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Safety and reliability assessment of personal electric kick-scooter riding with different tire types

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Highlights

- Tire type and pavement strongly influence vibration levels in electric kick-scooters.
- Airless tires transmit higher vibrations than pneumatic tires on urban pavements.
- Ride on brick pavements generate critical vibration levels at the handlebar safety lock.
- Vibrations reach the handlebar safety lock with minimal attenuation from wheel assembly.
- Elevated vibrations increase both component failure risk and rider discomfort.

Abstract

This study investigates the mechanical safety of personal electric kick-scooters, specifically the vibration-induced failure of handlebar safety lock. Utilizing a dual-methodology approach, pre-experimental modal analysis via laser scanning was combined with real-world field measurements on asphalt and brick pavements using pneumatic and airless tires. Modal analysis identified a primary resonance frequency at 20 Hz, where airless tires exhibited significantly lower damping coefficients compared to pneumatic tires. Research results quantified a critical vibration that limit correlates with the unintended disengagement of the folding mechanism. On brick surfaces, airless tires produced vibrations 40% higher than pneumatic tires. These findings demonstrate that the reduction in damping provided by aftermarket airless tires directly compromises structural reliability, necessitating secondary locking redundancies for safe urban operation.

Keywords
electric kick-scooter, pneumatic tire, airless tire, vibration, frequency, safety

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1. Introduction

Even though personal automobiles and public transportation remain the primary ways to navigate cities, micro-mobility options are gaining significant traction [1]. This trend, highlighted in [2], is driven by two key vehicles: electric bikes, which have existed for nearly two decades, and electric scooters, which have seen an explosion in popularity in the last few years. As mentioned in [3], e-scooters are lightweight and cost-effective vehicles designed for short-distance travel, particularly in densely populated urban areas. They offer a faster alternative to walking and hold the potential to address issues like pollution, traffic congestion, and parking difficulties associated with conventional motor vehicles and start to be one of main popular vehicle shared and personal micro-mobility applications (refer to Fig. 1a). However, the improper usage and inadequate safety measures surrounding e-scooters have led to a significant number of accidents [4]. The Global Plan for the Decade of Action for Road Safety 2021-2030 by the World Health Organization has recognized micro-mobility as an emerging safety concern in surface transportation [5]. Addressing this challenge necessitates a comprehensive understanding of the specific safety issues associated with micro-mobility systems.

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The growing utilization of e-scooters has indeed revealed significant drawbacks, sparking a debate and raising questions among both supporters and critics. Several research studies [5–8] focusing on the evolution of electric scooter systems have identified key research directions crucial for advancing this field, where the most of popular topic – safety considerations of use e-scooters. By exploring the research direction mentioned earlier, the understanding of electric scooter systems can be significantly enhanced, leading to the development of strategies and solutions that optimize safety, sustainability, and overall effectiveness. Although research has predominantly focused on studying injuries associated with e-scooters, fatalities are relatively rare, and there is limited documentation on their specific characteristics in scientific literature. As emphasized in [4], it is crucial to delve into technical aspects such as simulation and dynamics to gain a better understanding of how these factors influence the safe usage of e-scooters. Conducting research on these technical aspects allows researchers to uncover valuable insights that promote safer practices and enhance overall safety in e-scooter usage. Notably, the research conducted in [4,9] has revealed significant findings regarding e-scooter crashes. The majority of these crashes (86%) involve motor vehicles, with 28% of them classified as hit-and-run incidents. A significant portion of crashes occurs in low-light conditions (81%), with adverse environmental factors, such as precipitation and fog, present in 43% of cases. Two crash types were identified as the primary contributors to fatalities: collisions with motor vehicles from behind and instances where e-scooter operators lost control while transitioning between different pavement types or encountering obstacles on the road [4,9].

In personal-use electric kick scooters, there is a handlebar safety locking mechanism on the handlebar. This lock secures the handlebar both during riding and when the scooter is folded. While riding, the handlebar safety lock ensures that the handlebar remains firmly fixed, allowing the rider to maintain full control and stable steering, which improves overall riding safety. When folded, the same mechanism helps keep the scooter compact and secure for transport, making it convenient for travel and storage. In shared electric scooter applications, this handlebar safety lock is generally not included. Shared scooters are designed mainly for short-term use, robustness, and low maintenance. Since users do not need to fold or carry the scooter, and the design prioritizes simplicity and durability, a handlebar locking mechanism is unnecessary and therefore omitted. During the operation of a personal micro-mobility e-scooter, the author experienced a mechanical failure that resulted in a loss of control and subsequent physical injury. This type of risk was earlier not registered in research direction regarding safety use of e-scooter, but common problem for users of e-scooters, regarding personal communications with them. The problem was consisted that after while time use of e-scooter there was made maintenance by changing regular pneumatic tires on airless tire, since regarding researches for vehicles [10] the new type of tire (airless) more safety use for avoid a problem with blast under dynamic loads. The technical problem was connected with a suddenly open of handlebar safe locker (already broken after accident shown on Fig. 1b) after what e-scooter was not controlled. Rider on maximum allowed speed in Lithuania for electric micro-mobility vehicles (25 km/h) was dropped with a e-scooter on sidewalk pavement, should be pointed that pavement type was – small bricks.



