

EXPERIMENTAL INVESTIGATION OF ACCELERATION PERFORMANCE OF LOW-POWER TWO-WHEELED ELECTRIC VEHICLES

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Abstract. With the development of low-power electric mobility technologies, electrically powered bicycles and electric scooters have become widely used in urban environments. In Latvia, the use of electric scooters is strictly regulated by setting a minimum user age of 14 years and limiting the maximum travel speed to $25 \text{ km}\cdot\text{h}^{-1}$. A registration and identification system for electric scooters has also been introduced. Due to the rapid increase in the number of electric scooters and electric bicycles and the growing relevance of traffic safety concerns, it is important to understand the operational parameters of different two-wheeled electric vehicles, particularly those related to dynamic performance. These parameters include dynamic characteristics under various operating modes, such as travel speed, acceleration time, and the distance required to reach the maximum speed. These factors may significantly affect the safety of both vehicle users and other road users. Experimental investigations were carried out using three electric scooters and two electric bicycles with varying power ratings and technical specifications. Electric bicycles and electric scooters the technical parameters of which exceed the maximum speed limits specified in Latvian road traffic regulations are electronically restricted through programming to comply with the legally permitted speed limits. The experimental results indicated that the most powerful electric scooters and one electric bicycle demonstrated highly dynamic behaviour, achieving rapid acceleration that might pose a significant safety risk, particularly on sidewalks shared with pedestrians. The maximum measured acceleration for the electric bicycle was $1.93 \text{ m}\cdot\text{s}^{-2}$, while the maximum acceleration recorded for the electric scooter reached $3.31 \text{ m}\cdot\text{s}^{-2}$.

Keywords: electric scooter, electric bicycle, acceleration, acceleration time, speed, acceleration distance.

Introduction

With the development of low-power electric-vehicle technologies, electric-powered bicycles and scooters are increasingly prevalent in urban environments. Electric scooters are also offered for rent in cities. Not all countries have dedicated safe infrastructure for electric bicycles and electric scooters, such as separate cycle paths that are separated from pedestrian sidewalks and that meet all safety requirements. Therefore, new safety solutions are also needed both on the technological side of micromobility vehicles and through restrictive legislation by traffic supervision authorities.

One of the reasons to pay special attention to the safety of low-power electric vehicles driving on the sidewalk is their quiet operation and relatively high speeds. Although the speed of electric scooters and electric bicycles is limited to $25 \text{ km}\cdot\text{h}^{-1}$ in Latvia, and the regulations stipulate that when approaching pedestrians moving on the sidewalk the speed should be reduced to about $5 \text{ km}\cdot\text{h}^{-1}$, electric scooter drivers do not always reduce the speed. For this reason, Tim Walton et al. have developed special sound imitators that are designed to be installed on electric scooters for warning pedestrians. The frequency of the warning sound was optimized so that pedestrians could respond better [1]. Electric scooters are considered a good “last-mile solution” to get from a public transport terminal to work in urban areas. Sometimes an electric scooter is also convenient to use if one goes to work from the suburbs by car, but leaves the car parked outside the city centre, then the remaining distance can be easily covered by an electric scooter [2].

A. Pashevich et al. have found in their experiment that the average speed for pedestrians on sidewalks was $5.9 \text{ km}\cdot\text{h}^{-1}$, $16.8 \text{ km}\cdot\text{h}^{-1}$ for bicycles, and $16.5 \text{ km}\cdot\text{h}^{-1}$ for electric scooters. Given that this was the average speed, the maximum speed on some sidewalk sections could be 20% higher [3].

