Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 62 (2022) 743–751

Transportation Research Procedia

www.elsevier.com/locate/procedia

24th EURO Working Group on Transportation Meeting, EWGT 2021, 8-10 September 2021, Aveiro, Portugal

First experimental comparison between e-kick scooters and e-bike's vibrational dynamics

Stefania Boglietti[a], Andrea Ghirardi[a], Chiara Turri Zanoni[b], Roberto Ventura[a*], Benedetto Barabino[a], Giulio Maternini[a], David Vetturi[b]

[a] *Department of Civil, Environment, Land and Architecture Engineering and Mathematics (DICATAM), University of Brescia, Via Branze 43, Brescia 25123, Italy*

[b] *Department of Mechanical and Industrial Engineering (DIMI), University of Brescia, Via Branze 30, Brescia 25123, Italy*

Abstract

Being the most popular among electrical-powered Personal micro Mobility Vehicles (e-PMVs), e-kick scooters have recently been equated with bikes (or e-bikes) by some European regulations. However, the similarity between e-kick scooters and bikes could be somehow questionable, due to their different characteristics. While the literature has studied the dynamic behaviour of bikes and e-kick scooters separately and has made some theoretical comparisons based on analytical models, no study has compared these two vehicles using experimental data. This paper covers this gap by evaluating the vibrational response (which can affect users' comfort during a ride) of e-kick scooters and bikes at the pavement irregularities, using real data. First, kinematic data on accelerations were collected by two Inertial Measurements Units (IMUs) and then analysed adopting the basic vibration evaluation method proposed by ISO 2631-1. Then, several Z-test between the means of the vibrational magnitudes and two multiple regression analyses were performed: the first to investigate whether significative differences exist between the vibration magnitude acting e-kick scooter and e-bike, and the second to understand which factors affects this vibrational magnitude for each vehicle. A significant difference emerged between these vehicles as the mean of the vibration magnitudes measured on the e-kick scooter was higher than that measured on the e-bike. Hence, e-kick scooters appeared to be globally less comfortable than the e-bikes. Furthermore, the vibration magnitudes acting on the e-kick scooter appeared to be more influenced by the path, user, and speed factors than those acting on the e-bike. This analysis revealed insights that could challenge the recent European regulations that equated e-kick scooters with bikes. Moreover, the results could help public administrations in regulating the circulation of e-kick scooters along city paths.

Keywords: e-kick scooters; e-bikes; comfort; vibrations; frequency response; ISO 2631-1

---

* Corresponding author. Tel.: +39-030-371-1265.
E-mail address: r.ventura001@unibs.it

10.1016/j.trpro.2022.02.092

1. Introduction

Nowadays, urban micro-mobility is provoking tremendous changes to the mobility in dense urban environments because automobiles are being regarded as an unsustainable transport mode owing to many externalities produced such as greenhouse and noise emissions, traffic congestion, and road accidents (e.g., Zagorskas and Burinskienė, 2020). Therefore, mobility experts and urban planners are trying to change the people's transport mode selections by investigating less energy-intensive modes such as walking, cycling, and micro (personal)-mobility vehicles. In this context, a strong interest is emerging towards electrical-powered Personal micro Mobility Vehicles (e-PMVs). They are small and quite compact vehicles equipped with low power electric engines powered by a rechargeable battery, and they include many devices such as electric scooters, e-kick scooters, e-bikes, and self-balancing devices and are cost-effective, especially for covering short distances i.e., within 5 km (Boglietti et al, 2021). Nevertheless, the diffusion of e-PMVs in the United States since 2017, and in several large European cities later (e.g., Barcelona, Milan, and Paris) have triggered many issues as shown in a recent review: (i) endogenous issues due to the impact of the use of e-PMVs on transport and urban planning, and (ii) exogenous issues due to the impact of these devices on the environment and road safety (Boglietti et al., 2021).

These vehicles can affect the use of existing public transport systems as well as that of public spaces such as streets, squares and parks (Gössling, 2020). Moreover, recently, there was a relevant number of accidents where e-PMVs were involved, that raised several concerns owing to the lack of specific regulations (Bloom et al., 2020). Therefore, some European countries have taken remedial actions by issuing regulations for the circulation of e-PMVs. Some important and specific European regulations (e.g., the Italian: DL n°160, December 27, 2019, the Danish Executive Order BEK 14.1.2019 nr. 40, and the Norwegian Regulation FOR-2018-04-09-545) equated e-kick scooters with bikes (or e-bikes) and provided indications regarding their circulation in urban areas both on cycling paths and traditional roads. However, the similarity between bikes and e-kick scooters could be somehow questionable because these vehicles present different characteristics e.g., in term of trip pattern and technical features. As for the trip pattern, e.g., the average travel speed for e-bikes (i.e., 10-12 km/h) is higher than that of e-kick scooters (i.e., 7-10 km/h) (Almannaa et al., 2020). As for the technical features, a different vehicle-rider system scheme and a different position of the centre of mass occur. Furthermore, bikes have large wheels and tires, which could generate a stabilizing gyroscopic effect and dissipate the shocks induced by the pavement irregularities. Conversely, e-kick scooters are generally equipped with small diameter wheels, which may not be able to induce significant stabilizing and dissipative effects. Thus, both vehicles may behave differently when running along different paths.