(a) (b)

Figure 1. Electrical kick-scoter research introduction views: (a) Modern use of electric kick-scooters in shared applications on Vilnius (Lithuania) city case example; (b) Broken handlebar safety lock of electric kick-scooter after accident.

After accident, there was made a detail investigation to find what fact was led to risk factor, what is base for current research. First of all, problem comes after tire changes, in dynamic simulation of any vehicles, tire modelling plays a crucial role due to the tire being the sole component in contact with the ground, responsible for transmitting the necessary forces for motion and feedback from the road [11,12]. Secondary, the problems come after drive from asphalt sidewalk pavement on small brick type of pavement. The primary objective in the field of machine vibration impact analysis was to assess the correlation between vibration levels induced by motorways and the resulting of dynamic vibration to machine components operation. Notably, intriguing findings from experimental studies utilizing ambient vibration were highlighted in the paper [13]. In this context, determining the stiffness of the machine elements played a crucial role in evaluating the effects of recorded vibrations [14]. Conversely, paper [15] explored the impact of road surface roughness when heavy vehicles pass by, revealing that the characteristics of the road surface influence the propagation of vibration waves. This all mention above, well integrates and associated with micro-mobility vehicles dynamics. However, analysing of e-scooter components in real-time operations presents a challenge due to the widespread use of batch processing techniques. To enable real-time vibration analysis for its elements, a temporal approach must be integrated with the frequency technique using a method known as time-frequency representation [16]. The advantage of frequency-based methods is that they typically do not require parameter tuning, such as adaptive gains [17]. However, these methods inherently rely on batch processing, which necessitates vibration level measurements. They are widely employed for detecting and quantifying faults using vibration-based data [18]. Frequency domain characteristics, including frequencies, damping ratios, energy in different frequency ranges, and time-frequency domain characteristics like time-frequency spread [19], serve as key features for conducting structural health monitoring [20]. Notable techniques include linear non-parametric methods like the short-time Fourier transform, wavelet transform, or Wigner-Ville distribution [19,20]. Applying these methods involves a trade-off between vibration time and frequency response resolutions [21], yet they remain among the most effective methodologies for detecting and quantifying faults using vibration-based data.

Despite the growing scientific literature on micro-mobility safety, a significant research gap exists regarding the technical reliability of critical e-scooter components under real-world dynamic conditions. Current researches is predominantly focused on clinical injury patterns or rider behaviour, leaving a void in the understanding of vibration-induced mechanical failure modes. In particular, the influence of tire damping characteristics, specifically when switching from pneumatic to airless tires, on the structural integrity of safety-critical folding mechanisms remains unexplored. There is a lack of empirical data linking pavement-induced vibrations to the unintended operation of handlebar safety locks, which represents a critical yet under-researched safety risk in personal micro-mobility devices.

For current research-investigation its worth firstly create detail plan and methodology for each research steps (including describing of main research objects); provide preliminary pre-experiments measuring regarding e-scooter components frequency analysis and vibration transferring; provide an experimental measuring on real road conditions; finalize a measurement data proceeding in line of frequency analysis; analysis and discussion. The primary objective of current proposed research is to investigate a problem what was led to risk use of electric kick-scooters connected with opening of handlebar safe locker. Research includes a real-time operational analysis of dynamic characteristics and their influence on e-scooter element`s, based on vibration analysis and frequency response analysis with evaluation and discussion. The obtained results are expected to help define critical risk associated with riding of electric kick-scooters. The findings from this research can contribute to re-evaluating and improving the development of micro-mobility vehicle elements, like tire, lockers etc., and in some point re-evaluating road infrastructure to better accommodate micro-mobility safe options effectively.

2. Research-investigation methodology

The research was fundamentally based on vibration analysis, a method focused on tracking oscillation magnitudes and identifying characteristic patterns within signals. This analytical framework generally utilizes two primary techniques: the evaluation of the signals behaviour in the time domain

(waveforms) and the inspection of its frequency-domain components, which are extracted using the Fourier Transform. Vibration analysis is a technique used to assess the condition of machinery by measuring its vibration levels and frequencies [22,23]. The process begins by employing an accelerometer to measure the vibrations generated by the operating machinery. The accelerometer produces a voltage signal that corresponds to the magnitude and frequency of the machine's vibrations. The analysis entails measuring the vibration level and conducting additional Fourier Transform spectrum analysis.

For pre-experimental part used laser-measured field (time domain) and Fast Fourier Transform (FFT) of laser-measured signal. A laser scanning system measures surface displacement at a spatial point (r):

$$u(r,t) = u_x(r,t)i + u_y(r,t)j + u_z(r,t)k \quad (1)$$

For vibration analysis, the dominant normal direction is usually considered:

$$u(t) = u_z(r,t) \quad (2)$$

Laser systems often measure displacement or velocity, in this case, time differentiation yields:

$$v(t) = \frac{du(t)}{dt} \quad (3)$$

$$a(t) = \frac{d^2u(t)}{dt^2} \quad (4)$$

These signals are then directly comparable with accelerometer-based measurements.

The laser-measured signal is sampled at frequency (f_s):

$$u[n] = u(n\Delta t),\ \ \Delta t = 1/f_s \quad (5)$$

where, $n = 0, 1, \ldots, N-1$. N is the number of scanned time samples per point.

