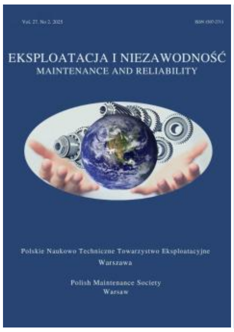

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Analysing the impact of electric kick-scooters on drivers: vibration and frequency transmission during the ride on different types of urban pavements

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Highlights

- Research on vibration transmission during the ride on different urban pavements.
- Determination vibration and frequency transmitted to the rider by electric scooters.
- Study on an assessment of ride comfort and considers potential health implications.
- Results facilitate the identification of critical risks associated with vibration.
- Findings provide insights into rethinking of road infrastructure for micro-mobility.

Abstract

The purpose of this research is to determine the vertical vibration and frequency spectrum transmitted to the rider by electric scooters travelling on different types of road surfaces. Vibration analysis involves the measurement of vibration levels of e-scooter elements, accompanied by the analysis of the Fourier Transform Spectrum and using a t-sample measurement design and a one-sample statistical method. Approach in the research allows overall driver comfort to be assessed through frequency and vibration analysis, considering vibrations received by the hands and the whole body. In addition, the natural frequencies of the electric scooter components and their stability are being investigated to assess vibration transformation. The study includes an assessment of ride comfort and considers potential health implications. The results obtained facilitate the identification of critical risks associated with vertical vibration frequencies transmitted to individuals when riding electric kick-scooters in urban areas with different types of pavements.

Keywords

micro-mobility, e-scooter, human riding comfort, sensitivity, vibration, frequency

1. Introduction

Mobility involves the physical movement of individuals and goods, quantified by factors such as frequency of travel, distance covered, and speed of travel. It is influenced by various socio-economic factors and is often categorized according to the purpose of the trip [19]. From these, commuting to and from work, school, etc. is the main purpose for most daily trips. Shopping, recreation, and leisure activities are other common reasons for daily travel. The specific purpose of a trip, along with factors such as distance, travel time, city location, and demographic characteristics of individuals or the population, significantly influence the choice of transport mode. In many cities, cars and public transport are still the dominant modes of transport, however, there is a trend towards growing popularity of micro-mobility options [13]. According to [40], two prominent examples of the emerging wave of modern micro-mobility are electric bicycles, which have been on the market for almost two decades, and electric scooters, which have seen significant growth in recent years.

The notable advantages of the increasingly popular use of electric kick scooters, can be attributed to their specific

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characteristics such as size, weight, speed, manoeuvrability, and flexibility. These attributes have made electric kick scooters a viable solution for "first" and "last mile" (short distance – up to 3 km) transport needs and in some case even for longer distances (from 5 km) [25, 45]. The first electric scooter was used in the early 1900s in the US Postal Service as a new environmentally friendly mode of transport [49] (Fig. 1a – based on [12, 49]). But with the coming era of oil and specific problems with electrically powered vehicles, the revolution in mobility applications was forgotten for a hundred years. Currently according to [4], shared e-scooters are lightweight, inexpensive vehicles which can be rented for short-distance trips, typically in dense urban areas. They are modern vehicles that offer a faster mode of transport than walking and can potentially address issues such as pollution, traffic, and parking associated with motor vehicles (Fig. 1b). However, the growing use of e-scooters has also revealed significant drawbacks, raising numerous questions and fuelling a debate between supporters and critics of their use.

(a) (b)

Fig. 1. Electric kick scoters through history: (a) The first electric scooters, photo by [49]; (b) Modern use of electric kick scooters: the case of the city of Vilnius (Lithuania) (partly based on [12]).

Research studies [29, 43, 56, 58] dedicated to the development of electric scooter systems have identified several main key research directions: Safety considerations; Assessing the energy efficiency and environmental footprint of e-scooters; Planning, design, and development issues related to electric scooter systems. Evaluating the comfort of different modes of transport produces different results, as each mode is associated with different travel behaviours and driving/riding characteristics. [53]. For example, the speed range, riding posture, and driving patterns of e-scooters differ from other forms of micro-mobility vehicles, as confirmed by [37]. In a similar domain concerning e-scooters, the examination of the research conducted over the last three decades on users' cycling experiences reveals the use of various methods to assess road user comfort, such as suitability, friendliness, comfort, stress levels, and quality-of-service (QOS) indices [1, 17]. According to [53], the concept of QOS has been widely used in recent decades to evaluate different modes of transport, including cycling, private cars, and public transport. At the same time, during the review of main research directions regarding e-scooter, a lack in the direction of comfortable use of e-scooters from a rider's point of view was identified.

The use of e-scooters in different urban environments and infrastructure layouts has potential. Assessing the usage patterns and distances travelled by e-scooters provides valuable insights for urban planners and practitioners, enabling them to improve infrastructure design and effectively manage travel demand. It is important to have an understanding of the distribution of trip distances for e-scooters as it has a significant impact on user comfort. Given the limited scientific knowledge specific to e-scooters, the evaluation and incorporation of comfort variables from other modes of transport with similar travel distances may be beneficial for e-scooters. Previous studies in the e-scooter literature have extensively examined travel distances, using open-source data from shared e-scooter companies and information on origin and destination information [20, 41]. Firstly, e-scooters were mainly identified as a suitable mode for short-distance trips, especially for first-last mile trips [26]. The definition of a short distance trip may vary across studies, but generally, it is associated with distances of less than 15 km [41]. Notably, e-scooter trips in the United States are frequently reported to be around 2 km [46], while longer trip distances are observed in Asian countries, such as 13.7 km [38]. Furthermore, the duration of e-scooter trips is typically reported to be around 30 minutes [27]. As trip duration is correlated with factors such as stress, fatigue, and comfort, evaluating both trip distance and duration becomes valuable for the advancement and improvement of e-scooter development. By studying and understanding trip distances and durations, researchers and practitioners can gain insights into user preferences, comfort levels, and design appropriate infrastructure and services to enhance the overall e-scooter experience.