On the one hand, the behaviour of two-wheeled vehicles is a well know vehicle dynamics research topic (e.g., Sharp, 1971, Meijaard et al, 2007). Some studies on e-bikes showed a relationship between the pavement quality and the perceived comfort (e.g., Feizi et al., 2020). This relationship affects the vibrations that increase at increasing speed (e.g., Gao et al., 2018). In addition, the macrostructure and properties of the road surface are crucial for vibrations on e-bikes (e.g., Chou et al., 2015). Gao et al. (2019) showed how the pneumatic pavement interface can be considered as a key connection between vibrations and the macro-texture of the pavement. Furthermore, the average effort and the contact area on the pavement of the rear wheel are greater than on the front.

On the other hand, much less can be said for e-kick scooters dynamics, because these are recent vehicles. A handful of research investigated the influence of e-kick scooters vibrations on human health and comfort (Cano-Moreno et al., 2019), the dynamics of e-kick scooters and users during a ride (Garman et al., 2020) and the longitudinal, lateral, and vertical motion of a benchmark e-kick scooter (García-Vallejo and García-Agúndez, 2020). For instance, the last study compared an e-kick scooter with a bike from a theoretical viewpoint through the development of an analytical mechanical model. The model showed that, while the bike was self-stable and could be ridden hands-free within a certain speed range (as it is well known from daily experience), e-kick scooter resulted unstable at any speed, so it could never be driven without the use of hands.

Nevertheless, as far as the authors know, no experimental study has been made to compare the e-bikes' and e-kick scooters' dynamic behaviour in term of vibrational acceleration. This paper covers this gap by focusing on the vehicular vibrational response at the pavement irregularities, to investigate the ride comfort of both vehicles. More precisely, through experimental data acquired by sensors placed on the vehicles' frames, this paper analyses the magnitude of the vibrational acceleration acting during several rides along different paths characterized by dissimilar pavement types. Indeed, this acceleration is generally recognized as one of the main factors affecting user comfort (e.g., Huang et al, 2012 and Huang et al, 2019). To achieve the former goal, the two following specific objectives have been considered. First, several statistical Z-test are performed to investigate whether significative differences exist between the vibration magnitude acting on e-kick scooter and e-bike. Next, two Multiple Linear Regression (MLR) analysis are developed to understand which factors affects this vibrational magnitude and their extent for each vehicle, respectively. The experimental trials were carried out in a mid-sized Italian city to provide valuable insights about the different vibrational dynamics of these vehicles. The empirical evidence showed that the recent European regulations that equated e-kick scooters with bikes are questionable.

The remaining paper is organized as follows. Section 2 presents material and methods to make the comparison between e-bikes and e-kick scooters' vibrational dynamics. Section 3 shows and discusses the results. Finally, Section 4 draws conclusions and provides future perspectives.

2. Material and methods

2.1. Research context

Research tests involved six voluntary users (3 males and 3 females, denoted by U_2, U_4, U_5 and U_1, U_3, U_6 respectively) aged between 23 and 35 years and selected to ensure a good variability in terms of mass (from 50 to 87 kg), heights (from 1.61 to 1.86 m), and different levels of experience with e-bikes and e-kick scooters (from no experience to great experience). They were asked to drive an e-bike (city bike, 26" wheel diameter, 26.9 kg mass, V-brakes, denoted by B) and an e-kick scooter (aluminium frame, 10" wheel diameter, 14.2 kg mass, electric and disc brakes, denoted by M) on five different paths located in the city of Brescia (Italy). As shown in Table 1, these paths were characterized by surfaces with different levels of irregularity, such as uneven cobblestones, bituminous conglomerate, metal ventilation grids, smooth stone pavement and dirt road (denoted by A, C, G, P and S respectively). The path lengths were representative of typical journeys made by e-kick scooter and e-bike users as suggested in Zagorskas and Burinskienė (2020). These lengths ranged from a minimum of 710 m and a maximum of 1154 m, except for the grids (355 m), which were analysed separately because considered as a possible variation of other types of paths. Users were instructed to move along the path at predetermined speeds to ensure consistency between the different trials. The travel speeds were showed by digital speedometers installed on the vehicles. Experimentation assistants ensured that no obstacles (i.e., other vehicles, objects, etc.) were present along the paths during the trials, inviting people who were on the vehicular trajectories to move away from it and preventing objects from being accidentally placed on the tracks. All tests were done during daylight, under good weather conditions and on dry pavement.