French scientists Claire Naude et al. have conducted experiments with low-speed two- and single-wheeled electric vehicles. Their experiments determined the dynamism and braking parameters of the widely used electric vehicle models: the electric scooter “Xiaomi Mi scooter Pro” (e-scooter), the electric bicycle “Lapierre Urban” (e-bicycle), and the unicycle “Inmotion V5F” (e-monowheel). The experiments were conducted on a dry go-kart track with good adhesion. A Samsung S8 smartphone with an accelerometer and gyroscope was used to log data. The experiments yielded the highest accelerations for an electric scooter at $0.71 \text{ m}\cdot\text{s}^{-2}$, an electric bicycle at $0.86 \text{ m}\cdot\text{s}^{-2}$, and a unicycle at $0.77 \text{ m}\cdot\text{s}^{-2}$ in sport or turbo mode [4].

M. Dozza et al. conducted experimental studies on an electric bicycle and an electric scooter. The experiments used existing sensors to obtain data on electric vehicles, but if necessary, additional sensors

could be installed. The experiments were conducted in a closed area, with traffic conditions as close as possible to city traffic conditions. The experiments were carried out by 6 operators aged 23-29 years and 178-188 cm tall [5]. In other experiments, M. Dozza et al. conducted experiments on 9 women and 25 men riding an electric bicycle, a regular bicycle, and an electric scooter. A data logger was used to collect data. The experiments were conducted at a distance of 50 meters, accelerating up to 17-20 km·h⁻¹ and braking moderately. The second series of experiments involved a 100 m distance. The acceleration experiments yielded an average acceleration of 0.76 m·s⁻² for the regular bicycle (without electric motor assistance), 0.95 m·s⁻² for the electric bicycle, and 0.70 m·s⁻² for the e-scooter, while a two-wheeled Segway self-balancing electric scooter achieved 1.01 m·s⁻² [6]. In their experiments, L. Bilstein and Svernlov achieved an average acceleration of 0.75 m·s⁻² for an e-scooter and 0.95 m·s⁻² for electric bicycles [7].

In some countries, e.g., Italy, electric bicycles and electric scooters are classified in the same vehicle category. Therefore, braking experiments were conducted with drivers of different weights, braking the vehicles on dry asphalt with no wheel slippage. An approximate braking distance was measured with a tape, while accurate braking data were obtained by filming the experiment with a video camera and then analysing in detail the video footage at a rate of 30 frames per second [8].

The results of most of the experimental studies revealed that bicycles were safer for movement, which is why many countries have set stricter road rules for electric scooters. It is useful to conduct comparative studies not only on electric scooters and electric bicycles officially permitted for use in road traffic, but also on vehicles of this class which speed and power exceed officially permitted limits. Earlier research studies have not analysed in detail the dynamics of acceleration and key parameters, such as the acceleration distance to reach a certain speed, as well as the acceleration time, which are important parameters for micromobility vehicles driven on sidewalks. The aim of the study is to conduct experimental investigations on road-legal and off-road electric scooters and electric bicycles to determine their acceleration performance and to perform a comparative analysis of these parameters.

Materials and methods

The present research conducted experiments to determine the acceleration parameters of electric scooters and electric bicycles under real driving conditions. The experiments used two electric scooters and one electric bicycle, which had been registered for road traffic in Latvia, and an electric scooter and an electric bicycle with increased power. The experiments were conducted on a hard, flat, and dry road surface with an average adhesion coefficient of 0.75 and a coefficient of rolling resistance in the range of 0.008-0.015, which depended on the tires used. The tire pressure was selected 90% of the maximum. The technical data for the electric bicycles and electric scooters are given in Table 1. The analysis of the electric vehicles uses the abbreviated designations given in the table to refer to a particular vehicle.

Table 1

Technical characteristics of the electric scooters and electric bicycles used in the experiments [9-13]

Technical characteristics and unit of measurement	ES-1 Xiaomi Electric Scooter 4 Lite	ES-2 Ninebot KickScooter Max G2	ES-3 Kaabo Mantis 8	EB-1 Taouroll	EB-2 Gogobest GF700
Wheel diameter	10"	10"	8"	26" off-road	26" off-road
Motor voltage, V	25.2	36	48	36	48
Engine power, W	300	900	2×800	250	2×500
Battery capacity, Ah	10.2	15.3	18.2	13	17.5
Range per charge, km	25	50	40	65, assist	50
Maximum speed, km·h ⁻¹	20	25	50	25	25
Weight, kg	16.2	24.3	26.5	21,7	31
Number of modes	3	3	12	3	3

The experiments for electric scooters and electric bicycles involved a driving mode to achieve a speed of at least 15 km·h⁻¹ and a mode in which the speed did not exceed 28 km·h⁻¹.