The road surface, usually in the city is made of standard mastic asphalt concrete with up to 11 mm of crushed stone (AC 11 pavement without damage regarding EN 13108), such road surface is common in the category of main roads in Lithuania [11]. Regarding pavements, it is pointed out that each municipality can create a sustainable municipal infrastructure - pavement design, construction, and maintenance - based on the needs identified by that municipality. [15]. At the same time research into vibration characteristics and human driving comfort is beginning to be one of the main directions associated with a road surface and driving on it [48]. The study mentioned has shed some light on the impact of road surface vibration on e-scooter users. However, there is still a need for further research which should consider various types of road surfaces and include frequency domain analysis to provide a more comprehensive understanding of the comfort and safety aspects associated with e-scooter riding.

The use of various forms of micro-mobility is linked to several factors, including health, flexibility of use, flexibility of departure time, and absence of fuel costs [16]. Generally, users find using an e-scooter enjoyable [2]. For example, e-scooters can be more enjoyable than walking for short journeys, especially in hot weather [10]. In addition, the electric-assisted driving experience of powered micro-mobility is fun [36]. Other variables include cost savings, convenience, environmental value, and health benefits associated with e-scooters [10, 44]. Given that e-scooters can also be used on cycling infrastructure, the availability of cycling infrastructure plays a crucial role in the overall e-scooting experience [9, 57]. To sum up, the experience of e-scooting shares some similarities with other forms of micro-mobility, especially e-bikes.

Recently, a relevant study carried out by [7] has focused on the analysis of the impact of the vibration of the road surface on the experience of e-scooter users. The experiment aimed to determine the threshold of discomfort and potential harm caused by different speeds of common e-scooters, specifically for short-distances on well-maintained pavements. Firstly, the research did not consider various types of pavements which may have different vibration characteristics and affect the user experience differently. Secondly, different tire pressures, a common maintenance factor that can affect the ride quality of e-scooters, were not considered in the study. Considering how tyre pressure affects vibration transmission and ride comfort would provide valuable insights. In addition, frequency domain analysis was not included in the study. It should be noted that modern electric scooters are increasingly being built using advanced composite materials which offer weight reduction with high strength and performance characteristics. However, these materials have non-linear dynamic mechanical characteristics and are difficult to model [42]. Therefore, the inclusion of frequency domain measurements in future research would enhance the understanding of the relationship between road pavement vibration and user experience.

During e-scooter use, there are two main types of human vibration exposure: hand-arm vibration (HAV) [3] from gripping the scooter handlebars and whole-body vibration (WBV) [23] from standing on the scooter. In general, the vibration for the rider when using an e-scooter comes from two main sources – engine operation and riding on the pavement. The vibrations generated by the contact between the tire and the road depend on the road quality and the speed of the vehicle [47]. These vibrations exhibit varying frequencies depending on the measurement position. The floor, seat, and backrest are different measurement points. According to a study by [21, 52], the measured frequency range of vehicle vibration is between 4 and 20 Hz. Regarding HAV and WBV research [24, 51, 55], it was found that vehicle drivers experience whole-body vibration exposure levels ranging from 0.4 to 2.0 m/s^2. The vibrations are found to be highest in the frequency range of 2 to 4 Hz. It is important to note that vibrations within the 4 to 8 Hz range can cause resonance in the entire upper torso of a seated person, which should be minimized and avoided. Research has shown that comfort levels related to vibration can be categorized as follows: vibrations below 0.315 m/s^2 are generally considered comfortable, vibrations between 0.315 m/s^2 and 2.5 m/s^2 are rather comfortable, and vibrations above 2.5 m/s² are considered uncomfortable. Health effects associated with body vibration, particularly in the context of driving environments, may include kidney disorders, high blood pressure, piles (haemorrhoids). It is vital that excessive vibration is addressed and mitigated to minimize the potential negative impact on driver health and well-being.

Research [54] has shown that the locations of body discomfort caused by vertical vibration are relatively consistent in male and female populations. When exposed to vertical vibrations, maximum sensitivity is typically observed within the frequency range of 4 to 16 Hz. During this range, discomfort is commonly experienced in the upper torso and head region. At higher frequencies above this range and lower frequencies below it, while maintaining the same acceleration level, the discomfort tends to decrease. In these cases, individuals may experience more discomfort in the lower body, particularly in the abdomen and buttocks. The studies [18, 22, 31, 54] found that at 2 Hz, the most common responses in terms of sensation are found in the legs and the lower abdomen. As the frequency increases to 4 and 8 Hz, the responses move up the body, with most of the discomfort being experienced in the head at 16 Hz. This suggests that vibrations within this frequency range have a higher impact on the upper torso and head region. At 32 Hz, the responses are divided between the head and the lower abdomen. This indicates that vibrations at this frequency affect both areas to some extent. Finally, at 64 Hz, most of the responses are close to the main vibration input – sitting or standing. This implies that vibrations at this frequency primarily affect the lower body, specifically the area in contact with the seating or standing surface. The threshold of sensation, or the minimum level of vibration required to be detected like discomfort, can be from 0.5 to 2 m/sec. This means that if the acceleration of a vibrating object is below this threshold, it may not be perceptible to humans.