Table 1. Path's characteristics

Path ID	Surface typology	Path description	Tot length [m]	Travel speed [km/h]
A	Uneven cobblestones	Three laps around a square	800	10
C	Bituminous conglomerate	Round trip along a cycle path	800	Way out: 10 Way back: 15
G	Metal ventilation grids	Two closed laps on the grids placed in a square.	355	First lap: 10 Second lap: 15
P	Smooth stone small tiles	One closed lap around a square	710	Average: 12.5
S	Dirt road, self-binding gravel, wooden bridge decks	Two laps around a closed cycle path	1155	First lap: 10 Second lap: 15

2.2. Data collection

Kinematic measurements were carried using Inertial Measurements Units (IMUs), equipped with accelerometer (triaxial, 0.1 m/s^2 accuracy, 160 m/s^2 measurement range, standard uncertainty 0.25 m/s^2), gyroscope (triaxial, $8.7 \cdot 10^{-5}$ rad/s stability, 34.91 rad/s measurement range, standard uncertainty $2.5 \cdot 10^{-4}$ rad/s) and inclinometer (triaxial, $8.73 \cdot 10^{-4}$rad x-y axes accuracies, $1.74 \cdot 10^{-2}$ rad z axis accuracy, $\pm \pi$ rad x-z axes measurement ranges, $\pm 0.5\ \pi$ rad y axis measurement range) sensors, placed on vehicular frames. The IMUs, small and lightweight (51 mm length, 36 mm width, 15 mm height, 0.02 kg mass), were firmly fixed to the e-bike handlebar and e-kick scooter handlebar (front position, denoted by F), and to the e-bike rear rack and e-kick scooter platform (rear position, denoted by R).The sensors were oriented so that the IMU's x axis coincided with the vehicular longitudinal axis, the IMU's y axis coincided with the vehicular transversal axis, and the IMU's z axis coincided with the vehicular vertical axis. Acceleration's data referred to the three IMU's reference axes were acquired during the first preliminary trials at a sampling frequency of 100 Hz, and at 200 Hz for weighted quantity, according to ISO 2631-1. The accelerometer range was chosen 16 *g* (160 m/s^2) to avoid saturation phenomena. The data were real time streamed by Bluetooth connection to two smartphones carried by the users and then stored in CSV files (raw data). The raw data were imported in Matlab^{TM} software and then analysed in both time and frequency domain.

2.3. Data analysis

Data analysis was performed by first computing a synthetic index for the magnitude of the vibrational acceleration acting on both vehicles during the experimental trials, and then by performing a statistical Z-test on the computed index to investigate whether significative differences exist between the means vibrational magnitude acting on e-kick scooter and e-bike. Furthermore, a MLR analysis is considered to understand which factors affects this vibrational magnitude.

It is worth noting that road pavements are characterized by random fluctuations of surface elevation, which are called road unevenness. When a two-wheeled vehicle travel along the surface (which can be modelled as a one-sided constraint) the road unevenness imposes vertical displacements to the two wheels generating vibrations, which are transmitted both to the vehicle's frame and to the rider. From automotive literature, these vibrations can be divided into three ranges of frequencies: (i) quasi-static range < 0.5 Hz, (ii) 0.5 Hz < ride range < 20 Hz and (iii) 20 Hz < acoustic range < 2000 Hz (Cossalter et al., 2006). Moreover, they cause discomfort, noise and, in the worst case, even the failure of vehicle's components. In addition, surface unevenness cause vibrations in tire load and hence tire adhesion may be impaired (Cossalter et al., 2006). The ride range is the most important for the user comfort because the human sensitivity to whole-body vibrations reaches its maximum in the range 1-8 Hz (ISO, 1997).

Analysing the vibration effects on human body is a complex task because it contains many sources, directions, frequencies and, in general, it is not constant in the time domain, and its effects can be different in each person. A useful reference is ISO 2631-1 that defines methods for the measurement of periodic, random, and transient whole-body vibration. It indicates the principal factors that contribute to determine the degree to which a vibration exposure will be acceptable. The frequency range considered is 0.5 Hz to 80 Hz for health, comfort, and perception, and 0.1 Hz to 0.5 Hz for motion sickness (ISO, 1997).

