

Measurement and Analysis of the Effect of Various Road Surfaces on the Vibration Riding Comfort of Electric Scooters

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Abstract

There are growing concerns about the safety and health implications of electric scooters, where the quality of road surfaces and speed are factors to be considered. The purpose of this study is to contribute to this research field by analyzing the effect of pavement types on vibration at various speeds.

This study was conducted in Győr, Hungary, where four types of road pavement were analyzed: concrete (bicycle lane), asphalt (shared use) and two types of brick pavers (bicycle lane and pedestrian walkway). Three speed categories, 10, 15, and 20 km/h, were considered. Peak and RMS acceleration data were gathered and analyzed using boxplots, cumulative distribution functions, and various statistical tests. Finally, ride comfort was investigated based on RMS acceleration.

Results show that both peak acceleration and RMS acceleration are affected by pavement type as well as riding speed. Concrete pavement yielded the lowest acceleration values followed by red brick pavers for bicycles and asphalt pavement, while gray brick pavers for pedestrians showed the worst results. The increase in speed resulted in higher peak and RMS acceleration values; however, the volume of this change depends on the type of pavement. Changing the type of pavement and the speed will result in statistically significant differences in vertical acceleration.

The study stresses the importance of considering the types of road pavement, their intended use as well as riding speed. With an increase in speed, pavement types with low level of quality contribute to a higher increase in acceleration values.

Keywords

e-scooter, vibration, peak acceleration, RMS acceleration, road surface, riding comfort

1 Introduction and review of previous work

Electric scooters, which are lightweight, affordable, and low-cost, have gained significant popularity in many countries. The use of e-scooters on public roads is showing a fast-growing trend in many areas around the world (Ma et al., 2021b). The annual number of e-scooter injuries is increasing; in America alone a 222% increase was recorded between 2014 and 2018 (Basky, 2020). What is even more alarming is that almost one-third of the injured had a head injury, more than double the rate experienced by cyclists. The need to investigate the impact of electric scooters on the health and comfort of riders has received increasing attention lately (Payne et al., 2025; Wen et al., 2025).

The comfort of e-scooter riding is influenced by several factors, including the design and engineering of the scooters themselves. Research of Cano-Moreno et al. (2023, 2024) indicates that many early e-scooter models lacked adequate

damping systems, leading to high levels of vibrations that can affect rider comfort and health. Vibrations experienced during rides can lead to discomfort, potentially discouraging use and impacting the overall user experience (Ma et al., 2023). Studies have established specific velocity limits for comfort and health, suggesting that e-scooters should be designed with these parameters in mind to enhance user satisfaction (Cano-Moreno et al., 2023). Kubik (2022) analyzed the vibrations of scooters on asphalt, stone pavement, and mixed surfaces. The highest vibration level was found on stone pavements, with a value of acceleration RMS (root mean squared) 1.22 m/s^2 at 20 km/h. The speed of the scooter played an important role in influencing vibrations. The study concluded that riding a scooter on stone pavement has a greater and more harmful effect on humans than riding on asphalt roads. An increase in vehicle speed may lead to

an increase in vibration acceleration, making stone pavement more harmful to human health. Cano-Moreno et al. (2022) found that electric scooters require vibrations between 0.5 Hz and 80 Hz to achieve comfort. A study by Cafiso et al. (2022) explores the use of smartphone sensors to monitor pavement conditions, revealing strong relationships between root mean square and pavement distress on bikes and e-scooters. Cano-Moreno et al. (2023) in their study focused on whole-body vibrations and hand-arm vibrations as they explored the effects of e-scooter vibrations on driver health. In the study by Chun et al. (2016), also by examining its structure and vibration, the research evaluated the safety of an electric scooter frame. The best vibration durability was found in a frame with a thickness of 4 mm, according to the results. The research by Oh et al. (2022) proposed a method to reduce the initial driving vibration of an electric scooter using low-resolution position sensors. In addition, Zehr et al. (2019) studied the relationship between pavement quality and electric scooters using a three-axis accelerometer. They tested four different roads, including concrete, asphalt, paving stones, and permeable pavement. The results showed that compressed air tires provided a smoother ride experience, while permeable pavement was better for comfort and smoothness. The study of Platt and Rybarczyk (2021) showed that the users appreciated the presence of smooth and soft road sections, evenly spaced road sections, and light hills to gain speed. However, cracks and potholes hindered riding comfort. In the study by Garman et al. (2020) a test was conducted to determine braking distances for electric scooters in various urban environments. The study involved evaluating acceleration, speeds, and stopping distances on surfaces such as asphalt, concrete, and dirt. In the study conducted by Ma et al. (2021a) the municipal guidelines for the use of electric scooters in 156 US cities were studied, revealing unclear guidelines and challenges in understanding and analyzing the data. The study classified cities into four categories according to their policies. Understanding riding surfaces and conditions is crucial, as scooters can be dangerous on uneven sidewalks and bicycle lanes. Vibration data from two tracks showed light vibrations on good surfaces and strong vibrations on cracked ones, affecting the application of municipal instructions. Examining variables such as vibration, speed, and acceleration on concrete or asphalt lanes is essential to establish safety foundations for passengers. The study also highlights that the infrastructure for cars does not provide comfortable riding conditions and scooters are often considered strangers in urban environments. Cano-Moreno et al. (2021) highlighted the importance of studying the impact of electric