This research aims to establish the specific types of vibrations and frequencies produced by e-scooters and how they influence the well-being of riders. By understanding these effects, it will be possible to determine the potential risks associated with vertical vibration frequencies transmitted to individuals while riding electric kick scooters in urban areas with different pavement conditions. The findings obtained from such research will provide valuable insights into defining critical risks related to vibration frequencies experienced by riders. This information can then be used to reconsider and optimize the development of road infrastructure to accommodate the needs of micro-mobility and ensure the comfort and safety of riders.

2. Research Explanation and Methodology

The analysis undertaken was based on vibration analysis, a method of monitoring vibration levels and studying patterns within vibration signals. This process encompasses two key aspects: direct analysis of the time waveforms of the vibration signal and examination of the frequency spectrum obtained by applying the Fourier transform to the time waveform. Secondly, a comfort and health assessment should be carried out according to the results of the vibration analysis.

Vibration analysis is a technique used to measure the vibration levels and frequencies of objects, primarily for dynamic evaluation [33]. In the context of e-scooters, this analysis involves using an accelerometer to measure the vibrations generated while the e-scooter is in motion. The accelerometer produces a voltage signal that corresponds to the magnitude and frequency of vibrations as the e-scooter rides on the road. The vibration analysis includes the measurement of vibration level and the additional analysis of Fourier Transform spectrum.

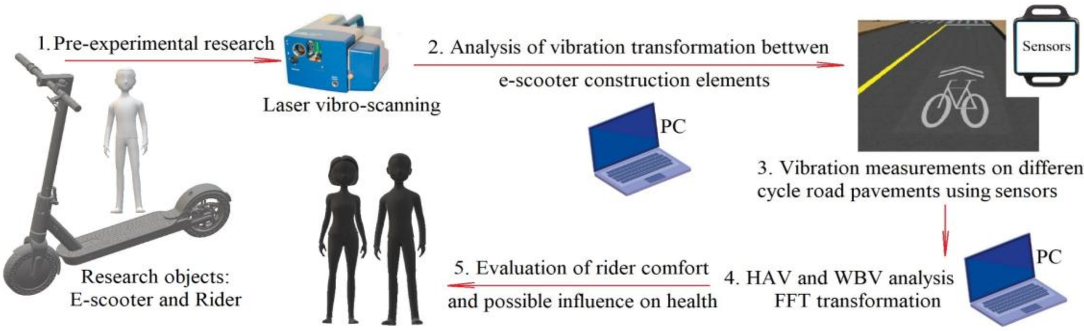
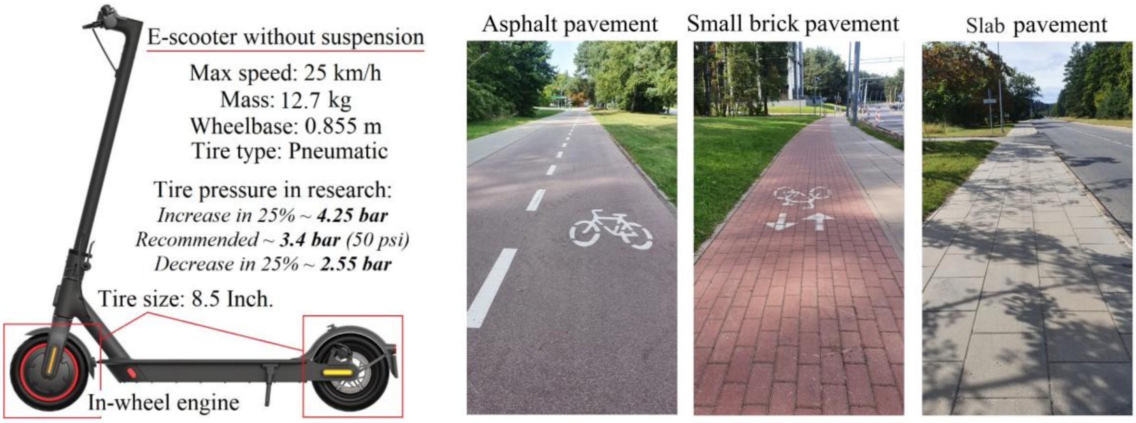


Fig. 2. Suggested steps for the research methodology.

The primary focus of this research is to determine the vibration level experienced by different elements of the e-scooter when riding on different pavements and taking into account different tire pressures. The objective is to compare and study vertical vibrations and how they affect driving comfort and health. To ensure a successful analysis, a series of steps have been developed and are illustrated in Fig. 2. These steps outline the process to be followed in order to obtain meaningful results and insights from the vibration analysis.