Table 2

Electric vehicle driving modes in the experiments and designations

Electric scooter	Experimental mode	Designation
Xiaomi Electric Scooter 4 Lite	Mode Drive Mode Sport	ES-1 Drive ES-1 Sport
Ninebot KickScooter Max G2	Mode Eco Mode Drive Mode Sport	ES-2 Eco ES-2 Drive ES-2 Sport
Kaabo Mantis 8	1 Motor, Mode 2 1 Motor, Mode 3 2 Motors, Mode 2 2 Motors, Mode 3	ES-3 1M2R ES-3 1M3R ES-3 2M2R ES-3 2M3R
Taouroll	Mode Medium Mode High	EB-1 Medium EB-1 High
Gogobest GF700	Mode 1 Mode 2 Mode 3	EB-2 Reg1 EB-2 Reg2 EB-3 Reg3

The acceleration parameters of the micromobility electric vehicles were obtained by a scientific radar Stalker ASTS II. The main technical characteristics of the radar are presented in Table 3.

Table 3

Technical characteristics of the radar Stalker ATS II [14]

Technical parameter, unit of measurement	Parameter value
Speed measurement limits, km·h ⁻¹	0 - 1287
Accuracy, % of reading value	± 3%
Maximum measuring distance, m	2800
Operating frequency, GHz	34.7
Operating temperature, °C	- 30 to + 70
Battery voltage and capacity, VDC/ Ah	7.4/ 2.4
Weight, kg	0.98
PC software	Stalker ATS II for Windows

The experiments were conducted by three operators. One operated the radar software application and saved data, while the other made acceleration experiments. The third operator was responsible for making ready the electric scooters for experiments and recording the parameters. The weight of the operator who drove was 78 kg. In the acceleration experiment, an electric scooter or electric bicycle was placed at a distance of 5 m from the radar. The radar was programmed for acceleration mode. After the radar operator gave a signal, the other operator drove a vehicle as fast as possible in the direction away from the radar. After reaching the maximum speed, data recording was stopped. If the maximum speed of an experimental electric vehicle was lower, the vehicle was accelerated to the maximum speed, and after 1-2 seconds, the data recording was stopped. The experiments were conducted in all standard modes of movement of the electric vehicles, except in pedestrian mode. Each experiment was replicated at least 5 times. If some interference was observed during the data recording, the experimental data were not saved, and the experiment was replicated.

After the experiments, all the data were processed by selecting three replications with the closest data set and calculating average parameter values.

Each experiment was repeated three times for every driving speed. The uncertainty of the mean values was evaluated at a 95% confidence level, with the uncertainty taken as twice the standard error of the mean ($2 \cdot SE$).

Results and discussion

Speed change curves, $v = f(t)$, were created based on the selected data. The curve data were used for further analysis. The acceleration curves for the most powerful electric scooter, Kaabo Mantis 8,

under all driving modes are presented in Fig. 1. A characteristic curve showing a faster change in speed indicates faster acceleration.

