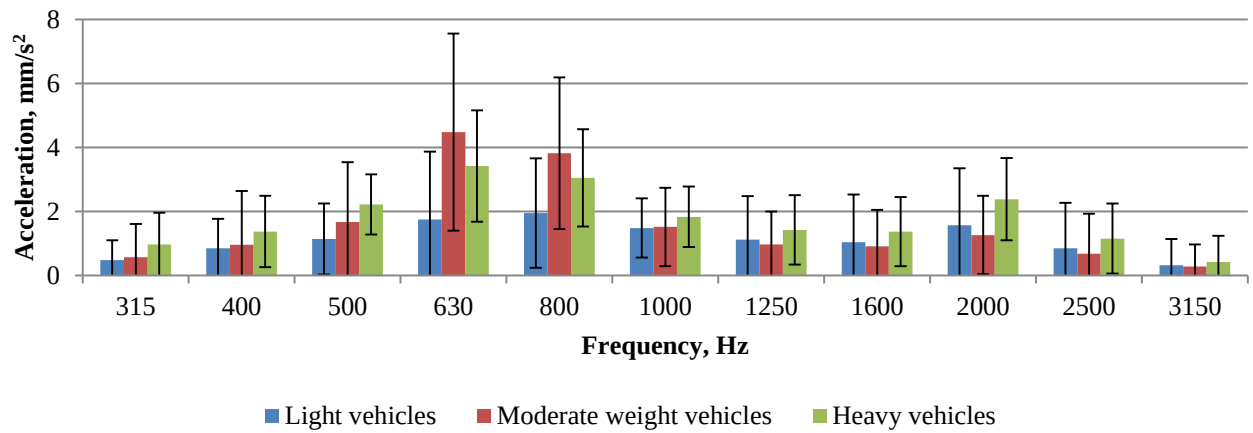


Fig. 3.103 Acceleration of the vibrations in reference point 10 m away from Asanavičiūtė Street in frequencies from 315 to 3150 Hz

Acceleration of the vibration was measured in reference point 10 m from L. Asanavičiūtė Street. Highest vibrations acceleration was found at 630 and 800 Hz frequencies (light vehicles 2,0 mm/s² at 800 Hz, moderate weight vehicles 4,5 mm/s² at 630 Hz, heavyweight vehicles 3,4 mm/s² at 630 Hz). In this measurement point was found that, acceleration of the vibrations is slightly bigger than in 1 m reference point. It might be because of building not far from this reference point, buildings near this street is close to road.

Summary of the results in measurement site

To sum up the results of measurement comparison between the different measurement points is done. Transport categories is separated.

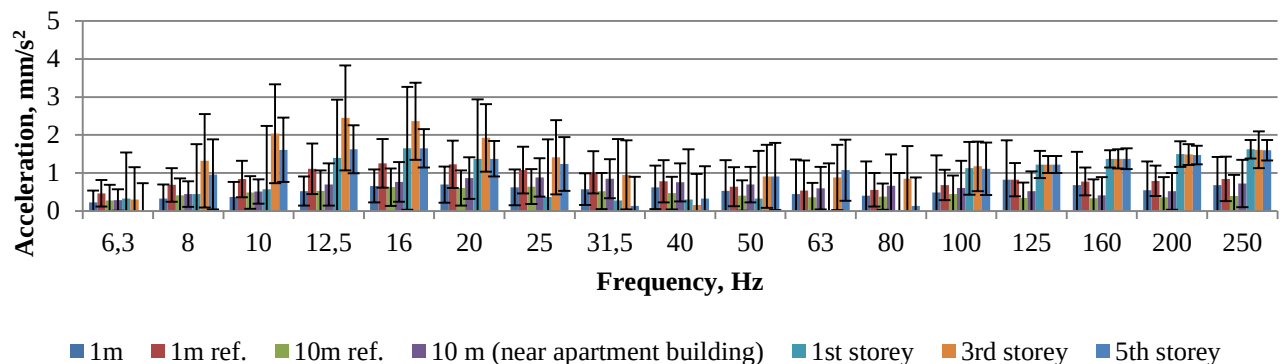


Fig. 3.104 Comparison of acceleration of the vibration when light vehicles is passing in different measurement points at frequencies 6,3 – 250 Hz.

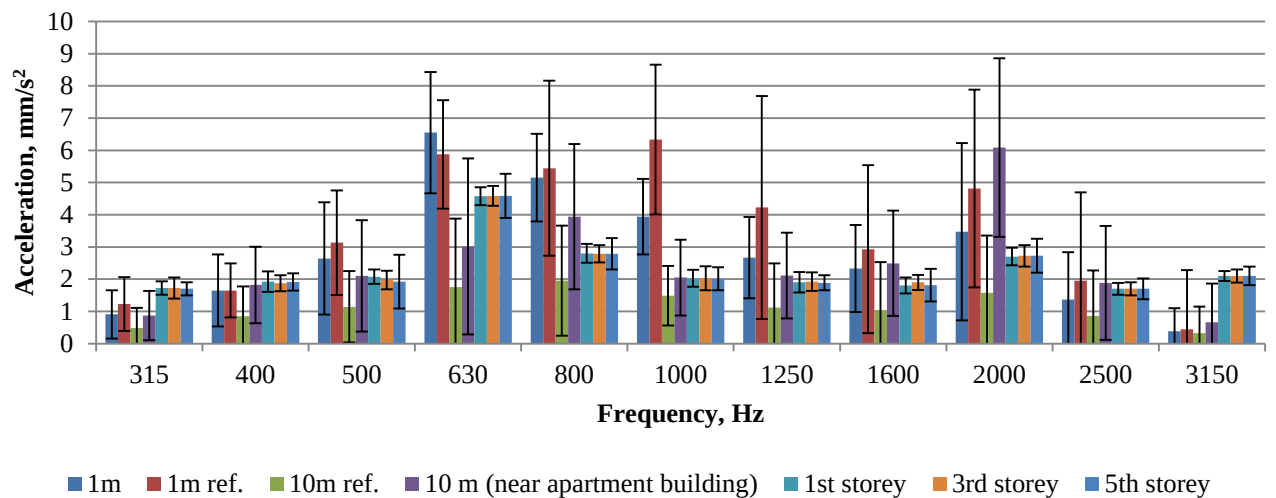


Fig. 3.105 Comparison of acceleration of the vibration when light vehicles is passing in different measurement points at frequencies 315 – 3150 Hz.

When light vehicles was passing in different measurements points (Fig. 3.104) was found that values of acceleration of the vibration reached to $2,45 \text{ mm/s}^2$ at frequencies $6,3 - 250 \text{ Hz}$. Lowest value of the acceleration was found in the 1st storey of apartment building, and the highest value was found in 3rd storey of apartment building. At frequencies from 315 to 3150 Hz (Fig. 3.105) acceleration of the vibrations differ from $0,3$ to $6,6 \text{ mm/s}^2$. Lowest value of the acceleration was found 10m reference point, and the highest value was found in 1 m near the speed table.

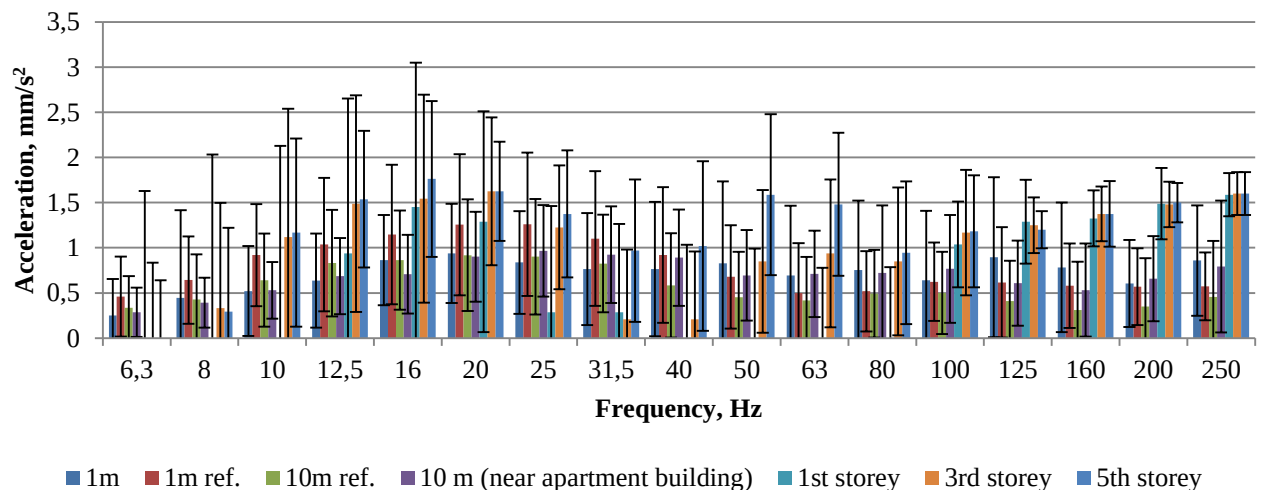


Fig. 3.106 Comparison of acceleration of the vibration when moderate weight vehicles is passing in different measurement points at frequencies $6,3 - 250 \text{ Hz}$.

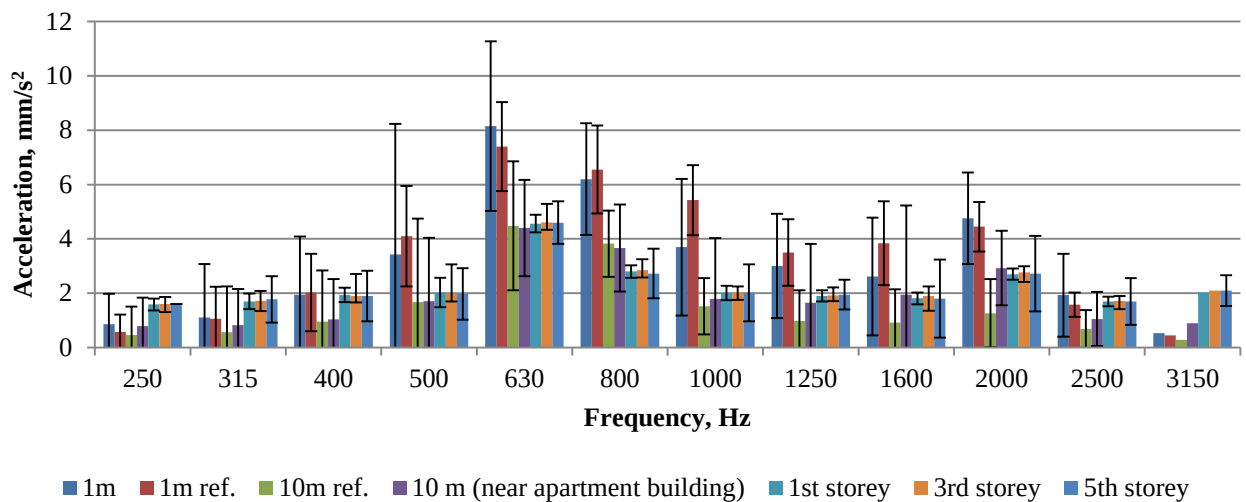


Fig. 3.107 Comparison of acceleration of the vibration when moderate weight vehicles is passing in different measurement points at frequencies 315 – 3150 Hz.

When moderate weight vehicles was passing in different measurements points (Fig. 3.106) was found that values of acceleration of the vibration reached to 1,8 mm/s² at frequencies 6,3 – 250 Hz. Lowest value of the acceleration was found in the 1st storey of the apartment building, highest value found in the 3rd storey of the apartment building. At frequencies from 315 to 3150 Hz (Fig. 3.107) acceleration of the vibrations differ from 0,5 to 8,2 mm/s². Lowest value of the acceleration was found in 10 m reference point, and the highest value was found in 1 m near the speed table.

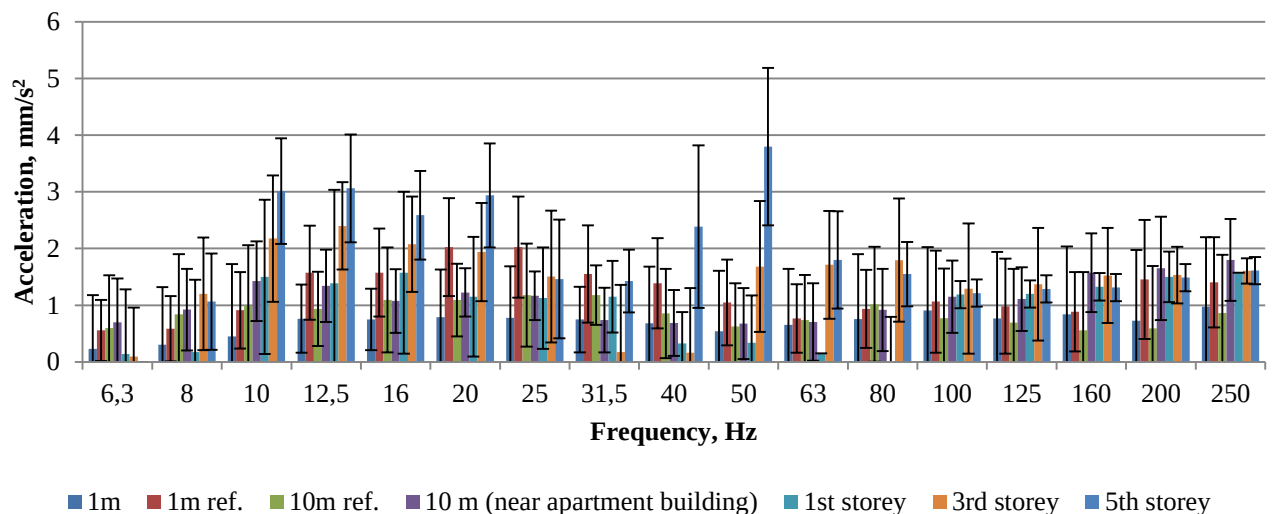


Fig. 3.108 Comparison of acceleration of the vibration when heavyweight vehicles is passing in different measurement points at frequencies 6,3 – 250 Hz.

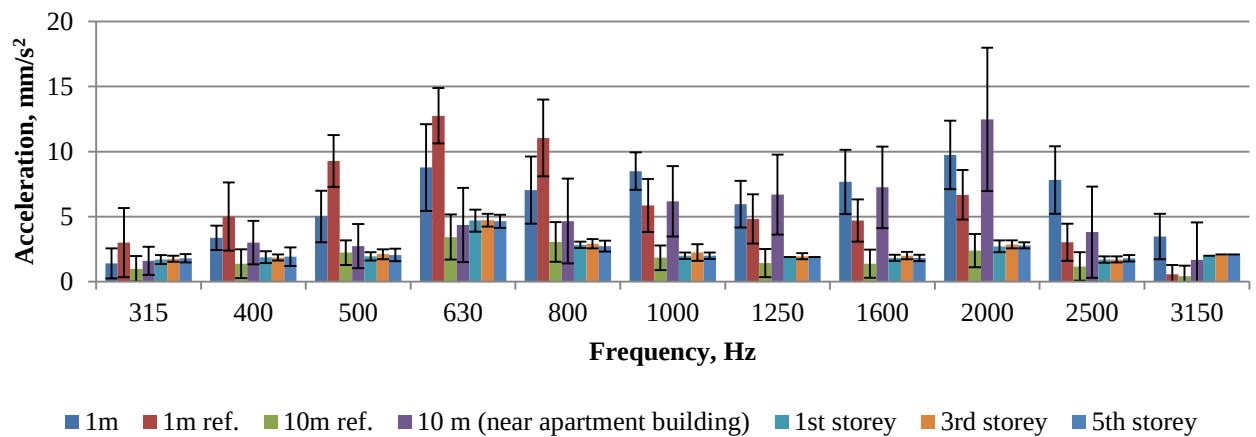


Fig. 3.109 Comparison of acceleration of the vibration when heavyweight vehicles is passing in different measurement points at frequencies 315 – 3150 Hz.

When heavyweight vehicles was passing in different measurements points (Fig. 3.108) was found that values of acceleration of the vibration differ reached to $2,0 \text{ mm/s}^2$ at frequencies 6,3 – 250 Hz. Highest and lowest value of the acceleration was found in 1st and 5th storey staircases. At frequencies from 315 to 3150 Hz (Fig. 3.109) acceleration of the vibrations differ from 1,0 to $12,8 \text{ mm/s}^2$. Lowest value of the acceleration was found in 10m reference point, and the highest value was found in 1 m reference point. The road surface near the reference points is cracked.

3.2.2. Research point No. 3. Verkių and Apkasų St. crossroad

Measurements of the ground borne vibration started 2016 – 05 – 11 d and finished in 2016-08-14. During measurements air temperature was 20 - 23 °C, wind speed 0,3 – 3,1 m/s, humidity 78-92 % , atmosphere pressure 99,6-105,5 kPa. The vibration measurements was done to the axis z, because in this axis was found biggest vibration. Apartment building (Apkasų St. 5, Vilnius) is built 10,1 m distance to the speed table.

Table 3.7 Number of vehicles measured.

Measurement point	Light vehicles	Moderate weight vehicles	Heavy weight vehicle
1 m from traffic calming measure	18	17	6
10 m away from speed table, near the testing apartment building	15	16	5
1st storey in apartment building staircase	15	11	5
3rd storey in apartment building staircase	15	12	5
5th storey in apartment building staircase	15	10	4
Reference point 1m distance to street	15	15	5
Reference point 10 m distance to street	15	16	4

At measurement point in first storey of apartment building that similar maximum vibration acceleration was found when different transport was passing, maximum vibration was found at 1250 Hz frequency and the acceleration was 4,6 mm/s². Graphs of measurement results shown in 3.110 And 3.111 Figures.

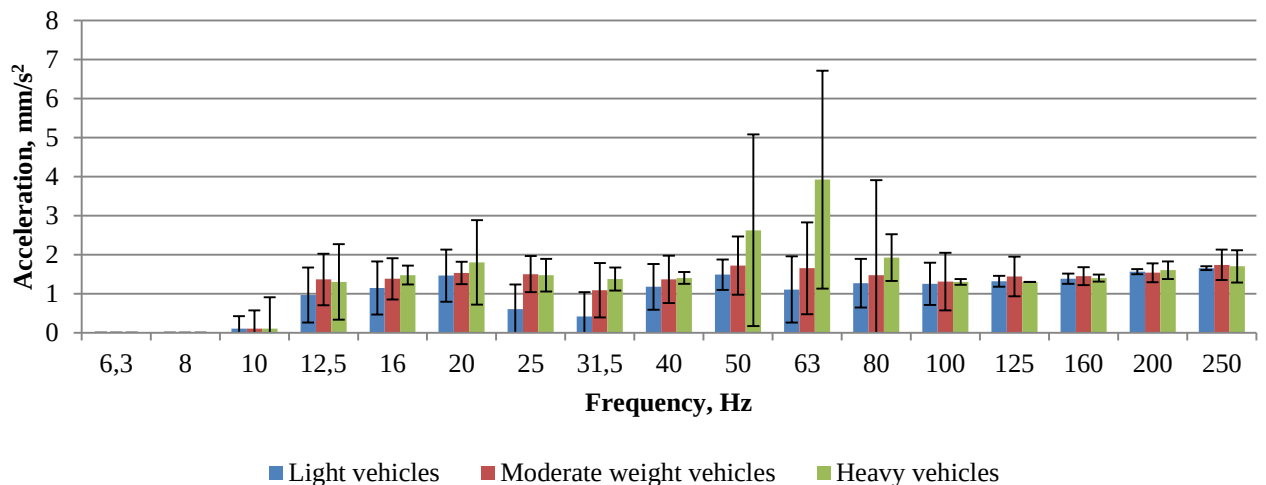


Fig. 3.110 Acceleration of the vibrations in first storey staircase in frequencies from 6,3 to 250 Hz

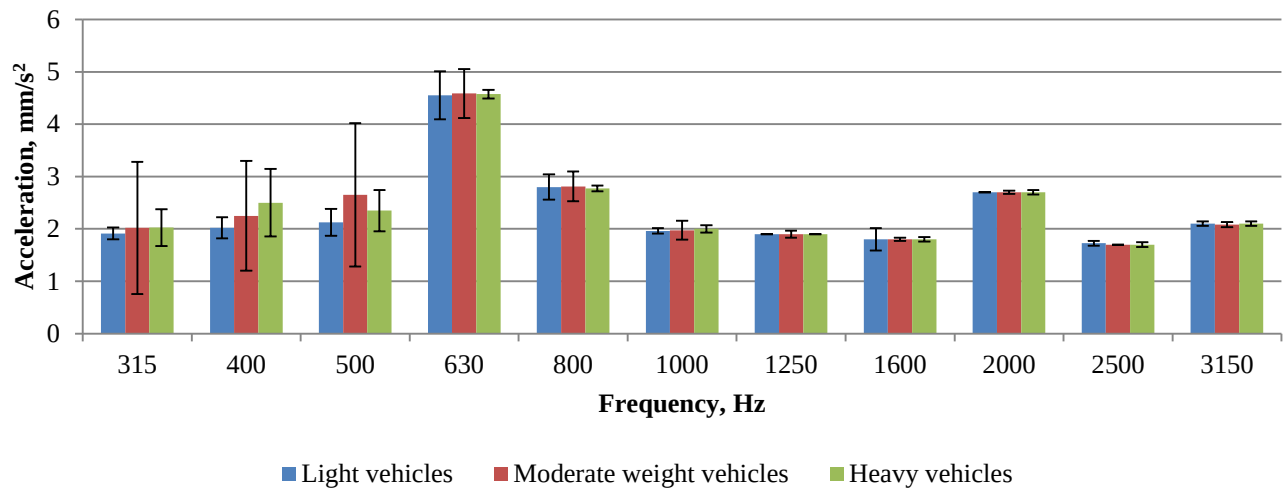


Fig. 3.111 Acceleration of the vibrations in first storey staircase in frequencies from 315 to 3150 Hz

Measurement results was compared with HN 50: 2003 threshold levels. At frequencies from 6,3 to 80 Hz vibration acceleration level, when light vehicles was passing was up to 12 % of the threshold level. When moderate weight vehicles was passing it reached up to 17 % of the threshold level. When heavy weight transport was passing vibrations in first storey of the building also reached up to 17 % of the threshold level. No exceeding of threshold level was found.

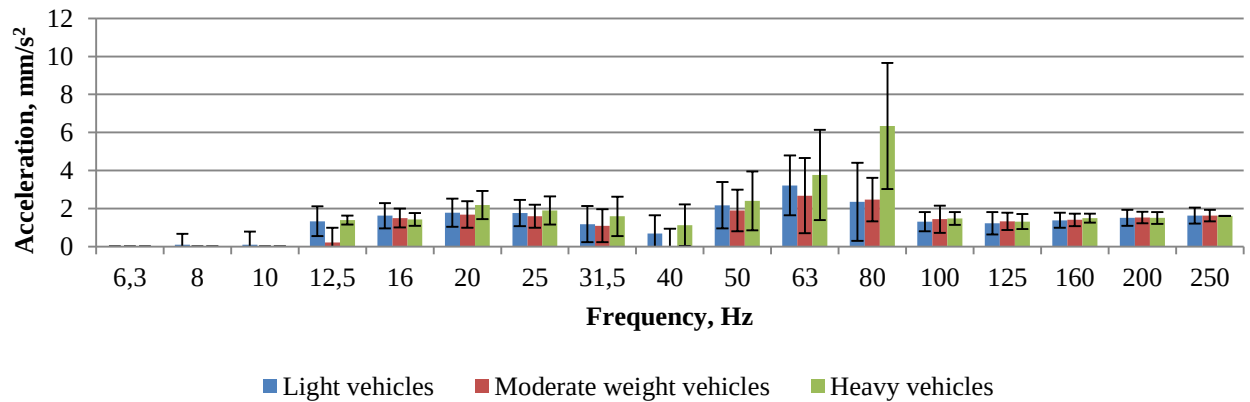


Fig. 3.112 Acceleration of the vibrations in third storey staircase in frequencies from 6,3 to 250 Hz

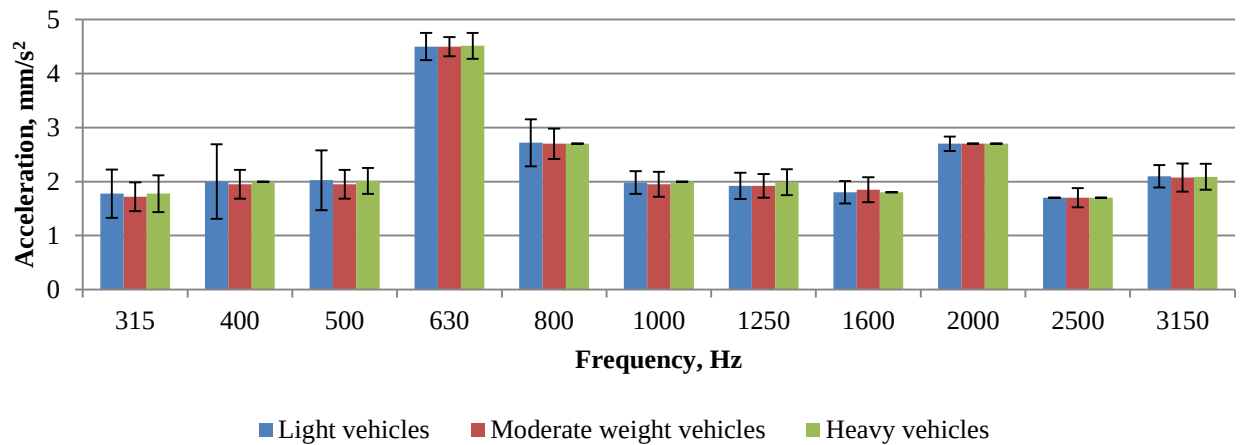


Fig. 3.113 Acceleration of the vibrations in third storey staircase in frequencies from 315 to 3150 Hz

At measurement point in third storey of apartment building maximum vibration acceleration was found when heavy vehicles was passing, maximum vibration was found at 80 Hz frequency and the acceleration was 6,3 mm/s². Light vehicles induced maximum vibrations was 4,5 mm/s² at 630 Hz frequency and moderate weight vehicles induced vibrations 4,5 mm/s² at the frequency of 630 Hz. Graphs of measurement results shown in 3.112 And 3.113 Figures.