scooter vibrations on user health. The experiment was carried out on a specific electric scooter and the comfort index was examined. The results showed that the higher the speed, the better the road condition should be to reduce vibration production, and the more solid the wheels, the lower the comfort index. Ma et al. (2021b) studied the safety risks of electric scooters in various environments, focusing on their light weight and environmental friendliness. The rapid spread of these vehicles raises concerns about their safety. To address this, a sensor system was developed to measure speed, acceleration, and vibration data during scooter trips. The vibration threshold was determined and the speeds were calculated on the basis of the rotational speed of the electric scooter. The experiment was carried out on pedestrian sidewalks and roads, revealing that scooter riders experience stronger vibrations on concrete surfaces than on asphalt. Cracks and potholes also affect riding quality and safety. In a similar context, Boglietti et al. (2022) compared bicycles and electric scooters based on their unique characteristics, evaluating vibrations that affect users' health and comfort. The study involved six people with different track characteristics and speeds. Uneven roads and sidewalks caused the highest vibrations, while the average vibration of the e-scooter was higher than that of the e-bike. Previous studies have focused on e-scooters' legislation, injuries, accidents and rider comfort. While e-scooters present a convenient and potentially environmentally friendly transportation option, their impact on health and comfort is complex. In reviewing the literature on the topic discussed above, the authors found a limited number of research that measures and analyzes the riding comfort of electric scooters in terms of acceleration and vibration levels. Furthermore, there is a scarcity of articles that focus on acceleration and vibration levels in relation to road conditions, which is crucial to understanding the vibrations generated and transmitted to riders causing discomfort. The purpose of this study is to contribute to the field by analyzing the effects of pavement types on e-scooter users in terms of riding comfort at various preset speeds. The remainder of the paper is structured as follows. Section 2 presents the methodology including data collection and analysis. Section 3 presents the results, followed by discussion and conclusions in Section 4.

2 Materials and methods

2.1 Data collection

Data collection was carried out through field measurements in various road sections in the city of Győr,

Hungary. Data were collected under good weather conditions (partly sunny, clear vision, no wind or any weather factor that would exceptionally affect riding quality).

Fig. 1 shows the road sections with different types of pavement and infrastructure. During the experiment, peak acceleration and Root Mean Square (RMS) data were recorded. The road sections were as follows, according to Fig. 1

1. Road section 1 (blue line): a one-way bicycle lane made of concrete (Continuously Reinforced Concrete Pavement- CRCP), from $47^{\circ}41'25.8''\text{N}$ $17^{\circ}37'33.4''\text{E}$ to $47^{\circ}41'29.9''\text{N}$ $17^{\circ}37'37.9''\text{E}$
2. Road section 2 (red line): a two-way bicycle lane made of red brick pavers (Small-Element Pavement- SEP), from $47^{\circ}41'39''\text{N}$ $17^{\circ}37'46''\text{E}$ to $47^{\circ}41'33.8''\text{N}$ $17^{\circ}37'42.1''\text{E}$
3. Road section 3 (yellow line): shared road made of asphalt (Asphalt Concrete Pavement ACP),

from $47^{\circ}41'32.8''\text{N}$ $17^{\circ}37'43.0''\text{E}$ to $47^{\circ}41'30.7''\text{N}$ $17^{\circ}37'52.1''\text{E}$

4. Road section 4 (green line): a pedestrian walkway made of gray brick pavers (Small-Element Pavement- SEP), from $47^{\circ}41'30.3''\text{N}$ $17^{\circ}37'40.6''\text{E}$ to $47^{\circ}41'29.5''\text{N}$ $17^{\circ}37'52.5''\text{E}$

It should be noted that the reason why two SEP road sections were selected was because of the difference in their quality. Road section 4 was built much earlier than Road section 2 and was designed to be used by pedestrians. Road section 2, on the other hand, is a recently constructed infrastructure designed exclusively for the smooth running of bicycles. Therefore, there is a difference in quality between these two types of small-element pavements, with Road section 2 providing a much better riding comfort.