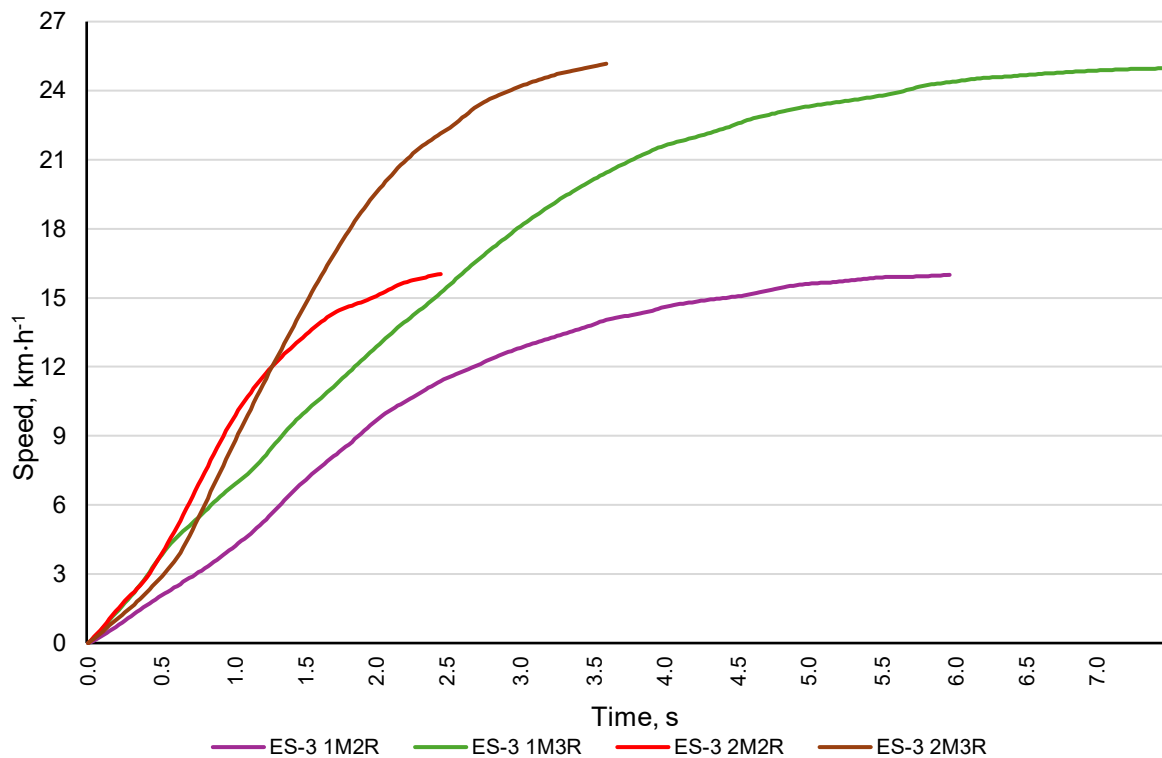


Fig. 1. Change in the speed of the electric scooter Kaabo Mantis 8 under various driving modes

When rapidly accelerating the Kaabo Mantis in driving mode 3, the drive wheels were slipping because this electric scooter, unlike the other electric scooters used in this experiment, could increase the speed with the accelerator lever. In modes 2 and 3, the maximum speed was reached, 16 and 25.2 km·h⁻¹, respectively. When accelerating with one motor in modes 2 and 3, acceleration intensities were very different, whereas in two-motor mode, it was up to 12 km·h⁻¹, with the acceleration intensities in both modes being very similar. After reaching a speed of 12 km·h⁻¹ the control unit of the electric scooter began to limit power, and the scooter accelerated more smoothly to the maximum speed.

A very important characteristic of electric scooters and electric bicycles is maximum acceleration. This parameter for all experimental electric vehicles was calculated during acceleration from 10 to 15 km·h⁻¹, with the acceleration time being read from the speed change data. The acceleration data under all modes for the experimental vehicles are presented in Fig. 2.