Measurement results was compared with HN 50: 2003 threshold levels. At frequencies from 6,3 to 80 Hz vibration acceleration level, when light vehicles was passing was from 0,9 to 3,6 % of the threshold level. When moderate weight vehicles was passing it reached up to 32 % of the threshold level. When heavy weight transport was passing vibrations in third storey of the building also reached up to 44 % of the threshold level. No exceeding of threshold level was found.

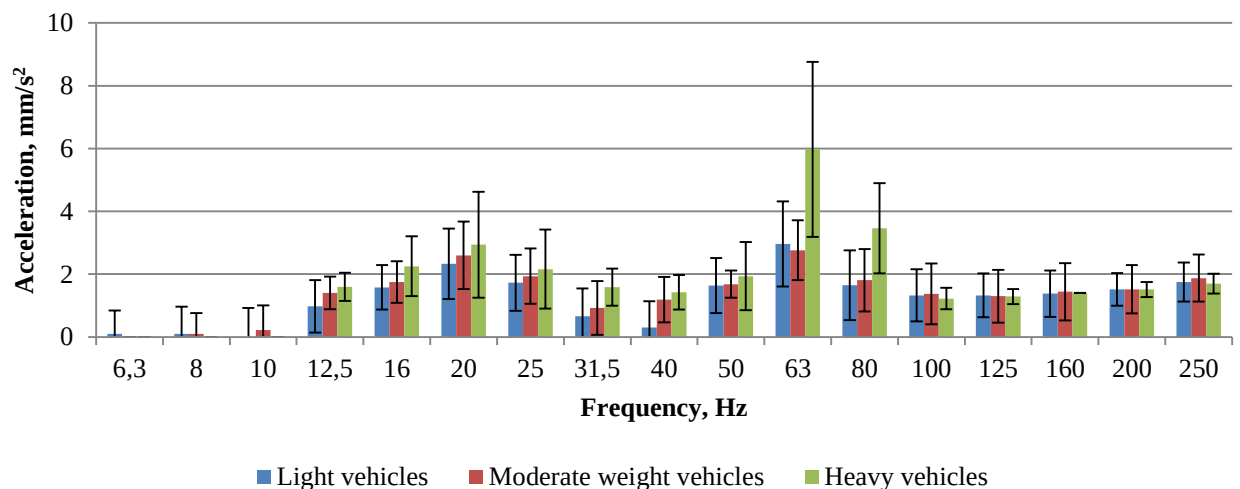


Fig. 3.114 Acceleration of the vibrations in fifth storey staircase in frequencies from 6,3 to 250 Hz

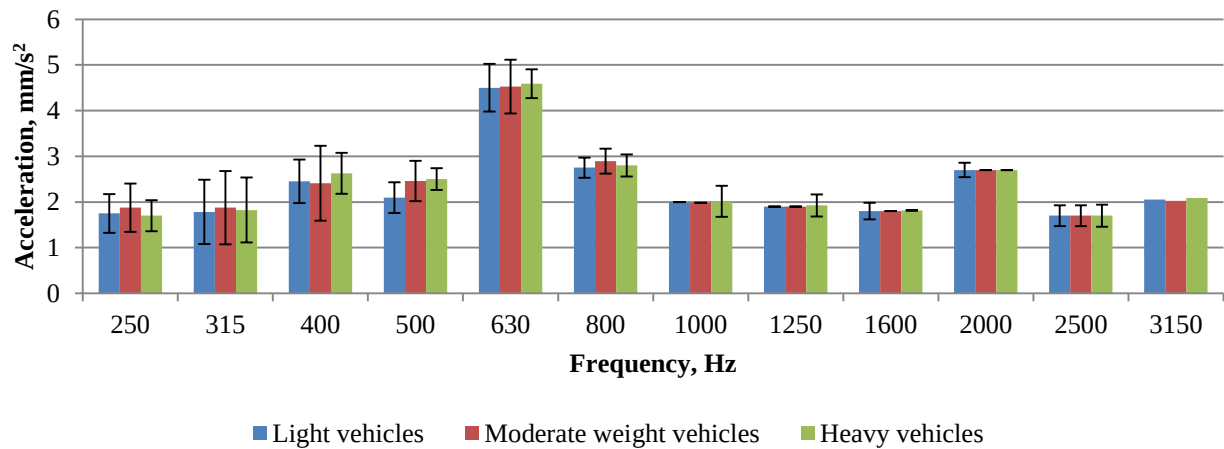


Fig. 3.115 Acceleration of the vibrations in fifth storey staircase in frequencies from 315 to 3150 Hz

At measurement point in fifth storey of apartment building maximum vibration acceleration was found when heavy vehicles was passing, maximum vibration was found at 63 Hz frequency and the acceleration was 6,0 mm/s². Moderate weight vehicles induced maximum vibrations was 4,5 mm/s² at 630 Hz frequency and light vehicles induced vibrations 4,5 mm/s² at the frequency of 630 Hz. Graphs of measurement results shown in 3.114 And 3.115 Figures. Heavyweight vehicles was mainly the public transport buses, these vehicles passed traffic calming measure very slowly.

Measurement results was compared with HN 50: 2003 threshold levels. At frequencies from 6,3 to 80 Hz vibration acceleration level, when light vehicles was passing reached 19 % of the threshold level. When moderate weight vehicles was passing it reached up to 21 % of the threshold level. When heavy weight transport was passing, vibrations in fifth storey of the building reached up to 21 % of the threshold level. No exceeding of threshold level was found.

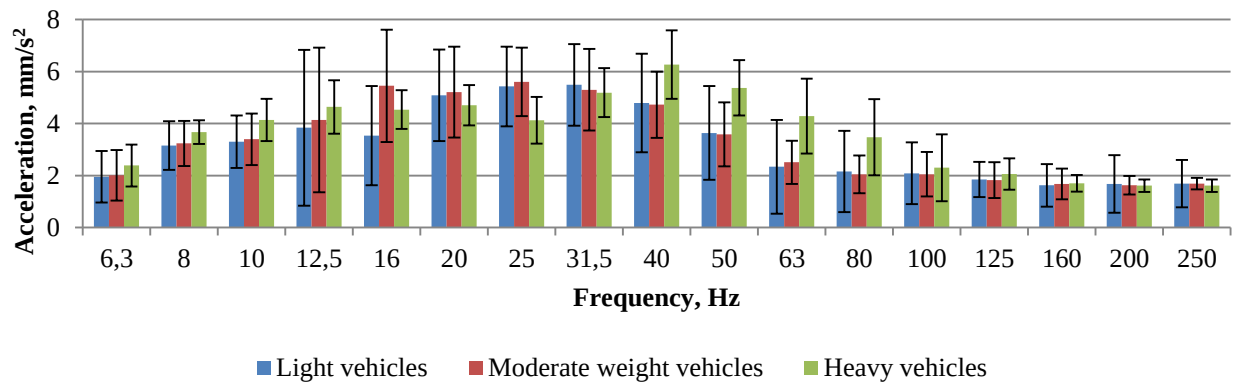


Fig. 3.116 Acceleration of the vibrations 1 m away from speed table in frequencies from 6,3 to 250 Hz

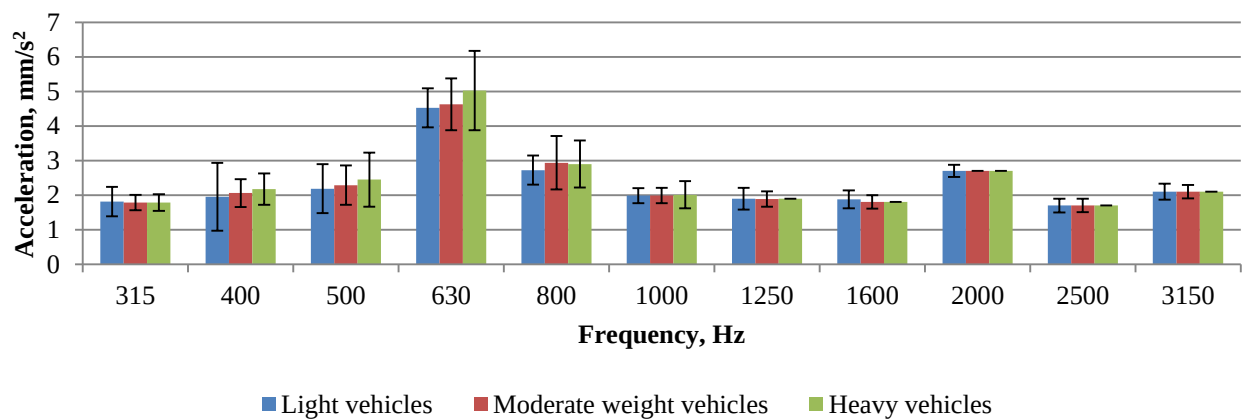


Fig. 3.117 Acceleration of the vibrations 1 m away from speed table in frequencies from 315 to 3150 Hz

In measurement one meter distance to the traffic calming measure, highest vibrations acceleration was found in 40 Hz and 630 Hz frequencies (light vehicles 4,5 mm/s² at 630 Hz, moderate weight vehicles 4,6 mm/s² at 630 Hz, heavyweight vehicles 6,3 mm/s² at 40 Hz). During measurement was noticed that light and moderate weight vehicles when passing speed table reduced their speed less than heavyweight vehicles. But still heavy weight vehicles induces highest vibrations at this measurement point.

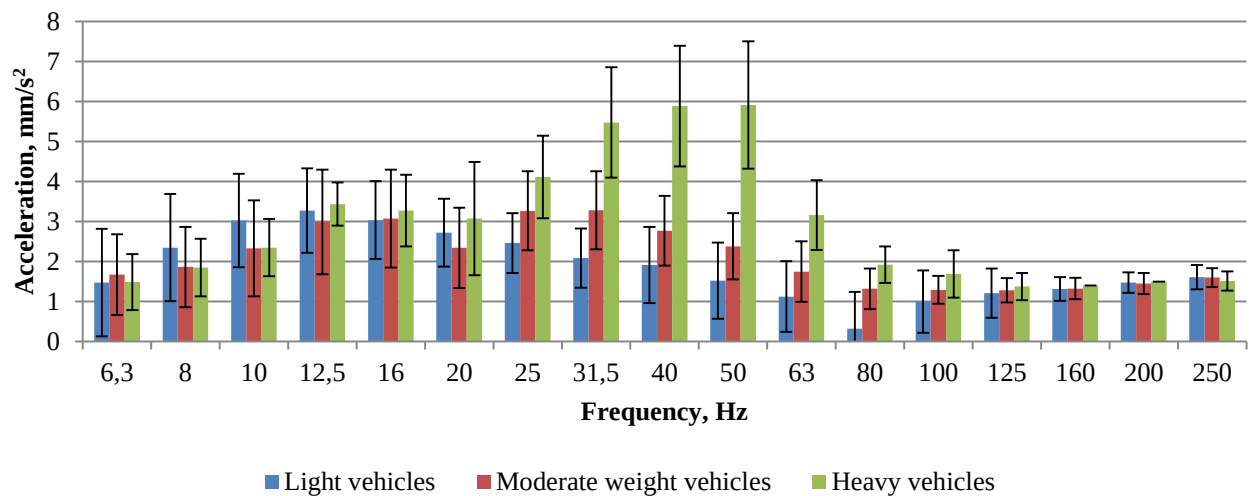


Fig. 3.118 Acceleration of the vibrations 10,1 m away from speed table, near the testing apartment building in frequencies from 6,3 to 250 Hz

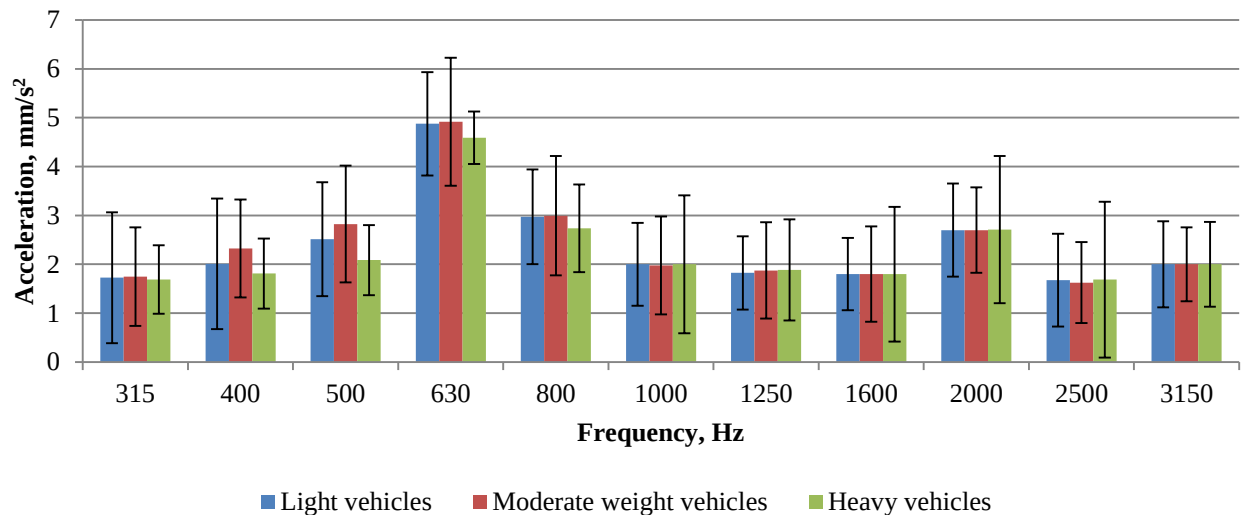


Fig. 3.119 Acceleration of the vibrations 10,1 m away from speed table, near the testing apartment building in frequencies from 315 to 3150 Hz

In measurement one meter distance to the traffic calming measure, highest vibrations acceleration was found in 50 and 630 Hz frequency (light vehicles 4,9 mm/s² at 630 Hz, moderate weight vehicles 4,9 mm/s² at 630 Hz, heavyweight vehicles 5,4 mm/s² at 2000 Hz). During measurement was noticed that light and moderate weight vehicles when passing speed table reduced their speed less than heavyweight vehicles.

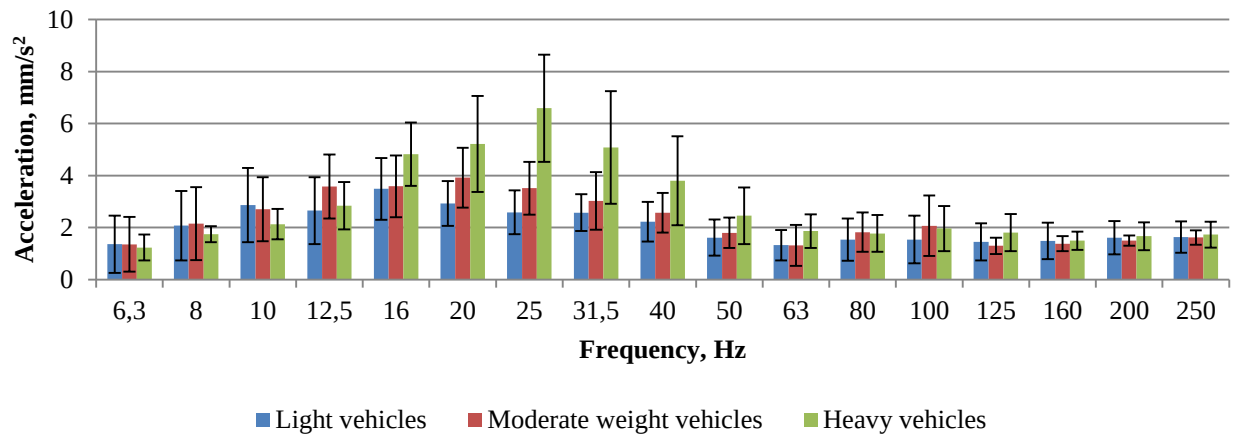


Fig. 3.120 Acceleration of the vibrations 1 m reference point in frequencies from 6,3 to 250 Hz

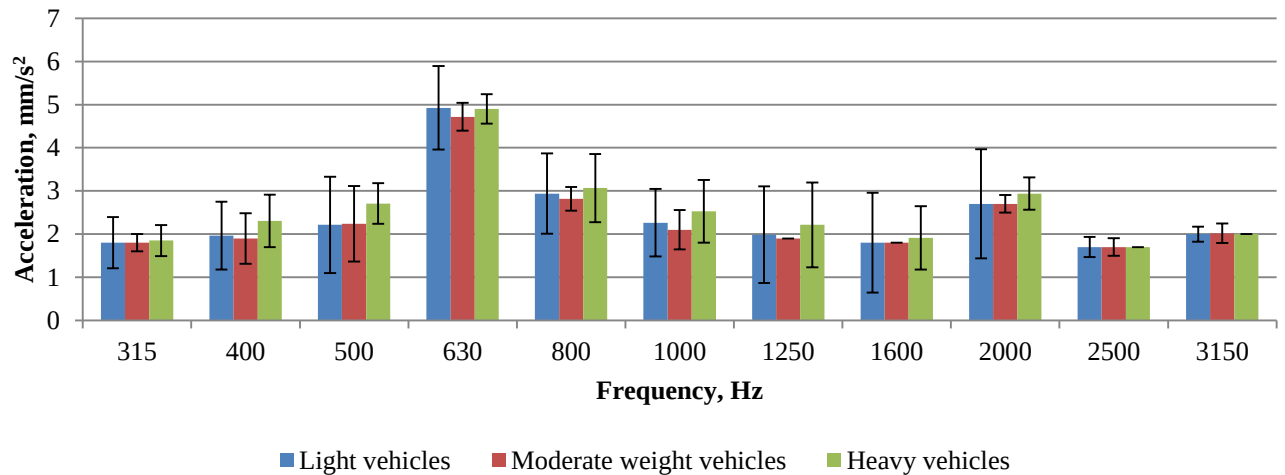


Fig. 3.121 Acceleration of the vibrations 1 m reference point in frequencies from 315 to 3150 Hz

In 1 m reference measurement point , highest vibrations acceleration was found in 50 Hz and 630 Hz frequencies (light vehicles 4,9 mm/s² at 630 Hz, moderate weight vehicles 4,7 mm/s² at 630 Hz, heavyweight vehicles 6,6 mm/s² at 25 Hz). Moderate weight and light vehicles gains speed faster than heavy vehicles after passing speed table.

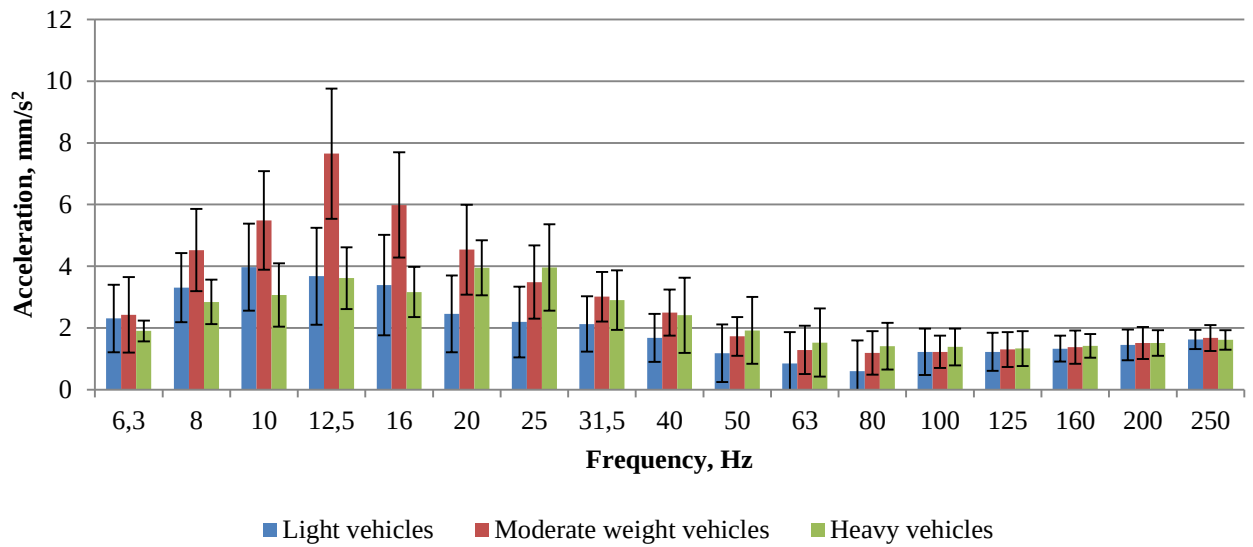


Fig. 3.122 Acceleration of the vibrations 10 m reference point in frequencies from 6,3 to 250 Hz

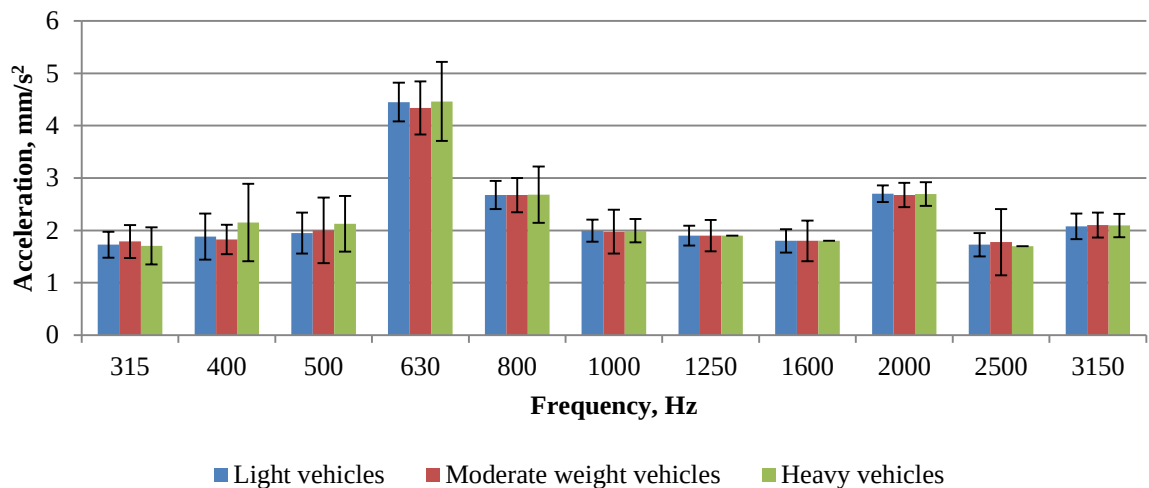


Fig. 3.123 Acceleration of the vibrations 10 m reference point in frequencies from 6,3 to 250 Hz

In 10 m reference measurement point, highest vibrations acceleration was found in 12,5 Hz and 630 Hz frequencies (light vehicles $4,5 \text{ mm/s}^2$ at 630 Hz, moderate weight vehicles $7,7 \text{ mm/s}^2$ at 630 Hz, heavyweight vehicles $4,5 \text{ mm/s}^2$ at 630 Hz). Moderate weight and light vehicles gains speed faster than heavy vehicles after passing speed table.

Summary of the results in measurement site

To sum up the results of measurement comparison between the different measurement points is done. Transport categories is separated.

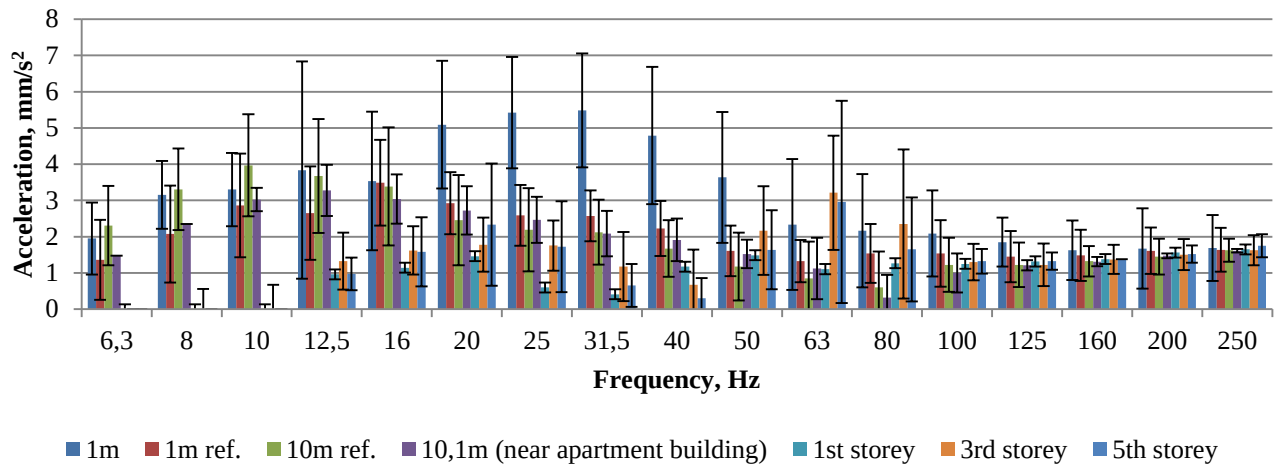


Fig. 3.124 Comparison of acceleration of the vibration when light vehicles is passing in different measurement points at frequencies 6,3 – 250 Hz.

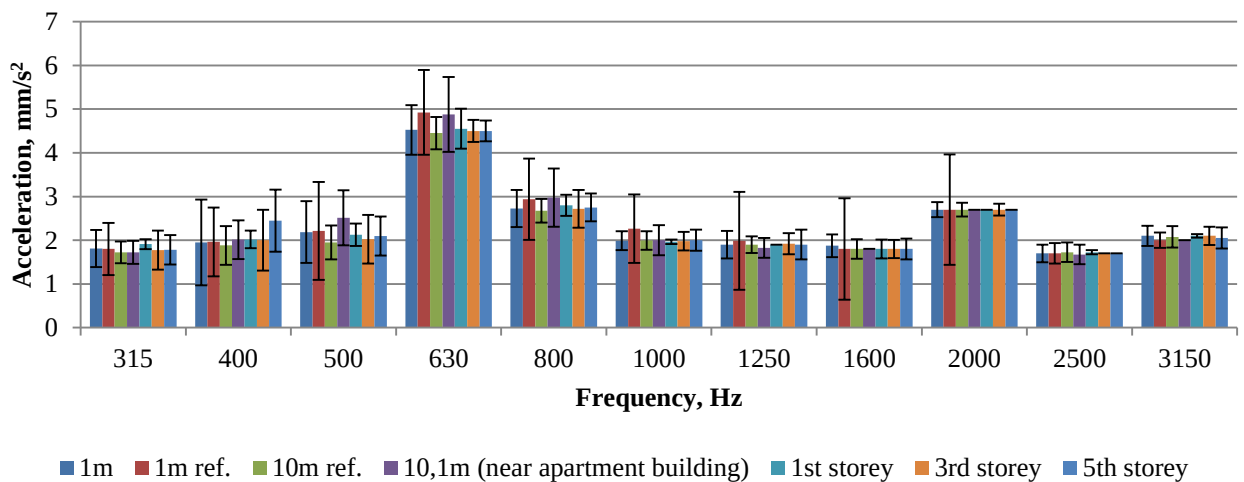


Fig. 3.125 Comparison of acceleration of the vibration when light vehicles is passing in different measurement points at frequencies 315 – 3150 Hz.