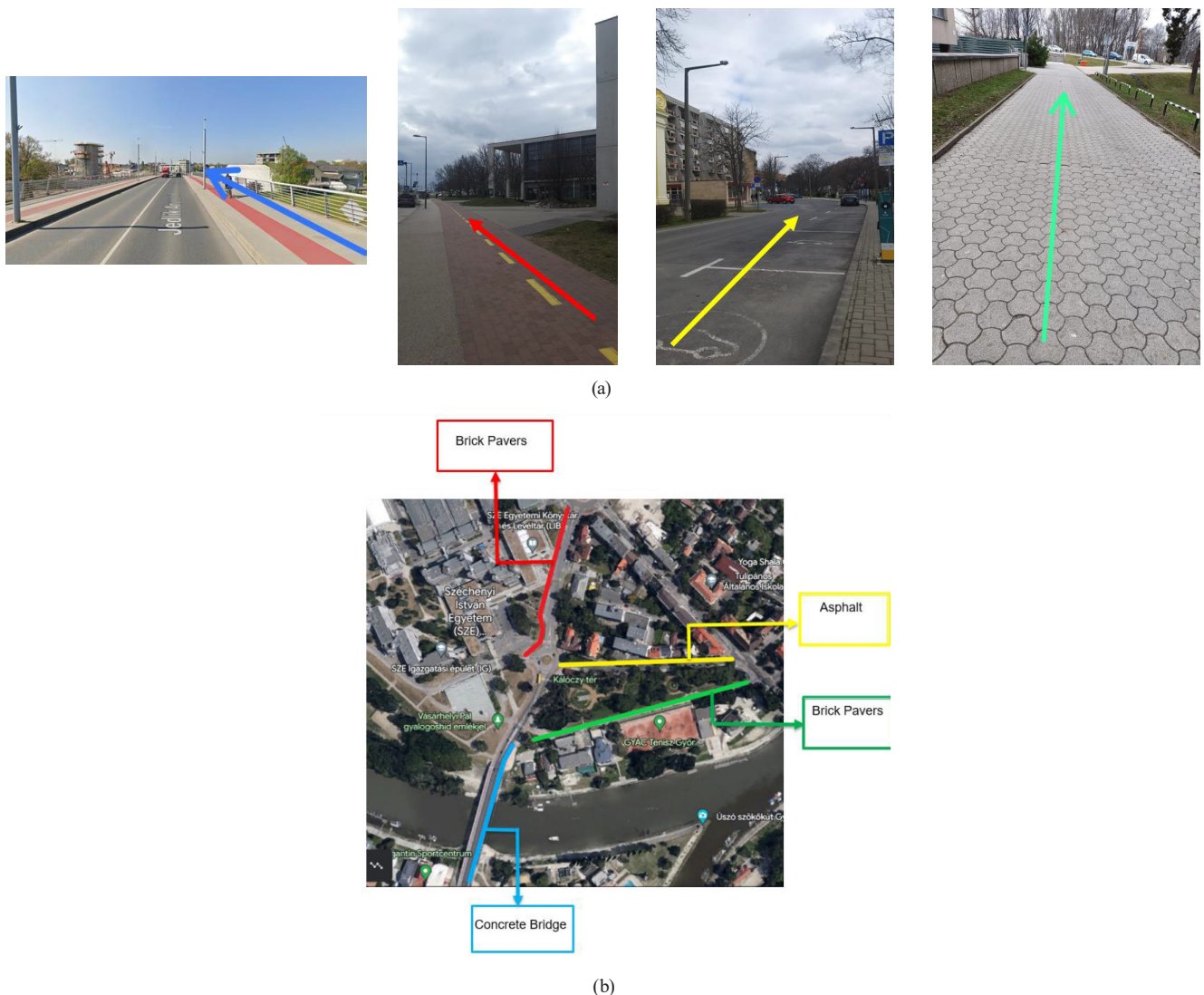


Fig. 1 Road sections selected for data collection: (a) surface views of the selected road sections; (b) aerial overview of their locations.

2.2 Design of the experiment

An E-Twow Booster S+ e-scooter was used for the experiment. This scooter can reach a speed of 30 km/h with a 500 W electric motor and has a manual rear drum brake. It supports a maximum load of 100 kg and weighs 11.1 kilograms. In addition, this scooter is equipped with front and rear suspension to absorb road shocks. Five individuals weighing between 70 and 90 kg and with a height ranging from 165 to 183 cm rode on the e-scooter.

They were randomly assigned to ride the four road sections, where the number of runs (Table 1) varies due to differences in the speeds and lengths of the road sections. The riders were instructed to ride the e-scooter at varying speeds (10 km/h, 15 km/h, and 20 km/h) and on random trajectories.

The acceleration and deceleration phases of the rides were filtered from the data to ensure that there were no variations in the preset speeds, otherwise adjustment of RMS for speed variability must have been applied (Cafiso et al., 2022).

A vibration measurement device (SAVER 3X90 field data recorder, Lansmont Corp., CA, USA) (Lansmont Corp., 2024) was mounted on the e-scooter as shown in Fig. 2.

The frequency was chosen based on the UNE-ISO-2631: 2008 criterion, which states that vibration frequency affects riding experience and smoothness. According to Nyquist's law, the sampling frequency must be twice the highest required frequency value, that is why we opted for a sampling frequency of 200 Hz. The settings of the recorder used for this study are shown below.

Table 1 Number of runs on the individual road sections

Road section/speed	(10 km/h)	(15 km/h)	(20 km/h)
Road section 1 (concrete)	5	7	9
Road section 2 (red brick)	5	7	9
Road section 3 (asphalt)	5	7	9
Road section 4 (gray brick)	4	5	6



Fig. 2 E-scooter with measurement device

1. Acceleration sensor: tri-axial piezoelectric accelerometer
2. Timer trigger: continuous signal recording
3. Sample/sec: 200 Hz
4. Anti-aliasing filter frequency: 80 Hz

2.3 Data analysis

The effect of road conditions on riding comfort levels was analyzed using the R-Studio software (R Core Team, online). The vibration data below 0.01 RMS acceleration was filtered out to remove all undesirable events, such as noise or non-vibration-related movements. Box plots with interquartile ranges (IQRs) were prepared and empirical cumulative distribution functions (CDFs) were plotted. In the boxplot, horizontal lines show the minimum, first quartile, median, third quartile, and maximum, while small circles are considered as outliers. IQR is the difference between the 75th and 25th percentiles. The CDF shows the percentage of events that are below a certain level of the measured value. As a final step, for each type of pavement, a Kolmogorov-Smirnov test was performed based on empirical distribution functions to determine if the samples come from a population with the same distribution, and the means were compared using Welch's ANOVA and pairwise t-test.

3 Results

This section first presents the peak acceleration and RMS acceleration results, followed by the analysis of the boxplots and CDFs. The CDFs are then compared using the Kolmogorov-Smirnov test. Section 3.4 addresses the comparison of means within and between road sections, and finally the fifth subsection discusses the evaluation of the riding comfort.

3.1 Peak acceleration and RMS acceleration

First the peak acceleration (Fig. 3, vertical axis range 0–60 m/s²) and the root mean square (RMS) acceleration data (Fig. 4, vertical axis range 0–15 m/s²) are analyzed for each road condition separately, at three different speeds. The acceleration values on the concrete pavement (Road section 1), the red brick pavement (Road section 2), and the asphalt pavement (Road section 3) showed slightly varying vibration levels, with the lowest values indicating the least impact on the ride experience. The results show that the speed of the e-scooter significantly impacts the acceleration experienced, with higher values at 20 km/h. Furthermore, gray brick pavement (Road section 4) has a more significant impact on acceleration, with higher values at higher speeds.