For the vehicles permitted to drive on sidewalks, i.e. Xiaomi Electric Scooter, Ninebot Kick Scooter, and Taouroll, acceleration in the main modes was in the range from 0.32 to 1.53 m·s⁻². The operator of the electric bicycle Taouroll accelerated it by pedalling and using the electric motor assistance. In sports mode, the electric scooter Ninebot Kick Scooter achieved an acceleration of 1.53 m·s⁻², which was the highest value for the vehicles permitted to drive on the sidewalk. For the off-road electric bicycle Gogobest GF700, the acceleration mode could be activated with the accelerator handle, and an acceleration of 1.93 m·s⁻² was achieved in mode 3. The off-road electric scooter Kaabo Mantis achieved a maximum acceleration of 3.31 m·s⁻², which was a very high and also dangerous parameter for such a vehicle. Such acceleration is achieved by a passenger car with good dynamic characteristics, accelerating to 100 km·h⁻¹ in 8 seconds. The safety of a car driver is significantly different from that of an electric scooter driver, as the car driver is seated and wears a seat belt, whereas the electric scooter driver is standing, and hitting a small pothole can lead to an accident. According to the subjective impressions of the operators of the experiments, the Gogobest GF700 electric bicycle was much more stable and safe during acceleration than the Kaabo Mantis electric scooter, although the acceleration also reached high values.