The basic vibrational evaluation method proposed by ISO 2631-1 include measurements of the weighted root mean square (RMS) acceleration $[m/s^2]$. Since the way which vibration affects the comfort is dependent on the vibration frequency content, different frequency weightings are prescribed for the different axes of vibration: W_d for x and y axes and W_k for z axis. Let $a_{wi}(t)$ $[m/s^2]$ be the weighted acceleration measured along the i^{th} axis as a function of time t, obtained by applying ISO 2631-1 frequency weightings, and let T $[s]$ be the duration of the measurement. The weighted RMS associated to acceleration measured along the i^{th} axis should be computed as follows:

$$RMS_{a_{wi}} = \left[\frac{1}{T}\cdot\int_0^T a_{wi}^2(t)\,dt\right]^{\frac{1}{2}} \ [m/s^2] \qquad \forall i \in \{x,y,z\} \tag{1}$$

According to ISO 2631-1, the frequency weightings can be performed in the frequency domain through the implementation of digital filters mathematically defined by the transfer function denoted by $H(f)$ and expressed as a product of several factors. Let:

- $a_i(t)$ $[m/s^2]$ be the acceleration measured along the i^{th} axis as a function of time t (time domain).
- $A_i(f)$ $[m/s^2]$ be the acceleration measured along the i^{th} axis as a function of the frequency f, i.e., the Fourier transformed of the signal $a_i(t)$ (frequency domain).
- $f_1, f_2, f_3, f_4, f_5, f_6$ and Q_4, Q_5, Q_6 be the frequencies and resonance quality factors respectively, that are parameters of the transfer function which determine the overall frequency weighting (see Table 2).
- $H_h(f) = \sqrt{\frac{f^4}{f^4+f_1^4}}$ be transfer function of the high pass filter.

- $H_l(f) = \sqrt{\frac{f_2^4}{f^4+f_2^4}}$ be transfer function of the low pass filter.
- $H_t(f) = \sqrt{\frac{f^2+f_3^2}{f_3^2}} \cdot \sqrt{\frac{f_4^4\, Q_4^2}{f^4 Q_4^2+f^2 f_4^2(1-2Q_4^2)+f_4^4 Q_4^2}}$ be the transfer function of the acceleration-velocity transition filter (proportionality to acceleration at lower frequencies, proportionality to velocity at higher frequencies).
- $H_s(f) = \frac{Q_6}{Q_5} \cdot \sqrt{\frac{f^4 Q_5^2+f^2 f_5^2(1-2Q_5^2)+f_5^4 Q_5^2}{f^4 Q_5^2+f^2 f_5^2(1-2Q_5^2)+f_6^4 Q_6^2}}$ be the transfer function of the upward step filter (proportionality to jerk, i.e., to the third derivative of the position vector with respect to time) ($H_s(f) = 1$ for W_d).
- $H(f) = H_h(f) \cdot H_l(f) \cdot H_t(f) \cdot H_s(f)$ be the total transfer function for health and comfort frequency weighting.
- $A_{wi}(f) = A_i(f) \cdot H(f)$ $[m/s^2]$ be the weighted acceleration measured along the i axis as a function of the frequency f.

Table 2. Parameters for the transfer functions of the principal frequency weightings (ISO, 1997).

Weighting	Band limiting		Acceleration-velocity transition			Upward step			
	$\boldsymbol{f_1}$ $[\boldsymbol{Hz}]$	$\boldsymbol{f_2}$ $[\boldsymbol{Hz}]$	$\boldsymbol{f_3}$ $[\boldsymbol{Hz}]$	$\boldsymbol{f_4}$ $[\boldsymbol{Hz}]$	**Q₄**	$\boldsymbol{f_5}$ $[\boldsymbol{Hz}]$	**Q₅**	$\boldsymbol{f_6}$ $[\boldsymbol{Hz}]$	**Q₆**
$\boldsymbol{W_k}$	0.4	100	12.5	12.5	0.63	2.37	0.91	3.35	0.91
$\boldsymbol{W_d}$	0.4	100	2.0	2.0	0.63	∞	-	∞	-

Therefore, according to the well know Parseval's theorem, the weighted RMS calculation in time domain (1) can be replaced by the equivalent, and more straightforward, discrete calculation in the frequency domain. Let: N_f be the number of the discrete Fourier transform frequency rows and f_k be the frequency associated at the *k^th^* row, the weighted RMS is computed as follows:

$$RMS_{a_{wi}} = \left[\frac{1}{2} \cdot \sum_{k=1}^{\frac{N_f}{2}} A_{wi}(f_k)^2\right]^{\frac{1}{2}} \quad [m/s^2] \qquad \forall i \in \{x, y, z\} \tag{2}$$