The frequency content of the scanned vibration is obtained using FFT:

$$U[k] = \sum_{n=0}^{N-1} u[n]e^{-j2\pi kn/N} \quad (6)$$

or equivalently expressed as:

$$U[k] = \text{FFT}\{u[n]\} \quad (7)$$

where, $U[k]$ represents the complex displacement spectrum. In final, frequency response of scanned structure can be displayed by the amplitude spectrum of laser-measured vibrations:

$$|U(f_k)| = \frac{2}{N}|U[k]| \quad (8)$$

This allows identification of structural full and resonant frequencies. The use of FFT analysis is justified by the need to isolate the discrete resonance frequencies of the e-scooter's unsuspended structure, allowing for a precise comparison between the damping characteristics of pneumatic and airless tires across the critical 0–200 Hz range. This method enables the identification of harmonic energy distributions that time-domain analysis alone cannot resolve.

For experimental part vibrations are typically measured using accelerometers mounted on the scooter in form:

$$a(t) = a_x(t)i + a_y(t)j + a_z(t)k \quad (9)$$

Maximum acceleration represents the highest instantaneous absolute value recorded in the time-domain signal, used to identify singular shock impacts:

$$a_{max} = \max\ |a(t)| \quad (10)$$

Mean acceleration calculated as the arithmetic average of the rectified acceleration signal over the measurement duration:

$$\bar{a} = \frac{1}{T}\int_0^T |a(t)|dt \quad (11)$$

Root Mean Square (RMS) acceleration is the primary metric used for safety assessment, representing the average power of the vibration. It is defined as the square root of the mean of the squares of the acceleration values:

$$a_{RMS} = \sqrt{\frac{1}{T}\int_0^T a^2(t)dt} \quad (12)$$

RMS acceleration was selected as the representative metric for vibration severity because it effectively quantifies the cumulative energy transmitted to the handlebar safety lock. Unlike peak acceleration, which may capture isolated shocks, RMS provides a statistically stable measure of the sustained cyclic loading that leads to mechanical loosening and fatigue failure, aligning with international standards for both structural health and human vibration sensitivity.

In this particular research-investigation, the objective is to determine the vibration level of e-scooter elements while being driven on two different sidewalk pavements using two different types of tires. The aim is to compare and investigate the factors contributing to the handlebar's secure locking opening and brake. To ensure an effective analysis, a series of steps were devised and depicted in Fig. 2.

Preliminary pre-experiments measuring include a vibration and modal analysis of e-scooter components and experimental measuring include a real-time operational analysis on road

conditions. A measurement data proceeding performed in line of vibration level and frequency analysis. The main analysis and discussion include investigation of problem what was led to risk use of electric kick-scooters connected with brake of handlebar safe locker. Some details regarding a methodology of investigation and analysis: ***Measurement Setup***: Accelerometers are employed to measure the vibrations generated by the e-scooter during its operation; ***Data Collection***: The e-scooter is ridden on various sidewalk pavements with different tires, and data from the accelerometers is collected. This data includes vibration levels and associated frequency information; ***Fourier Transform Analysis***: To gain further insights, the collected data undergoes Fourier Transform analysis, which provides a frequency spectrum of the vibrations; ***Comparative Analysis***: The vibration levels and frequency spectra obtained from different sidewalk pavements and tires types are compared. This comparative analysis allows for the identification of variations and trends; ***Risk Interpretation***: The findings obtained from the analysis are interpreted and discussed within the context of safety and reliability; ***Conclusions/Recommendations***: Conclusions are drawn based on the research outcomes, and recommendations may be provided to avoid provided problem for another users of e-scooter and for manufactories company a point for re-thinking for improving a structure components of e-scooter associated with vibrations.

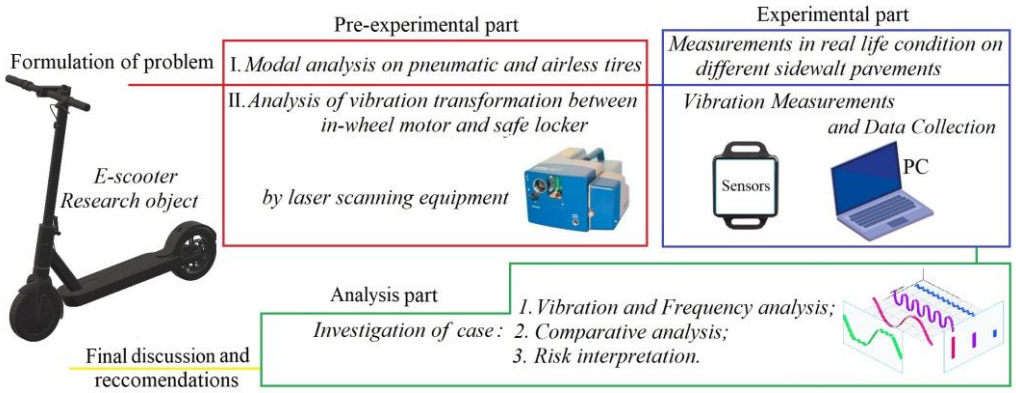


Figure 2. The view of developed methodology for research-investigation.



(a) (b)

Figure 3. Research objects: (a) Electrical kick-scooter and tires under research; (b) View of the sidewalk/cycle road pavements in research-investigation (Vilnius city, Lithuania, typical cycle road pavements).