The preliminary experiments include vibration and modal analysis on various components of the e-scooter, such as the desk on which the rider stands, and the handlebars used to control the e-scooter. The analysis aims to evaluate the inherent vibration generated by the operation of the engine at different speeds. The experimental measurements include real-time operational analysis under different road and e-scooter conditions to evaluate the vibration amplitudes transmitted to the rider. E-scooter under research shown on Fig. 3a and sidewalk/cycle lane pavements on which the measurements were taken shown on Fig. 3b. This analysis provides an insight into the actual vibrations experienced by the rider during e-scooter riding. The collected measurement data is then processed and analysed, focusing on vibration levels and frequency analysis. This analysis helps to identify the dominant frequencies and assess the overall vibration levels experienced by the rider. The main analysis and subsequent discussion revolve around the evaluation of rider comfort, primarily based on the frequencies of vibrations transmitted to the rider. By considering the frequencies that have the most significant impact on the rider comfort, the study can provide an informed assessment of the overall comfort level during e-scooter riding.



a) (b)

Fig. 3. View of some research objects: (a) E-scooter under research; (b) Sidewalk/cycle lane pavements in the city of Vilnius (Lithuania) case on which the measurements were taken.

The measurements were carried out on these specific sidewalk and cycle lane pavements to capture the vibration levels and frequencies experienced by e-scooter riders. By selecting different types of pavements, the study aims to investigate how road irregularities affect the vibration profiles. The three main types of sidewalk and cycle lane pavements identified in Vilnius city serve as representative samples for the research: asphalt pavement, small brick pavement, and slab pavement. This allows the analysis to provide insight into the variations in vibration levels and their possible impact on rider comfort and health across different pavement types. In addition, it can be used as a recommendation for riders and municipalities regarding comfortable riding of e-scooters and for manufacturers a point for re-thinking how to improve a structural component of e-scooters associated with vibrations.

3. Pre-experimental Research on Electric Kick-Scooter

The first phase of the pre-experiment part was to evaluate the inherent vibration levels generated by the in-wheel electric motor of the e-scooter. This evaluation was essential to convert the vibration data into elements relevant to the HAV and WBV analysis. The data collected was then used in the final analysis to eliminate the effects of the e-scooter own vibrations and frequencies, and to focus solely on the effects of the road surface. To determine the vibration characteristics of the mechanical structure of the e-scooter's components under its own vibration loading conditions, a laser scanning technique was employed. This technique allowed for the identification of the natural frequencies and mode shapes associated with the structure, for more details on the technique [35]. These parameters are important in the design of structures intended to withstand dynamic loading conditions. The tests in this research employ a t-sample measurement design, which uses a one-sample statistical method to assess the uncertainty in the repeated measurement of data processing [34]. This approach allows for a comparative analysis of data from different groups or conditions and helps to determine whether there are significant differences between them. The one-sample statistical method is used to estimate the population mean of a single group by comparing it to a known value or hypothesized value. By using this method, the measurement results can be effectively evaluated and interpreted, and meaningful conclusions can be drawn about the effects of in-wheel engine vibration on the scooter's components.

In the current pre-experiment, the research pre-experiment consists of a test bench (Fig. 4), which includes several key components. These components include a metal base with a specially designed support element to accommodate the research object, an e-scooter. To minimize external interference, the support element is fitted with low-frequency influence shielding rubber. In addition, a scanning system is integrated into the setup to accurately measure the level of vibration. The focus of the measurement tests is to analyse how vibrations from the in-wheel engine are transmitted through the e-scooter's joints to the desk surface (for WBV analysis) and the handlebars (for HAB analysis). To accurately capture these vibrations, the PSV sensor head is used, which records data points for a duration of 1 second. The in-wheel engine is operated at a speed of 25 km/h (legal maximum speed [14]), specifically for the e-scooter.