Next, the weighted RMS associated to the accelerations measured along the three orthogonal axes and computed through equation (2) ($RMS_{a_{wx}}, RMS_{a_{wy}}, RMS_{a_{wz}}$) can be combined adopting three multiplying factors (k_x, k_y, k_z) to obtain a synthetic index for vibrational magnitude, as follows:

$$RMS_{a_w} = \left(k_x^2\, RMS_{a_{wx}}^2 + k_y^2\, RMS_{a_{wy}}^2 + k_z^2\, RMS_{a_{wz}}^2\right)^{\frac{1}{2}} \; [m/s^2] \tag{3}$$

In the case of the human sensitivity to whole-body vibrations, that can affect the comfort on a ride, the multiplying factors can all be assumed equal to 1 for both a seated and a standing person (ISO, 1997). Therefore, RMS_{a_w} coincides with the Euclidean norm of the RMS vector.

Subsequently, to discover if significant differences exist among the paths, the averages RMS_{a_w} measured on the e-kick scooter and on the e-bike were computed, and the differences between these average values were tested through the Z-test. As well known, the Z-test is a statistical test to determine whether the means (μ_1 and μ_2) of two population are different when the variances ($\sigma_1^2$and σ_1^2) are known. The null hypothesis (H_0) is that there is no difference between the two means ($\mu_1 = \mu_2$). If the observed z value (z_{oss}) is greater than z_{crit} or smaller than $-z_{crit}$, being z_{crit} the z value associated to the significance level (α) adopted for the two tailed test, then then null hypothesis can be rejected and the alternative hypothesis (H_1: $\mu_1 \neq \mu_2$) is accepted.

Finally, to understand which factors influence the magnitude of the vibrational solicitation acting on the vehicles, two MLRs models were employed, one for the e-bike (B) and the other for the e-kick scooter (M) set of trials, respectively. Let: *N* be the set of trials performed on the vehicle (B or M); $\widehat{RMS_{a_{w_J}}}$ be the predicted weighted acceleration associated to the trial $j \in N$; X_{jk} be the value of the *k^th^* predictor in the trial $j \in N$; b_k be the regression coefficient associated with *k^th^* variable; *C* be the constant of the regression (hyperplane intercept); m be the total number of explanatory variables considered in MLR model. The MLR model for weighted acceleration prediction is given by e.g., Greene (1993):

$$\widehat{RMS}_{a_{w_j}} = \sum_{k=1}^{m} b_k X_{jk} + C \qquad \forall j \in N \tag{4}$$

The ordinary least squares method was used to estimate the best possible coefficients of the MLR models. Once the model has been estimated, it has been evaluated by the following goodness-of-fit statistics: the R^2_{adj} and the linear correlation between predictors and the response variable, indicated by global F-test and the corresponding significance value. The sign of the coefficients and their significance were also evaluated.

3. Preliminary results and discussion

Approximately, a total of $9 \cdot 10^6$ acceleration samples were collected along the three IMU's axes channels, corresponding to a total recording duration of 500 minutes.

The considered experimental dataset is composed of 168 observations, 88 related to e-kick scooter (M) and 80 related to e-bike (B), referring to the different paths (A, C, G, P, S), sensor positions (F, R), users (U_1, U_2, U_3, U_4, U_5, U_6) and speeds (10 km/h, 12.5 km/h, 15 km/h).

The results of the Z-test, concerning the averages RMS_{a_w} computed for the five paths and for the two vehicles, are shown in Table 3. As for the e-kick scooter, the highest and the lowest mean weighted accelerations were recorded on paths A and C respectively, while as for the e-bike, the highest and the lowest mean weighted accelerations were recorded on paths A and G, respectively. Therefore, as expected, the uneven cobblestones path (A) induces stronger vibrational accelerations than other paths. For the paths C, G, P, and S, the Z-test showed that the differences between the means are statistically significant at the 5% significance level ($\alpha = 0.05$), i.e., the null hypothesis ($H_0: \mu_1 = \mu_2$) can be rejected. More specifically, the mean weighted accelerations acting on e-kick scooter resulted always higher than those acting the e-bike. Conversely, the means of the vibrational acceleration acting on both vehicles during the rides performed along the uneven cobblestones path (A) are not significantly different, thus both vehicles exhibit the same behaviour. This observed non significance could be due to the higher data dispersion (variance) induced by the strong vibrational response at the high surface irregularities present along path (A). Nevertheless, the difference between the means computed on the entire data set (row Total in Table 3) resulted also statistically significant and the highest means is still associated to the acceleration acting on the e-kick scooter. Therefore, e-kick scooter appears to be globally less comfortable than the e-bike in terms of vibrational solicitation. This lower e-kick scooter comfortability could be explained by its different technical and structural characteristics (e.g., smaller wheels, stiffer frame, smaller damping factor) and deserves to be further investigated in future studies.