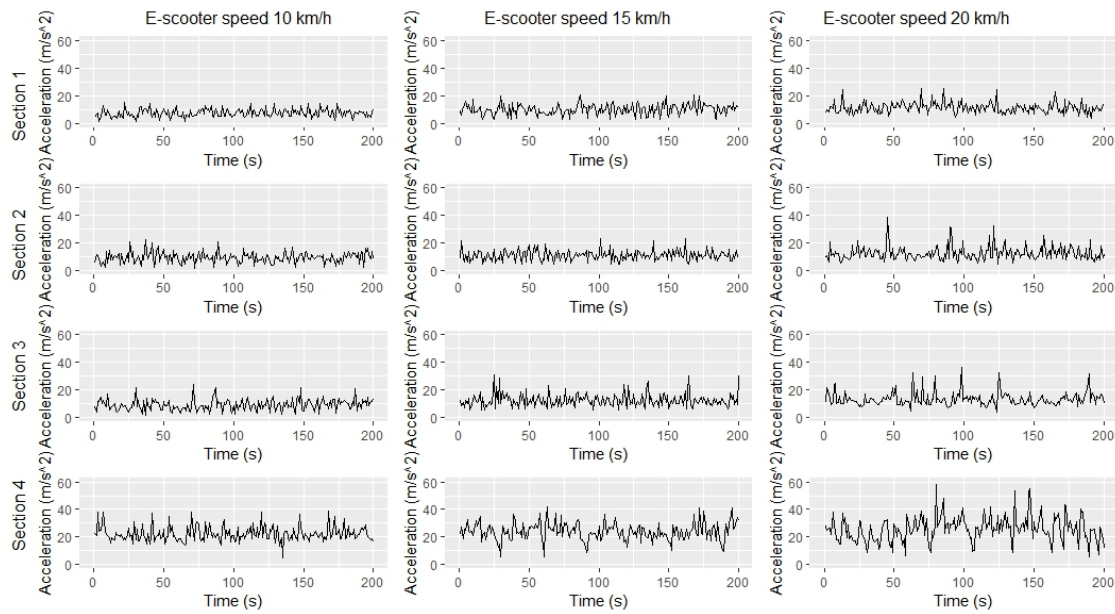


Fig. 3 Acceleration time history for the four road sections

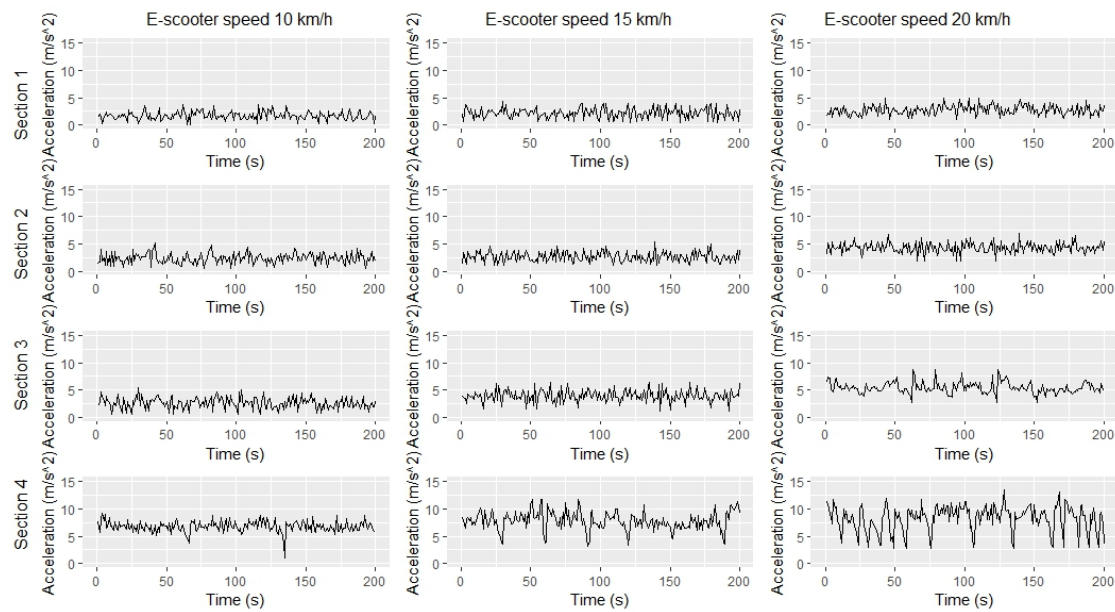


Fig. 4 RMS acceleration time history for the four sections

The type of road surface affects the acceleration experienced, with rougher surfaces resulting in higher acceleration values. In general, the acceleration values increase with speed in all road sections, suggesting that the speed of the e-scooter and the roughness of the road surface both contribute to an uncomfortable and unstable riding experience. Concrete pavement (Road section 1) had the lowest RMS acceleration values across all speeds, indicating the least vibration. The RMS acceleration values are relatively low and consistent at speeds of 10 and 15 km/h. However, at 20 km/h, the RMS acceleration values are noticeably higher, suggesting that the impact of road roughness becomes more

significant at higher speeds. Red brick pavement and asphalt pavement (Road sections 2 and 3) show higher RMS acceleration values at all speeds compared to Road section 1, indicating that riding on rough road surfaces can result in a more uncomfortable and unstable riding experience. Gray brick pavement (Road section 4) consistently produces the highest RMS acceleration values across all speeds, indicating that it is the most prone to vibration. The effect of road type and speed on RMS acceleration values is evident: Road section 4 produces the highest vibration at all speeds, Road section 1 produces the lowest, while Road sections 2 and 3 produce intermediate levels of vibration. The RMS acceleration

analysis supports these findings, Road section 1 resulting in the most comfortable and stable riding experience, followed by Road sections 2, 3, and 4. However, the differences between Road sections 1 and 2 are relatively small, and the impact of road roughness becomes more visible at higher speeds.

3.2 Boxplot analysis

Fig. 5 shows the boxplots for the peak acceleration values for the four different pavement types. Acceleration data showed a trend of increasing median acceleration values as speed increased from 10 km/h to 20 km/h. Boxplots also indicate more variability in the data at higher speeds, with a smaller range for the 10 km/h boxplot. The range of acceleration values is relatively consistent across the three speeds, with the exception of Road section 4 (gray brick pavement), where boxplots cover a wider range of values. Road section

4 also has the highest median acceleration value for all three speeds, indicating the strongest vibrations experienced by the riders. Road section 1 (concrete pavement) has the lowest median values, suggesting the least vibration and is possibly the most comfortable road section. Road sections 2 (red brick pavement) and 3 (asphalt pavement) fall between Road sections 1 and 4, with Road section 3 generally having slightly higher acceleration values compared to Road section 2, especially at speeds of 15 km/h and 20 km/h. Overall, Road section 4 produced the most vibrations, while Road section 1 produced the least.