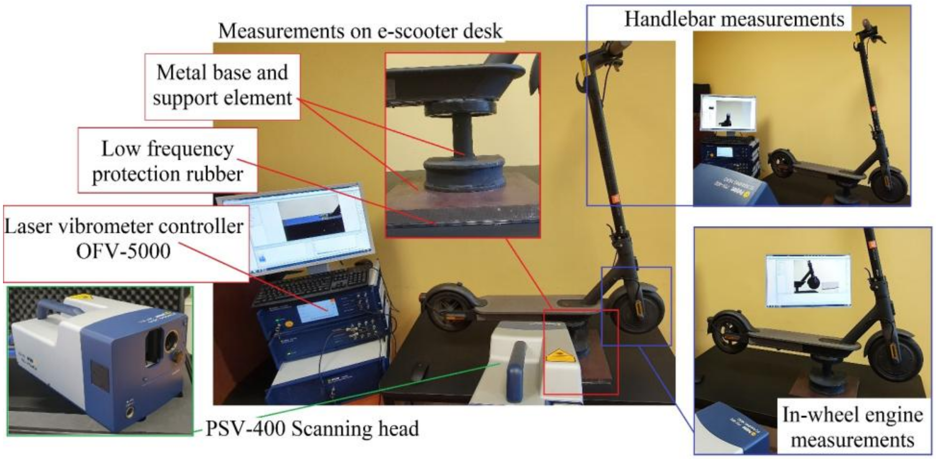


Fig. 4. Test bench for measuring pre-experimental research

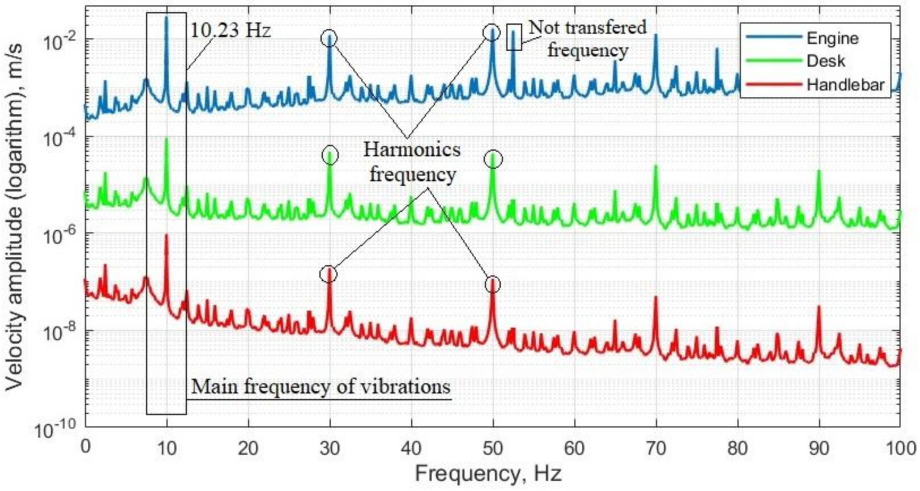


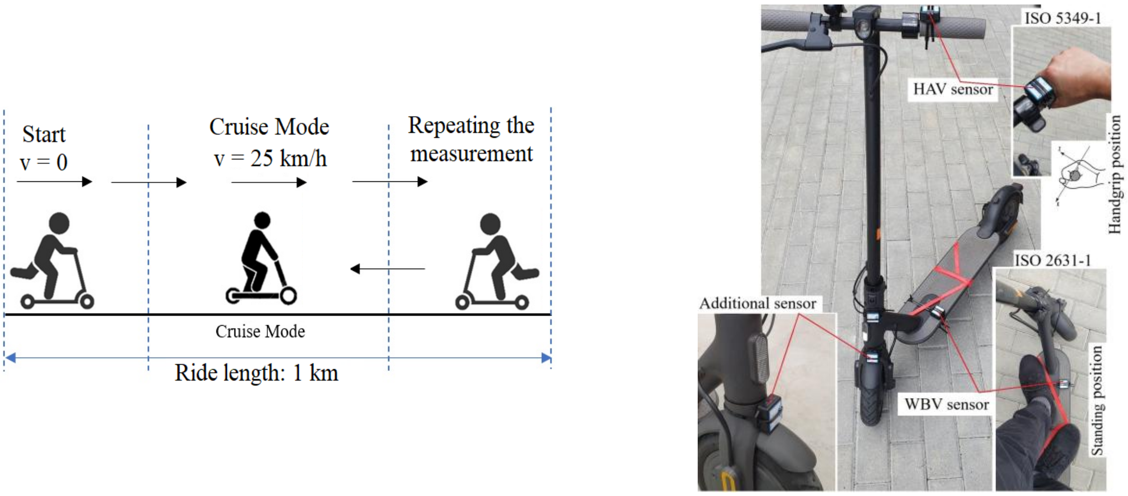
Fig. 5. Frequency response of e-scooter elements in line with in-wheel vibration.

In the vibration analysis, the recorded vibration data is subjected to a Fast Fourier Transform (FFT) spectrum analysis using specialized measurement equipment, as shown on Fig. 5. This transformation is a powerful mathematical tool that enables the examination of frequency responses and mode shapes within the vibration data. The use of the FFT provided valuable insights into the vibration characteristics of the electric scooter and its response to the engine vibration within the wheel.

The maximum vibration level produced by the electric engine in the e-scooter during the test at a speed of 25 km/h was recorded at different positions: the in-wheel engine surface, the desk surface where the rider stands, and the handlebar arm. The measurements showed vibration levels of approximately $5.25 \cdot 10^{-3}$ m/s, $5.19 \cdot 10^{-4}$ m/s, and $5.17 \cdot 10^{-5}$ m/s, respectively. The analysis of the measurements shows that there are significant differences between the vibration levels at these measurement positions, but the profile of vibrations is similar. The significant damping effect observed at the desk and handlebars can be attributed to their combination with rubber material, which effectively absorbs vibrations. Looking at the frequency response, it becomes clear that all the vibrations from the engine -wheel are directly transmitted to various positions on the e-scooter, but with a significant damping effect. The main resonance frequency was found to be 10.23 Hz, confirming that all the vibrations are indeed transmitted correctly and depend only on the in-wheel operation conditions (specifically, the e-scooter speed of 25 km/h or engine 614 rpm). It is also worth noting that the vibration values recorded, for the engine, desk, and handlebar, are well below 0.5 m/s, which is unlikely to cause any discomfort. Therefore, vibrations caused solely by the operation of the e-scooter should not have a significant impact on the analysis. In general, the e-scooter's own vibration is well damped and does not significantly affect the rider's comfort during the ride. However, the main vibrations that could affect the comfort of the e-scooter rider and possibly affect the health assessment are the vertical vibrations experienced while driving on sidewalk pavements.