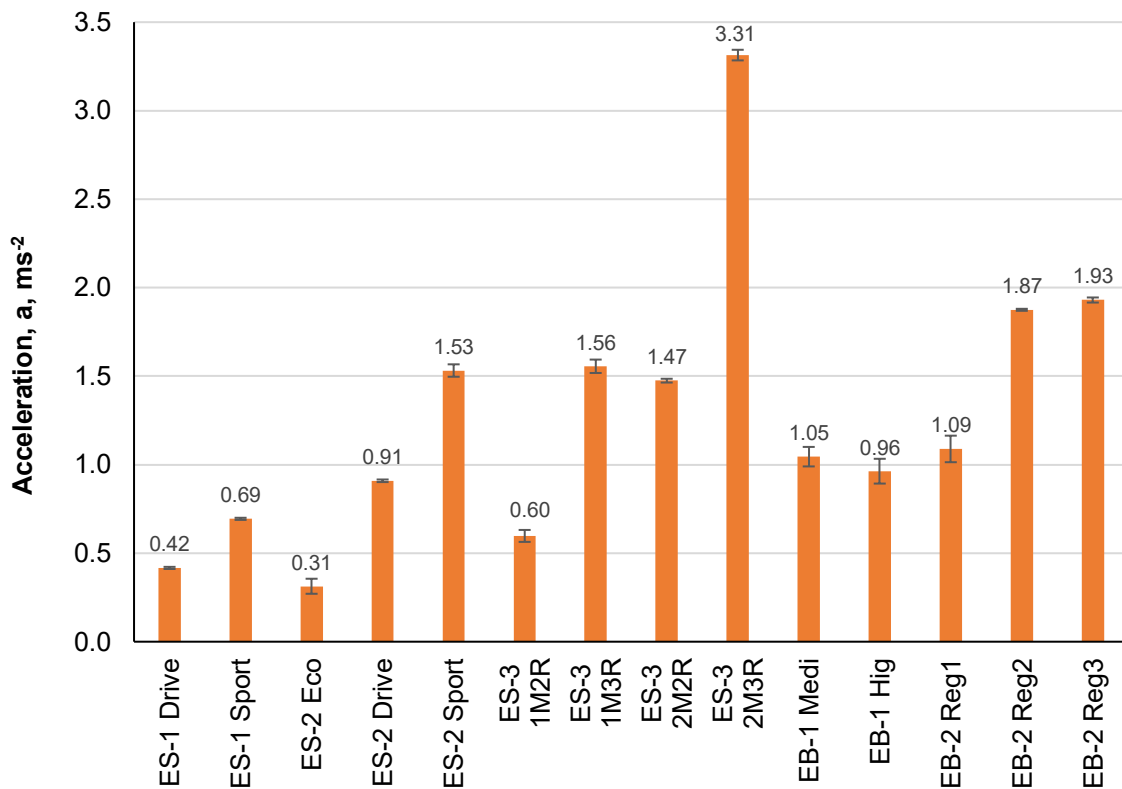


Fig.2. Acceleration of the electric scooters and electric bicycles

Since the electric vehicles were accelerated at maximum intensity, and the experiments also used electric scooters with a power of 1.6 kW and an electric bicycle with a power of 1.0 kW, much higher acceleration values than in other scientific research studies were reached under some driving modes. Claire Naude et al., M. Dozza et al. and L. Billstein and Svernlöv [4-7] achieved maximum acceleration of no more than $0.75 \text{ m}\cdot\text{s}^{-2}$ for electric scooters and $0.95 \text{ m}\cdot\text{s}^{-2}$ for electric bicycles. In our experiments, the maximum acceleration of the street-legal e-scooter was $1.53 \text{ m}\cdot\text{s}^{-2}$, while the electric bicycle achieved $1.05 \text{ m}\cdot\text{s}^{-2}$, which was consistent with the results achieved by other scientists. In contrast, the acceleration of the off-road two-wheeled electric vehicles was more than 2 times that of street-legal vehicles, which can be considered vehicles particularly dangerous for driving on the sidewalk.

When electric scooters drive along the sidewalk, their speed is much higher than the speed of pedestrians, which can negatively affect their safety. In the event of the fast acceleration of an electric scooter, a pedestrian might react incorrectly to this vehicle, which could lead to an accident. Acceleration times for the experimental electric vehicles to achieve different speeds are presented in Fig. 3. The acceleration times to different speeds were established based on the curves of average acceleration.

For the electric vehicles permitted to drive on sidewalks, the average time to reach $10 \text{ km}\cdot\text{h}^{-1}$ was in the range of 1.79-4.76 seconds, while $20 \text{ km}\cdot\text{h}^{-1}$ was reached in 3.78- 7.64 seconds. The longest acceleration times are safe for traffic. However, in the case where the electric scooter and pedestrians are waiting for the green traffic light signal at a pedestrian crossing, the electric scooter Ninebot Kick Scooter can reach a significant speed in less than 4 seconds, which can lead to a dangerous situation. For this reason, electric scooters, in accordance with the Latvian legislation, must cross at a speed not exceeding $5 \text{ km}\cdot\text{h}^{-1}$, which, unfortunately, is rarely observed. A special threat to safety on sidewalks can be caused by the electric scooter Kaabo Mantis, which can reach $20 \text{ km}\cdot\text{h}^{-1}$ in two-motor acceleration mode in 2.05 seconds, and $25 \text{ km}\cdot\text{h}^{-1}$ in 3.46 seconds. Although the Gogobest GF700 electric bicycle can reach $20 \text{ km}\cdot\text{h}^{-1}$ in 2.86 seconds, such electric vehicles are usually used for off-road driving or movement on the roadway, where the safety of pedestrians is not endangered.

An important parameter for safely driving electric vehicles on sidewalks is the acceleration distance for achieving various speeds, which is summarized for all experimental electric vehicles in Fig. 4. A short acceleration distance is characterized by very fast acceleration and a moment of surprise for pedestrians if the small electric vehicle has changed its position very rapidly, for which the pedestrian

may not be ready. If the driver of an electric vehicle is not sufficiently trained, they might also be unprepared for the rapid movement.