The research incorporates an analysis of an electrical kick-scooter, which is as an author personal micro-mobility vehicle, with what was accident scenario. The e-scooter utilized for this study was a standard urban model with a total mass of 14.2 *kg* and 8.5-*inch* wheels. Primarily, the particular e-scooter being studied lacks wheel suspension but is equipped with two types of tires: pneumatic tires (PT) with a recommended inflation pressure of 3.4 bar (50 psi) and airless tires (AT). The airless tires (AT) were of a perforated honeycomb design, which is commonly used to reduce weight while providing some degree of structural flexibility. These tire variations are of interest for the purpose of comparing the vibration characteristics of

e-scooter elements (as depicted in Fig. 3a). The research secondary centres around the investigation of road irregularities. In this context, the study identifies and examines two specific types of sidewalk/cycle road pavements where measurements are conducted. By focusing on these two pavement types (Fig. 3b), the research aims to gain insights into the impact of road conditions on the vibration characteristics experienced by the e-scooter and its various components. This initial problem definition allows for a focused analysis on how road irregularities may influence the vibrations and potentially contribute to accidents or safety concerns regarding accident investigation.

It is worth noting that the specific details of the two pavement types (in the different city places), such as their surface conditions, composition, or geometries, may have a significant influence on the vibration characteristics observed and subsequently analysed in the research. It is important to note that the provided methodology is a general outline, and specific details and variations may exist depending on another research design and instrumentation used for the study.

3. Pre-experiment part of the research-investigation

The initial phase of the pre-experiment focused on the investigation of e-scooter tires involved by hammer-based vibration tests and modal analyses to determine the structural constants, including natural frequency and damping ratio, since tires it`s an element connected e-scooter with road in interaction through all impact of pavement type transferred to whole e-scooter. The hammer-based vibration technique incorporates modal analysis, which is instrumental in identifying the vibration characteristics, such as natural frequencies and mode shapes, of mechanical structures or components, more detail can be found in [24]. The research incorporates a test bench and measurement setups (Fig. 4 – left side). The laser scanning system utilized in the pre-experimental modal analysis featured a velocity sensitivity of 25 mm/s/V and a displacement resolution of 1 μm. This high sensitivity ensured that even low-amplitude resonant modes of the tires and frame were captured with a high signal-to-noise ratio within the 0–200 Hz frequency range. In addition, evaluating the inherent vibration level produced by the in-wheel e-motor of the e-scooter investigated. The objective was to gain an understanding of the vibrations originating from the e-scooter itself and their impact on various components. The data collected during this phase was later combined with information about road pavements for the final analysis. In order 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 utilized, more detail about this technique can be found in [24]. The research incorporates a modification of previously presented test bench and measurement setups (Fig. 4 – right side). These parameters, such as frequency response and vibration level, are crucial in designing structures capable of withstanding dynamic loading circumstances. To minimize the influence of external structural noise, the tires and e-scooter was mounted on a laboratory test bench using specialized low-frequency vibration isolation rubber pads. This setup served to decouple the objects from the mounting surface, ensuring that the measured vibration response was not affected by the susceptibility or resonance frequencies of the test table itself. By isolating the system in this manner, the modal analysis accurately reflected the damping properties of the tires and the structural integrity of the in-wheel motor holder and handlebar safety lock without interference from the laboratory environment. The e-scooter speed during a test was set a 20 km/h regarding specifies EN 15194 standard of requirements and test methods for electric-engine power micro-mobility vehicles [25] and ordinance on the use of personal light electric vehicles [26]. To perform the vibration study, the captured data is processed using Fast Fourier Transform (FFT) algorithms via high-precision instrumentation. This conversion enables a detailed evaluation of frequency response functions and modal characteristics, yielding essential data regarding the e-scooter's structural dynamics.

Pre-experimental tests utilize a t-sample measurement design and rely on a one-sample statistical method to assess the uncertainty in the repeated measurement of data processing [27,28]. Descriptions of the test bench and measurement setups are provided for each individual test conducted with a result from both part of pre-experimental research showing at Fig. 5 and Fig. 6. The frequency analysis results shown in logarithm form for better displaying different in t-sample measurements.