When light vehicles was passing in different measurements points (Fig. 3.124) was found that values of acceleration of the vibration reached 5,1 mm/s² at frequencies 6,3 – 250 Hz. Lowest value of the acceleration was found in 1st storey of apartment building, and the highest value was found in 1 m near the speed table. At frequencies from 315 to 3150 Hz (Fig. 3.125) acceleration of the vibrations differ

from 1,7 to 4,5 mm/s². Lowest value of the acceleration was found near the apartment building 10,1 distance to the speed table, and the highest value was found in 1 m distance to the speed table.

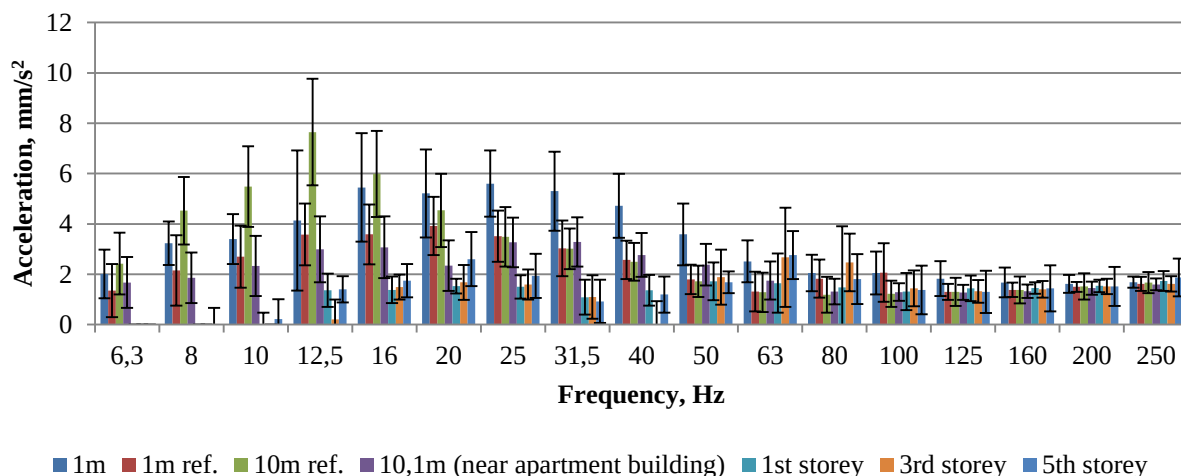


Fig. 3.126 Comparison of acceleration of the vibration when moderate weight vehicles is passing in different measurement points at frequencies 6,3 – 250 Hz.

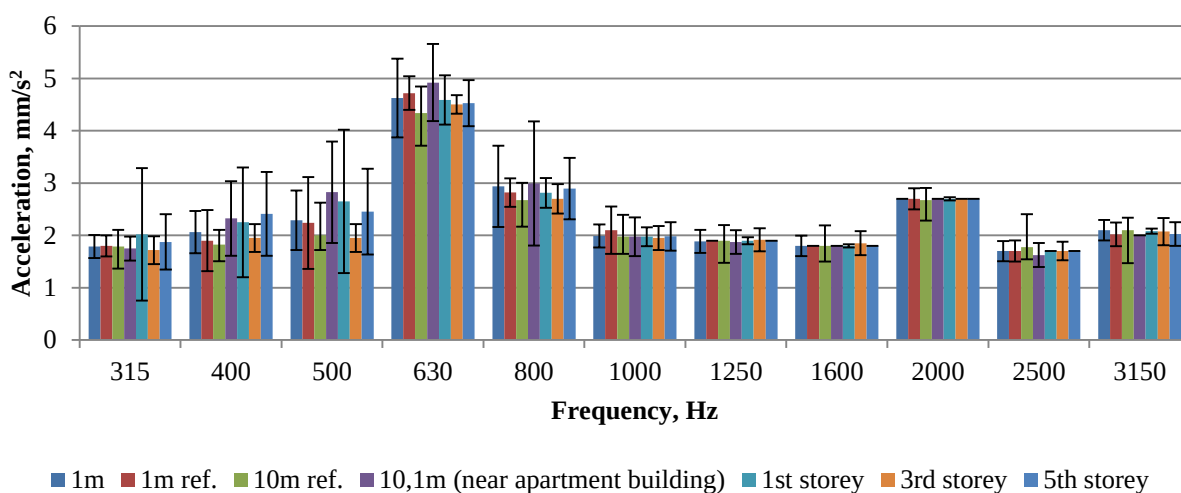


Fig. 3.127 Comparison of acceleration of the vibration when moderate weight vehicles is passing in different measurement points at frequencies 315 – 3150 Hz.

When moderate weight vehicles was passing in different measurements points (Fig. 3.126) was found that values of acceleration of the vibration reach to 5,1 mm/s² at frequencies 6,3 – 250 Hz. Lowest value of the acceleration was found in 1st storey of apartment building, and the highest value was found in 1 m near the speed table. At frequencies from 315 to 3150 Hz (Fig. 3.127) acceleration of the vibrations differ from 1,7 to 4,5 mm/s². Lowest value of the acceleration was found near the apartment building 10,1 distance to the speed table, and the highest value was found in 1 m distance to the speed table.

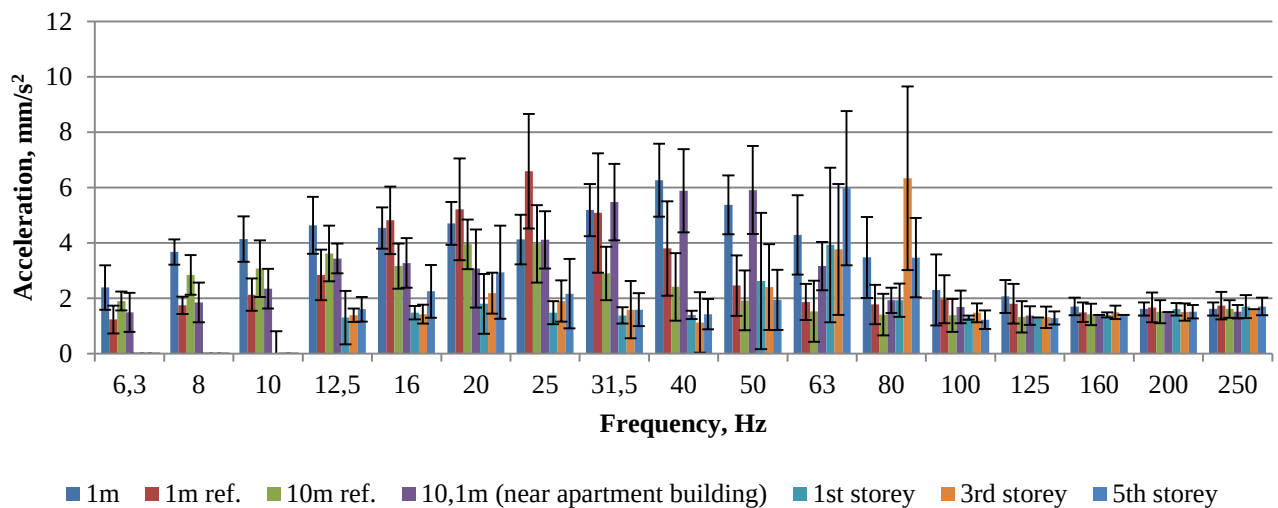


Fig. 3.128 Comparison of acceleration of the vibration when heavyweight vehicles is passing in different measurement points at frequencies 6,3 – 250 Hz.

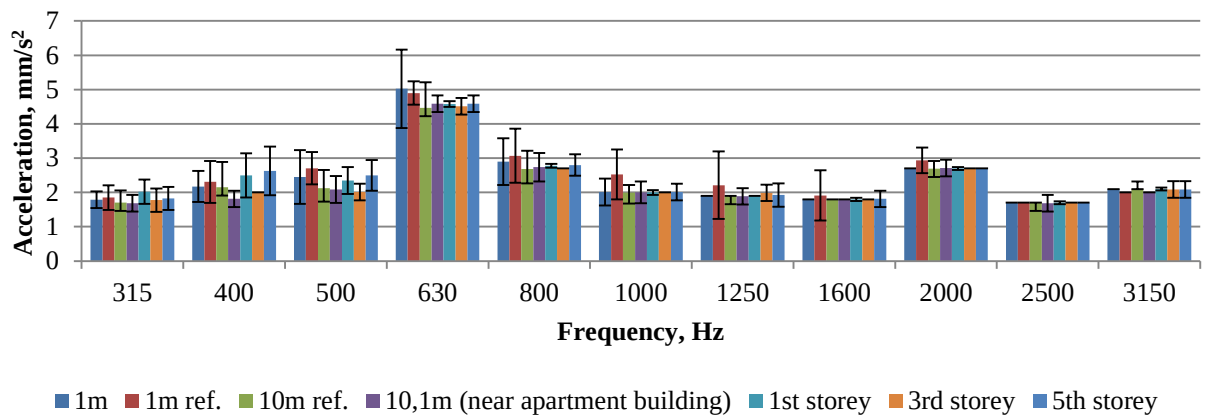


Fig. 3.129 Comparison of acceleration of the vibration when heavyweight vehicles is passing in different measurement points at frequencies 315 – 3150 Hz.

When heavyweight vehicles was passing in different measurements points (Fig. 3.128) was found that values of acceleration of the vibration reach up to $6,6 \text{ mm/s}^2$ at frequencies 6,3 – 250 Hz. Lowest value of the acceleration was found in the first storey of the apartment building, highest value found in 1m reference point. At frequencies from 315 to 3150 Hz (Fig. 3.129) acceleration of the vibrations differ from 1,7 to $5,0 \text{ mm/s}^2$ Lowest value of the acceleration was found near the apartment building 10,1 distance to the speed table, and the highest value was found in 1 m distance to the speed table.

3.2.3. Research point No. 4. Gurių 51 St., Vilnius

Measurements of the ground borne vibration was done in 2016 – 07 – 28 d. During measurements air temperature was 27 °C, wind speed 0,5 m/s, humidity 42 % , atmosphere pressure 100,2 kPa. The vibration measurements was done to the axis z, because in this axis was found biggest vibration.

Table 3.8 Number of vehicles measured.

Measurement point	Light vehicles	Moderate weight vehicles	Heavy weight vehicle
1 m from traffic calming measure	17	10	0
15 m away from speed table, near the testing apartment building	16	10	0
Reference point 1m distance to street	15	10	0
Reference point 10 m distance to street	16	10	0
1st storey in apartment building corridor	16	10	0
3rd storey in apartment building corridor	16	10	0

Apartment building (Gurių St. 51, Vilnius) is built 15 m distance to the speed table. In this measurement site heavy weight transportation is forbidden, in this measurement site heavy weight vehicles was not measured.

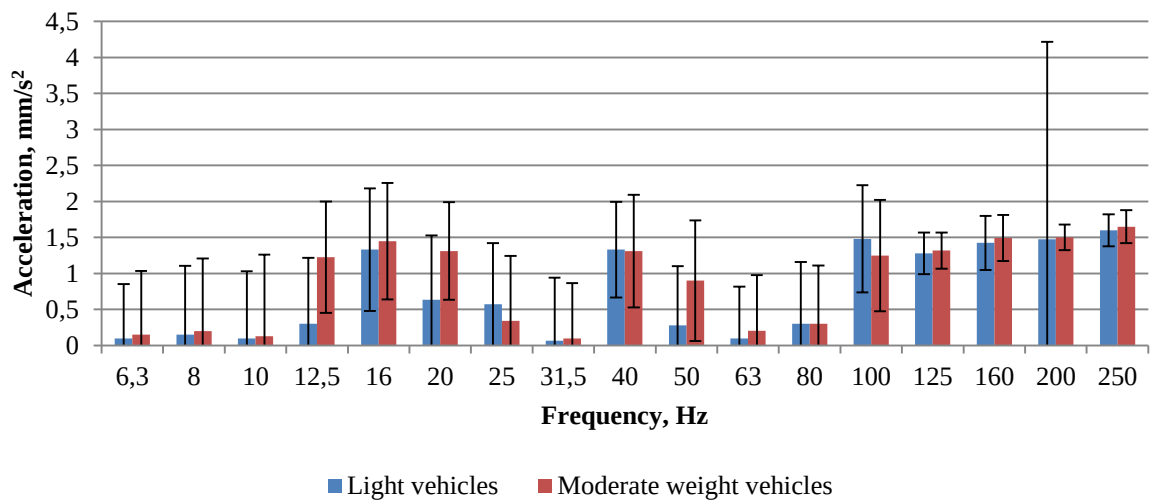


Fig. 3.130 Comparison of acceleration of the vibration when heavyweight vehicles is passing in different measurement points at frequencies 315 – 3150 Hz.

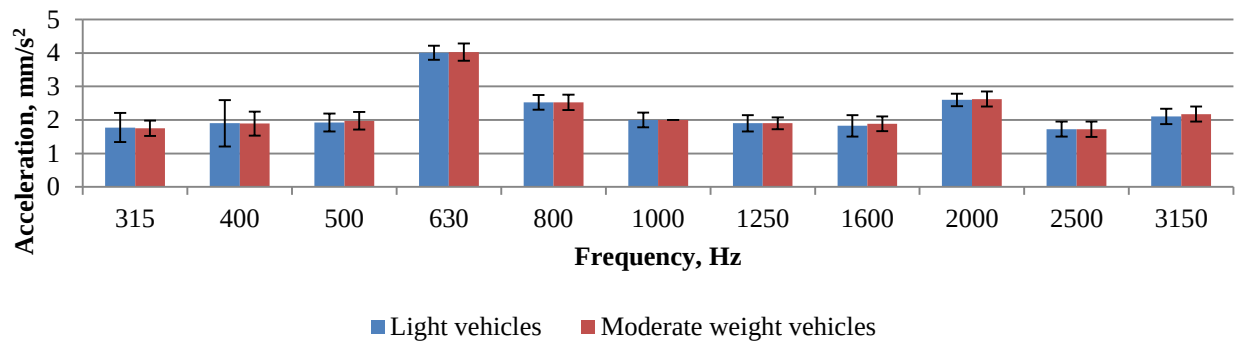


Fig. 3.131 Acceleration of the vibrations in first storey corridor in frequencies from 315 to 3150 Hz

At measurement point in first storey of apartment building maximum vibration acceleration was found that acceleration was similar, maximum vibration was found at 630 Hz frequency and the acceleration was $4,0 \text{ mm/s}^2$ (light vehicles). Moderate weight vehicles maximum induced vibration was $4,0 \text{ mm/s}^2$ at 630 Hz frequency. Graphs of measurement results shown in 3.130 And 3.131 Figures.

Measurement results was compared with HN 50: 2003 threshold levels. At frequencies from 6,3 to 80 Hz vibration acceleration level, when light vehicles was passing was up to 13 % of the threshold level. When moderate weight vehicles was passing it also reached up to 15 % of the threshold level.

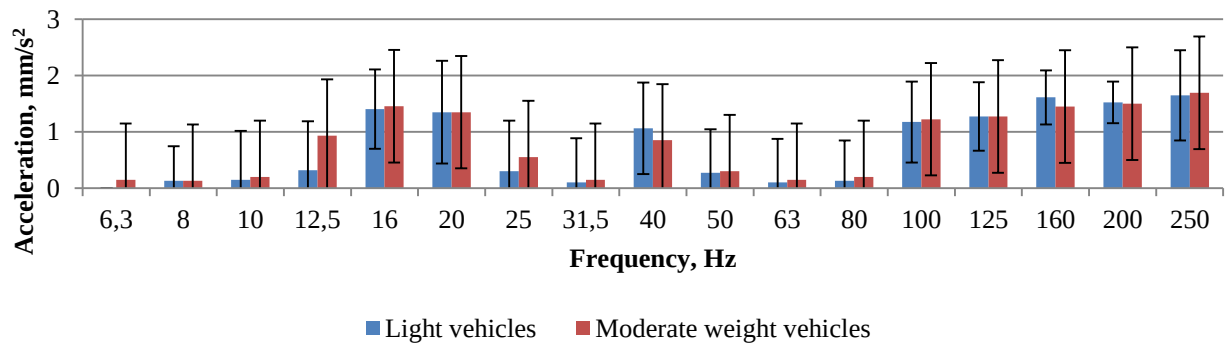


Fig. 3.132 Acceleration of the vibrations in third storey corridor in frequencies from 6,3 to 250 Hz

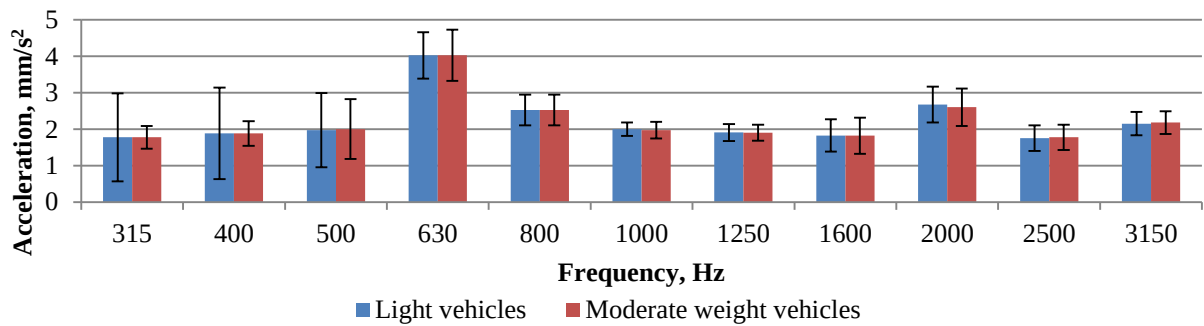


Fig. 3.133 Acceleration of the vibrations in third storey corridor in frequencies from 315 to 3150 Hz

At measurement point in first storey of apartment building maximum vibration acceleration was found that acceleration was similar, maximum vibration was found at 630 Hz frequency and the acceleration was $4,0 \text{ mm/s}^2$ (moderate weight vehicles). Light vehicles maximum induced vibration was $4,0 \text{ mm/s}^2$ at 630 Hz frequency. Graphs of measurement results shown in 3.132 And 3.133 Figures.

Measurement results was compared with HN 50: 2003 threshold levels. At frequencies from 6,3 to 80 Hz vibration acceleration level, when light vehicles was passing was up to 14 % of the threshold level. When moderate weight vehicles was passing it also reached up to 15 % of the threshold level.

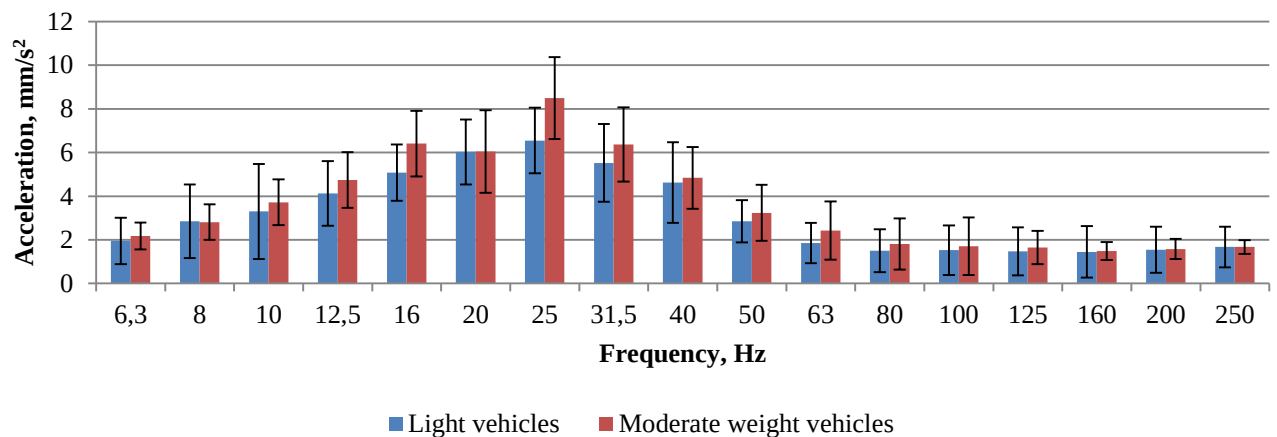


Fig. 3.134 Acceleration of the vibrations 1 m away from speed table in frequencies from 6,3 to 250 Hz

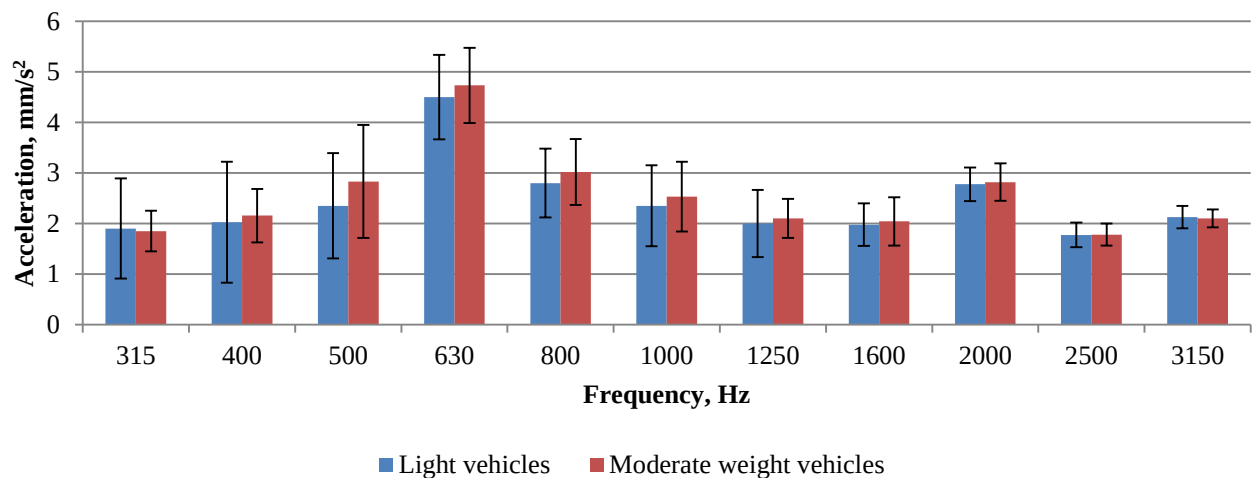


Fig. 3.135 Acceleration of the vibrations 1 m away from speed table in frequencies from 315 to 3150 Hz

In measurement one meter distance to the traffic calming measure, highest vibrations acceleration was found in 25 Hz frequency (light vehicles $6,6 \text{ mm/s}^2$ at 25 Hz, moderate weight vehicles $8,5 \text{ mm/s}^2$ at 25 Hz). Results are shown in Fig. 134 And Fig. 135 Vehicles passed speed table in similar speed.

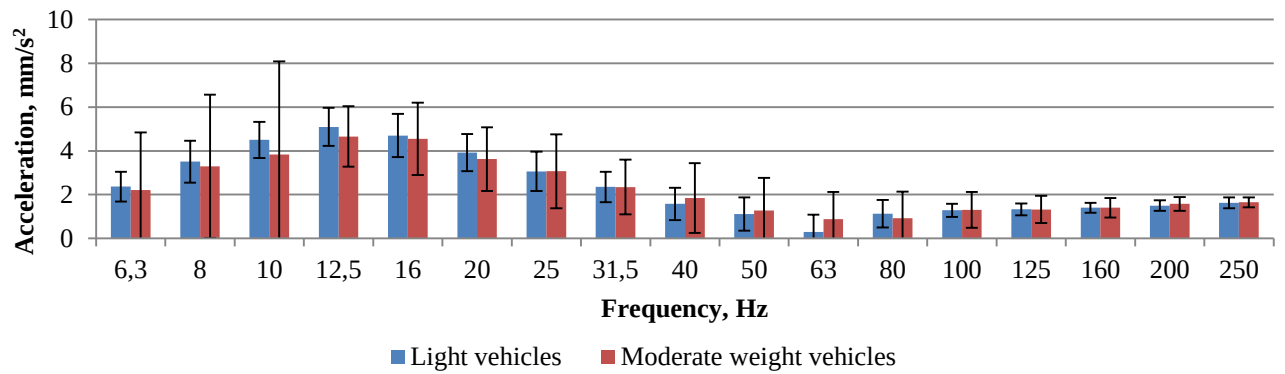


Fig. 3.136 Acceleration of the vibrations 15 m away from speed table, near the apartment building in frequencies from 6,3 to 250 Hz

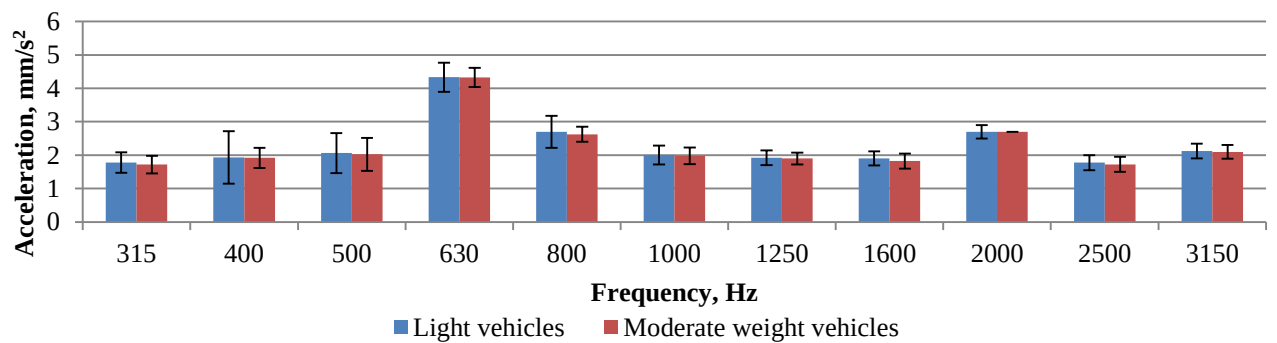


Fig. 3.137 Acceleration of the vibrations 15 m away from speed table, near the apartment building in frequencies from 6,3 to 250 Hz

In measurement 15 m distance to the traffic calming measure, near the testing residential apartment building, highest vibrations acceleration was found in 12,5 Hz frequency (light vehicles 5,1 mm/s², moderate weight vehicles 4,7 mm/s²). Results are shown in Fig. 136 and Fig. 137.