4. Main Experimental Part of the Research

The main measurements regarding vertical vibration during e-scooter riding were performed in the streets of the city of Vilnius (Lithuania) on cycle sidewalk pavements (shown in Fig. 3b). For better explanation, the type of pavement named: asphalt pavement (A), small brick pavement (B) and slab pavement (S). The task was to measure the vertical vibration for HAV and WBV analysis while riding the e-scooter on a straight road following the instructions as shown in Fig. 6a. It starts with the rider gently accelerating until the maximum speed of the e-scooter is reached – 25 km/h. After that, the rider should drive the scooter in cruise mode. The e-scooter used in the research with additional setups used in measurements shown in Fig. 6b. The e-scooter was equipped with acceleration sensors mounted on the desk and handlebar for measuring vertical vibration generated by drive on different road surfaces. Handgrip position on handlebar - cylindrical bar was setup regarding ISO 5349-1 standard [30]. All the tests were performed with the same foot positions marked with tape on the platform of the e-scooter and carried out regarding ISO 2631-1:1997 [29]



(a) (b)

Fig. 6. Main experiment of the research: (a) Instruction of ride; (b) E-scooter equipped for measuring.

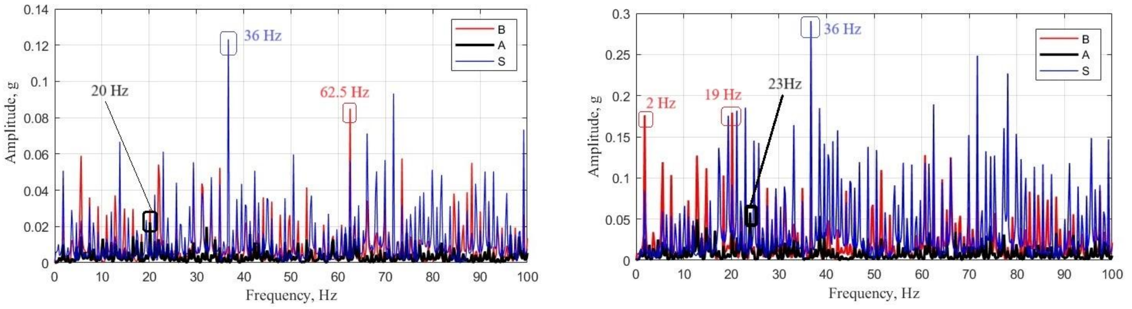
With regard to review section the duration of e-scooter rides is typically reported to be around 30 minutes and the distance ranges from half-kilometre to over 10 km. In the current research, a ride on the length of 1 km was used by repeating ride regarding t-sample method of testing. The rider drives 1 km in one direction after what return and drive on the same pavements in the opposite direction. The total of 10 km was driven, and vibration measured on it for each type of pavement. The one-sample statistical method to assess the uncertainty in the repeated measurement of data processing was used.

The next step involves taking the data collected by measuring the acceleration vibration, processing it by Fourier Transform Spectrum Analysis to find at what main frequency a vibration is generated. The frequency analysis based on Short-time Fourier transform (STFT) algorithms in continuous-time and performed regarding the study [50]. In the continuous-time scenario, the function to be transformed is multiplied by a non-zero window function. Mathematically, the two-dimensional representation of the signal is obtained by taking the Fourier transform of resulting signal (which is obtained by multiplying the original one-dimensional function by a non-zero window function) and sliding the window along the time axis to the end:

$$\textbf{STFT}\,\{x(t)\}(\tau,\omega) \equiv X(\tau,\omega) = \int_{-\infty}^{\infty} x(t)\omega(t-\tau)e^{-i\omega t}dt, \quad (1)$$

where, *x(t)* – vibration signal to be transformed; *X(τ, ω)* – essentially the Fourier transform of *x(t)ω(t-τ)*; *e* – complex function representing magnitude and phase of the signal over time and frequency; *ω(t-τ)* – window function (Hann window) centred around zero.

The maximum level of vibration generated by the e-scooter while riding on the different types of surfaces during the test at a speed of 25 km/h was on the slab pavement (S). The measurements showed vibration levels of approximately 3.19g, 3g, and 1.28g, in the handlebars for S, B and A types of road surfaces respectively (in vertical vibration). For correct analysis, however, a frequency-amplitude transformation should be used (Fig. 7), since in this case the main vibration tendency is pavement dependent, excluding high vibration caused by some accidental impacts.

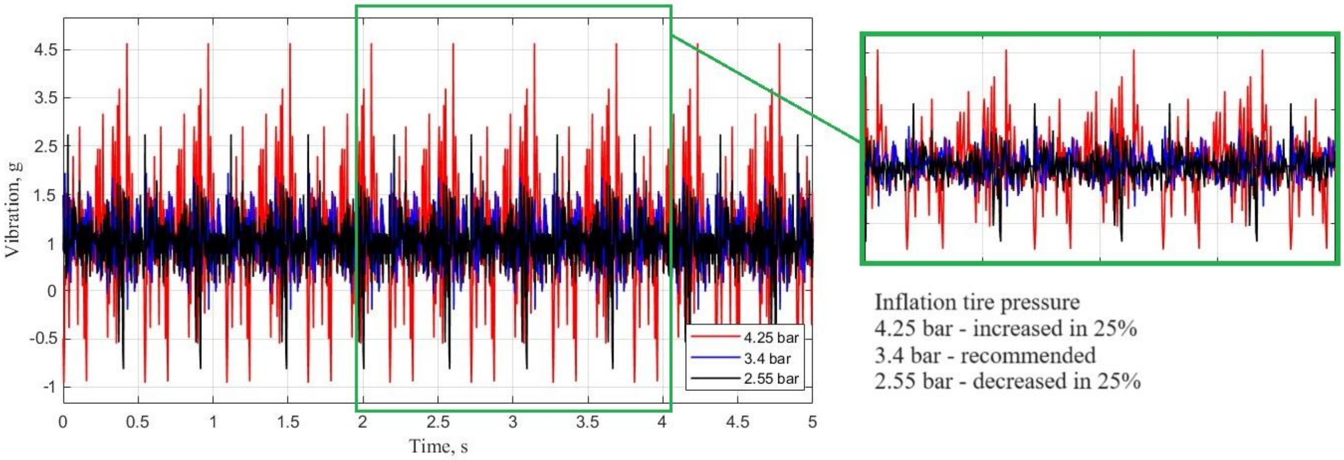


(a) (b)