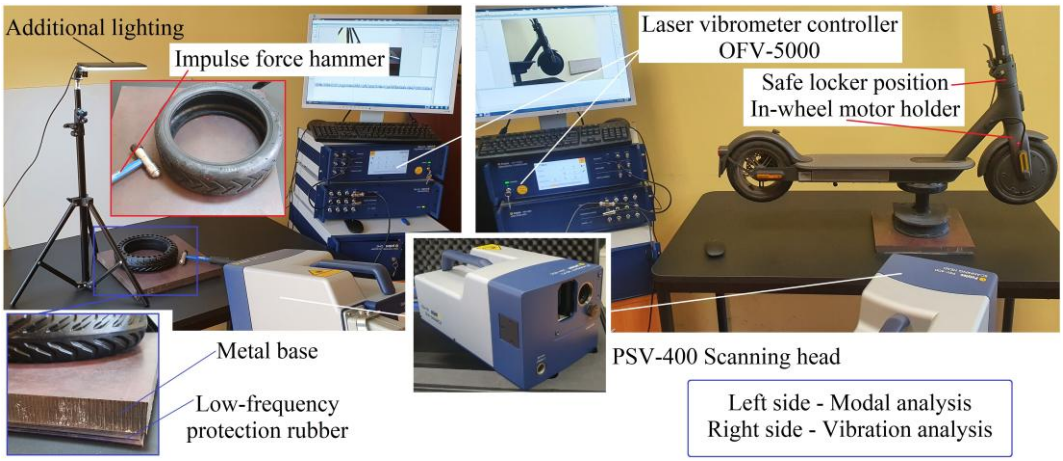
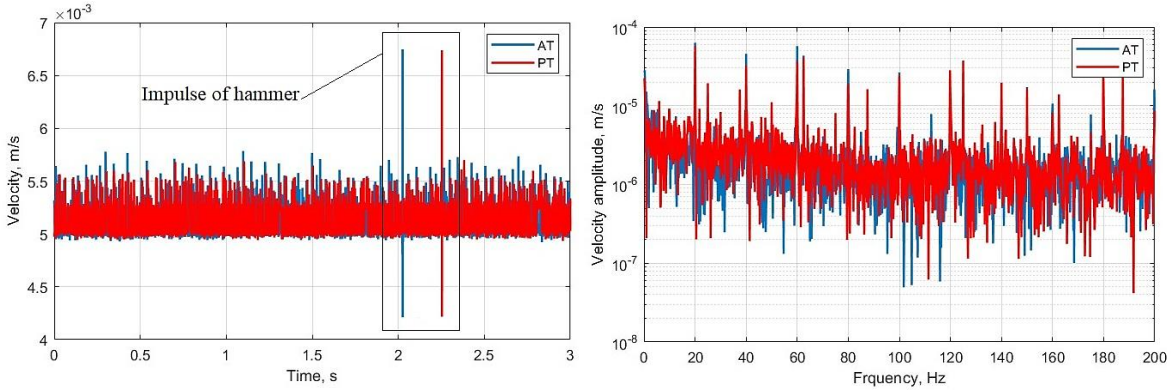
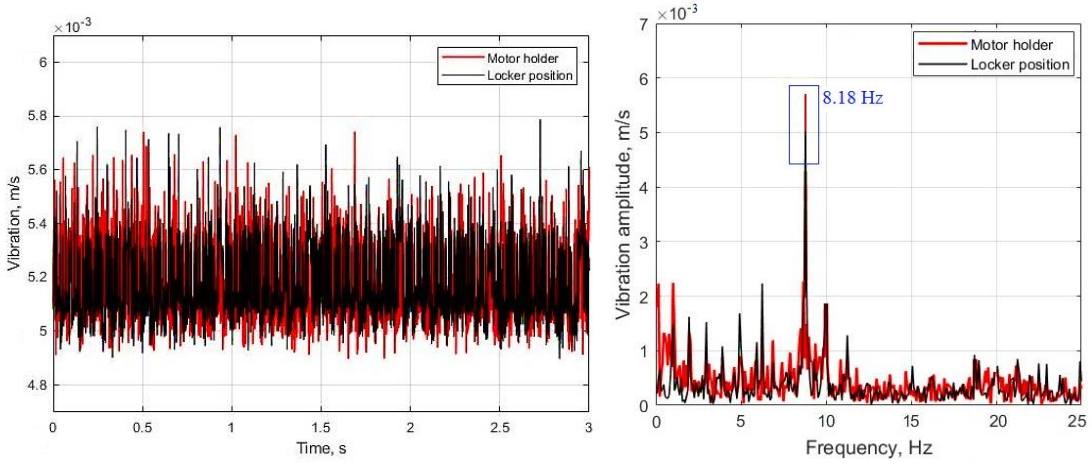


Figure 4. Test benches and setups for measuring's: Left side – tires modal analysis; Right side – vibration transformation analysis.



(a) (b)

Figure 5. Results from tires modal analysis (AT – airless tire; PT – pneumatic tire): (a) Tires vibration velocity by laser scanning; (b) Frequency response of tires under modal analysis.



(a) (b)

Figure 6. Results from e-scooter vibration transformation analysis: (a) Velocity vibration at e-scooter elements; (b) Frequency response at vibration transformation analysis.

The impulse value of hammer for both tires its similar, the different not more than 2% (Fig. 5a), more or less the different in the time of action not influence on frequency transformation in modal analysis. Moreover, the primary focus of the conducted model analysis lies within the frequency range of up to 200 Hz, as illustrated in Fig. 5b. This specific frequency range captures the essential resonant modes under investigation. Furthermore, the frequency analysis reveals that the main resonance

frequency for both tires is found at 20 Hz, and interestingly, the first resonance frequency also occurs at the same value of 20 Hz. Moreover, harmonics are observed at regular intervals, precisely at every 20 Hz (20/40…etc. Hz). This outcome is quite logical, given that both tires are rubber-based objects. The consistent harmonic pattern further supports the resonant behaviour of the rubber material.

The maximum vibration level produced by the in-wheel motor for the e-scooter at a speed of 20 km/h was recorded at the motor-wheel holder and measured to be approximately 5.78×10^{-3} m/s, and at the locker position, the maximum vibration was approximately 5.61×10^{-3} m/s (refer to Fig. 6a). Upon analysing the measurements, it appears that, for most of the registered vibration range, the difference between the two measurement positions is not significant. By studying the frequency response, it is evident that all vibrations from the motor-wheel holder are directly transmitted to the handlebar safety locker position with a slight dampening effect of up to 9% during observed frequency points (Fig. 6b). The analysis revealed a resonance frequency of 8.18 Hz during operation at 20 km/h (491 rpm). This finding confirms that the recorded vibrations are transmitted accurately and are dependent solely upon the mechanical conditions of the hub-motor system.