Fig. 6 presents boxplots of the RMS acceleration values. Road section 4 has the highest median values for all speeds, suggesting higher overall vibration levels experienced by the rider. Road sections 1 and 2 have similar median values, Road section 2 has slightly higher values at all speeds; however, at 20 km/h, the median RMS acceleration is

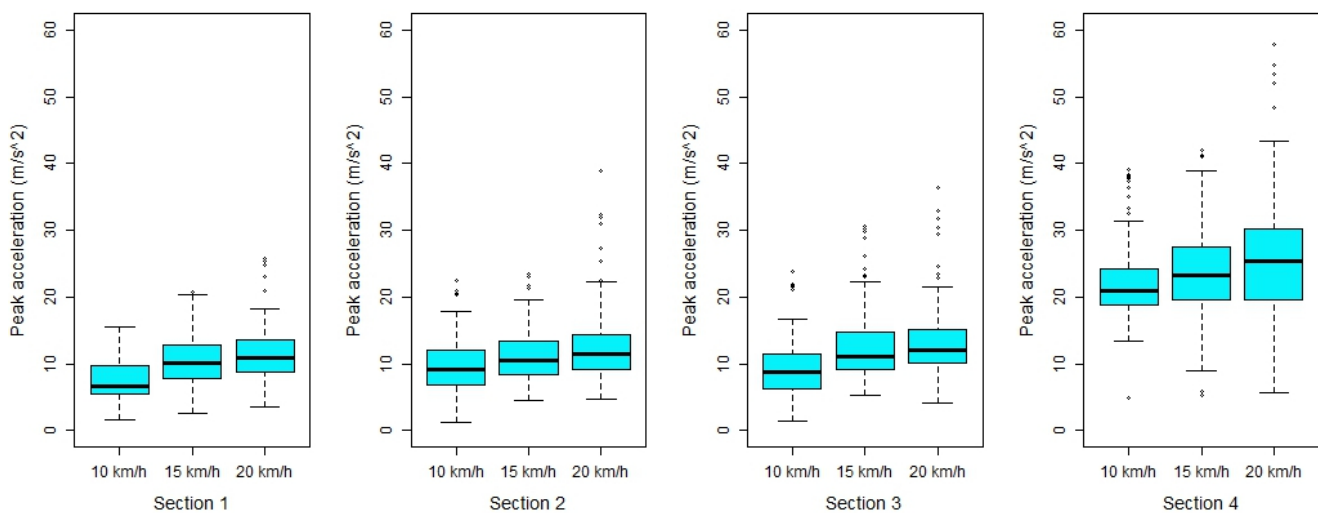


Fig. 5 Boxplots of peak acceleration values

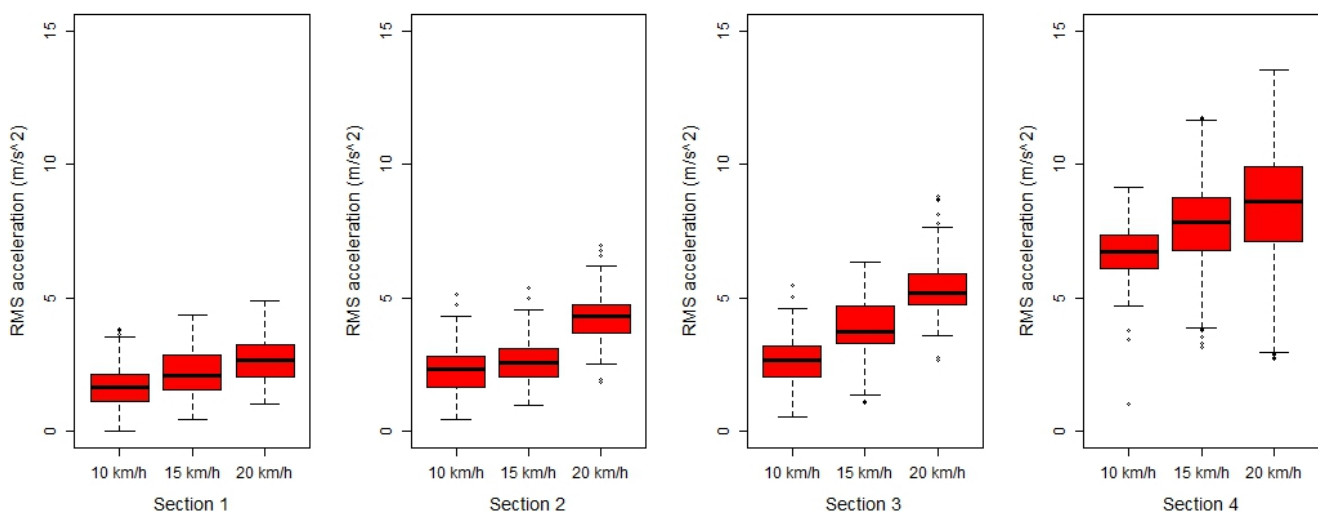


Fig. 6 Boxplots of RMS acceleration values

about twice as high as at 10 km/h. Road section 4 has the highest interquartile ranges (IQR) at all speeds, indicating higher variability in vibration levels. Road section 1 has the smallest IQR for all three speeds, as well as the smallest increase in the median across the three speed values, while the other three road sections show a more characteristic increase in the median speeds. Overall, the boxplot analysis reveals that as speed increases, the median of RMS acceleration also increases. The increase in speeds can also lead to an increasing IQR, this is most visible on low-quality pavements (Road section 4).