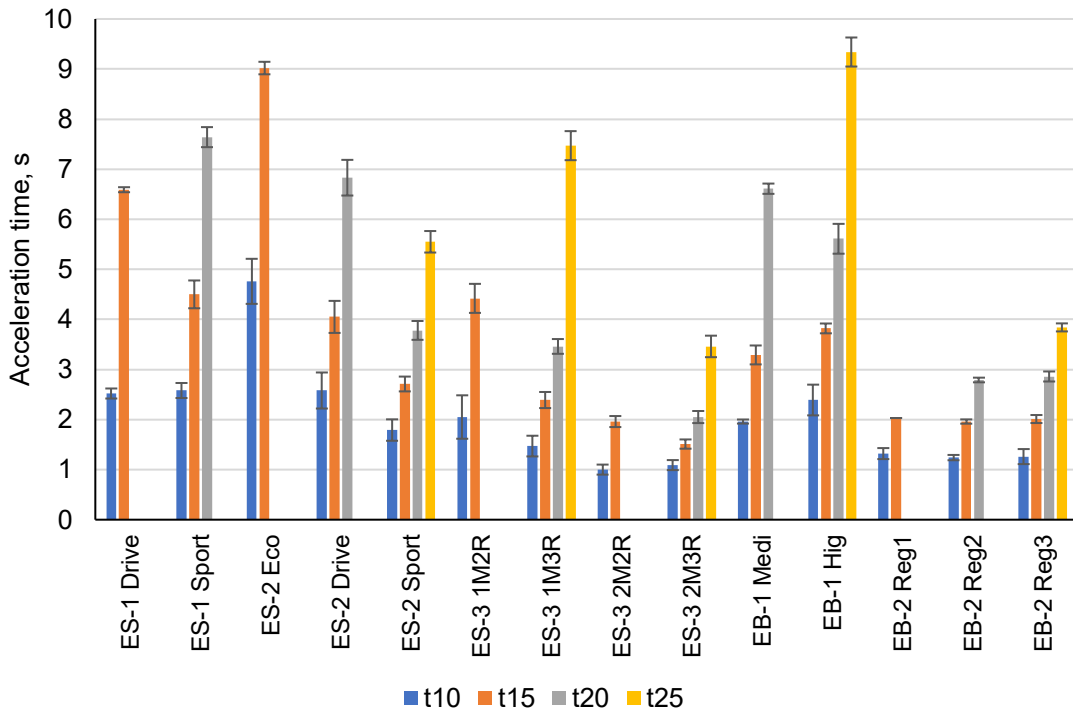


Fig. 3. Acceleration times of the electric scooters and electric bicycles to achieve various speeds: t10- acceleration time to reach 10 km·h⁻¹; t15- acceleration time to reach 15 km·h⁻¹; t20- acceleration time to reach 20 km·h⁻¹; t25- acceleration time to reach 25 km·h⁻¹

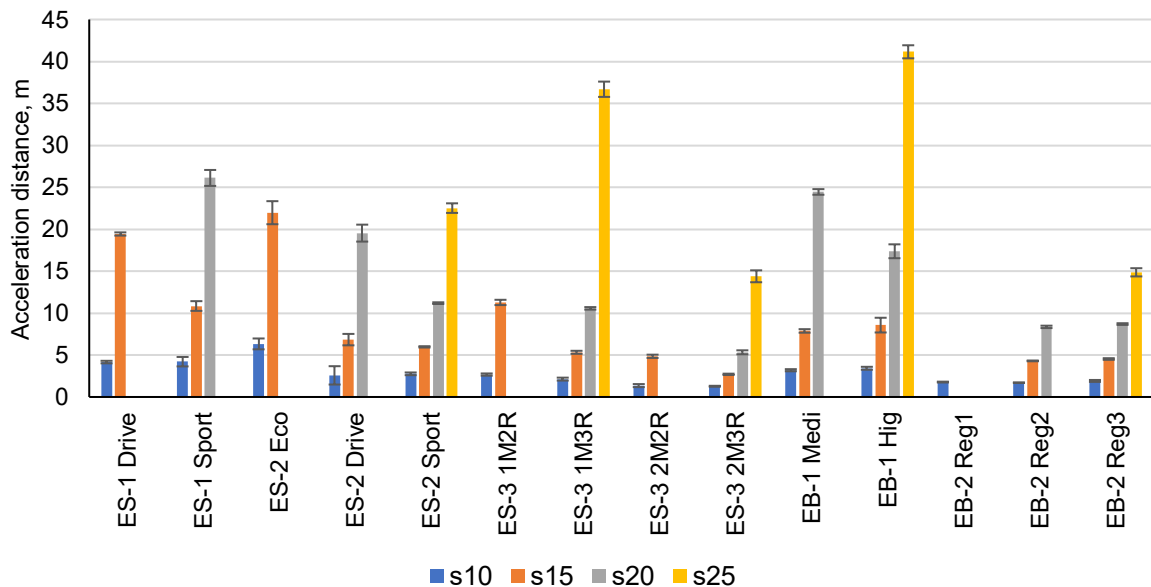


Fig. 4. Acceleration distances of the electric scooters and electric bicycles to achieve various speeds: s10- acceleration distance to reach 10 km·h⁻¹; s15- acceleration distance to reach 15 km·h⁻¹; s20- acceleration distance to reach 20 km·h⁻¹; s25- acceleration distance to reach 25 km·h⁻¹