Fig. 7. Frequency analysis results: (a) Vibration on desk of e-scooter; (b) Vibration on handlebar of e-scooter.

The analysis of the measurements shows that there are significant differences between the vibration levels at the desk and the handlebars, but the vibration profile is similar. The significant damping effect is observed at the e-scooter's desk compared to the handlebars. Vibrations caused solely by the e-scooter's motion have a significant impact on the rider and the rider's comfort during the ride. By studying the frequency response, all vibrations from the e-scooter riding on different types of surfaces are directly transmitted to different positions on the e-scooter, with transfer to the rider. In this case, the influence on the comfort of the e-scooter rider, and possibly on the health assessment, is due to the vertical vibrations experienced when riding on pavements, which are discussed in the next sections.

The research also analysed how tyre inflation pressure affected vertical vibration during e-scooter ride. The tests include a measurement when driving on the most vibration-generating type of road surface (S). The same e-scooter was used with a sensor installed on the in-wheel engine support element (Fig. 6b - additional sensor) to measure the direct influence of tire inflation pressure on the vibration generated by driving on the road. The tires were evaluated at the recommended inflation pressure of 3.4 bar (50 psi) and with additional inflation and deflation of 25% (to 2.55 bar and 4.25 bar). A one-sample statistical method was used to assess uncertainty in repeated measurement data processing, and averaged vertical vibration results are shown in Fig. 8 for each inflation pressure in electric scooter tires.



Inflation tire pressure
4.25 bar - increased in 25%
3.4 bar - recommended
2.55 bar - decreased in 25%

Fig. 8. Effect of tire inflation pressure on vibration - recorded vibration value on S type pavement.

Examination of the measurements reveals significant differences in vibration levels as a function of tire inflation pressure, while the vibration profiles show similarities. A marked damping effect can be seen when comparing the recommended tire pressure (ride vibration level up to 2.55g) with both reduced (ride vibration level up to 2.35g) and increased pressures (ride vibration level up to 4.6g). Reduced tire pressure demonstrates better vibration absorption, although not significantly so at around 8%. At the same time, according to [32], there is a proportional increase in the risk of tire blowout at lower pressures, a factor that is considered acceptable in terms of overall use. Reduction in tire inflation pressure results in a significant increase of tire deformation. Increased tire deformation corresponds to an increased susceptibility to tire damage, thereby increasing the potential for road accidents. Notably, when operating near the maximum permissible external load, tires manifest inferior deformation characteristics, resulting in an increased risk of micro crack failure and an increased likelihood of a blowout [54]. Consequently, based on the analytical findings, a strong recommendation is made to adhere strictly to the manufacturer's recommended inflation pressure for pneumatic tires.

5. Analysis of Results & Discussion

The results obtained showed that the vibrations generated when riding an e-scooter on different pavements affect the rider's senses in different ways (more detailed information can be obtained by combining the information from *Section 1*). In addition to the vibrations transmitted to the rider's legs and hands, there are also different frequencies of vibration. These can prolong an uncomfortable ride.

Individual variations in perception and discomfort in response to mechanical vibrations are influenced by factors such as personal sensitivity, posture, body composition, and individual preferences. It is essential to consider these factors when studying the effects of vibrations on individuals, the current example, only provides a general case tendency. Individual variations in perception and discomfort in response to mechanical vibration are influenced by factors such as personal sensitivity, posture, body composition and individual preferences. It is essential to take these factors into account when studying the effects of vibration on individuals; the current example only provides a general case tendency. Table 1 summarises the results of experimental measurement research and provides comparison of the comfort levels regarding vibration experienced by the human body in terms of frequency distribution.

It has been taken in account that comfort levels related to vibration are categorized as follows: vibrations below 0.315 m/s^2 are generally considered comfortable, vibrations between 0.315 m/s^2 and 2.5 m/s^2 are rather comfortable, and vibrations exceeding 2.5 m/s^2 are considered uncomfortable. Note regarding the data extracted from Fig. 8 for Table 1: an object at rest on Earth's surface experiences a gravitational force of 1g, corresponding to the conventional value of gravitational acceleration on Earth, approximately 9.8 m/s^2. This implies that the depicted 1g load represents the gravitational force transferred to the rider's body and subtracted from the vibration level generated by riding e-scooter on different sidewalk pavements.

Table 1. Summary of results for e-scooter riding on different type of pavements (in vertical vibration).