3.3 CDFs and Kolmogorov-Smirnov tests

The CDF plots in Figs 7 and 8 display peak acceleration and RMS acceleration values for speeds of 10 km/h, 15 km/h, and 20 km/h, respectively. The distribution

of values for all four road sections and for all the three speeds have a positive value for skewness, indicating that the tail is on the right side of the distribution, which extends towards higher acceleration levels. To determine whether distribution functions are significantly different, the nonparametric Kolmogorov–Smirnov test is used.

The maximum difference (D) between the cumulative distribution functions is compared with a critical value based on the sample size and the significance level ($p < 0.05$). If the calculated value of D is less than the critical value, the null hypothesis (that the two road sections have the same distribution) is not rejected. Otherwise, the two datasets have different underlying distributions.

The test was conducted for both within and between road sections.

Comparison within road sections: as for peak acceleration,

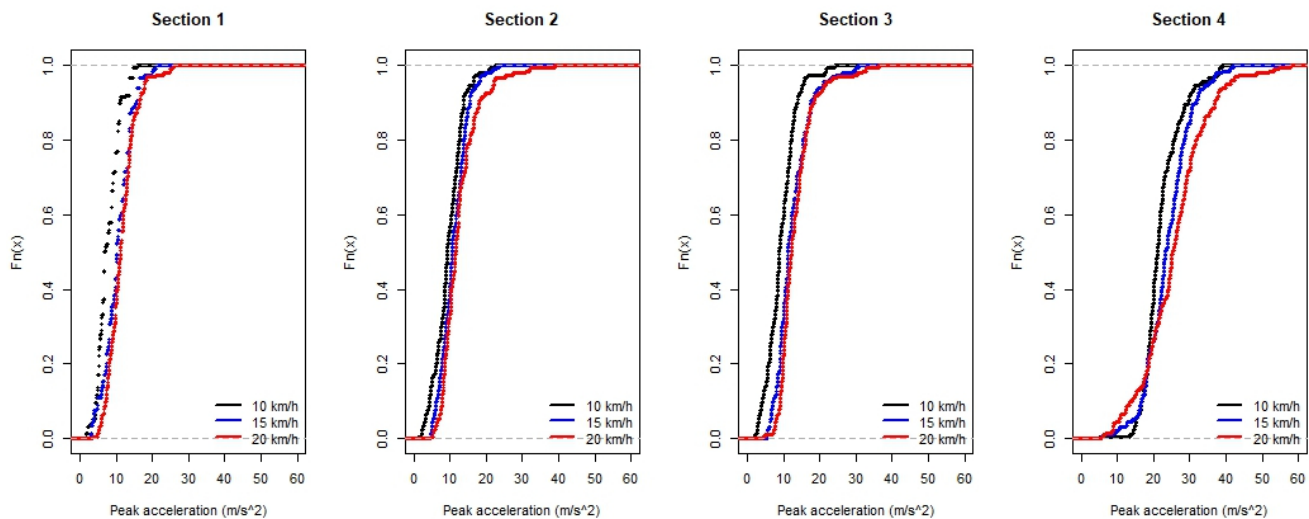


Fig. 7 Empirical cumulative distribution functions of peak acceleration

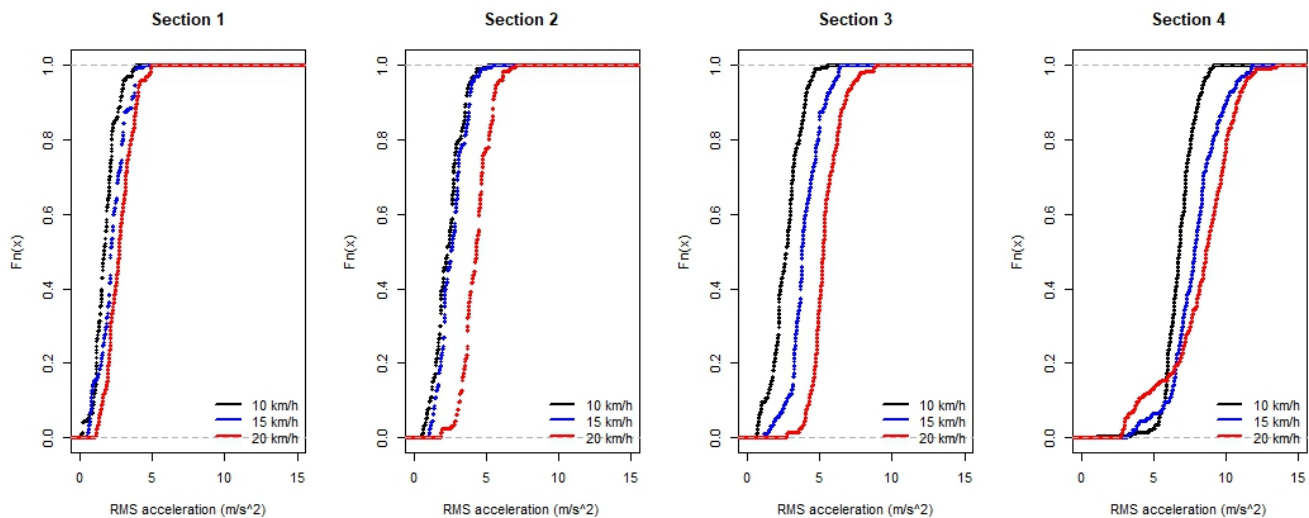


Fig. 8 Empirical cumulative distribution functions of RMS acceleration

within Road sections 1, 3, and 4, all speed categories are significantly different, within Road section 2, speed categories 15 km/h and 20 km/h are not. As for RMS acceleration all the distributions are significantly different.

Comparison between road sections: as for peak acceleration, with only three exceptions (Road sections 2 and 3 at 10 km/h; Road sections 1 and 2 at 15 km/h; Road sections 1 and 2 at 20 km/h), all the distributions are significantly different. As for RMS acceleration all the distributions are significantly different.