Table 3. Results of the Z-test concerning the averages RMS_{a_w}computed for the different paths and for the two vehicles. The z_{crit} associated to the 5% significance level is 1.96.

	E-kick scooter (M)		**E-bike (B)**		**Z - test**	
Path ID	Mean $[\boldsymbol{m/s^2}]$	Variance $[\boldsymbol{m^2/s^4}]$	Mean $[\boldsymbol{m/s^2}]$	Variance $[\boldsymbol{m^2/s^4}]$	z_{oss}	Can be H_0 rejected?
A	8.34	0.61	7.23	13.12	1.03	No
C	2.79	0.23	1.95	0.77	3.60	Yes
G	2.94	0.34	1.87	0.33	5.94	Yes
P	4.16	0.16	2.98	2.11	2.70	Yes
S	3.70	0.28	2.26	1.02	5.68	Yes
Total	3.98	3.56	2.96	6.01	3.01	Yes

As for the MLR models, the explanatory factors adopted for the analysis are showed in Table 4. It is noteworthy that path, sensor position, and user factors are categorical variables, therefore a binary coding that compare the different trials with a reference condition was necessary. The assumed reference condition is C for path, F for sensor position and U_1 for user. The MLR results are reported in Table 4 where the numerical entries in bold represent significant variables at <.05 level. Generally speaking, the e-kick scooter and the e-bike regression model overall have a good fit and can explain the 97% ($R^2_{adj} = 0.97$) and the 80% ($R^2_{adj} = 0.80$) of the observed deviances from the means, respectively.

As for the e-kick scooter model, the path factors A, P, S, the sensor position factor R, the user factors U_2, U_3, U_4, U_5, U_6, and the speed factor resulted highly significant ($p - value \ll \alpha = 0.05$). The regression coefficient positive signs indicate that uneven cobblestones (A), smooth stone small tiles (P) and dirt road (S) surfaces induces higher vibrational magnitudes than the bituminous conglomerate (C). Furthermore, as expected, the vibrational magnitude appears to increase with the speed. Conversely, the vibrational magnitudes acting on the e-kick scooter during the trials conducted on the metal ventilation grids (G) are not statically different to those recorded on the bituminous conglomerate (C).

As for the e-bike model, only the path factors A and P, the sensor position factor R, and the speed factor are statistically significant at the 5% significance level ($p < \alpha = 0.05$), therefore the surface typology and the user characteristics appeared to have less influence on the measured vibration magnitudes. More specifically, the vibrational magnitudes acting on the e-bike during the trials conducted on the metal ventilation grids (G) and on the dirt road (S) surfaces are not statically different to those recorded on the bituminous conglomerate (C). Similarly, the vibration magnitudes acting on the e-bike during the trials performed by users U_2, U_3, U_4, U_5 and U_6, are not statically different to those performed by the reference user (U_1). Furthermore, the regression coefficient of the speed factor, even remaining statistically significant and positive in sign, is closer to zero than in the e-kick scooter, so a speed increase could have less influence on the vibration magnitude increase.

Interestingly, the dissimilarity in p-values between the two vehicle's MLR models could be a symptom of a different behaviour. Particularly, all the user factors are significant in the e-kick scooter model, while no user factor is significant in the e-bike model. This evidence could indicate a greater influence of the user mass and height on the e-kick scooter, or a more heterogeneous driving style among the e-kick scooter users, perhaps imputable to the less familiarity with this new vehicular typology with respect to e-bike.

Table 4. Multiple linear regression explanatory factors and analysis results for e-kick scooter and e-bike vehicles.