4. Experiment part of the research-investigation

The experimental part of the research-investigation included measurements of vibrations transmitted to the locker position during e-scooter riding with different tire types. The experiments were conducted on city streets in Vilnius, Lithuania, specifically on cycle sidewalk pavements (shown in Fig. 3b). The asphalt surface utilized for testing was a standard fine-graded wearing course in good condition, presenting a relatively smooth profile with minimal stochastic irregularities. Brick pavement consisted of standard rectangular pavers measuring 200 mm in length and 100 mm in width. The joints between bricks had an average width of 5 mm and were partially filled with sand. The pavement exhibited moderate age-related wear, including localized settlement and vertical unevenness (lippage) of up to 2–4 mm between adjacent bricks. Each test began with the rider gently accelerating until the maximum e-scooter speed was reached, which corresponds to the maximum permitted speed for electric micro-mobility vehicles in Lithuania (25 km/h). After reaching this speed, the rider continued riding in cruise mode. The e-scooter used in the study, along with the measurement setup, is shown in Fig. 3a, while the sensor installation and tested e-scooter is presented in Fig. 7. The rigidity of the sensor mounting was a primary consideration to ensure data fidelity. Each accelerometer was attached to the e-scooter frame using specialized magnetic mounts characterized by high pull-force to maintain structural coupling, it`s a standard acceleration mounting. To prevent any relative movement or resonance of the sensor body during high-amplitude excitation on uneven surfaces, the mounting was further secured with secondary mechanical restraints (industrial-grade tensioning straps). This redundant fixation method ensured that the measuring tracks captured the true structural response of the vehicle, eliminating the risk of signal distortion caused by sensor displacement against the frame. The handgrip position on the cylindrical handlebar was set in accordance with ISO 5349-1 [29]. All tests were performed using identical foot positions, which were marked with tape on the e-scooter platform. The experiments were conducted in compliance with ISO 2631-1:1997 [30]. To ensure consistency across measurements, the test rider had a mass of ~80 kg. This mass remained constant across all trials to minimize variations in the damping effect provided by the rider's body.

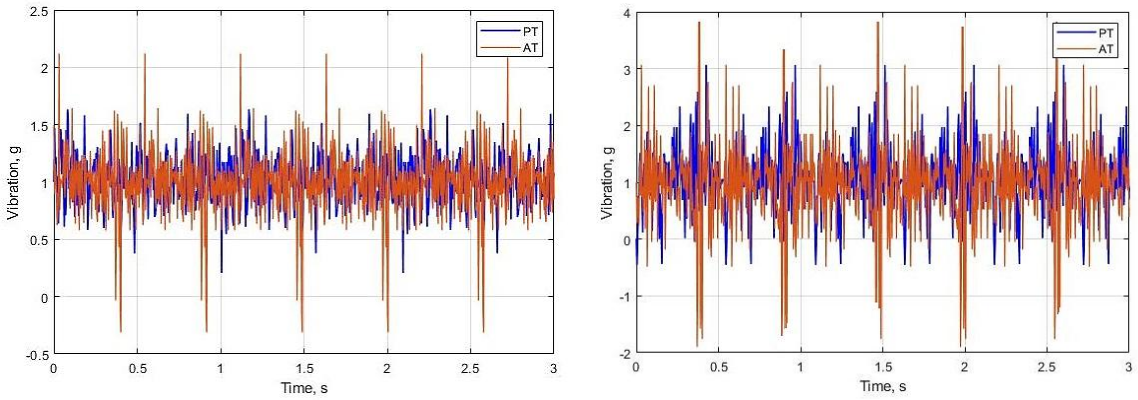


Figure 7. Experimental part of the research-investigation – electric kick-scooter for measuring test.

Several measurements were performed for each pavement type with each tire type. A one-sample statistical method was used to assess the uncertainty associated with repeated measurements during data processing. A total of 5th repeated runs was performed for each experimental scenario (2 pavement types × 2 tire types), with the average RMS values calculated to account for minor fluctuations in surface interaction. The

vibrations at the handlebar safety lock were measured using tri-axial piezoelectric accelerometers. These sensors had a nominal sensitivity of 100 *mV/g* and a linear frequency response up to 5000 *Hz*. The measurement tracks were calibrated prior to the experiments to ensure a measurement uncertainty of less than 1.5%. All tests were conducted at a constant velocity of 25 km/h ±0.25 km/h, monitored via sensors high-frequency GPS and the vehicle internal telemetry to ensure a velocity deviation of less than 3%. The same 500th *m* stretches of asphalt and brick pavements were used for all trials, with the rider following a pre-marked trajectory to encounter the same surface irregularities. Furthermore, the statistical consistency of the forcing was verified by calculating the standard deviation across five repeated trials; the resulting coefficients of variation were below 5%, indicating that the differences in vibration response are attributable to the mechanical properties of the tires rather than variations in the road input.

The results of the vibration measurements recorded in the mid-frequency range near the locker position are presented in Fig. 8. While the initial time-domain waveforms provide a snapshot of the raw data acquisition, they are insufficient for a complete characterization of the vibration environment. Therefore, each experimental trial consisted of a 60-second continuous recording to ensure statistical convergence of the data.