3.4 Comparison of means within and between road sections

To further analyze the datasets, their means are compared. To check whether there are differences between the means of peak acceleration and RMS acceleration values within and between road sections, a one-way ANOVA test can be used, the assumptions of which are that the dataset is normally distributed and shows homoscedasticity (similar variances in the groups being compared). A Shapiro-Wilk test was used to check normality, the null hypothesis of which is that the data set is normally distributed. At a confidence level of 95%, a p -value greater than 0.05 indicates that the data set is normally distributed, and a lower p -value indicates that it is not. With only two exceptions, all the data sets show non-normality (peak acceleration at 15 km/h on Road section 4 and RMS acceleration at 20 km/h on Road section 2 proved to be normally distributed).

To check for equal variances (homoscedasticity) the Bartlett's test is used. If the p -value of the test statistic is less than a certain significance level (in our case 0.05) then we can reject the null hypothesis and conclude that not all groups have the same variance. If the assumption of equal variances is violated, an alternative to the typical one-way ANOVA, the Welch's ANOVA can be used. This, however, gives an overall result proving that at least one of the means of the groups is different from the others. To see which groups are different from each other, pairwise t -tests can be performed using the Bonferroni's correction.

Comparison within road sections: As for peak acceleration, all four locations show significantly different variances by the three speed groups. As for RMS acceleration, Road sections 1 and 4 show significantly different variances, while Road sections 2 and 3 yielded non-significant results, that is, there is no significant difference between the variances of the three speed groups. The Welch's ANOVA yielded highly significant results in all cases, which means that we can reject the null hypothesis that the peak and

RMS acceleration values are equal between the three speed categories within road sections. The pairwise t -tests further prove that in all cases both peak acceleration and RMS acceleration values are significantly different for the three speed categories within the road sections.

Comparison between road sections: With the same logic as above, peak acceleration and RMS acceleration data are compared for the same speed categories between road sections. Bartlett's test yielded highly significant results, proving that datasets show different variances for all speed categories between road sections. Welch's ANOVA yielded highly significant results in all cases meaning that the data in the three speed categories are overall different over the four road sections. Pairwise comparison gave mixed results. As for peak acceleration, in most of the cases significant differences were found with the following exceptions: at 10 km/h between Road sections 2 and 3; at 15 km/h between Road sections 1 and 2; at 20 km/h between Road sections 1 and 2 as well as Road sections 2 and 3. As for RMS acceleration all the datasets are significantly different.

3.5 Evaluation of riding comfort

This part of the analysis aims to assess the comfort of e-scooters by comparing their RMS acceleration values with established comfort criteria or thresholds. Typically, the discomfort threshold for electric scooters ranges between 0.5 m/s^2 and 1.5 m/s^2 for frequencies in the 1–80 Hz range. In the study by Ma, Yang, Mayhue, et al. (2021), a 2.5 m/s^2 threshold was chosen, and vibration values exceeding this threshold were considered strong enough to cause inconvenience for users. The degree of strong vibration was calculated to evaluate the comfort or annoyance of the trip.

Similarly, in the study by Cano-Moreno et al. (2019) the comfort of electric scooter riding was assessed by measuring longitudinal and vertical acceleration values over a distance of 3 km at a speed of 25 km/h. These values were evaluated against criteria established by the ISO 2631-1 standard (ISO, 1997) to determine comfort levels. In a later study (Cano-Moreno et al., 2022) the comfort of riding two different types of scooters under various conditions was assessed, again with results evaluated according to the ISO 2631-1 standard. The aforementioned ISO standard specifies indicative vibration thresholds in six overlapping comfort bins, where from 1.25 to 2.5 m/s^2 is considered very uncomfortable and above 2.5 m/s^2 it is extremely uncomfortable. The reason why adjacent classes overlap with each other is due to various factors such as the level of acoustic noise, temperature, and age (Cafiso et al., 2022).

In our study, the 2.5 m/s^2 threshold is used in accordance with the ISO standard. The results of this analysis from Fig. 9 suggest that increasing the speed when riding an e scooter decreases the comfort of the rider. The best result is found with concrete pavement (Road section 1), where at 10, 15 and 20 km/h, 14.5%, 36.5% and 59.0% of observations are below the comfort threshold. Red brick pavement (Road section 2) and asphalt pavement (Road section 3) show worse results in this order. Finally, gray brick pavement (Road section 4) only yielded RMS acceleration values that are above the comfort threshold of 2.5 m/s^2 .

4 Discussion and conclusions

To measure the comfort of e-scooters, several factors can be considered, including the design and ergonomics of the scooter (Ma et al., 2023; Michelangelo-Gulino et al., 2022; Parnell et al., 2023), the vibrations experienced during rides (Cano-Moreno et al., 2023, 2024), and the infrastructure in which they are used (Sievert et al., 2023). Comfort encompasses not only physical sensations, but also user perceptions and safety considerations.

In our study, out of the above-mentioned aspects, our objective was to evaluate the vibrational dynamics considering four different types of pavement (concrete, asphalt and two types of small-element pavement) at three different speeds (10, 15, and 20 km/h). Peak and RMS acceleration data were analyzed using boxplots, empirical cumulative distribution functions, and various statistical tests. Finally, ride comfort was investigated using a preset threshold for RMS acceleration.

Our study concluded that both peak acceleration and RMS acceleration are affected by pavement type as well as riding speed. Concrete pavement yielded the lowest acceleration values followed by red brick and asphalt pavement, while gray brick pavement showed the worst results. The increase in speed resulted in higher peak and RMS acceleration values; however, the volume of this change depends on the type of pavement. Pavement types with a low level of quality contribute to a proportionally higher increase in acceleration values. This can be illustrated by our results for red brick versus gray brick pavements, where the purpose of the infrastructure (red pavers for bicycles, gray pavers for pedestrians) and the quality of construction showed great differences between the two.