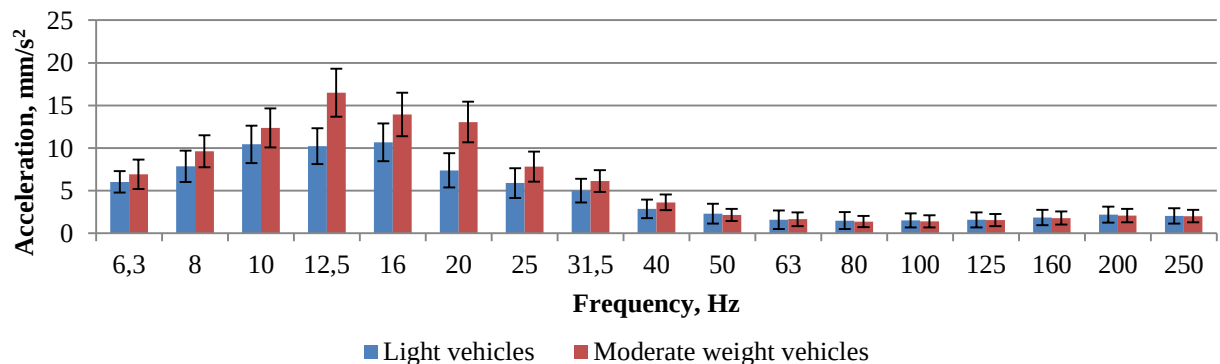


Fig. 3.138 Acceleration of the vibrations 1 m reference point in frequencies from 6,3 to 250 Hz

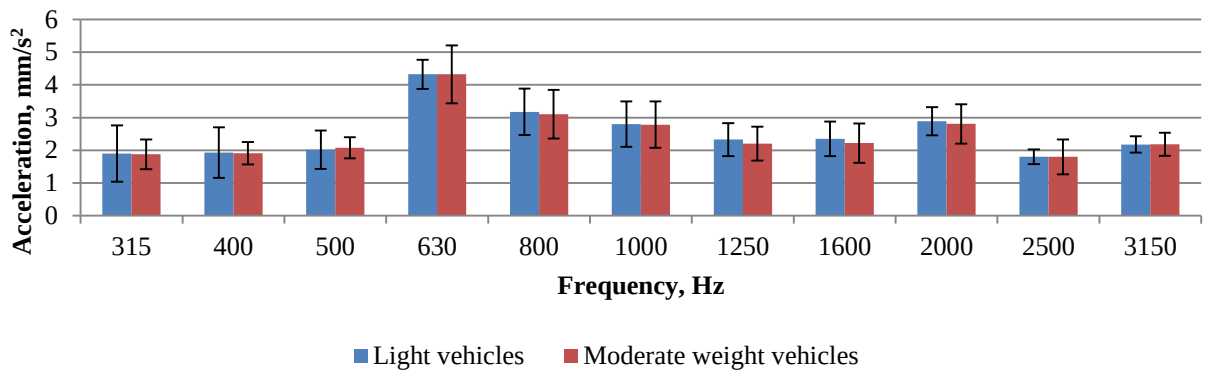


Fig. 3.139 Acceleration of the vibrations 1 m reference point in frequencies from 315 to 3150 Hz

In 1 m reference measurement point, highest vibrations acceleration was found in 10 Hz and 12,5 Hz frequencies (light vehicles 10,4 mm/s² at 10 Hz, moderate weight vehicles 16,5 m/s² at 12,5 Hz). Moderate weight and light vehicles ran in similar speed through this measurement point.

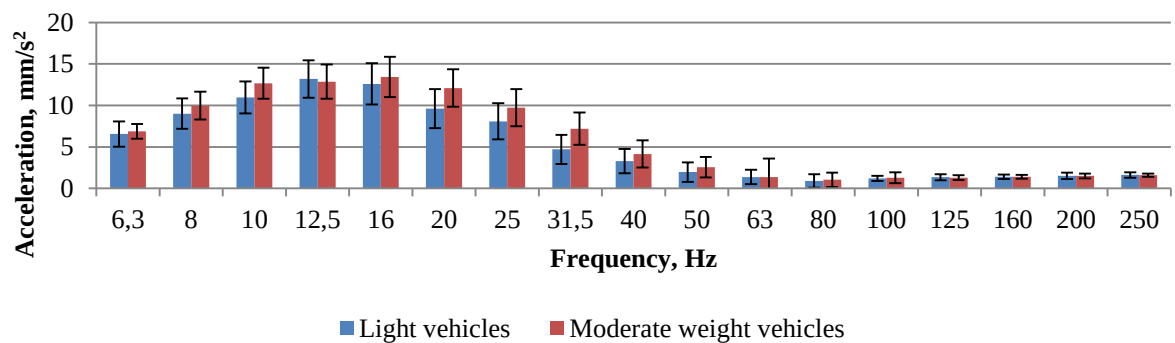


Fig. 3.140 Acceleration of the vibrations 10 m reference point in frequencies from 6,3 to 250 Hz

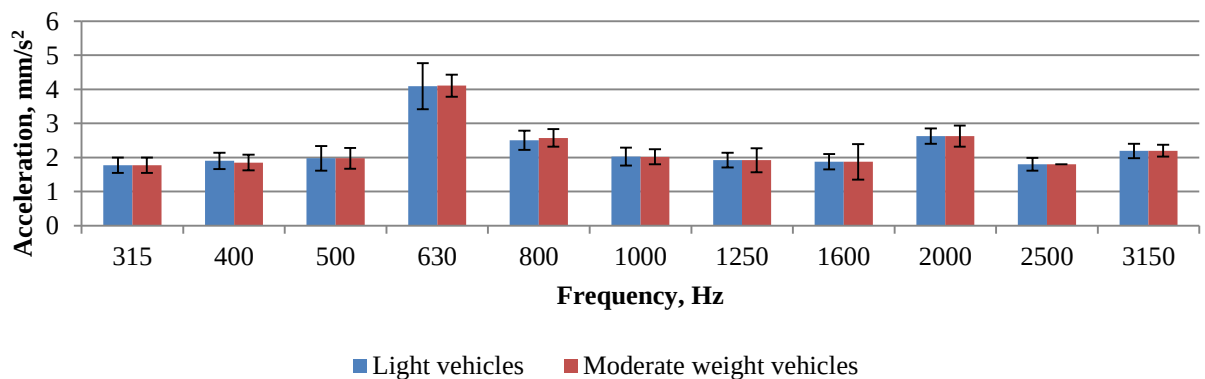


Fig. 3.141 Acceleration of the vibrations 10 m reference point in frequencies from 315 to 3150 Hz

In 10 m reference measurement point, highest vibrations acceleration was found in 12,5 Hz and 16 Hz frequencies (light vehicles 13,2 mm/s² at 12,5 Hz, moderate weight vehicles 13,4 mm/s² at 16 Hz). Moderate weight and light vehicles ran in similar speed through this measurement point.

Summary of the results in measurement site

To sum up the results of measurement comparison between the different measurement points is done. Transport categories is separated.

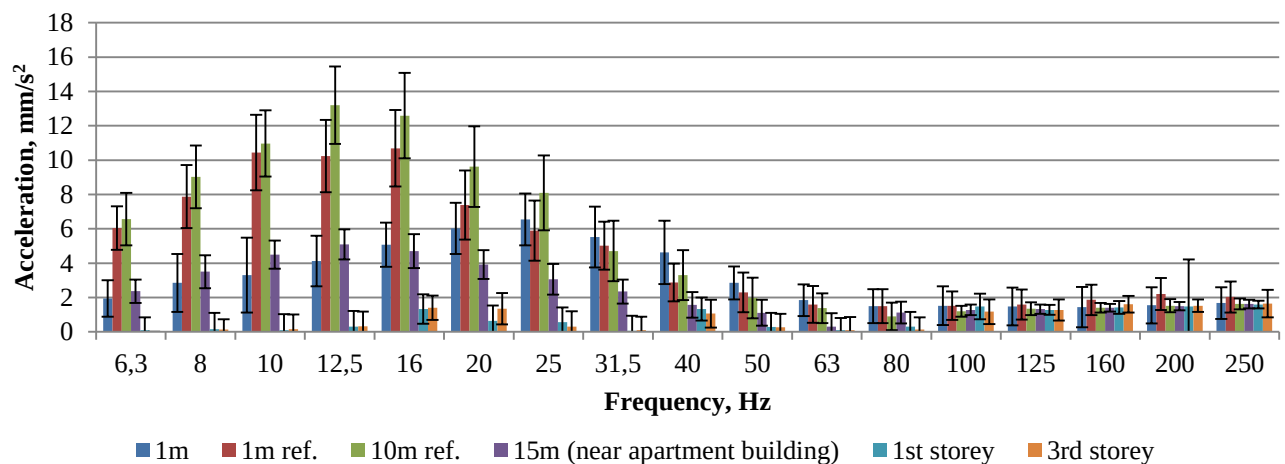


Fig. 3.142 Comparison of acceleration of the vibration when light vehicles is passing in different measurement points at frequencies 6,3 – 250 Hz.

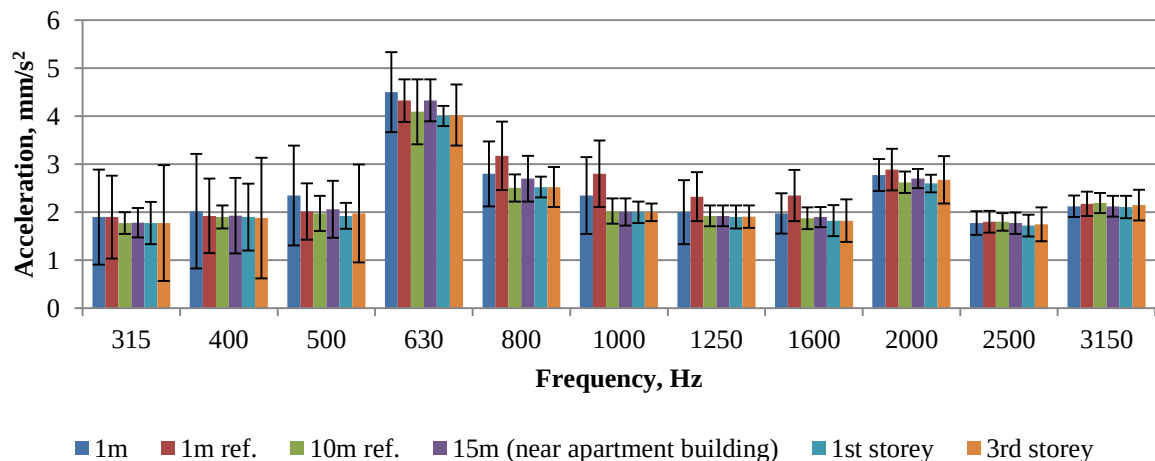


Fig. 3.143 Comparison of acceleration of the vibration when light vehicles is passing in different measurement points at frequencies 315 – 3150 Hz.

When light vehicles was passing in different measurements points (Fig. 3.143) was found that values of acceleration of the vibration reached to 13,2 mm/s² at frequencies 6,3 – 250 Hz. Lowest value of the acceleration was found in the 1st and 3rd storey of the apartment building, and the highest value was found in 10 m reference point. At frequencies from 315 to 3150 Hz (Fig. 3.144) acceleration of the vibrations differ from 1,8 to 4,5 mm/s². Lowest value of the acceleration was found in 10 m reference point, and the highest value was found in 1 m distance to the speed table.

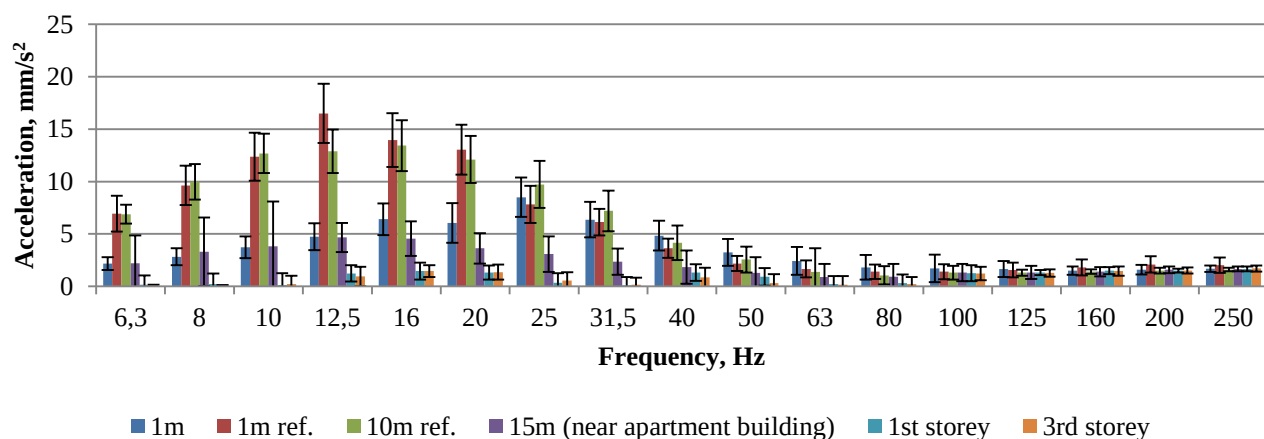


Fig. 3.144 Comparison of acceleration of the vibration when moderate weight vehicles is passing in different measurement points at frequencies 6,3 – 250 Hz.

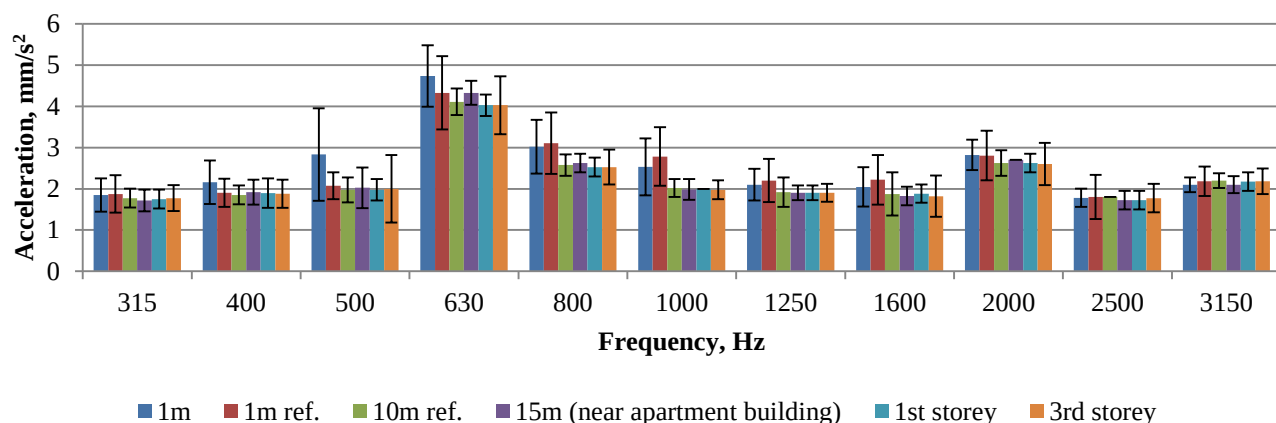


Fig. 3.145 Comparison of acceleration of the vibration when moderate weight vehicles is passing in different measurement points at frequencies 315 – 3150 Hz.

When moderate weight vehicles was passing in different measurements points (Fig. 3.144) was found that values of acceleration of the vibration reached to 16,5 mm/s² at frequencies 6,3 – 250 Hz. Lowest value of the acceleration was found in the 1st and 3rd storey of the apartment building, and the highest value was found near the speed table. At frequencies from 315 to 3150 Hz (Fig. 3.145)

acceleration of the vibrations differ from 1,8 to 4,7 mm/s². Lowest value of the acceleration was found in 3rd storey corridor, and the highest value was found near the speed table.

Summary of results

In this research mainly was found that vertical traffic calming measures increases traffic induced vibrations. Where the road pavement condition is worse, on this section of road traffic calming measure do not influence road traffic induced vibrations. At average, near the speed tables, traffic induced vibration is 19 % higher than near the road without these devices. Even though there is no risk to the resident health living near the pedestrian crossings where all tested speed tables are built. All tested speed tables are built in the Vilnius city streets where traffic speed is relatively low (allowed 50 km/h).

During summer season vibration acceleration is higher at frequencies from 6.3- 250 Hz compared with winter results got during winter season. In average during summer season vibration acceleration is 1,5 mm/s² higher compared with winter season. At frequencies from 315 to 3150 Hz vibration acceleration is higher during winter season. During winter season traffic induces 3,1 mm/s² higher vibration acceleration compared with summer season. Visually looked that the vehicles run faster during summer season. Such change in measurement conditions cause higher vibration acceleration in low frequencies during the warm season.

Results comparison with other authors is complicated because most authors measured vibration parameter is peak particle velocity (PPV). Other authors (Clemente P. and Rimaldis D. 1998, Crispino M. D'apuzzo M. 2000, Francois et. al. 2005) found that traffic induced ground vibration peaks are at 10 to 31,5 Hz frequency. During their measurements season was not specified. In this research similar peaks during summer season was found.

Conclusions of the 3rd chapter

1. Highest road traffic induced vibrations was found near the speed tables. In average higher vibration acceleration was induced during the summer season. In average during summer season vibration acceleration was 32 % higher compared with winter season. This could be caused by the traffic going faster. All measurements were done in the city near the apartment and commercial buildings, and they are heated during winter season it is possible that soil did not freeze during winter season.
2. During summer season vibration acceleration is higher at frequencies from 6.3- 250 Hz compared with winter results got during winter season. In average during summer season vibration acceleration is 1,5 mm/s² higher compared with winter season.
3. At frequencies from 315 to 3150 Hz vibration acceleration is higher during winter season. During winter season traffic induces 3,1 mm/s² higher vibration acceleration compared with summer season.
4. During winter season heavyweight transport induces 25 % higher vibration acceleration compared with light and moderate weight vehicles. Light and moderate weight induced vibrations are similar.
5. During winter season in three of four measurement sites, speed table influence to the road traffic induced vibrations was found. At frequencies from 6,3 to 250 Hz vibration acceleration is 3,9 mm/s² higher compared with similar reference point. At frequencies 315 – 3150 this difference reaches 6,5 mm/s². Speed table impact is not found in Asanavičiūtė St. Measurement site.
6. During summer season heavyweight transport induces 24 % higher vibration acceleration compared with light vehicles. Compared with moderate weight vehicles, heavyweight vehicles induce 13 % higher acceleration of ground vibrations.
7. During summer season in two of four measurement sites, speed table influence to the road traffic induced vibrations was found. At frequencies from 6,3 to 250 Hz vibration acceleration is 19 % higher compared with similar reference point. At frequencies 315 – 3150 this difference reaches 1 %. Speed table impact is not found in Asanavičiūtė St. and Gurių St. measurement sites.

4. Modelling of ground-borne vibration in environment and buildings

In this chapter numerical modelling of ground borne vibrations is presented. For modelling is used “New vibration model” presented by Banedanmark company, Denmark. The numerical modeling includes two parts: modelling of traffic induced vibration spreading in different soils, second part includes vibration modelling in buildings. Second part includes examined traffic calming measures.

4.1. Methodology

In this thesis Banedanmark's new vibration model is used. Banedanmark's new vibration model is based on the fact that a source strength can be used to calculate vibration comfort estimates for buildings nearby a train alignment, provided a number of corrections to account for the effects of geology, distances between the track and the building as well as the properties of the buildings are applied. This model is mainly used to calculate train induced ground borne vibration, but it is adapted for road transport. (Banedanmark, 2015)

Transmission of vibrations through a given type of soil consist of several components:

- › Geometric spreading
- › Viscous damping

Geometric spreading

Vibrations propagates as waves in the ground. The wave field will be plane within a vehicle length from track and at low frequencies, and will therefore not propagate as it moves away from the source. For higher frequencies the wavelength becomes shorter and the wave front more circular. Thus, a certain geometric spreading is expected since vibrations will propagate to a continuously wider area when moving away from the source.(Connolly et. Al. 2013)

In general, it can be expected that the wave front will propagate in line with following expression:

$$a = a_k \left(\frac{r_k}{r} \right)^{m(f)}, \quad (4.1)$$

Where a is the acceleration in a distance r from the source, and a_k is the source strength (acceleration) in a distance $r_k (= 8,0 \text{ m})$. The exponent $m(f)$ is expected to be frequency dependent, and in the most cases to be determined from tests.

For surface waves (Rayleigh waves) the value of $m(f)$ is expected to be 0 at low frequencies and 1 at high frequencies.

In order to be capable of setting up a model for the progress of $m(f)$ it is important to determine the frequency range where the wave field transforms from having plane to curved wave fronts. The transition of wave field type will not be very distinct, instead a more gradual effect is expected in the frequency range where the wavelengths are of same magnitude as the distance from track centre to source point, approx. 8,0 m. (Banedanmark, 2015) The following function for $m(f)$ has the exact characteristic that it takes the value 0 at low frequencies and 1 at high frequencies:

$$m(f) \approx 1 - \exp\left(-\frac{f}{f_b}\right), \quad (4.2)$$

Where f_b is the frequency where the wave field transforms from having plane to curved wave fronts.

In order to apply the above expression for calculating the transmission loss it is necessary to determine $f_b = c/r_k$ which is a function of wave propagating velocity c and the distance track centre to source point r_k . (Banedanmark, 2015)

Viscous damping

The longer a distance a wave travels from source to recipient and the higher a frequency, the more wavelengths will occur between the source and recipient, and therefore a greater frictional loss. The phenomenon can be described by a viscous damping model:

$$a = a_k \cdot \exp\left(-\left(\frac{2\pi f \eta}{c} |r - r_k|\right)\right), \quad (4.3)$$

Where c is the propagating velocity of the wave, η is the viscous damping constant for the current media the wave is traveling in, and $|r - r_k|$ is the distance from source to receiver point, f – frequency of calculation.

$$c \approx 0,9 \sqrt{\left(\frac{E}{2\rho(1+\nu)}\right)}, \quad (4.4)$$

The equation No. 4.4 is the calculation of wave propagation velocity in the given media. Wave propagation in soil is mainly decided by dynamic properties of soil. These parameter are got during laboratory testing, because these paramerts got when soil is moving (stress testing) (William G. R. and Vanden Berg G.E. 1968) The wave propagating velocity is a function of the physical characteristic of the ground, including E-modulus, density ρ , Poisson's ratio ν and the damping constant. (Banedanmark, 2015, Yang W. et. Al. 2013)

Soil parameters for calculation is shown in the 1st table. Vibration input $a_k=10 \text{ mm/s}^2$, $r_k=7,5 \text{ m}$.

Table 4.1 Parameters of selected soils.(Bolton M. D. and Wilson J. M. R. 1990, Gibson G. C. and Coyle H. M. 1968, Obrzud R. and Truty, A. 2012, Kezdi, A. 1974, Mott P. H. and Roland C. M. 2012.)

No.	Name of media	E- modulus	Density ρ (kg/m ³)	Poisson ratio $\nu(-)$	Viscous damping coefficient $\eta (-)$
1.	Peat	$5,6 \cdot 10^7$	1500	0,40	0,05
2.	Clay	$5,0 \cdot 10^6$	1600	0,45	0,05
3.	Sandy loam	$8,0 \cdot 10^6$	1440	0,25	0,102
4.	Loam	$1,3 \cdot 10^7$	1360	0,35	0,092

Vibration map creation

The numerical analysis was conducted using the equations shown before and represented as vibration maps (Fig. 4.1). Every ground borne vibration map is 80x50 m length and width and created using Surfer software. Grid is created using kriging method and contains 100x200 nodes. During calculations traffic flow is assumed as continuous and vehicle speed is constant. The width of the road is 6 m.

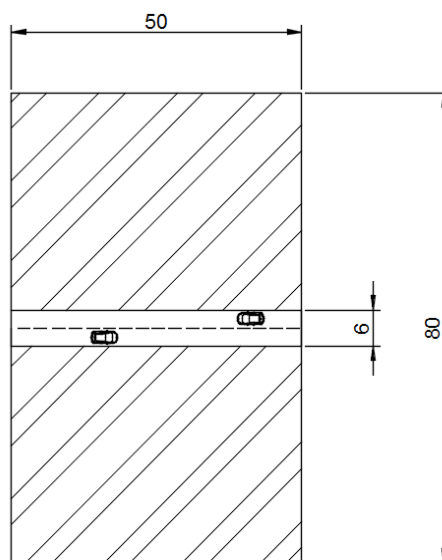


Fig. 4.1 Principle scheme of vibration model boundaries and modelled road

Vibration modelling in buildings

Each transfer functions depends on a few parameters. For example, the coupling from the soil to the foundation depends on the building type (detached house, apartment building), foundation type (strip foundations, direct foundation, pile foundation), etc.

Table 4.2. Transmission loss due to coupling from soil to foundation (Banedanmark, 2015)

Frequency, Hz	Loss from soil to foundation in single-family houses, dB	Loss from soil to foundation in apartment buildings, dB	Loss in Ground floor, dB	Loss in first floor, dB
6,3	-0,4	1,7	3,0	0,3
8	-0,5	2,4	7,0	6,7
10	-0,4	0,8	10,3	11,4
12,5	-0,3	2,6	8,3	13,1
16	-0,3	7,6	9,6	11,7
20	0,0	13,7	9,3	9,9
25	1,4	20,3	5,3	11,8
31,5	3,1	24,3	4,4	9,6
40	1,9	24,2	2,3	7,5
50	3,5	22,5	3,8	9,5
63	5,3	21,4	7,6	13,9
80	7,0	25,1	9,2	20,0

The finer the division becomes, the more data is required to describe the influence of a parameter. The finest possible and most practical division of the data is used. The transfer functions of the buildings are available up to the 3rd floor.

It is seen that the coupling loss is about 25 dB for apartment buildings, while it is about 10 dB for single-family houses. This difference is probably an expression of that apartment buildings are significantly heavier, and therefore respond more 'stickier' than lighter single-family houses. Below are the values of the transfer functions tabulated. In the table 4.2 values shown negative means that vibration is increased. To calculate vibrations in the 2nd and 3rd floor model is using indexes (Formula 4.5) for calculation in the 2nd floor F is 1,1, for 3rd floor F = 3,6.

$$TL = TL_{1st} - F \quad (4.5)$$

Where: TL – transmission loss in dedicated floor; TL_{1st} – transmission loss in first floor; F – transmission loss factor for dedicated floor.