Measurement place and Pavements		**Rider**	
	Frequency	**Amplitude**	**More sensitive**
B type - desk	62.5 Hz	5.39 m/s²	Both – in foots
B type - handlebar	2 Hz and 19 Hz	19.6 m/s²	Men – in legs and abdomen
A type - desk	20 Hz	2.35 m/s²	Women – in head
A type - handlebar	23 Hz	2.44 m/s²	Both – in head and abdomen
S type - desk	36 Hz	11.66 m/s²	Women – in head and abdomen
S type - handlebar	36 Hz	21.46 m/s²	Women – in head and abdomen

According to the data obtained, it can be assumed that theoretically women should be more sensitive to vertical vibrations when riding an e-scooter on the (S) type of surface, while men will feel more discomfort when riding on the (B) type of surface. At the same time not one of the pavement type not provide comfortable vertical vibration, only A pavement type going in range of rather uncomfortable, what is basically confirmed by rider during measurements. By understanding these effects, it will be possible to determine the potential risks associated with vertical vibration frequencies transmitted to individuals while riding electric kick scooters in urban areas with different pavement conditions. The findings obtained from this research will provide valuable insights into defining critical risks associated with vibration frequencies experienced by riders. This information can then be used to reconsider and optimize the development of road infrastructure to meet the needs of micro-mobility and ensure the comfort and safety of riders.

Individual variations in perception and discomfort in response to mechanical vibrations are influenced by factors such as personal sensitivity, posture, body composition, and individual preferences, all of which should be considered in any type of analysis associated with an individual. The collected measurement data is processed and analysed, focusing on vibration levels and frequency analysis in HAV and WBV analysis. These vibrations potentially lead to discomfort in different places of the rider's body during long journeys, depending on the road surface and can lead to various health problems for the rider [55]. Combining findings obtained by the current research and the information from the Institution of Occupational Safety and Health [28] and the Canadian Centre for Occupational Health and Safety [5] the effects of vibration on humans - Whole Body Vibration (WBV) and Hand-Arm Vibration (HAV) - can lead to various health problems over time:

– **Whole body vibration** (**WBV**): Prolonged exposure to whole-body vibration can lead to various health issues, including fatigue, stomach problems, headaches, loss of balance, and a sensation of "shakiness" either shortly after or during exposure. With consistent daily exposure over several years by driving e-scooter on (S) pavement type, whole-body vibration has the potential to affect the entire body and contribute to the development of many health disorders. The cumulative effects of factors such as body posture, postural fatigue, dietary habits, and whole-body vibration are considered potential contributors to the onset of these disorders.

– **Hand-arm vibration** (**HAV**): Vibrations can cause alterations in tendons, muscles, bones, joints, and affect the nervous system. The comprehensive set of consequences resulting from these effects is collectively identified as Hand-Arm Vibration Syndrome. Of course, it all depends on the vibration time, but it must be pointed out that such riding on (S) type and (B) type pavement surfaces can lead to painful and disabling conditions involving the nerves, joints, tendons, muscles and blood vessels in the hand.

In summary, these factors collectively contribute to our understanding of how vibration exposure affects individuals, with variations in sensitivity and the relationship between exposure and health outcomes playing pivotal roles in this assessment. As a future research initiative, building on the foundation laid by [6, 7 and 8], it is recommended to investigate the impact of vibrations on different designs of emerging electric transport models, already available on the market. The research should include the integration of a health index to assess potential discomfort during extended rides, considering diverse surfaces and their effects on different parts of the rider's body. In addition, the use of the IMU (Inertial Measurement Unit) human sensor for extensive research is imperative for comprehensive health assessments. Future research should include gender and age considerations in the measurements. Furthermore, for enhanced research outcomes, it is essential to evaluate e-scooter suspension systems, including both suspension and wheels, with a primary focus on human comfort and health. This observation is becoming an emerging trend in the next generation e-scooter design. Improvements in suspension systems should therefore be a key consideration to enhance the overall rider experience and well-being.

6. Conclusions

In the research was found that inherent vibrations of the e-scooter are effectively damped, minimising the impact on the rider's comfort during the ride. However, a startling discovery has revealed that the rider's arms experience a vibration level that is almost twice as high as that experienced by the legs throughout the ride. The rider's overall comfort during the ride is significantly affected by the vibrations emanating exclusively from the e-scooter. Comprehensive frequency analysis shows that vibration manifests itself over a spectrum ranging from 2Hz to 62.5Hz, depending on the type of pavement surface being travelled on. In the WBV analysis the vibration level varies from a minimum of 2.35 m/s² to 11.66 m/s² and in the HAV analysis from 2.44 m/s² to 21.46 m/s².

As a result of this analysis, a strong recommendation is made to strictly adhere to the manufacturer's recommended inflation pressure for pneumatic tires. The frequency response analysis emphasises that vibrations from the scooter's ride are directly transmitted to various parts of the scooter and subsequently affect the rider. The data obtained suggests that, in theory, women may be more sensitive to vertical vibrations when riding e-scooters on slab surfacing, whereas men may experience increased discomfort on small brick surfacing. Importantly, none of the pavement surfacing tested provided a truly comfortable experience in terms of vertical vibration, with only asphalt surfacing falling within a range of relative discomfort, a sentiment confirmed by driver feedback during the measurement. Understanding these effects offers the potential to identify risks associated with vertical vibration frequencies transmitted to riders of electric kick scooters, particularly in urban areas with varying pavement conditions. The knowledge gained from such research can be used to evaluate and optimise road infrastructure to meet the demands of micro-mobility, while ensuring the safety and comfort of drivers.

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