From the boxplots, the analysis of medians and the inter-quartile ranges (IQR) shed more light on the sample characteristics. The medians of peak and RMS acceleration naturally increase with higher speeds, where the RMS acceleration shows a much more interesting pattern. In terms of concrete and asphalt pavement, there is a proportional increase in the RMS acceleration values from 1.6, 2.1, to 2.7 m/s^2 in the three speed categories on concrete pavement and from 2.7, 3.7 to 5.2 m/s^2 on asphalt pavement. The data remain within a range (minimum-maximum) of $5\text{--}6 \text{ m/s}^2$. However, small-element pavements showed more unique characteristics. The red brick pavers showed a jump in the medians between 15 and 20 km/h (from 2.6 to 4.3 m/s^2). Gray brick pavers produced much higher RMS acceleration values ($6.8, 7.8, 8.6 \text{ m/s}^2$) and, more interestingly, their range of values and their IQRs grow rapidly with increasing speed.

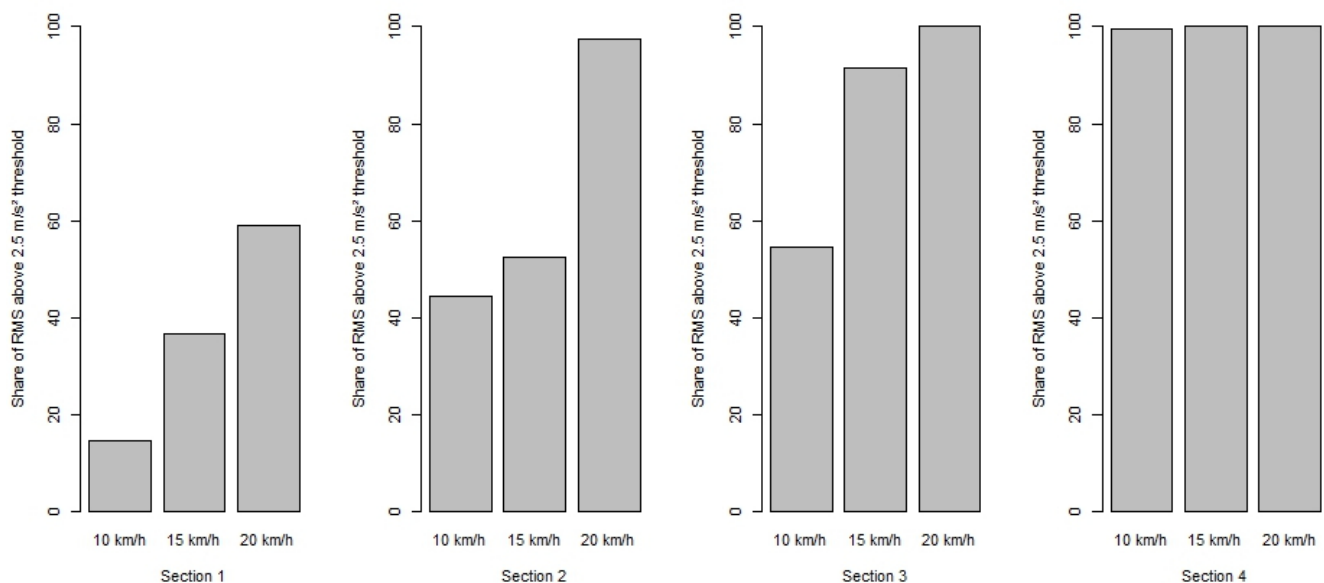


Fig. 9 Share of RMS acceleration values above 2.5 m/s^2 threshold

At 10 km/h these ranges are comparable to the rest of the road sections and speed bins, but for 15 and 20 km/h they almost double in size for every 5 km/h incremental increase in the speed.

By analyzing the CDFs with the Kolmogorov-Smirnov test, it was confirmed that with just a few exceptions for peak acceleration and no exception for RMS acceleration, samples have different distributions. This is a valid statement not only for within road sections but also for between road sections, i.e. not only the different speed categories for the same pavement, but also the different pavement types for the same speed categories are from different distributions. Using Welch's ANOVA and pairwise t-tests, the comparison of means proved that with just a few exceptions, for both the within and between road sections, means are significantly different. In general, this shows that the change in the type of pavement and the speed will result in statistically significant differences in acceleration.

Ride comfort was analyzed using the RMS acceleration with a threshold of 2.5 m/s². Concrete pavement was shown to be the most comfortable type, where the best comfort index was at 10 km/h (only 14.5 % of observations was above 2.5 m/s²). This was followed by red brick pavers, asphalt pavement, and gray brick pavers. The infrastructure in which e-scooters operate significantly affects the comfort of the rider, also according to the perception of users

(Buehler et al., 2021; Sievert et al., 2023). Our study also showed that dedicated bicycle infrastructure (concrete and red brick pavers) showed better results in terms of comfort. Similarly to the study by (Cano-Moreno et al., 2019, 2021), our study indicates that both the speed of the e-scooter and the quality of the road surface are critical factors in assessing comfort. The discomfort score increases with speed, which is consistent with previous research (Cafiso et al., 2022) indicating that higher speeds can lead to increased discomfort for e-scooter riders. A new finding of our research is that with an increase in speed, the worsening of ride comfort shows different patterns for different types of pavements.

Our research has a few limitations that can also be considered as potential future research directions. In our study, one e-scooter make/model was used for the experiment. Vibrations also depend on the design of the e-scooter (shock absorbers, frame characteristics, etc.). The composition of users (weight, height, etc.), as well as the range of speeds can be further extended.

In conclusion, this study emphasizes the importance of considering the types of road surface in the design and maintenance of transport infrastructure, especially given the increasing popularity of e-scooters. Certain pavement types are simply not suitable for riding e-scooters, while dedicated infrastructure that has good pavement quality can pose fewer health risks to e-scooter users.

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