Upper floors cannot be modelled because other factors should be considered such as wind.

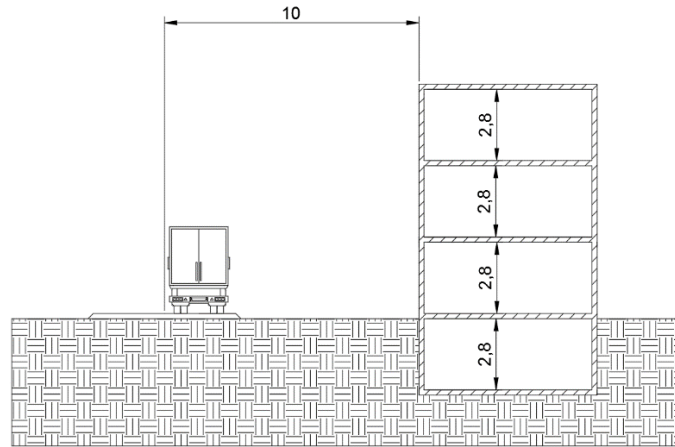


Fig. 4.2 Principle scheme of vibration modelling in buildings

The parameters of source power is taken from experimental research. The buildings is standing 10 m distance from the road. The soil is used loam, because it is one of the most common soil. Principle scheme of modelling in buildings shown in Fig. 4.2.

4.2. Ground- borne vibration modelling results in environment

In first part of modelling chapter vibration spread in different soils is modelled. In figure 4.3 is shown graph and map of vibration spread in the peat soil. In the graph is shown that maximum modelled vibration in the road section reach 18,6 mm/s². In 1 m distance to road, vibration decreases to 15 mm/s². In 40 m distance to the road acceleration decreases to 3 mm/s².

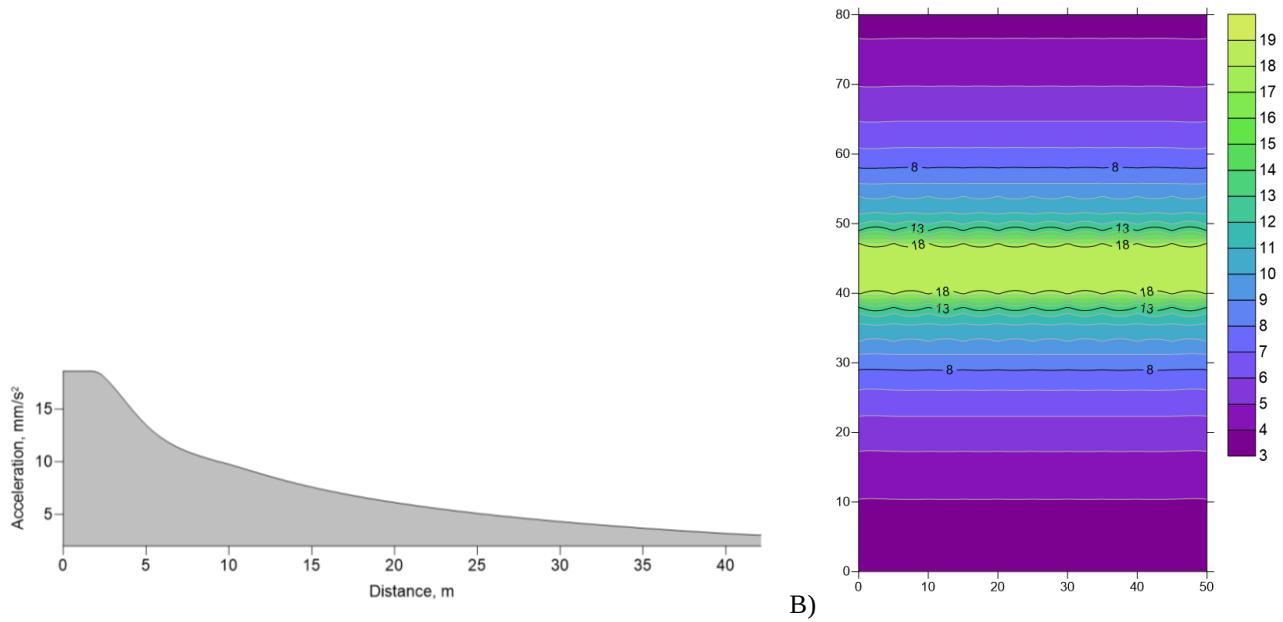


Fig. 4.3 Vibration spread in the peat soil. A) Graph of vibration spread in distance, B) Vibration map in peat soil.

In figure 4.4 is shown graph and map of vibration spread in the clay soil. In the graph is shown that maximum modelled vibration in the road section reach 34,3 mm/s². In 1 m distance to road, vibration decreases to 20,8 mm/s². In 40 m distance to the road acceleration decreases to 0,3 mm/s². In clay soil the vibration near the source increases higher, but in long distance acceleration decreases more compared with peat soil.

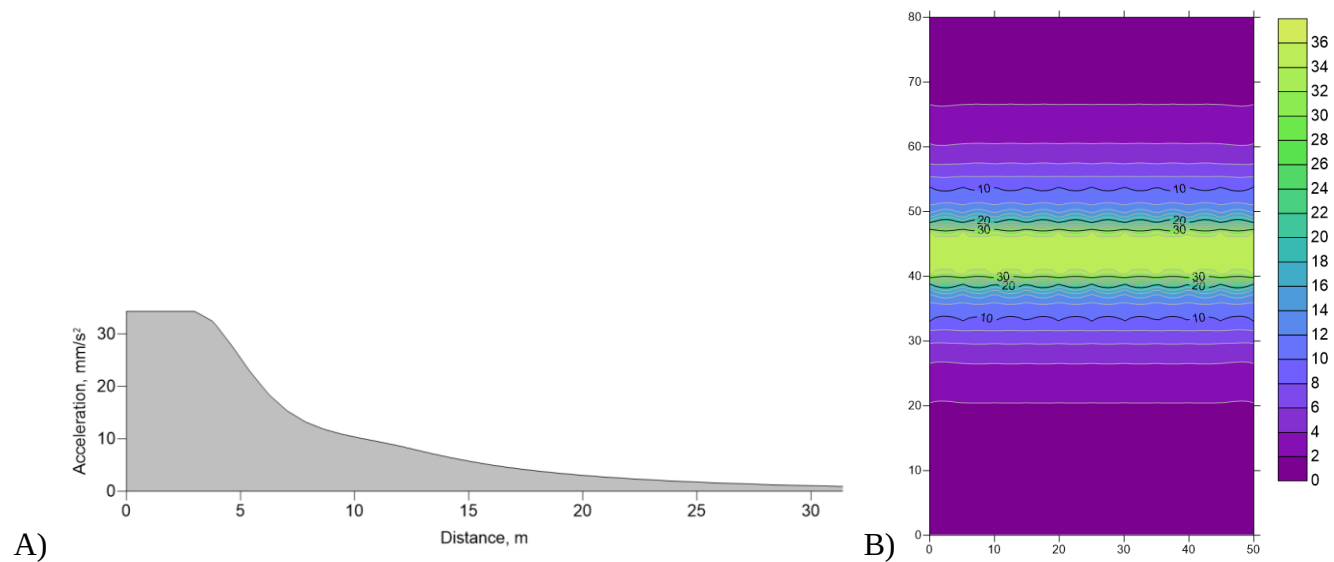


Fig. 4.4 Vibration spread in the clay soil. A) Graph of vibration spread in distance, B) Vibration map in clay soil.

In figure 4.5 is shown graph and map of vibration spread in the sandy loam soil. In the graph is shown that maximum modelled vibration in the road section reach 21,8 mm/s².

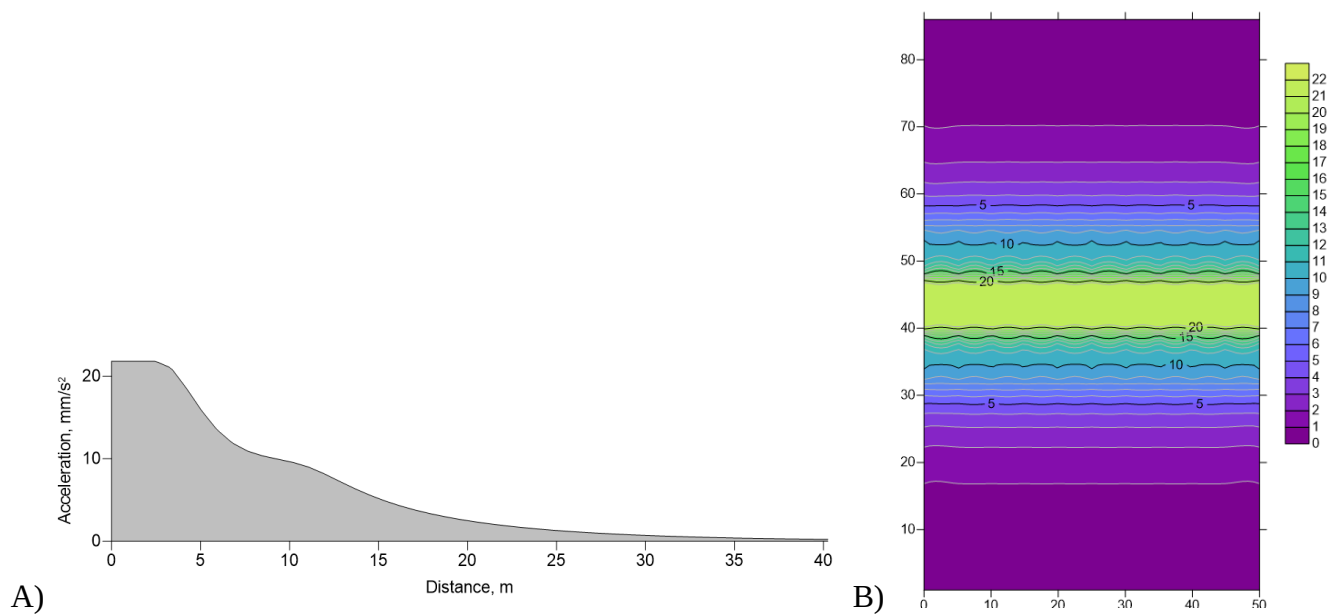


Fig. 4.5 Vibration spread in the sandy loam soil. A) Graph of vibration spread in distance, B) Vibration map in sandy loam soil.

In 1 m distance to road, vibration decreases to 14,8 mm/s². In 40 m distance to the road acceleration decreases to 0,2 mm/s². In sandy loam soil the vibration near the source is higher than in peat soil but lower than in the clay. In distance of 40 m to the road section modeled vibration acceleration was lower compared with both: peat and clay soils.

In figure 4.6 is shown graph and map of vibration spread in the loam soil. In the graph is shown that maximum modelled vibration in the road section reach 22,1 mm/s². In 1 m distance to road, vibration decreases to 15,5 mm/s². In 40 m distance to the road acceleration decreases to 0,4 mm/s². In loam soil the vibration near the source is lower than in clay soil but higher than in the peat and sandy loam soils. In distance of 40 m to the road section modeled vibration acceleration was lower compared with peat soil but higher compared with another two types of soil.

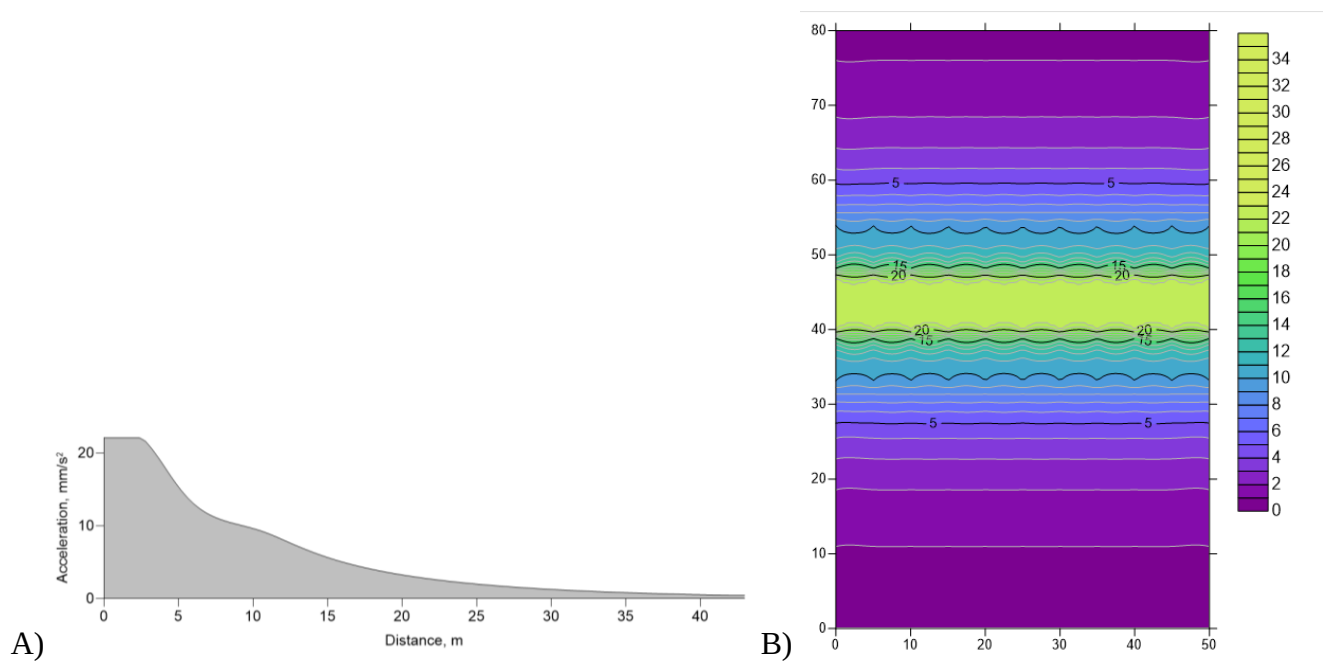


Fig. 4.6 Vibration spread in the loam soil. A) Graph of vibration spread in distance, B) Vibration map in loam soil.

In the different types of soils the main parameters that influence vibration spread in soils is damping and density. If damping coefficient is low the vibrations gained from traffic is higher and spread distance is relatively longer.

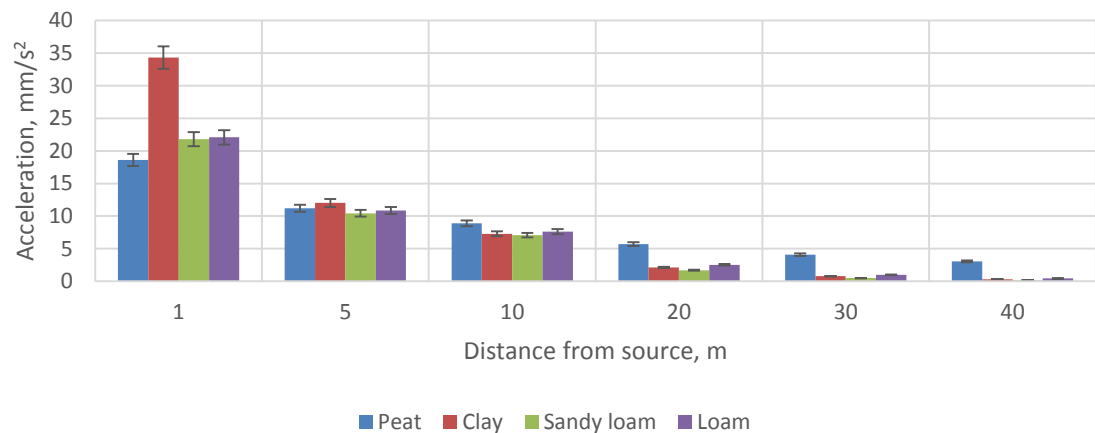


Fig. 4.7 Comparison of vibration spread in different types of soil.

In figure No. 4.7 is shown the comparison of transmission loss in different types of soil. Near the road significantly higher acceleration was calculated in the clay soil (34,3 mm/s²). In two soils (sandy loam and loam) acceleration was similar in whole calculated area, the vibration acceleration near the source was 14,8 mm/s² and 15,5 mm/s² respectively, in the 40 m distance to the road modelled

acceleration was $0,2 \text{ mm/s}^2$ and $0,4 \text{ mm/s}^2$. The vibrations calculated in the peat soil was lower near the vibration source ($18,6 \text{ mm/s}^2$) but in 40 m distance from road acceleration calculated reached $3,0 \text{ mm/s}^2$.

The difference is based on dynamic soil resistance. The phenomenon is based on physical and dynamic soil parameters. The most influencing factor is surface wave speed which is based on soil e-modulus, density and Poisson ratio. The geometric damping (or energy dissipation) occurs due to the decrease of the energy density with distance from source. Geometric damping coefficient can be analytically determined by assessing the type of the propagating wave, source type and location. Meanwhile, the ground is not perfectly elastic and the vibration energy is reduced due to the friction and cohesion between soil particles. This attenuation due to material damping is affected by the soil type and frequency of vibration. (Kim D. and Lee J. 1999, Gutowski T. G. and Dym C. L. 1976).

While peat and clay soil damping ratio is the same (5%), young's modulus of peat is much higher than clay, which means peat is less elastic than clay. Because of relatively big young's modulus difference and low damping ratio vibrations spread in the peat soil is farthest. Vibration acceleration in loam and sandy loam soils is relatively low and reduction is high due to higher damping ratio.

4.3. Ground borne vibration modelling in buildings

In the second part of modelling the ground borne vibration spread into the buildings is modelled. Source vibrations is used from experimental part of modelling. These modelled buildings are 10 m distance to the vibration source (road) and the soil where building are standing is loam. All three types of transport are considered in this part modelling.

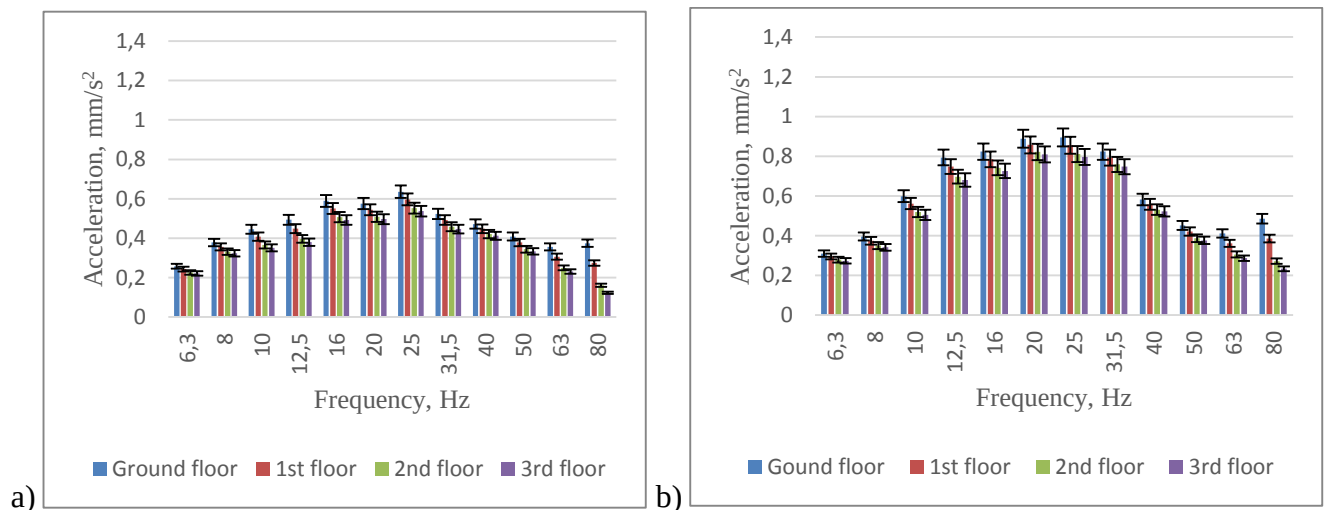


Fig. 4.8 Comparison of acceleration values in buildings. a) light vehicles; b) moderate weight vehicles

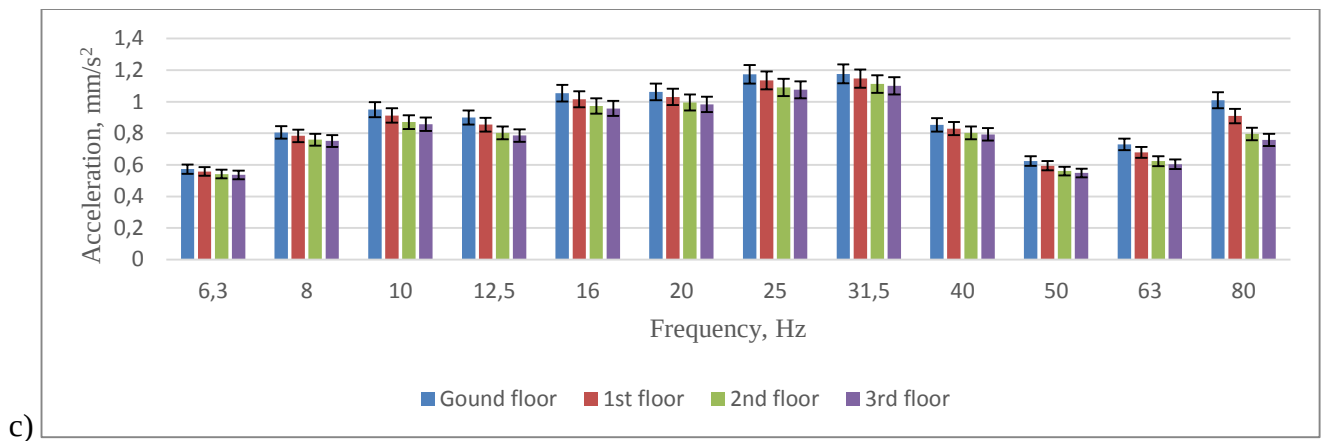


Fig. 4.9 Comparison of acceleration values in buildings. c) heavy vehicles

In figure 4.8 is acceleration values in buildings is shown. The modelled vibration in buildings do not reach the limit values inside buildings. According to the modelling results buildings could be built 10 m distance to the road, without danger of ground borne vibrations reaching limit values of HN 50:2003. In figure also shown that ground borne vibration in the building is just slightly higher when heavy transport is passing.

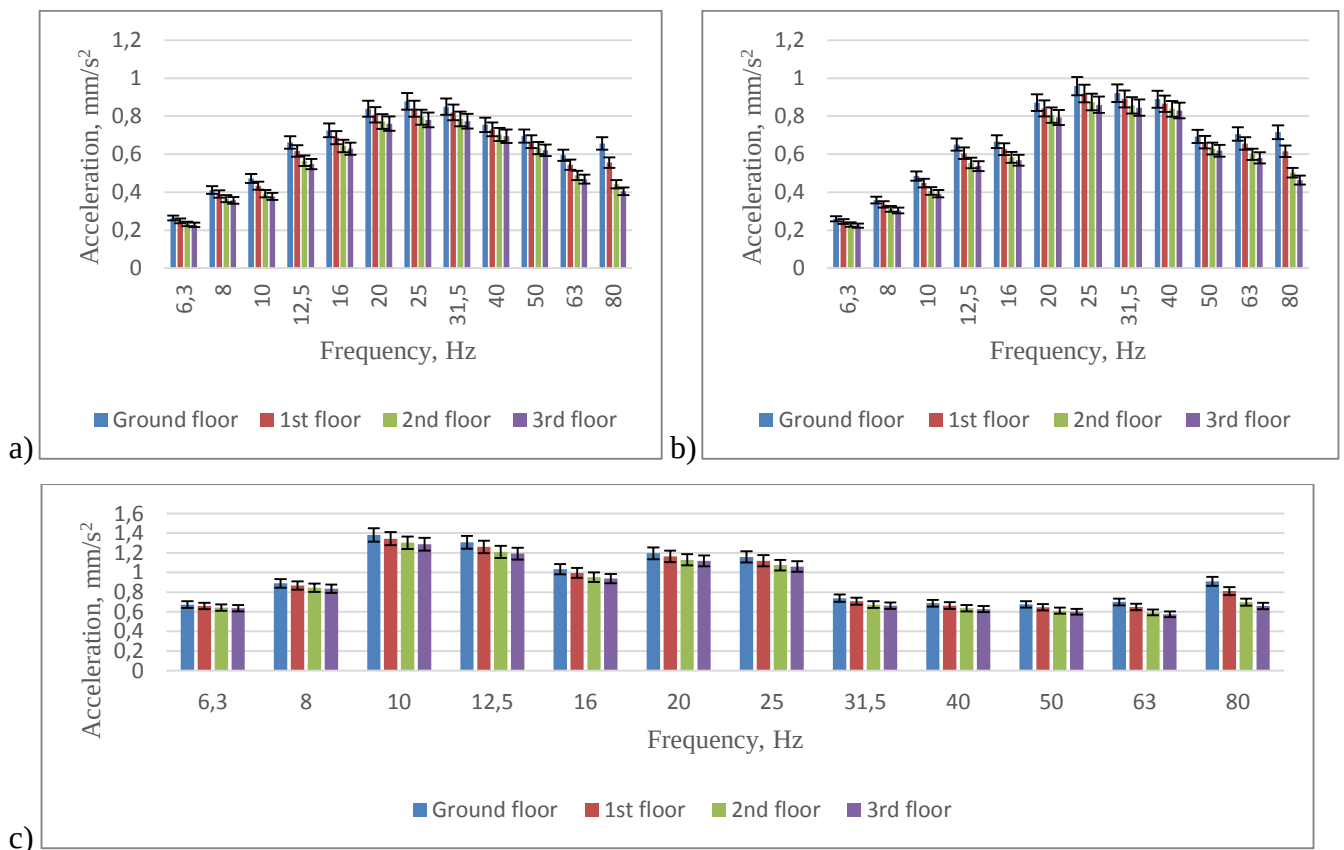


Fig. 4.10 Modelled acceleration of the ground-borne vibration in buildings. 10 m distance to the speed table a) light vehicles b) moderate weight vehicles c) heavy weight vehicles

In figure 4.10 is shown modelled vibration in buildings 10 m distance to the traffic calming measures. Modelling results show that 10 m distance to the speed table is enough to reduce vibrations from the speed table. Modelling and experimental results show that there is no risk to the residents if such traffic calming measure is built.