(a) (b)

Figure 8. Vibration near handlebar safety locker riding on: (a) Asphalt cycle road pavement; (b) Bricks cycle road pavement.

When observing the measured vibration results (Fig. 8), it should be noted that the sensors were recorded with a standard calibration for vertical vibration at *g* (*g* = 1 – zero-base overview point). The 3-second time waveform shown in Fig. 8 was intended only as a visual representative sample to illustrate the raw signal characteristics and the data acquisition interface. The maximum level of vibration generated by the e-scooter while riding with a different tire type on the different types of surfaces during the test at a speed of 25 km/h was on the brick's pavement with AT tire types (at this condition was accidents before). At the same time, it is worth noting that the registered vibration level between the in-wheel holder and the locker position sensors did not exceed approximately 10% (see the pre-experimental part). This confirms that the vibrations experienced by the locker are predominantly influenced by the tire with pavement contact dynamics and that all measured vibrations were correctly detected. The measurements showed maximum vibration levels of approximately 1.62*g* for PT (mean value 1.28*g*) and 2.23*g* for AT (mean value 1.63*g*) when riding on asphalt pavement. On brick pavement, the maximum vibration levels increased to 3.1*g* for PT (mean value 2.29*g*) and 3.89*g* for AT (mean value 2.87*g*). The analysis indicates significant differences in the vibration levels transmitted to the locker when riding with different tire types on different pavement surfaces. Vibrations induced by e-scooter motion on brick pavements have a pronounced impact on e-scooter components, particularly when using the AT tire type.

5. Analysis part of the research-investigation

From Pre-experimental part is consequently that the choice of tire could have implications on the vibration isolation. Simultaneously, it is important to note that all vibrations transmitted to the handlebar safety locker position are entirely dependent on the interactions between the tires and the road pavement. The impact of vibration from in-wheel motor holder

(tire location) on the handlebar safe locker's vibration is critical, with a maximum reduction of vibration transmission only up to 9% in the middle range. This indicates that the handlebar safety locker's vibration is significantly affected by variations in tire properties or damping characteristics. As a result, the handlebar safety lock position remains relatively not stable and all time under almost maximum vibration obtained by e-scooter with an affect by the small changes in tire behaviour. Overall, the preliminary pre-experiments involving frequency analysis and vibration disperse analysis on the e-scooter components play a crucial role in establishing a solid foundation for accurate expertise on the e-scooter's dynamics. Furthermore, both tires exhibit nearly identical damping properties with a negligible difference of less than 5% at a frequency of 20 Hz. However, noteworthy distinctions arise at certain resonance points where PT demonstrates higher damping properties compared to AT. Specifically, at 40 and 60 Hz, the damping difference reaches ~15%. This observation lead made conclusion that when used, AT might transfer more vibrations from road pavements to the e-scooter, as it exhibits less damping capacity in comparison to PT.

From Experimental part is consequently that the vibration levels transmitted to the handlebar safety lock are strongly dependent on both the tire type and the pavement surface. The experimental results clearly demonstrate that riding conditions combining brick pavement and airless tires generate the highest vibration amplitudes at the handlebar safety lock location, which corresponds directly to the accident scenario described in the introduction. The measured vibration amplitudes indicate that, in comparison with pneumatic tires, airless tires transmit significantly higher vibration levels to the e-scooter structure, particularly when riding on irregular pavement surfaces. This behaviour can be explained by the lower vibration damping capability of airless tires, as identified in the pre-experimental modal analysis. While both tire types exhibit similar resonance frequencies, the reduced damping of airless tires results in higher vibration energy being transferred from the tire-pavement contact interface to the e-scooter components.

Furthermore, the experimental results confirm that vibrations originating at the wheel-motor holder are transmitted to the handlebar safety lock with only minor attenuation. The vibration reduction between the two measurement locations does not exceed approximately 10%, indicating that the handlebar safety lock is exposed to nearly the full vibration loading generated during riding. As a result, the handlebar safety lock operates under continuous dynamic excitation, especially when riding at the maximum permitted speed of 25 km/h on brick pavement. The combination of elevated vibration amplitudes and sustained exposure to cyclic loading creates unfavourable operating conditions for the handlebar safety lock mechanism. Repeated dynamic excitation in the measured frequency range may promote loosening, wear, or fatigue damage of the locking components, ultimately increasing the risk of unintended unlocking during riding. This risk is significantly amplified when airless tires are used, due to their increased vibration transmission characteristics. In addition, the results suggest that pavement irregularities play a dominant role in the generation of harmful vibration levels. Brick pavements, characterized by discontinuities and surface roughness, induce higher vibration responses compared to asphalt surfaces, regardless of tire type. However, the effect becomes critical when combined with airless tires, highlighting the importance of considering tire-pavement interaction in e-scooter safety assessments.

Overall, the experimental findings confirm that the observed failure of the handlebar safety lock is not a random event but rather a consequence of unfavourable dynamic conditions arising from the interaction between tire type, pavement surface, and e-scooter structural design. These results emphasize the necessity of incorporating vibration-based safety considerations into the design of e-scooter components, particularly for unsuspended vehicles operating on urban pavements. The experimental results indicate that when the RMS vibration level at the handlebar safety lock exceeds approximately 2.5g, the system enters a critical operating regime where cyclic excitation may accelerate fatigue-related loosening of the locking mechanism. The combination of airless tires and brick pavement consistently produces vibration amplitudes within this critical range, explaining the observed unintended unlocking event.