	Explanatory factors	**E-kick scooter model**				**E-bike model**			
Symbol	**Description**	**Estim.**	**p-val.**	**Low. 95%**	**Upp. 95%**	**Estim.**	**p-value**	**Low 95%**	**Upp. 95%**
Constant	Hyperplane intercept	0.92	**<0.001**	0.39	1.45	-0.45	0.63	-2.30	1.40
C	***Bituminous Conglomerate (reference path)***								
A	Uneven cobblestones	5.91	**<0.001**	5.64	6.17	5.66	**<0.001**	4.78	6.54
G	Metal ventilation grids	0.07	0.51	-0.14	0.28	-0.44	0.24	-1.17	0.30
P	Smooth stone small tiles	1.29	**<0.001**	1.03	1.54	1.10	**0.01**	0.27	1.93
S	Dirt road, self-binding gravel, wooden bridge decks	0.92	**<0.001**	0.70	1.13	0.46	0.20	-0.25	1.17
F	***Front position (reference sensor position)***								
R	Rear position	0.33	**<0.001**	0.19	0.48	2.46	**<0.001**	1.96	2.96
U_1	***User 1 (reference user)***								
U_2	User 2	-0.41	**0.01**	-0.71	-0.10	-0.72	0.19	-1.82	0.38
U_3	User 3	-0.47	**0.003**	-0.78	-0.17	-0.25	0.64	-1.33	0.83
U_4	User 4	-0.35	**0.024**	-0.66	-0.05	-0.72	0.20	-1.84	0.40
U_5	User 5	-0.51	**0.001**	-0.82	-0.21	-0.49	0.37	-1.57	0.59
U_6	User 6	-0.66	**<0.001**	-0.96	-0.36	-0.49	0.37	-1.57	0.59
Speed	***Travel speed during the trial***	0.17	**<0.001**	0.14	0.21	0.12	**0.04**	0.01	0.24

E-kick scooter model: 88 observations, $R^2_{adj} = 0.97, F = 235.23, p - value = 5.94 \cdot 10^{-54}$. E-bike model: 80 observations, $R^2_{adj} = 0.80, F = 30.17, p - value = 6.49 \cdot 10^{-22}$.

4. Conclusions

Some European regulations equated e-kick scooters with bikes (or e-bikes). However, this similarity could be somehow questionable because these vehicles present different characteristics. Thus, they may behave differently when running along different paths. Since no experimental study compared the e-kick scooters' and bikes' dynamic behaviour, this paper improved the state-of-the art by focusing on the vehicular response at the pavement irregularities, to investigate the vibrational comfort of both vehicles. The vibration induced acceleration acting on the vehicles during several rides along different paths was considered. A dataset of approximately $9 \cdot 10^6$ acceleration samples was collected in Brescia (Italy) and processed adopting the basic vibration evaluation method proposed by ISO 2631-1. Then a Z-test and a multiple regression analysis were performed to investigate whether significative differences exist between the vibration magnitude acting on e-kick scooter and e-bike, and to understand which factors affects this vibration magnitude, respectively.

This first empirical evidence showed a statistically significant difference between the two vehicles in most of the analysed surfaces: the mean of the vibrational magnitudes measured on the e-kick scooter was statistically significantly higher than the mean of the vibration magnitudes measured on the e-bike. Therefore, e-kick scooter appeared to be globally less comfortable than the e-bike in terms of vibrational solicitation. Furthermore, the vibration magnitudes acting on the e-kick scooter appeared to be more influenced by the path, user, and speed factors than those acting on the e-bike. Few users and two vehicles were employed; thus, more research is still needed to corroborate these results. Nevertheless, this empirical evidence has confirmed the different vibrational dynamic behaviour between e-kick scooters and e-bikes and suggested that the recent European regulations equating e-kick scooters with bikes are questionable. This result could indicate the need of a redefinition of those paths intended for e-kick scoters but designed according to bicycles technical characteristics to improve the safety and the comfortability of the users. Moreover, the analysis of the experimental data collected in a one city might be a limiting factor. However, the investigated paths have been carefully chosen to include almost all road surfaces typologies frequently observed in a typical European city (i.e., uneven cobblestones, bituminous conglomerate, metal ventilation grids, smooth stone pavement and dirt road). Future experiments are already planned to expand the sample size and increase the general validity of the conclusions. The different behaviour between the two vehicles should be investigated in future studies, not only in terms of acceleration analysis, but also considering the vehicular rotational motion (yaw, pitch, roll). Moreover, research aimed at relating objective (kinematic data) and subjective (perceived) comfort measures could be useful to better understand the differences between e-kick scooters and e-bikes. Finally, the need to investigate the interactions of e-kick scooters' and e-bike' users with other road users through the measuring of further parameters (e.g., lateral distance) is a challenging issue that will be addressed in future research.

Acknowledgements

Authors thank Ingenera S.r.l. and Brescia Mobilità S.p.A for providing the e-kick scooter and e-bike they used in the study, respectively. Authors also thank Michela Bonera, Enrico Faccin, Lucia Licciardello, Stefano Giuseppe Mantelli and Valentina Martinelli for their help in the experimental trials.