Conclusions of 4th chapter

1. The highest transmission loss in soil was found in clay soil, the lowest in the peat. Highest ground-borne vibration near source was gained in clay soil (34,3 mm/s²) and lowest in peat (18,6 mm/s²).
2. In the different types of loam traffic induced vibrations were similar (sandy loam - 22,1 mm/s², loam - 22,1 mm/s²)
3. In the 40 m distance from road highest calculated vibration acceleration was in the peat (3,0 mm/s²), and lowest in the sandy loam (0,2 mm/s²)
4. When buildings are 10 m distance to the road and there is no traffic calming measure vibration values is relatively low inside the buildings. Modelling results show that when buildings in such distance from road vibrations in the buildings in acceptable level.
5. When building is 10 m distance to the speed table modelled vibrations is acceptable level. The residents living in the buildings in such distance to the traffic calming measures should not disturbed.

Conclusions

1. The experimental and modelling data is showing that speed tables do not increase transport induced ground borne vibrations significantly. According the data of vibration measurement data inside buildings vibrations level is low and not fellable (disturbing) to residents. Compared with limit values of Lithuania (HN 50:2003) measured vibration values was lower in all measured buildings. In one measurement site speed table did not influence the traffic induced ground borne vibrations during both, winter and summer seasons. For this research was used real traffic flow conditions, this means vehicles speed was not controlled. Usually vehicles was going slower when passing traffic calming measures compared to reference measurement point.
2. During summer season vibration acceleration is higher at frequencies from 6.3- 250 Hz compared with winter results got during winter season. In average during summer season vibration acceleration is 1,5 mm/s² higher compared with winter season. During winter season visually seen that cars were passing slower compared to the summer season. At frequencies from 315 to 3150 Hz vibration acceleration is higher during winter season. During winter season traffic induces 3,1 mm/s² higher vibration acceleration compared with summer season.
3. Vehicle weight influence the transport induced ground-borne vibration. Heavy weight vehicles induce highest ground-borne vibration. The average difference of ground acceleration recorded was 25 % higher compared to other categories of transport. Moderate weight and light vehicle induced ground vibrations was similar during winter season but during summer season induced 13 % higher ground acceleration than light vehicles.
4. According to the modelling data ground borne vibration father spreads in clay and peat soils. In the 40 m distance from road highest calculated vibration acceleration was in the peat soil.

Recommendations

1. Acceleration of the vibration value decreases significantly when distance to source of vibration increased (road). When distance to road is 10 m acceleration of ground motion decreases by 53 %. It is recommended to build commercial or residential buildings 10 m or further distance to roads where the traffic flow is big.
2. When road (street) pavement is worn, bumpy, traffic induced ground motion is bigger than near the traffic calming measures. It is recommended to maintain the road (street) pavement in good condition to avoid higher values of ground vibration.

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Annex 1

List of author's publications

Participation in scientific conferences

Oral presentation on “Investigation and evaluation of speed table influence to traffic noise propagation in residential Area” in The 19th Conference of Lithuanian Junior Researchers “Science – Future of Lithuania” Environmental Protection Engineering, April 7th, 2016

Oral presentation on “Modelling of ground borne vibration induced by road transport” in The 19th Conference of Lithuanian Junior Researchers “Science – Future of Lithuania” Environmental Protection Engineering, March 20th, 2017

Poster presentation on “Investigation and evaluation of speed table influence on road traffic induced ground borne vibration” in 10th International Conference „Environmental Engineering” April 27, 2017 – April 28, 2017

Articles in journals

2016 - Astrauskas Tomas; Grubliauskas Raimondas. Investigation and evaluation of speed table influence on traffic noise propagation in residential area. Mokslas - Lietuvos ateitis : Aplinkos apsaugos inžinerija = Science - Future of Lithuania : Environmental protection engineering. Vilnius: Technika. ISSN 2029-2341. T. 8, Nr. 4 (2016), p. 425-430. (published)

2017 - Astrauskas Tomas; Grubliauskas Raimondas. Modelling of ground borne vibration induced by road transport. Mokslas - Lietuvos ateitis : Aplinkos apsaugos inžinerija = Science - Future of Lithuania : Environmental protection engineering. Vilnius: Technika. (Accepted for publishing)

2017 – Astrauskas Tomas, Grubliauskas Raimondas, Januševičius Tomas. Investigation and evaluation of speed table influence on road traffic in-duced ground borne vibration. International Conference “Environmental engineering” ISI proceedings. (Accepted for publishing)

Annex 2

Copies of author's publications

INVESTIGATION AND EVALUATION OF SPEED TABLE INFLUENCE ON TRAFFIC NOISE PROPAGATION IN RESIDENTIAL AREA

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Abstract. Speed table is an artificial road (street) surface irregularity, which is used to reduce speed of road traffic or maintain allowed speed limit in road (street) section. These measures are used to reduce risk for pedestrians by reducing speed of passing vehicles. Before speed table, vehicles usually reduce speed, after passing it, vehicles usually increase their speed and this could increase traffic noise. Measurements were carried out during the day time in L. Asanavičiūtės Street 5, Vilnius. Measurements were divided into two parts, inside the residential apartment building and in its environment. Near the speed table recorded sound level was 69 dB, inside the residential apartment building noise level was approximately 41 dB. In this paper speed table influence on traffic noise propagation in residential area is investigated.

Keywords: traffic noise, speed table, residential area.

Introduction

To reduce accidents in roads traffic calming measures were developed. Traffic calming is the combination of mainly physical measures that reduce the negative effects of motor vehicle use, alter driver behaviour and improve conditions for non-motorized street users (Lockwood 1997). It is indicated that traffic calming could mean anything from lowering speeds to an all-encompassing transportation policy. To decrease the speed of vehicles in urban conditions, various types of road bumps can be used. These measures require the vehicle to slow before the bump and usually its speed increases after the bump, adding an accelerating engine to the noise sources (Elioy, Vogiatzis 2012).

A speed table is a raised flat-topped device, which is placed across the roadway. Speed tables are usually 76 to 101 millimetres in height. The flat-top is approximately 3 metres in the direction of travel and each ramp is 1,8 metres. The flat-top is usually constructed of asphalt, concrete, brick, or other textured materials. The ramps are parabolic in shape and are usually made of asphalt. Speed tables extend fully across the roadway but are tapered on each side to allow unimpeded water flow in curb and gutter system. The design speed for a speed table is approximately 30 kph, which is a safe and comfortable speed for passenger vehicles (Seidel 2007)

Vehicle approaching traffic calming measure decelerates and after crossing it accelerates. A speed bump reduces traffic noise levels during the deceleration phase and increases them during the acceleration phase (Kokowski, Makarewicz 2005). A road bump affects noise emission from a moving vehicle as a result of the enforced deceleration and acceleration.

In Kokowski and Makarewicz research it was shown that between deceleration and acceleration phase sound level difference is equal approximately to 10 dB (Kokowski, Makarewicz 2005)

The traffic noise depends on the intensity of traffic flow. According to Gražulevičienė and Bendokienė study in Kaunas city, Lithuania, highest noise levels were at the street where the traffic flow is most intense (Gražulevičienė, Bendokienė 2009; Paožalytė *et al.* 2012).

Noise exposure causes a number of predictable short-term physiological responses mediated through the autonomic nervous system. Exposure to noise causes physiological activation including increase in heart rate and blood pressure, peripheral vasoconstriction, and thus increases peripheral vascular resistance (Stansfeld, Matheson 2013; Rabinowitz 2005; Butkus *et al.* 2015).

It has been postulated that noise exposure creates annoyance which then leads on to more serious psychological

effects. This pathway remains unconfirmed; rather it seems that noise causes annoyance and, independently, mental ill-health also increases annoyance (Stansfeld, Matheson 2013)

According to a recent study by the World Health Organization Regional Office for Europe (WHO 2011), 20 % of the population of EU countries is exposed to traffic noise levels of above 65 dB during the day and 30% is exposed to levels of over 55 dB at night, which translates as a loss of 61,000 disability-adjusted life years. For levels above these values, which are considered health-protective, many studies report statistically significant associations between exposure to noise and sleep disturbance, cardiovascular disease, endocrine responses and psychiatric disorder. Exposure to continuous noise of 85–90 dB, particularly over a lifetime in industrial settings, can lead to a progressive loss of hearing, with an increase in the threshold of hearing sensitivity.

In this paper the traffic noise emissions in the residential area and, more precisely, the noise which is made by the vehicles passing through speed tables is investigated

Methodology

The aim of noise measurement is to identify noise levels in measurement points, and define minimum L_{AFmin} , equivalent L_{AeqT} and maximum L_{AFmax} sound levels.

Sound level measurements was taken by precise first class handheld sound level analyser “Bruel & Kjaer 2270” (Fig. 1). Danish manufactured equipment is one of the most modern first class sound level meters and analysers. This handheld analyser is capable of all required sound level analysis. This analyser meets requirements of sound level meters standard IEC 61672, and other older standards as IEC 60651, IEC 60804 and newest ANSI standards. “Bruel & Kjaer 2270” is capable of measuring sound at frequencies from 1 Hz to 20 kHz. With this tool the effective sound level, defined as A or C characteristics or in different frequency bands, which are identified by standardized filters, can be measured. In direct measurement “Bruel & Kjaer 2270” hand held sound analyser gives uncertainty of 1.5%.



Fig. 1. Handheld sound analyser “Bruel & Kjaer 2270” with mounted windscreen

Noise measurements were taken according LST ISO 1996-1:2003 and standard ISO 1996-2:2007. Sound levels in building was evaluated according HN 33:2011 thresholds and recommendations will be given.

When measurements are being taken outside a windscreen is required. Sound level analyser “Bruel & Kjaer 2270” automatically detects when the windscreen is being mounted or removed, and applies the corresponding correction filter. The specific windscreen information is saved permanently with the measurement setup and data. Equipment is being calibrated before and after measurements according to the manufacturers’ manual.

Noise measurements were taken outside near the speed table (1 meter from speed table), near the chosen building to analyse (2 meters away from closest wall to the speed table). Microphone handling height in all measurement points was 1.5 meter from pavement. Noise measurements in residential building were taken in first, third and fifth floors to cover noise propagation in whole building, microphone handling height was also 1.5 meter from floor. During every measurement passing cars were counted and divided into light and heavy transport.

Noise measurements were taken in L. Asanavičiūtės Street. The speed table is 9.0 m length, 0.1 m height, width is the same as of road – 11.0 m. Chosen building is the 5 storey residential apartment building. Two measurement points were chosen in the environment of apartment building (1 meter from speed table and 8 meters distance from speed table, 2 meters near the chosen building), three measurement points were chosen inside the chosen building in first, third and fifth floor of building. And two other reference points were chosen where speed table doesn’t do impact on traffic noise. In Figure 2 scheme of measuring points in the apartment building environment and inside the building is shown.

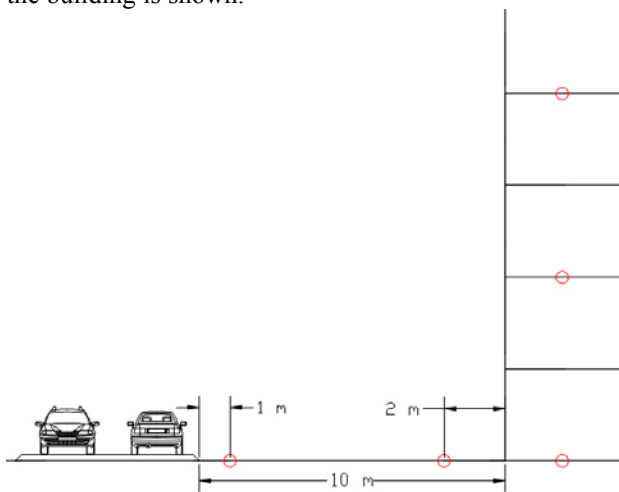


Fig. 2. Scheme of measurement points near speed table and inside residential apartment building

First measurement point was chosen near the 1 m near the speed table. Another point was chosen 2 m near the closest wall of apartment building. Chosen building for study is five floors residential apartment building, measurement was taken in first, third and fifth floors staircases according to the standard ISO 1996-1:2003. Other two reference points were chosen on the same street in the distance of 100 m from speed table. Reference points are shown on the map in Figure 3.

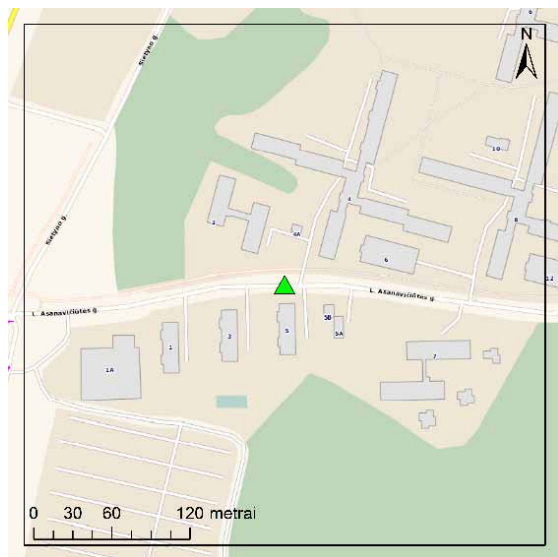


Fig. 3. Plan of measurement site. Green triangle is a place of speed table, black dots reference measuring points

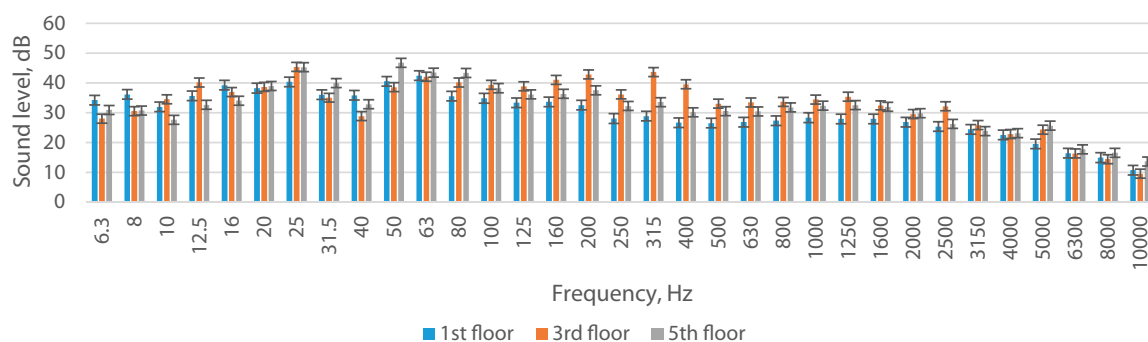


Fig. 4. Noise levels in different frequency bands. Measurement points inside the apartment building

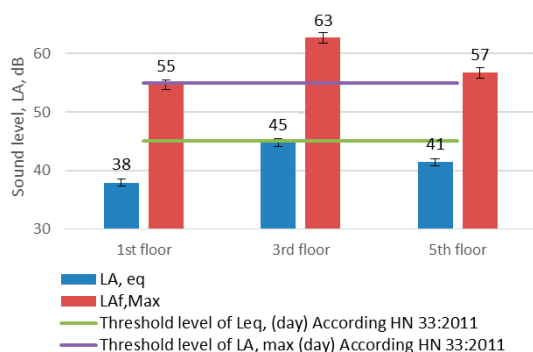


Fig. 5. Noise levels comparison inside the residential apartment with Lithuanian hygiene norm HN 33:2011 threshold levels

Results

During the measurements different cars were measured. While measuring first floor of apartment building 39 light vehicles passed the speed table, third floor – 63 light vehicles and 3 heavy vehicles, fifth floor – 60 light vehicles passed by.

The chart of traffic noise (Fig. 4) inside the residential apartment building shows that the infrasound frequencies are higher at the first floor (from 6.3 to 16 Hz). In other frequencies higher traffic noise level is in the upper floors (3rd and 5th). The measurements shown that the biggest noise at the most frequencies was identified in the third floor of apartments building.

In Figure 5 measurement noise levels comparison with Lithuanian hygiene norm HN 33:2011 is shown. Measurement were taken during the day. During the day threshold level of equivalent sound level is 45 dB and for maximum sound level is 55 dB. In the first and fifth floor the equivalent sound levels is lower than the threshold sound level 38 dB and 41 dB respectively, but in third floor sound level is the same as threshold sound level 45 dB.

Maximum sound levels reach threshold level in all measured floors. In the first floor maximum sound level was 55 dB, same as threshold level. But in the third and fifth floor sound level was higher than threshold level by 8 and 2 dB respectively.

During measurements outside the apartment building at measurement point 1 m away from speed table passed by 42 light vehicles, near the apartment building – 42 light vehicles, reference point 1 m away from street – 66 light vehicles, reference point 10 m away from street – 42 light vehicles.

The noise measurements outside, in the residential apartment building environment (Fig. 6) shown that the highest noise levels at low (6.3 – 200 Hz) frequency were at measurement point in 1 meter distance from the speed table. In comparison with the reference point 1 m away from the speed table induced higher noise at low (6.3 – 200 Hz) and middle (250 Hz – 6300 Hz) frequencies, at high frequencies

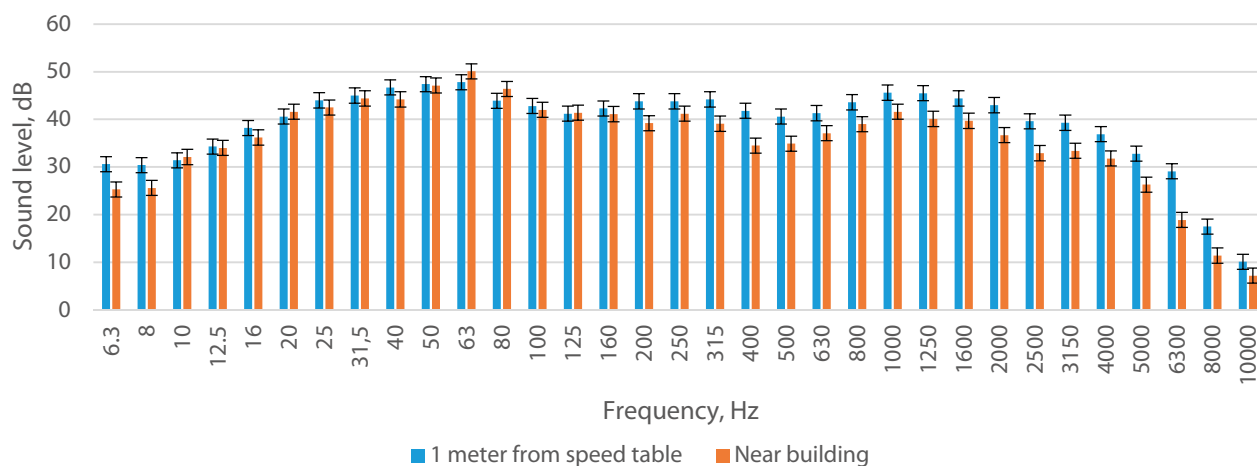


Fig. 6. Noise levels in different frequency bands. Measurement points in apartment building environment

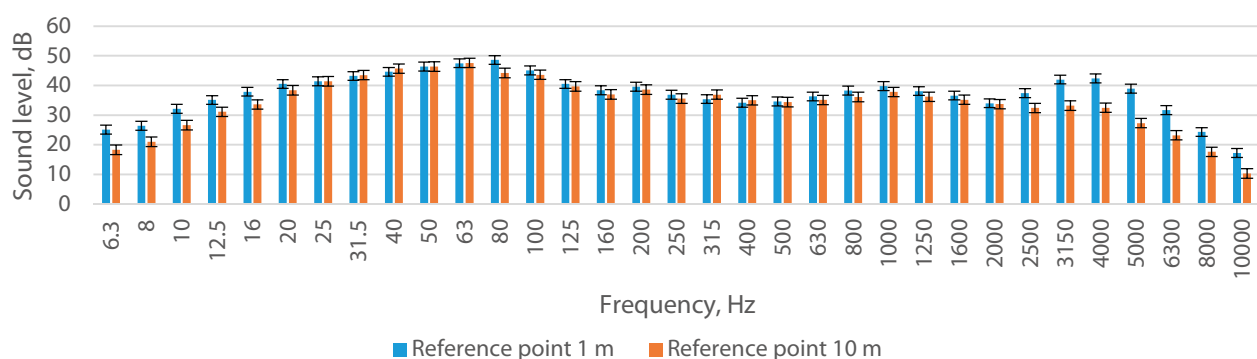


Fig. 7. Noise levels in different frequency bands. Reference measurement points

(8000 Hz – 20000 Hz) noise level was higher at reference point. Difference between these two measurement points at low frequencies on average is 1 dB, at middle frequencies 4 dB and at high frequencies 5 dB.

Noise levels near apartment building were higher at frequency 63 Hz. It could be caused by reflections from the residential apartment building. In all other frequencies noise near apartment building was slightly lower or similar than in measurement point in 1 m distance from the speed table.

Reference measurements (Fig. 7) shown that the increasing distance from the road has influence on traffic noise.

Noise in reference measuring point in 1 m distance from the street is bigger in whole spectrum than in reference point 10 m away from the same street section. Noise 1 m away from street is higher at low and high frequencies, but similar at middle frequencies.

Highest sound levels were near the speed table and at the reference point 1 meter near the same street where speed table has no impact on traffic noise.

Minimum noise level show the minimum sound level recorded during whole measurement, it means that minimum sound level could be described as sound level without traffic noise. Minimum sound level is not regulated in Lithuanian

hygiene norms. Minimum sound levels do not differ significantly indifferent floors inside apartment building, difference is equal to 3 dB. Maximum difference of minimum sound level in outside measurement points is 7 dB.

Equivalent sound levels were highest at reference measurement point 1 meter near the street (69 dB) and at measurement point near the speed table (65 dB). These

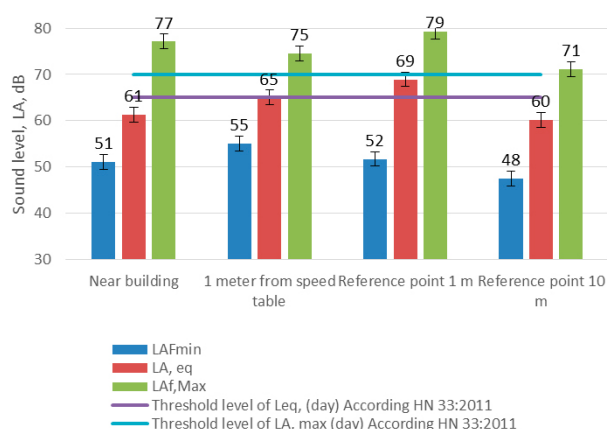


Fig. 8. Minimum, equivalent and maximum noise levels comparison in apartment building environment and reference points

results are higher and equal with noise threshold level in residential building environment in Lithuania, noise level at other measurement points does not reach the threshold noise level. The equivalent sound level is higher at reference point because vehicles run faster in this section of street and the street pavement is bumpy. Equivalent sound level in 10 m reference point was smaller (60 dB). In comparison equivalent sound level at measurement point near the residential apartment building was 61 dB.

Similar study was done by VGTU researchers Akelaitytė and Januševičius. They measured noise induced by different vertical traffic calming measures near the different traffic calming measures. Near the speed table the results of evaluation of their equivalent sound level was around 70 dB. Their measured speed table was made of bricks and this could cause gained higher sound levels than are presented in this paper. Speed table in Asanavičiūtė street is made of asphalt. Similar studies inside the buildings were not found (Januševičius, Akelaitytė 2015).

Maximum sound levels were highest at the same measurement points where equivalent sound level was highest and also in the measurement point near the apartment building. 1 m away from speed table – 74.5 dB, at reference point one meter away from street – 79.2 dB. In comparison of reference point 1 m away from the street and the measurement point 1 m away from the speed table maximum sound level was higher at the reference point, because cars run faster in this section of the street. All maximum sound levels recorded were higher than threshold level in Lithuania. At measurement point 2 m near the apartment building maximum sound level was higher than in reference measurement point 10 m away from the same street. Maximum noise level was higher than threshold level in all measurements.

After measurements inside the building no noise relation was found. These results could show that in different floors there are different apartment building facade characteristics. Small trees are growing near the facade, this could also reduce noise level inside the first floor of the building.

Pavement of L. Asanavičiūtės Street in Vilnius is uneven and asphalt is not in a very good condition. Vehicle drivers slow down before the speed table enough to emit less noise than near the reference point. In order to prove this assumption more speed tables in different streets should be studied.

Conclusions

1. Equivalent sound levels were highest at the reference measurement point 1 meter near the street, equal to

69 dB and at the measurement point near the speed table equivalent noise level was equal to 65 dB.

2. When traffic passes through the speed table, the noise at the measurement point which is at 1 m distance from speed table is higher than at the reference measurement point of 1 m. Noise at low frequencies (6.3 – 200 Hz) on average is higher by 1 dB, and at middle frequencies (250 Hz – 6.3 kHz) on average by 4 dB. At high frequencies (8 kHz – 20 kHz) reference point noise on average is higher by 5 dB.
3. The noise relation inside the residential apartment building between different floors was not found. In the first (38 dB) and fifth (41 dB) floor the equivalent sound levels is lower than the threshold sound level (45 dB) according to Lithuanian hygiene norm, but at third floor sound level (45 dB) is the same as threshold sound level.

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GREITŲ MAŽINANČIŲ KALNELIŲ ĮTAKOS TRIUKŠMO SKLIDIMUI GYVENAMAJAME RAJONE TYRIMAI IR VERTINIMAS

T. Astrauskas, R. Grubliauskas

Santrauka

Greičio mažinimo priemonė – dirbtinis kelio (gatvės) dangos nelygumas, skirtas transporto priemonių greičiui sumažinti arba leistinam greičiui palaikyti kelio (gatvės) ruože. Šių įrenginių paskirtis yra sumažinti pavojų pėstiesiems mažinant važiuojančių automobilių greitį. Automobiliai prieš greičio mažinimo priemonę greitį sumažina, pervažiavę ją, dažniausiai vėl didina greitį, todėl transporto keliamas triukšmas gali padidėti. Tyrimai buvo atlikti dienos metu L. Asanavičiūtės g. 5, Vilniuje. Tyrimai buvo išskirti į dvi dalis: tyrimai gyvenamojo pastato viduje ir tyrimai gyvenamojo pastato aplinkoje. Triukšmo lygis prie vertikaliosios trapecinės greičio mažinimo priemonės buvo 69 dB, tiriamojo gyvenamojo pastato viduje apie 41 dB. Šiame straipsnyje yra nagrinėjama greičio vertikaliosios trapecinės greičio mažinimo priemonės įtaka transporto keliamo triukšmo sklaidai į gyvenamąją aplinką.