From another perspective of risk interpretation, it is also important to recognize that humans are highly sensitive to vibration, especially to those induced by vehicles [31–33]. Human exposure to whole-body vibration can lead not only to

discomfort and reduced control performance but also to longer-term health effects when exposure is sustained or repetitive. According to studies on vehicle-induced vibrations, the frequency content and magnitude of vibrations experienced at the hands and torso have a direct influence on perceived discomfort and physical strain. Based on the vibration data obtained in this research, the level of rider discomfort can also be assessed. The measured vibration amplitudes content fall within ranges known to contribute to increased discomfort and potential adverse effects, particularly in the case of brick pavement and airless tire combinations. Previous analyses of electric kick-scooter vibrations have shown that higher vibration levels in specific frequency bands, those to which the human body and upper limbs are most sensitive, are associated with elevated discomfort and reduced ride quality, which can impair rider stability and increase accident risk [11,12,34,35]. When evaluated against established human vibration sensitivity criteria, the experimental results indicate that the combination of high amplitude and sustained vibration exposure is likely to produce a higher subjective discomfort level for riders. This is especially true for vertical and near-vertical components of vibration transmitted through the handlebars, as these directly affect the hands and arms a region of the body particularly sensitive to vibration. Therefore, the observed vibration characteristics not only elevate mechanical risks to scooter components but also significantly influence rider comfort and control, further emphasizing the safety implications of tire with pavement interaction.

6. Final discussion and recommendations

An important outcome of this research-investigation is the confirmation that vibrations originating at the wheel-motor holder are transmitted to the handlebar safety lock with minimal attenuation. The measured reduction in vibration amplitude does not exceed approximately 10%, indicating that the handlebar safety lock is subjected to nearly the same dynamic loading as the wheel assembly itself. Consequently, the handlebar safety lock operates under continuous cyclic excitation during riding, especially at the maximum permitted speed of 25 km/h. Such operating conditions can accelerate wear, promote loosening of mechanical interfaces, and increase the likelihood of fatigue-related failures, ultimately leading to unintended unlocking of the handlebar during use. From a broader safety perspective, the implications of elevated vibration levels extend beyond mechanical reliability. Humans are particularly sensitive to vibration, especially those transmitted through vehicle handlebars to the hands and arms. The measured vibration amplitudes and frequency content observed in this study fall within ranges known to increase rider discomfort and reduce perceived ride stability. Increased discomfort and hand-arm vibration exposure may impair rider control, reaction time, and steering precision, thereby elevating the risk of accidents. This dual impact, simultaneous degradation of component reliability and rider comfort, highlights vibration as a critical safety factor in e-scooter operation.

The findings of research have several important implications for e-scooter design, maintenance, and infrastructure planning. From a design standpoint, manufacturers should carefully consider the vibration transmission characteristics of tire types, particularly for unsuspended e-scooters. While airless tires offer advantages such as puncture resistance and reduced maintenance, their increased vibration transmission may pose a safety risk when used on irregular pavements. Enhanced damping solutions, improved handlebar safety lock designs with higher vibration resistance, or the integration of suspension elements could significantly reduce this risk.

From a usage and maintenance perspective, riders and service providers should be aware that changing tire types can substantially alter the dynamic behaviour of an e-scooter. The use of airless tires on brick or similarly irregular pavements should be approached with caution, especially for scooters lacking suspension systems. Regular inspection of safety-critical components, such as handlebar locking mechanisms, is recommended to identify early signs of wear or loosening caused by vibration exposure.

Finally, from an infrastructure and policy perspective, the results underline the importance of pavement quality for micro-mobility safety. Brick pavements, while common in urban environments, may not be suitable for safe e-scooter operation, particularly at higher speeds. Urban planners and policymakers should consider smoother pavement solutions for cycle paths and shared micro-mobility routes, or alternatively implement speed limitations and warning signage in areas with high surface

roughness.

7. Conclusions

The investigation into the safety and reliability of personal electric kick-scooters under dynamic urban conditions reveals that the structural integrity of safety-critical components is directly compromised by vibration-induced energy. By synthesizing the results from the pre-experimental modal analysis and real-world field testing, this study identifies a critical failure threshold at a vibration level of 2.5g RMS. Beyond this specific limit, the mechanical handlebar safety lock of the folding handlebar mechanism becomes susceptible to unintended disengagement, presenting a severe stability risk to the rider. The comparative analysis confirms that the interaction between tire material and pavement topology is the primary determinant of this risk. Specifically, airless tires exhibit significantly lower damping capabilities compared to pneumatic tires, particularly at the identified 20 Hz resonance frequency. On brick pavements, this lack of damping leads to a substantial increase in vibration energy, approximately 40% higher than pneumatic alternatives, often pushing the system into the 2.5g – 3.0g RMS danger zone. In contrast, pneumatic tires-maintained vibration levels below 2.0g RMS on asphalt surfaces, demonstrating their superior ability to isolate the vehicle frame from high-frequency excitation. These findings suggest that the widespread aftermarket transition to airless tires for maintenance-free riding introduces a latent mechanical safety hazard when operated on uneven urban surfaces. Therefore, it is recommended that manufacturers implement secondary mechanical redundancies for folding locks and that urban safety standards account for the damping characteristics of micro-mobility wheel assemblies to prevent vibration-induced structural failures.

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