References

Almannaa, M., Ashqar, H., Elhenawy, M., Masoud, M., Rakotonirainy, A., & Rakha, H. 2021. A Comparative Analysis of E-Scooter and E-Bike Usage Patterns: Findings from the City of Austin, TX. International Journal of Sustainable Transportation, 15(7), 571-579.

Bloom, M., Noorzad, A., Lin, C., Little, M., Lee, E., Margulies, D., & Torbati, S. 2020. Standing electric scooter injuries: Impact on a community. The American Journal of Surgery, 221(1), 227-232.

Boglietti, S., Barabino, B., & Maternini, G. 2021. Survey on e-Powered Micro Personal Mobility Vehicles: Exploring Current Issues towards Future Developments. Sustainability, 13 (7)(3692).

Cano-Moreno, J. D., Marcos, M. I., Haro, F. B., D'Amato, R., Juanes, J. A., & Heras, E. S. 2019. Methodology for the study of the influence of e-scooter vibrations on human health and comfort. ACM Int. Conf. Proceeding Ser., October, 445-451.

Chou, C.-P., Lee, W.-J., Chen, A.-C., Wang, R.-Z., Tseng, I., & Lee, C.-C. 2015. Simulation of bicycle-riding smoothness by bicycle motion analysis model. J. Transport. Eng., 141(12).

Cossalter, V., Doria, A., Garbin, S., & Lot, R. 2006. Frequency-domain method for evaluating the ride comfort of a motorcycle. Veh. Syst. Dyn, 44(4), 339-355.

Feizi, A., Oh, J.-S., Kwigizile, V., & Joo, S. 2020. Cycling environment analysis by bicyclists' skill levels using instrumented probe bicycle (IPB). International Journal of Sustainable Transportation, 14:9, 722-732.

Gössling, S. 2020. Integrating e-scooters in urban transportation: Problems, policies, and the prospect of system change. Transportation Research Part D: Transport and Environment, 79.

Gao, J., Sha, A., Huang, Y., Hu, L., Tong, Z., & Jiang, W. 2018. Evaluating the cycling comfort on urban roads based on cyclists' perception of vibration. Journal of Cleaner Production, 192, 531-541.

Gao, J., Sha, A., Huang, Y., Liu, Z., Hu, L., Jiang, W., & Wang, Z. 2019. Cycling comfort on asphalt pavement: Influence of the pavement-tyre interface on vibration. Journal of cleaner production, 223, 323-341.

García-Vallejo, D., W., S., & García-Agúndez, A. 2020. Dynamics, Control and Stability of Motion of Electric Scooters. Adv. Dyn. Veh. Roads Tracks.

Garman, C., Como, S. G., Campbell, I. C., Wishart, J., O'Brien, K., & McLean, S. 2020. Micro-Mobility Vehicle Dynamics and Rider Kinematics during Electric Scooter Riding. 2020-April. SAE Technical Papers.

Greene, W.H., 1993. Econometric Analysis. Macmillan Publishing Company, New York.

Huang, Y., & Griffin, M. 2012. The effects of sound level and vibration magnitude on the relative discomfort of noise and vibration. Journal of acoustical Society of America, 131(6), 4558-4569.

Huang, Y., & Li, D. 2019. Subjective discomfort model of the micro commercial vehicle vibration over different road conditions. Applied Acoustics, 145, 385-392.

International Organization for Standardization. 1997. ISO 2631-1: Mechanical vibration and shock - evaluation of human exposure to whole body vibration.

Meijaard, J., Papadopoulos, J. M., Ruina, A., & Schwab, A. L. 2007. Linearized dynamics equations for the balance and steer of a bicycle: A benchmark and review. Proc. R. Soc. A Math. Phys. Eng. Sci, 463(2084), 1955–1982.

Ministerium Transportog Boligministeriet 2019, Bekendtgørelse om forsøgsordning for motoriseret løbehjul, nr 40 af 14/01/2019

Repubblica Italiana. 2019. DL 27 dicembre 2019, n.160. Bilancio di previsione dello Stato per l'anno finanziario 2020 e bilancio pluriennale per il triennio 2020-2022. Gazzetta ufficiale della Repubblica Italiana.

Samferdselsdepartementet 2018, Forskrift om endring i forskrift om krav til sykkel FOR-2018-04-09-545

Sharp, R. S. 1971. The stability and control of motorcycles. J. Mech. Eng. Sci.

Zagorskas, J., & Burinskienė, M. 2020. Challenges Caused by Increased Use of E-Powered Personal Mobility Vehicles in European Cities. Sustainability, 12(1), 273.