Reikšminiai žodžiai: transporto triukšmas, vertikalioji trapecinė greičio mažinimo priemonė, gyvenamoji aplinka.

MODELLING OF GROUND BORNE VIBRATION INDUCED BY ROAD TRANSPORT

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Abstract. Ground-borne vibrations induced by road transport is common source of environmental problem for residents living near roads where large flow of vehicles is. Any irregular unevenness of road surface increase the transport induced ground borne vibrations. The ground-borne vibrations travel through soil, different types of soil have different properties and transmission loss of vibrations is different. In this paper the spread of ground borne vibration is modelled using numerical modelling and represented using Surfer software. In this research is considered most common soil types in Lithuania: Peat, clay, sandy loam and loam. Calculated soil particle acceleration near vibration source was highest in Clay soil (34,3 mm/s²). The calculations show that in peat soil vibration travel further than in other soils.

Key words: transport, ground-borne vibration, numerical modelling, vibration map

Introduction

Transportation is the means to carry people and goods from one place to another. This has become very important in each stage of human civilization. If the present means of transportation were not developed, situation of the world would be totally different. In today's world we use car every day. Ground traffic causes ground-borne vibrations. This impact could cause annoyance of residents who lives near streets or roads.

Random pavement surface irregularities exist on all pavements and are typically characterized by measures of pavement smoothness or roughness such as the International Roughness Index (IRI). Typically, random surface irregularities can result in randomly occurring dynamic forces that are up to 15 percent higher than the corresponding static forces. The impact of these dynamic forces on pavements results in randomly occurring ground-borne vibration. Although random ground-borne vibration is always present (the pavement is never completely smooth and highway vehicles are never completely dynamically inert), it is too low to be perceived even by observers very close to the source. (Hajek et. al., 2006)

The propagation of traffic-induced vibration from the source depends on the distance from the receiver, frequency of vibration, topography between the source and the receiver, and on the soil and other geotechnical characteristics of the ground. Vibration propagates through the ground in the form of body waves (compressional and shear waves), and in the form of surface or Rayleigh waves

The Rayleigh waves are the most important form for the propagation of traffic induced vibration because at the ground level the amplitude of the Rayleigh waves decreases (due to geometric spreading) as the inverse of the square root of the distance from the source, while the amplitude of body waves decrease as the inverse of the square of the distance from the source (Hajek et. al., 2006, Athanasopoulos, G. A. et. Al. 2000).

Like most vibration problems, traffic vibrations can be characterized by a source-path receiver scenario (Figure 1). Vehicle contact with irregularities in the road surface (e.g., potholes, cracks and uneven manhole covers) induces dynamic loads on the pavement (Hunaidi, 2000).

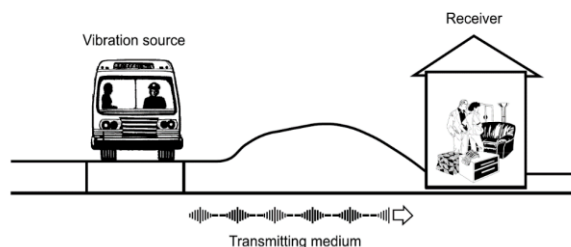


Fig. 1 Source path-receiver scenario.(Hunaidi, 2000)

When a vehicle strikes an irregularity in the road surface, it generates an impact load and an oscillating load due to the subsequent “axle hop” of the vehicle. The impact load generates ground vibrations that are predominant at the natural vibration frequencies of the soil whereas the axle hop generates vibrations at the hop frequency (a characteristic of the vehicle’s suspension system). If the natural frequencies of the soil coincide with any of the natural frequencies of the building structure or its components, resonance occurs and vibrations will be amplified. (Hajek et. al., 2006)

In this research mainly transmitting medium is considered. Loam is soil composed mostly of sand (particle size $> 63 \mu\text{m}$), silt (particle size $> 2 \mu\text{m}$), and a smaller amount of clay (particle size $< 2 \mu\text{m}$). Its composition is about 40–40–20% concentration of sand-silt-clay, respectively. These proportions can vary to a degree, however, and result in different types of loam soils: sandy loam, silty loam, clay loam, sandy clay loam, silty clay loam, and loam. (Kaufmann R. K. and Cutler J. C. 2008). Sandy loam soil is when sand 1/3 more amount in composition than other components (Ingels J. E. 2003)

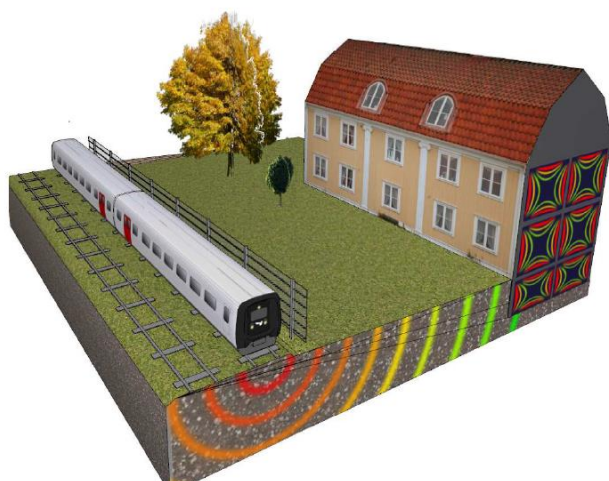


Fig. 2. Principle scheme of Banedanmark's vibration model (Banedanmark, 2015)

In this research Banedanmark's new vibration model is used. Banedanmark's new vibration model is based on the fact that a source strength can be used to calculate vibration comfort estimates for buildings nearby a train alignment, provided a number of corrections to account for the effects of geology, distances between the track and the building as well as the properties of the buildings are applied. This model is mainly used to calculate train induced ground borne vibration, but it is adapted for road transport. (Banedanmark, 2015)

The aim of this research to evaluate what soil of Lithuania has vibration higher transmission loss.

Method

In this research Banedanmark's new vibration model is adapted to evaluate the vibration transmission loss the different soils.

The numerical modelling used to evaluate the vibration waves attenuation in the different soils. For the result show is used Surfer software to represent map of vibration spread in different soils. In this research were chosen four soils that is typical in Lithuania which are clay, loam, sandy loam and peat.

Transmission of vibrations through a given type of soil consist of several components:

- › Geometric spreading
- › Viscous damping

Geometric spreading - Vibrations propagates as waves in the ground. The wave field will be plane within a vehicle length from track and at low frequencies, and will therefore not propagate as it moves away from the source. For higher frequencies the wavelength becomes shorter and the wave front more circular. Thus, a certain geometric spreading is expected since vibrations will propagate to a continuously wider area when moving away from the source.

In general, it can be expected that the wave front will propagate in line with following expression:

$$a = a_k \left(\frac{r_k}{r} \right)^{m(f)}, \quad (1)$$

Where a is the acceleration in a distance r from the source, and a_k is the source strength (acceleration) in a distance r_k ($= 7,5 \text{ m}$). The exponent $m(f)$ is expected to be frequency dependent, and in the most cases to be determined from tests.

For surface waves (Rayleigh waves) the value of $m(f)$ is expected to be 0 at low frequencies and 1 at high frequencies.

In order to be capable of setting up a model for the progress of $m(f)$ it is important to determine the frequency range where the wave field transforms from having plane to curved wave fronts. The transition of wave field type will not be very distinct, instead a more gradual effect is expected in the frequency range where the wavelengths are of same magnitude as the distance from track centre to source point, approx. $7,5 \text{ m}$. (Banedanmark, 2015) The following function for $m(f)$ has the exact characteristic that it takes the value 0 at low frequencies and 1 at high frequencies:

$$m(f) \approx 1 - \exp\left(-\frac{f}{f_b}\right), \quad (2)$$

Where f_b is the frequency where the wave field transforms from having plane to curved wave fronts.

In order to apply the above expression for calculating the transmission loss it is necessary to determine $f_b = c/r_k$ which is a function of wave propagating velocity c and the distance track centre to source point r_k . (Banedanmark, 2015)

Viscous damping

The longer a distance a wave travels from source to recipient and the higher a frequency, the more wave-lengths will occur between the source and recipient, and

therefore a greater frictional loss. The phenomenon can be described by a viscous damping model:

$$a = a_k \cdot \exp\left(-\left(\frac{2\pi f \eta}{c} |r - r_k|\right)\right), \quad (3)$$

Where c is the propagating velocity of the wave, η is the viscous damping constant for the current media the wave is traveling in, and $|r - r_k|$ is the distance from source to receiver point, f – frequency of calculation.

$$c \approx 0,9 \sqrt{\left(\frac{E}{2\rho(1+\nu)}\right)}, \quad (4)$$

The equation No. 4 is the calculation of wave propagation velocity in the given media. The wave propagating velocity is a function of the physical characteristic of the ground, including E-modulus, density ρ , Poisson's ratio ν and the damping constant. (Banedanmark, 2015)

Table 1. Parameters of selected soils.(Bolton M. D. and Wilson J. M. R. 1990, Gibson G. C. and Coyle H. M. 1968, Obrzud R. and Truty, A. 2012, Kezdi, A. 1974, Mott P. H. and Roland C. M. 2012.)

No.	Name of media	E- modulus	Density ρ (kg/m3)	Poisson ratio ν (-)	Viscous damping coefficient η (-)
1.	Peat	$5,6 \cdot 10^7$	1500	0,40	0,05
2.	Clay	$5,0 \cdot 10^6$	1600	0,45	0,05
3.	Sandy loam	$8,0 \cdot 10^6$	1440	0,25	0,102
4.	Loam	$1,3 \cdot 10^7$	1360	0,35	0,092

Soil parameters for calculation is shown in the 1st table. Vibration input $a_k=10 \text{ mm/s}^2$, $r_k=7,5 \text{ m}$.

Vibration map creation

The numerical analysis was conducted using the equations shown before and represented as vibration maps. Every ground borne vibration map is 80x50 m length and width and created using Surfer software. Grid is created using kriging method and contains 100x200 nodes. Principle scheme is shown in fig. 3.

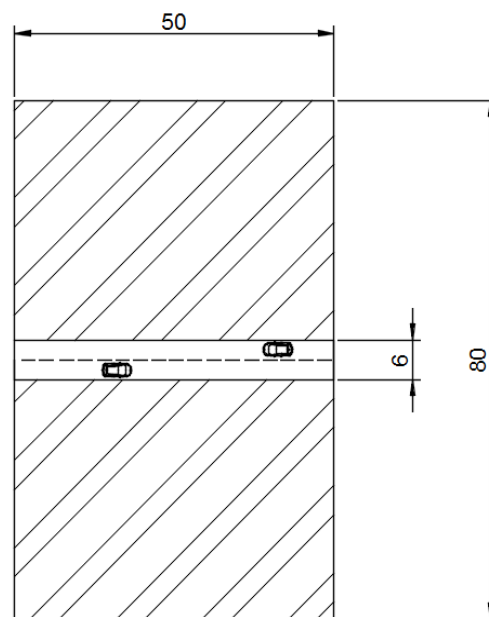
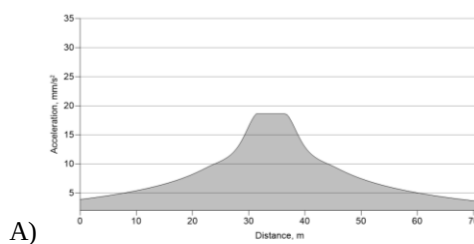


Fig. 3 Principle scheme of vibration model boundaries and modelled road

During calculations traffic flow is assumed as continuous and vehicle speed is constant. The width of the road is 6 m.

Results

In this paper is four soil types are considered. In figure 4 is shown graph and map of vibration spread in the peat soil. In the graph is shown that maximum modelled vibration in the road section reach $18,6 \text{ mm/s}^2$. In 1 m distance to road, vibration decreases to 15 mm/s^2 . In 40 m distance to the road acceleration decreases to 3 mm/s^2 .



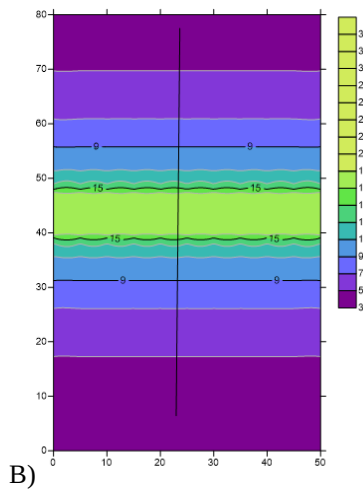


Fig. 4 Vibration spread in the peat soil. A) Graph of vibration spread in distance, B) Vibration map in peat soil.

In figure 5 is shown graph and map of vibration spread in the clay soil. In the graph is shown that maximum modelled vibration in the road section reach $34,3 \text{ mm/s}^2$. In 1 m distance to road, vibration decreases to $20,8 \text{ mm/s}^2$. In 40 m distance to the road acceleration decreases to $0,3 \text{ mm/s}^2$. In clay soil the vibration near the source increases higher, but in long distance acceleration decreases more compared with peat soil.

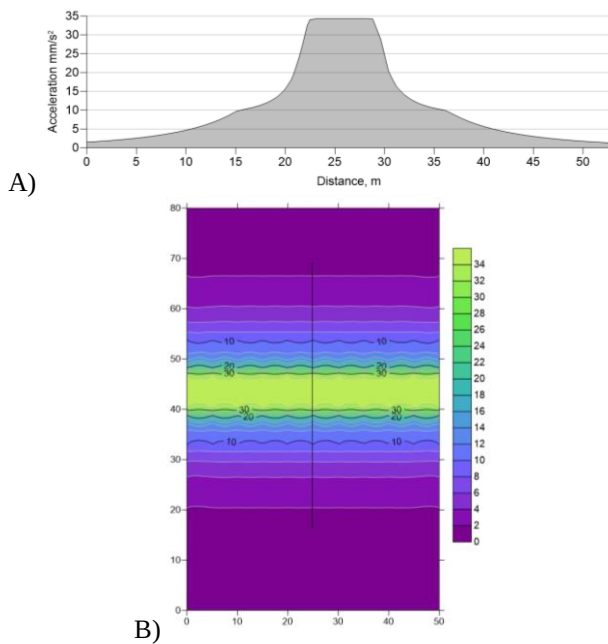


Fig. 5 Vibration spread in the clay soil. A) Graph of vibration spread in distance, B) Vibration map in clay soil.

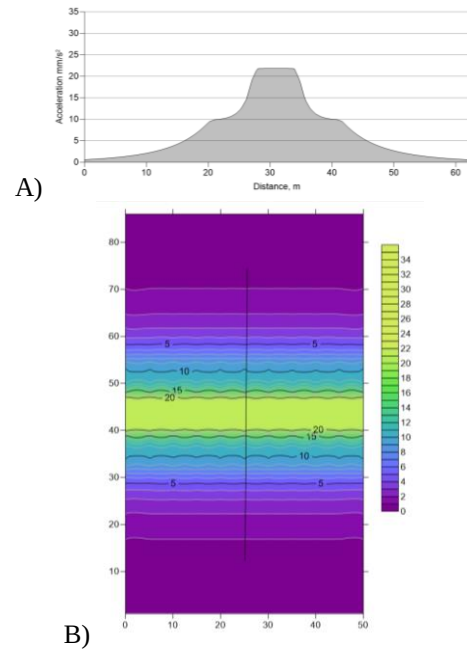


Fig. 6 Vibration spread in the sandy loam soil. A) Graph of vibration spread in distance, B) Vibration map in sandy loam soil.

In figure 6 is shown graph and map of vibration spread in the sandy loam soil. In the graph is shown that maximum modelled vibration in the road section reach $21,8 \text{ mm/s}^2$. In 1 m distance to road, vibration decreases to $14,8 \text{ mm/s}^2$. In 40 m distance to the road acceleration decreases to $0,2 \text{ mm/s}^2$. In sandy loam soil the vibration near the source is higher than in peat soil but lower than in the clay. In distance of 40 m to the road section modeled vibration acceleration was lower compared with both: peat and clay soils.

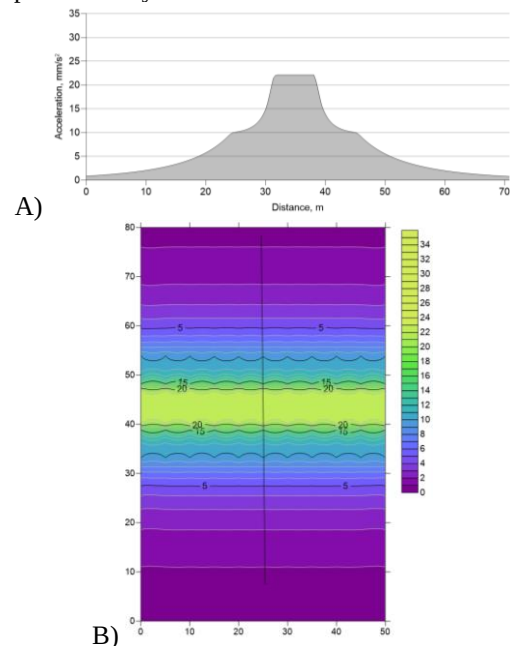


Fig. 7 Vibration spread in the loam soil. A) Graph of vibration spread in distance, B) Vibration map in loam soil.

In figure 7 is shown graph and map of vibration spread in the loam soil. In the graph is shown that maximum modelled vibration in the road section reach $22,1 \text{ mm/s}^2$. In 1 m distance to road, vibration decreases to $15,5 \text{ mm/s}^2$. In 40 m distance to the road acceleration decreases to $0,4 \text{ mm/s}^2$. In loam soil the vibration near the source is lower than in clay soil but higher than in the peat and sandy loam soils. In distance of 40 m to the road section modeled vibration acceleration was lower compared with peat soil but higher compared with another two types of soil.

In the different types of soils the main parameters that influence vibration spread in soils is damping and density. If damping coefficient is low the vibrations gained from traffic is higher and spread distance is relatively longer.

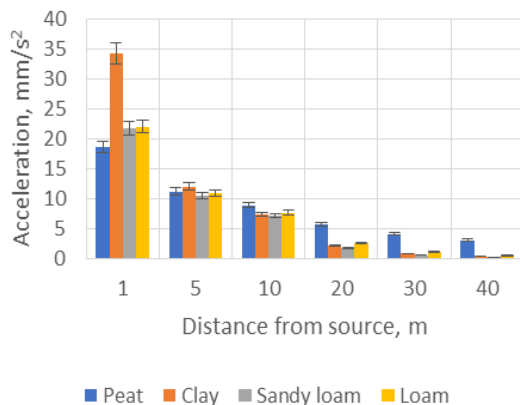


Fig. 8 Comparison of vibration spread in different types of soil.

In figure No. 8 is shown the comparison of transmission loss in different types of soil. Near the road significantly higher acceleration was calculated in the clay soil ($34,3 \text{ mm/s}^2$). In two soils (sandy loam and loam) acceleration was similar in whole calculated area, the vibration acceleration near the source was $14,8 \text{ mm/s}^2$ and $15,5 \text{ mm/s}^2$ respectively, in the 40 m distance to the road modelled acceleration was $0,2 \text{ mm/s}^2$ and $0,4 \text{ mm/s}^2$. The vibrations calculated in the peat soil was lower near the vibration source ($18,6 \text{ mm/s}^2$) but in 40 m distance from road acceleration calculated reached $3,0 \text{ mm/s}^2$. The most influencing parameter of soil properties is viscous damping constant (VDC) (Beards, C. F. 1995). This parameter shows how much medium is able to vibrate. In peat and clay soils this parameter is low and in sandy loam and loam soils VDC is much higher.

These gained values could not be compared with other authors experimental results because source strength a_k is used same in all types soil, and in natural conditions it would be different in different soils

The gained results compared with other authors are similar, sandy and loam soils absorb vibration more, while in peat and clay soils this parameter is low and in sandy loam and loam soils VDC is much higher.

The gained results compared with other authors are similar, sandy and loam soils absorb vibration more, while

clay and peat soils less. (Hajek 2006, Harris Miller Miller and Hanson Inc. 1995, Kouroussis G. et. Al. 2012)

Conclusions

1. The highest transmission loss in soil was found in clay soil, the lowest in the peat. The difference is based on dynamic soil resistance. The phenomenon is based on physical and dynamic soil parameters. The most influencing factor is surface wave speed which is based on soil modulus, density and poisson ratio.
2. Highest ground-borne vibration near source was gained in clay soil ($34,3 \text{ mm/s}^2$) and lowest in peat ($18,6 \text{ mm/s}^2$).
3. In the different types of loam traffic induced vibrations were similar (sandy loam - $22,1 \text{ mm/s}^2$, loam - $22,1 \text{ mm/s}^2$)
4. In the 40 m distance from road highest calculated vibration acceleration was in the peat ($3,0 \text{ mm/s}^2$), and lowest in the sandy loam ($0,2 \text{ mm/s}^2$)

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AUTOMOBILIŲ TRANSPORTO SUKELIAMOS ŽEMĖS VIBRACIJOS MODELIAVIMAS

Tomas Astrauskas¹, Raimondas Grubliauskas²

Santrauka. Automobilių sukeliamos žemės vibracijos yra dažnai pasitaikanti aplinkosauuginė problema, gyventojams kurių būstai yra netoli kelių, kuriuose automobilių srautas yra didelis. Kiekvienas kelio važiuojamosios dalies paviršiaus nelygumas didina automobilių sukeliamas žemės vibracijas. Vibracija sklinda per dirvožemį, kiekvienas dirvožemio tipas turi skirtingas fizines savybes, o tai reiškia skirtingą vibracijos bangų pralaidumą. Šiame straipsnyje yra nagrinėjamas vibracijos sklidimas skirtinguose dirvožemiuose pasitelkiant skaitinį modeliavimą, o rezultatų atvaizdavimui naudojama Surfer programinė įranga. Šiame straipsnyje tyrinėjami Lietuvoje dažnai pasitaikantys dirvožemio tipai: durpės, molis, priemolis ir priemolis. Skaičiavimai rodo, kad vibracija toliausiai sklinda durpėse palyginus su kitais skaičiuotais dirvožemių tipais.

Reikšminiai žodžiai: transportas, žeme sklindančios vibracijos, skaitinis modeliavimas, vibracijos žemėlapis

Investigation and evaluation of speed table influence on road traffic induced ground borne vibration

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Abstract. Vertical Speed Control Measures are vertical elevated segments of roadway that require a vehicle to slow. Typical vertical speed control measures include speed humps, speed tables, raised sidewalks and raised intersections. These engineering measures are used to reduce risk to pedestrians of crossing streets where transport flow is big. The object of this research is speed table. Measurements of ground borne vibration was done 1 m near the speed table and in reference point, in the same street where the speed table do not influence the traffic speed. Reference measurement point is in the same distance to the street as to the speed table. Measurements was done in two seasons: cold and warm. Ground borne vibration measurements took place in L. Asanavičiūtės st., Vilnius. In this research was found that highest acceleration value near the speed table was 21,8 mm/s² when heavy weight vehicles was passing, in reference point highest value was 38,1 mm/s². Heavy weight vehicles induce highest ground borne vibration peaks.

Keywords: Speed table, Ground borne vibration, traffic calming, traffic induced vibration

Conference topic: Environmental protection.

Introduction

Traffic calming is the combination of mainly physical measures that reduce the negative effects of motor vehicle use, alter driver behaviour and improve conditions for non-motorized street users. (I. M. Lockwood, 1997)

It is indicated that traffic calming could mean anything from lowering speeds to an all-encompassing transportation policy.

To decrease the speed of vehicles in urban conditions, various types of road bumps can be used.

These measures require the vehicle to slow before the bump and usually its speed increases after the bump, adding an accelerating engine to the noise sources. (N. Elioy, et. Al. 2012)

Vertical Speed Control Measures are vertical elevated segments of roadway that require a vehicle to slow. Typical vertical speed control measures include speed humps, speed tables, raised sidewalks and raised intersections.

Traffic calming measures can be implemented whenever the authority with jurisdiction over the road or street believes that they are necessary and appropriate to the situation. This can be on roads under municipal jurisdiction. However, the function and design of vertical traffic calming measures makes them more appropriate for relatively low speed roads than for roads with higher speed limits. Since the majority of highways typically carry traffic moving at speeds over 50 kilometres per hour, they are not usually considered appropriate for highways. But municipalities have many more residential style streets for which they may be useful as way of further calming traffic. (J. J. Fazzalaro, 2006)

Ground-borne vibrations are produced when vehicles pass over these profiles and in some cases they can reach perceptible levels in adjacent buildings. G.R. Watts and V.V. Krylov took measurements of peak particle velocity alongside a selection of hump and cushion designs using a range of vehicles under controlled driving conditions. Ground-borne vibrations are generally perceptible in situations where the road surface is uneven and buildings are situated close to the road. (Watts G.R., Krylov V.V. 2000.)

When a bus or a truck strikes an irregularity in the road surface, it generates an impact load and an oscillating load due to the subsequent “axle hop” of the vehicle. The impact load generates ground vibrations that are predominant

at the natural vibration frequencies of the soil whereas the axle hop generates vibrations at the hop frequency (a characteristic of the vehicle's suspension system)(Hunaidi O. 2000, Lak M.A. et. Al. 2001). If the natural frequencies of the soil coincide with any of the natural frequencies of the building structure or its components, resonance occurs and vibrations will be amplified. (Hajek, 2006)

The propagation of traffic-induced vibration from the source depends on the distance from the receiver, frequency of vibration, topography between the source and the receiver, and on the soil and other geotechnical characteristics of the ground. Vibration propagates through the ground in the form of body waves (compression and shear waves), and in the form of surface or Rayleigh waves (Figure 1) (Hajek, 2006, Kramer, 1996, Massarsch, 2000)

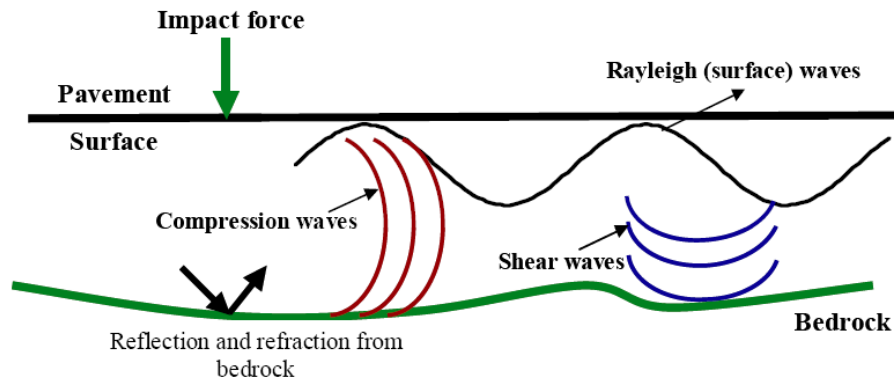


Fig. 1. Propagation of ground borne vibration (Hajek, 2006)

The Rayleigh waves are the most important form for the propagation of traffic induced vibration because at the ground level the amplitude of the Rayleigh waves decreases (due to geometric spreading) as the inverse of the square root of the distance from the source, while the amplitude of body waves decrease as the inverse of the square of the distance from the source (Hajek, 2006, Aster R. 2011, Borman P., et. Al. 2012). The wave propagation of ground borne vibration when road traffic hits road unevenness is shown in fig. 1.

In this research speed table influence on traffic induced vibrations is investigated. The aim of this research is to evaluate the impact of the speed table due to concerns of ground borne vibration.

Method

Measurement

Measurements was taken in two seasons winter and summer season. According the same methodology to evaluate freezing influence on the traffic vibrations.

Distance from buildings to vertical traffic calming measure, relief, pavement ground structure, area building environment is being taken into account when selecting measuring points.

Measurement method was adopted and modified from Lithuanian hygiene norm HN 50:2003. To measure traffic induced vibration is used sound level and vibration meter Bruel&Kjaer Mediator 2260. In the set of equipment 3-axis accelerometer Delta Tron 4506 and amplifier 3-channel Human Vibration Front-end — Type 1700 is also used. Set of equipment used for vibration measurement is shown in figure 2. The use of equipment in field measurements shown in fig. 3.

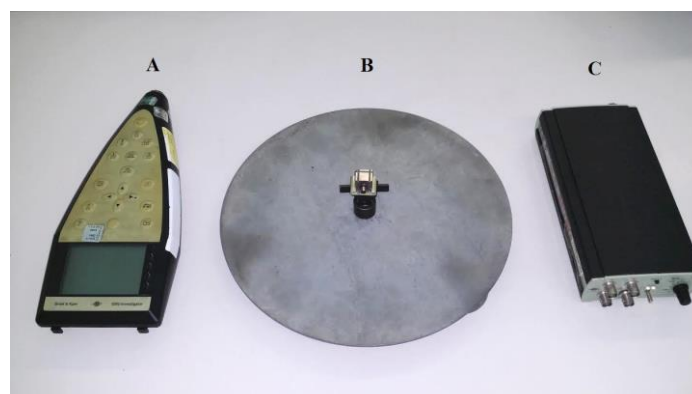


Fig 2. Set of equipment used for vibration measurement A – Sound level and vibration meter Bruel&Kjaer Mediator 2260; B – Steel plate with 3-axis accelerometer Delta Tron 4506; C – amplifier 3-channel Human Vibration Front-end — Type 1700 (author's picture)

Acceleration of the vibration is being measured in all three axis (X, Y, Z). After the check, measurements are taken in that axis in which acceleration of the vibration is highest. Z axis is vertical axis, X axis parallel to the road, y axis crossing the road. Measuring parameter is acceleration of vibrations (mm/s^2).



Fig. 3. Steel plate and accelerometer use in field measurement (author's picture)

Every vehicle crossing the vertical traffic calming measure was measured separately. Vehicles are separated into 3 categories:

1. Light vehicles (Light passenger vehicles)
2. Moderate weight vehicles (Light cargo or light passenger vehicle with trailer)
3. Heavy weight vehicles (Buses or heavy cargo vehicles)

Measuring parameters are:

- Acceleration of the vibration in 1/3 octave band. Measurement units (mm/s^2). Measuring in frequencies from 6,3 Hz to 3150 Hz

The selected measurement points representing vibration acceleration near the speed table and without it. The measurements were taken 1 m distance to the speed table and 10 m further to evaluate the propagation of the ground borne vibration near the speed table. Other two measurement points selected in area of the same street where the speed table do not influence the traffic induced ground borne vibrations.

Data processing

Huge amount of data was received after measurements. In every octave band trimean is being calculated. This characteristic is not "sensitive" to extreme values, trimean is used in asymmetric value distribution. (Čekanavičius V. and Murauskas G. 2000)

$$\text{Trimean} = \frac{Q_1 + 2Md + Q_3}{4} \quad (1)$$

Where: Md – median; Q_1 – First quartile; Q_3 – Third quartile

In descriptive statistics, the quartiles of a ranked set of data values are the three points that divide the data set into four equal groups, each group comprising a quarter of the data. A quartile is a type of quantile. The first quartile (Q_1) is defined as the middle number between the smallest number and the median of the data set. The second quartile (Q_2) is the median of the data. Median is the number separating the higher half of a data sample, a population, or a probability distribution, from the lower half. The third quartile (Q_3) is the middle value between the median and the highest value of the data set.

Observational error (or measurement error) is the difference between a measured value of quantity and its true value. In statistics, an error is not a "mistake". Variability is an inherent part of things being measured and of the measurement process.

Root mean square error (RMSE) is a frequently used measure of the differences between values (sample and population values) predicted by a model or an estimator and the values actually observed.

$$S_{\bar{x}} = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n(n-1)}}; \quad (2)$$

Where:

$S_{\bar{x}}$ – root mean square error; X_i – measured value; $\bar{x}$ – Arithmetic mean; n – Number of observations

In mathematics and statistics, the arithmetic mean, or simply the mean or average when the context is clear, is the sum of a collection of numbers divided by the number of numbers in the collection.

$$\bar{x}_n = \frac{1}{n} \sum_{i=1}^n x_i, \quad (3)$$

Where: $\bar{x}_n$ – Arithmetic mean; n – Number of observations; X_i – measurement value.

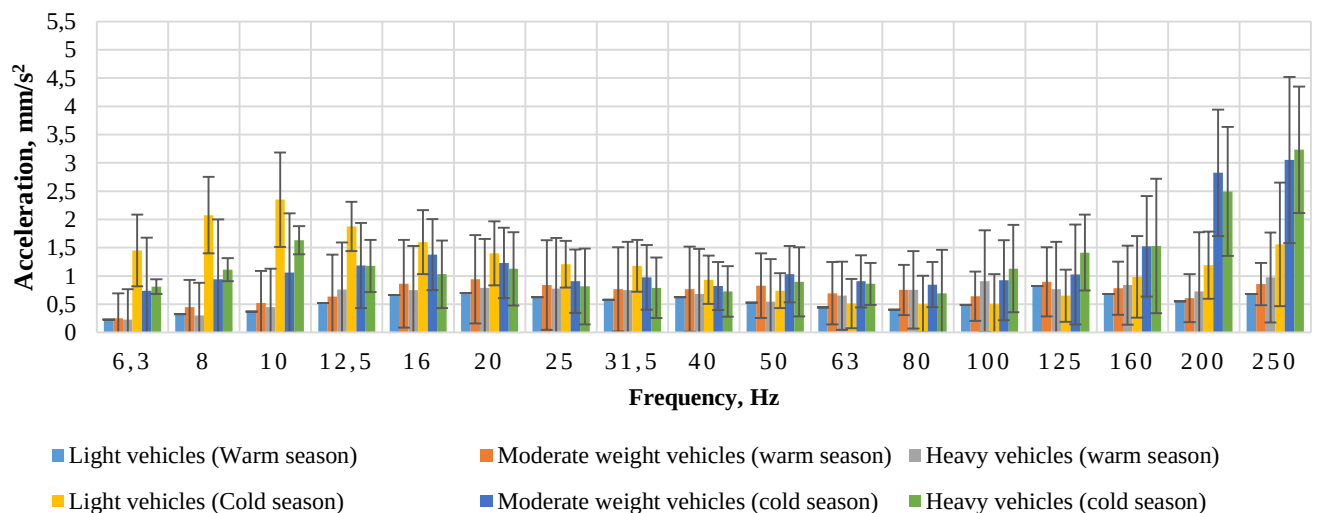
All ground borne vibration measurement data and error is presented using this methodology.

Results

The number of vehicles measured differs in between two seasons cold (winter) and warm (Summer). During the cold season measurements air temperature was $-5,6^\circ\text{C}$, wind speed 1,2 m/s, humidity 78,4, atmosphere pressure 99,8 kPa. During the warm season measurements air temperature was 18°C , wind speed 1,1 m/s, humidity 61 %, atmosphere pressure 100,4 kPa. Presented vibration acceleration data is in Z axis, because values found highest in this axis.

1 table. Number of vehicles passed during measurements

Measurement site	No. of vehicles passed					
	Cold season			Warm season		
	Light vehicles	Moderate weight vehicles	Heavy vehicles	Light vehicles	Moderate weight vehicles	Heavy vehicles
1m near speed table	15	9	4	15	14	6
1m reference point	15	9	4	15	11	5



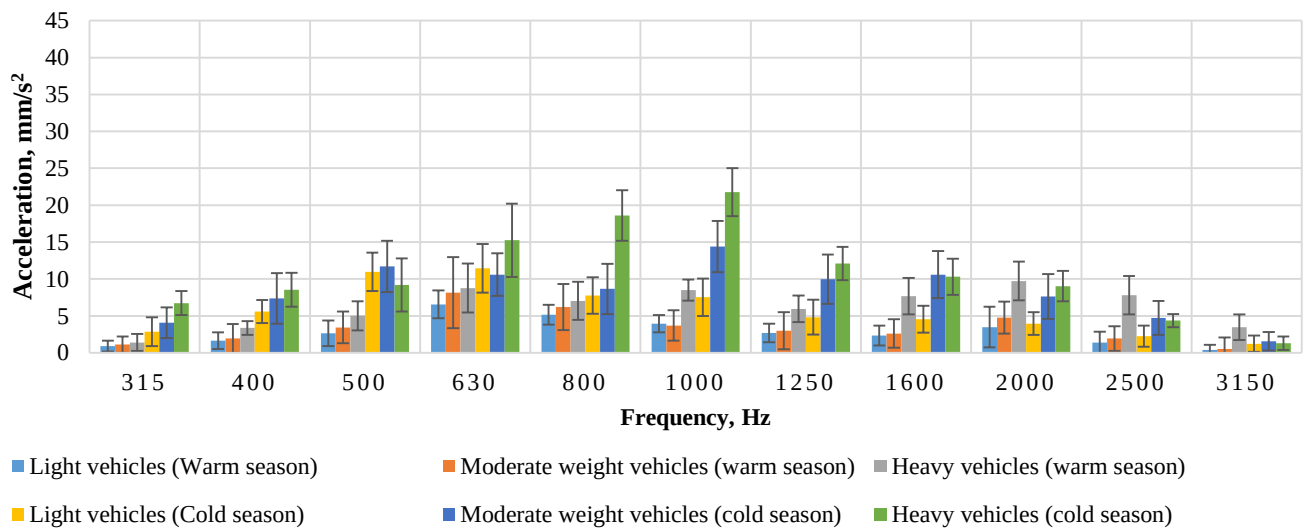
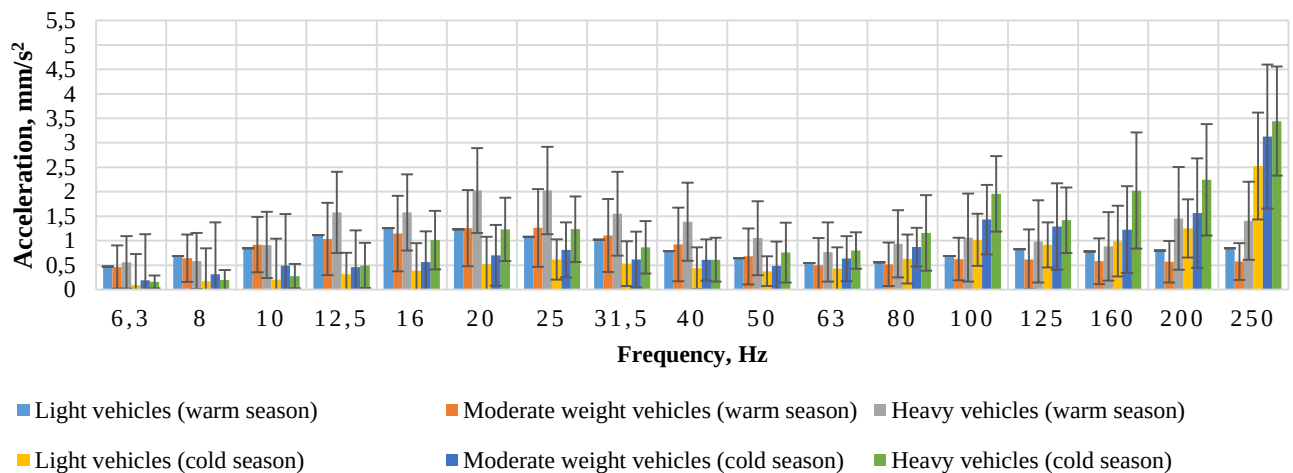


Fig. 4. Results at measurement site 1 m distance to the speed table, during cold and warm season

In measurement site one meter distance (cold season) to the traffic calming measure, highest vibrations acceleration was found in 1000 Hz and 630 Hz frequencies (light vehicles 11,5 mm/s² at 630 Hz, moderate weight vehicles 14,4 mm/s² at 1000 Hz, heavyweight vehicles 21,8 mm/s² at 1000 Hz). During measurement was noticed that light and moderate weight vehicles when passing speed table reduced their speed less than heavyweight vehicles. But still heavy weight vehicles induces highest vibrations at this measurement point.

The same vibration measurements was done during the warm season in summer time. In measurement point one meter distance to the traffic calming measure, highest vibrations acceleration was found in 630 Hz frequency (light vehicles 6,5 mm/s² at 630 Hz, moderate weight vehicles 8,2 mm/s² at 630 Hz, heavyweight vehicles 8,2 mm/s² at 630 Hz). During measurement was noticed that light and moderate weight vehicles when passing speed table reduced their speed less than heavyweight vehicles. But still heavy weight vehicles induces highest vibrations at this measurement point. Graph of results is shown in fig. 4



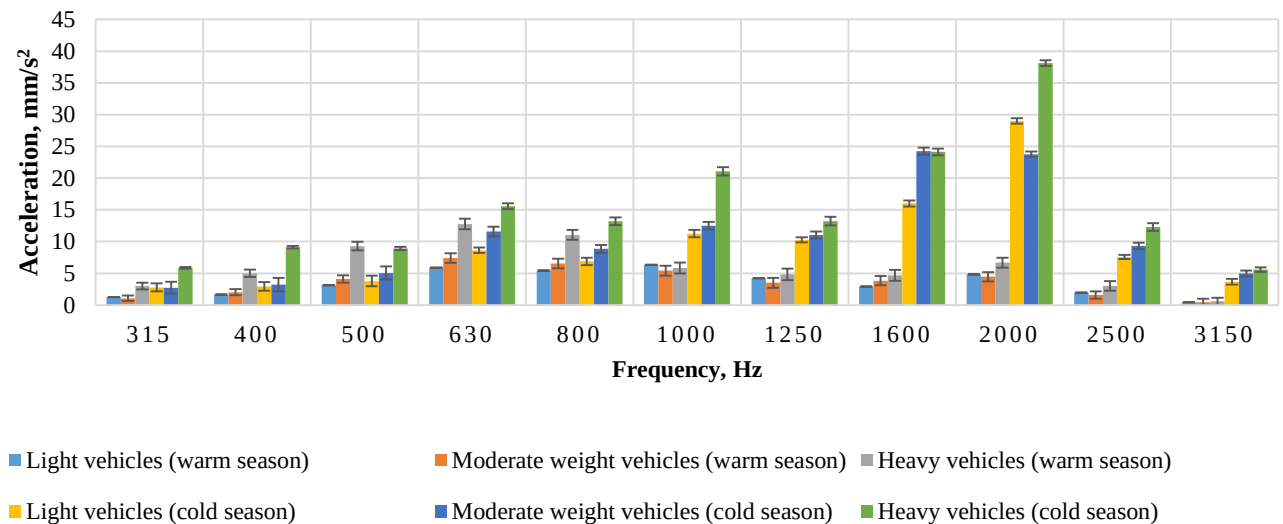
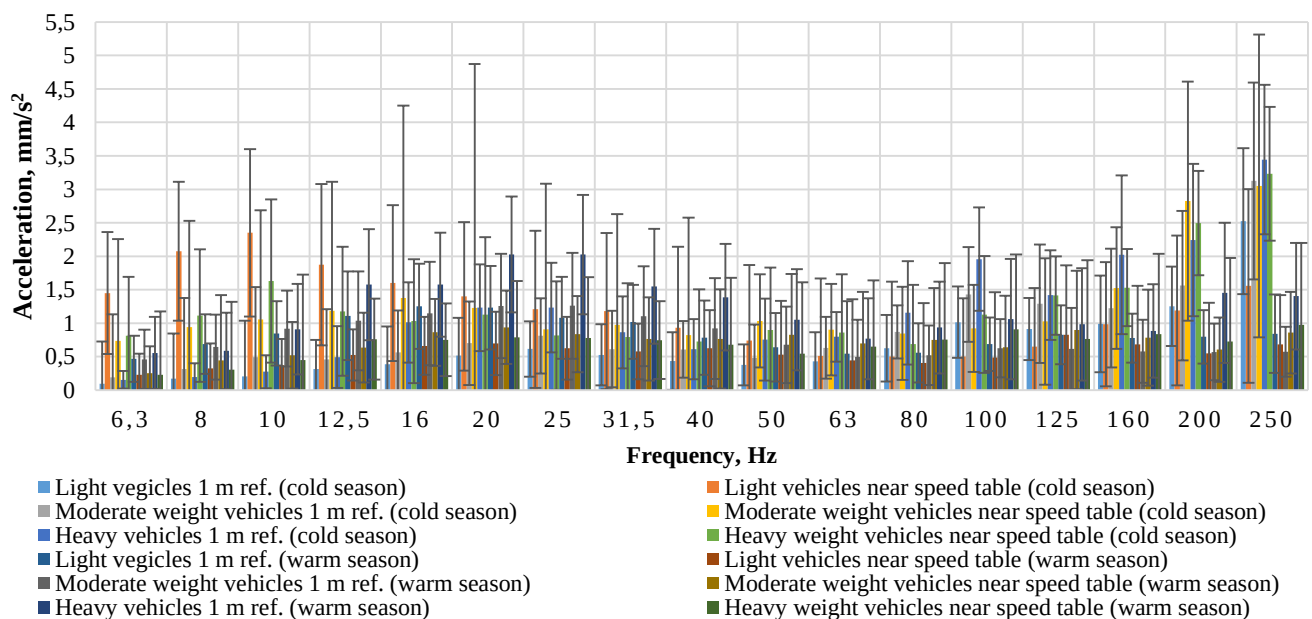


Fig. 5. Results at reference measurement point, during cold and warm season

Acceleration of the vibration was measured in reference point 1 m from L. Asanavičiūtė Street where vertical traffic calming measure has no impact on the traffic induced vibrations during the cold season. Highest vibrations acceleration was found at 2000 and 1600 Hz frequencies (light vehicles 29,0 mm/s² at 2000 Hz, moderate weight vehicles 24,8 mm/s² at 1600 Hz, heavyweight vehicles 38,1 mm/s² at 2000 Hz).

During the warm season, highest vibrations acceleration was found at 630 Hz frequency (light vehicles 5,9 mm/s², moderate weight vehicles 7,4 mm/s², heavyweight vehicles 12,8 mm/s²). Graph of results is shown in fig. 5.



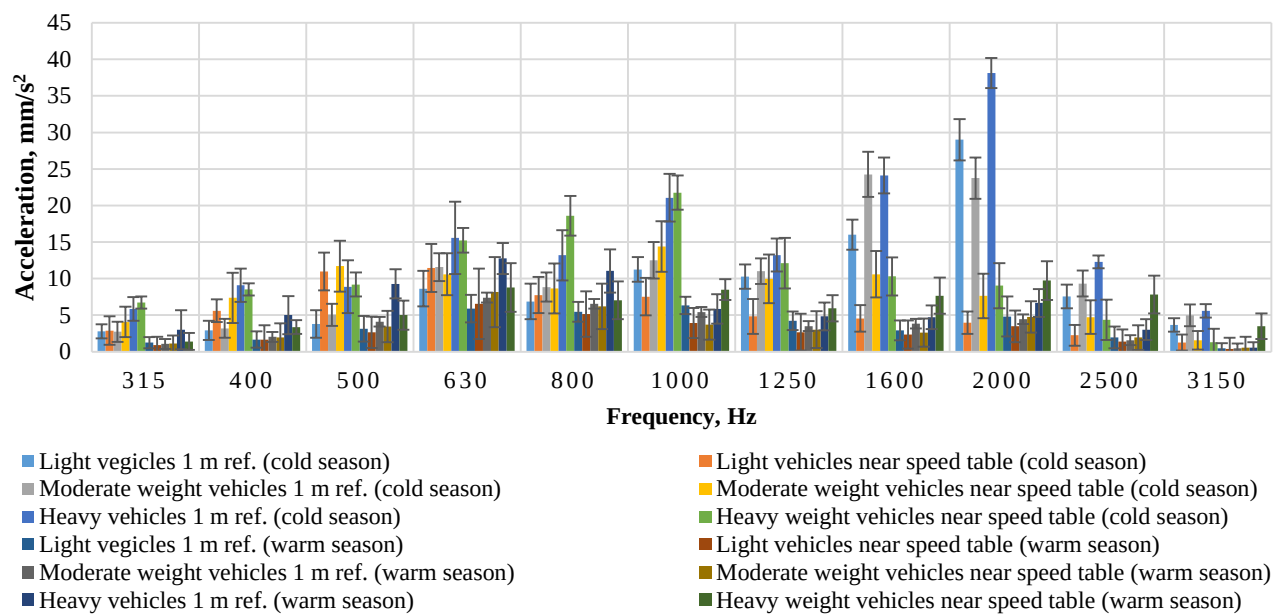


Fig. 6. Comparison of results, between measurement point near the speed table and reference point

During the cold season (fig. 6) when light vehicles was passing measurement results show that at lower frequencies (6,3 – 63 Hz) higher values of vibration is near the speed table, but in higher frequencies vibrations higher in reference point. When moderate weight vehicles was passing at the most frequencies (6,3 – 500 Hz and 630 – 1000 Hz) higher values of vibration is near the speed table, but in higher frequencies vibrations higher in reference point. The peak of acceleration gained near in reference point is 58 % higher than near the speed table. When heavy weight vehicles was passing results show that at the most frequencies (6,3 – 500 Hz and 630 – 1000 Hz) higher values of vibration is near the speed table, but in higher frequencies vibrations higher in reference point. The peak of acceleration gained near in reference point is much higher than near the speed table.

During the warm season (fig. 6), when light vehicles was passing gained results show that at the most frequencies (except 630 Hz) higher values of vibration is at the reference point. The peak of acceleration gained near in reference point is higher than near the speed table. The peak acceleration found near the speed table reached 6,6 mm/s². When moderate weight vehicles was passing vibration acceleration values at the most frequencies (except 630 Hz) found higher in the reference point. The peak of acceleration gained near in reference point is higher than near the speed table. In the fig. 13 is shown comparison of results gained in different measurement sites. Results show that at the most frequencies (except 1000-3150 Hz) higher values of vibration is at the reference point. The peak of acceleration gained near in reference point is higher than near the speed table. Highest peak of acceleration was found at 630 Hz in reference point, value reached 12,8 mm/s².

Summary and discussion

The measurements was done in real traffic conditions. Every vehicle passes with different speed which is unknown. The vehicle suspension stiffness is also unknown.

Higher vibration acceleration was found during cold season, highest peak value reached 38,1 mm/s² when heavy vehicles was passing through the reference measurement point. During warm season highest peak of acceleration was found also in the reference point when heavy vehicles was passing, the value reached to 12,75 mm/s².

Heavy vehicles induce higher vibrations than other categories of transport. Even though it was noticed that visually noticed that heavy vehicles passed measurement site slower than other two categories of transport, light and moderate weight vehicles induce smaller acceleration of vibrations than heavy transport. When light and moderate weight vehicles mass is similar 1,5 – 3,5 t, heavy vehicles is much heavier typical heavy vehicle weights around 18 t (Kansas, 2012) based on assumption that most of heavy transport was garbage trucks and busses. This difference of weight let heavy vehicles induce higher vibration acceleration than other two types of transport.

The difference of vibration acceleration between the reference point and measurement point near the speed table indicates that speed table influence on traffic induced vibration is low or it's lowering the vibrations. However street pavement is uneven and repaired several times. Also the huge factor is the vehicle speed, visually the vehicles passes speed table at relatively low speed and runs faster through the reference measurement point.

Conclusions

- Higher vibration acceleration was found during cold season, highest peak value reached 38,1 mm/s² when heavy vehicles was passing.
- Heavy vehicles induce higher vibrations than other categories of transport. The peak value registered when heavy vehicles was passing reached 38,1 mm/s², light and moderate weight vehicles induced vibrations reached 29,0 mm/s² and 24,3 mm/s² respectively.
- Speed table reduces ground borne vibrations in L. Asanaviciute str. Vehicles passing the speed table reduces speed enough to induce lower values of vibration acceleration. Highest acceleration value found near the speed table was 21,8 mm/s² when heavy weight vehicles was passing, in reference point highest value was 38,1 mm/s².

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Appendix 1

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Received and accepted dates	10 pt	Centred, Italic	04_DATES
Abstract	9 pt	Justified	05_ABSTRACT
Keywords	9 pt	Justified	05_KEYWORDS
Topic	9 pt	Justified	05_TOPIC
First level section headings	10 pt	Left, Bold	06_HEADING 1st
Second level section headings	10 pt	Left, Italic	06_HEADING 2nd
Main Text without indentation	10 pt	Justified	07_PARAGRAPH_1st
Main Text with indentation 0.75 cm	10 pt	Justified	07_PARAGRAPH
Figure captions	9 pt	Centered	08_FIGURE
Equation centred 8 cm, number – right, 16.5 cm	10 pt	Centred	09_DISPLAYED_EQUATION
Table captions	9 pt	Centered	10_TABLE
Table text	9 pt	Left	10_TABLE_line
References list	9 pt	Justified	11_REFERENCES
Bullets, indentation 0.75 cm	10 pt	Justified	12_BULLETS
Numbering	10 pt	Justified	12_NUMBERING