An analysis of the acceleration distances revealed that the 10 km·h⁻¹ speed was achieved by the experimental electric vehicles in distances ranging from 1.27 to 6.33 m. For the vehicles that were permitted to drive on the sidewalk, the shortest distance to reach this speed was 2.57 m, which is also a very short section of the road for adequate pedestrian response. To reach 20 km·h⁻¹, the Ninebot Kick

Scooter required only a distance of 11.19 m in sport mode, which also indicated very good dynamic characteristics and potential danger to pedestrians. The electric scooter Kaabo Mantis could reach $20 \text{ km}\cdot\text{h}^{-1}$ in two-motor mode already in a distance of 5.32 meters, which can endanger both pedestrians and other drivers of electric scooters and bicycles. The different manoeuvrability of electric scooters and electric bicycles can also cause danger when there are several electric vehicles on the road at the same time. Besides, the electric bicycle Gogobest GF700 could reach a speed of $20 \text{ km}\cdot\text{h}^{-1}$ in a distance of 8.36 meters, which can cause insecurity when driving on sidewalks.

Conclusions

1. The good dynamic performance of electric scooters, due to their electric drive providing high torque at low speeds, can negatively impact road safety if used irresponsibly and if traffic regulations are violated.
2. In the acceleration experiments, the street-legal electric scooters achieved maximum acceleration in the range of 0.32 to $1.53 \text{ m}\cdot\text{s}^{-2}$ at speeds between 10 and $15 \text{ km}\cdot\text{h}^{-1}$, depending on driving mode. The acceleration of the off-road electric scooter was 122% faster, which created the potential danger of such electric vehicles when driving on sidewalks and cycle paths integrated into a single system with sidewalks.
3. When accelerating the electric bicycle with electric motor and pedal assistance, an average acceleration of $1.05 \text{ m}\cdot\text{s}^{-2}$ was achieved at speeds from 10 to $15 \text{ km}\cdot\text{h}^{-1}$. This dynamism characteristic is very similar in value to that of most electric scooters in average acceleration mode.
4. Electric scooters may pose a safety risk on sidewalks due to their high dynamic performance, as even street-legal e-scooters can reach $20 \text{ km}\cdot\text{h}^{-1}$ in as little as 3.78 seconds.
5. Electric scooters also have a very short acceleration distance. From a standing start, street-legal electric scooters can reach the maximum speed at a distance of 22.5 m, and $20 \text{ km}\cdot\text{h}^{-1}$ at a distance of 11.19 meters.
6. Analysis of the dynamic performance parameters of the off-road electric scooter indicates that it can reach $20 \text{ km}\cdot\text{h}^{-1}$ within a distance of 5.32 m. In maximum acceleration mode, it may present a risk of loss of control, as wheel slip of both driven wheels was subjectively observed by the test operator during acceleration.
7. Based on the subjective assessment of the test operator and the acceleration data, the electric bicycle appears to be a safer vehicle than the electric scooter, which is supported by the analysis of the obtained results. The street-legal electric scooter Ninebot KickScooter Max G2 reaches $25 \text{ km}\cdot\text{h}^{-1}$ over a distance that is 82.8% shorter than that of the Taouroll electric bicycle. Furthermore, the acceleration time of the electric bicycle is 69.8% longer compared to the electric scooter.

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Author contributions

D. B.: Conceptualization, methodology, validation, experiment, visualization, writing. I. J.: formal analysis, literature analysis, schedule administration, experimental investigation, writing – editing, references. J.L.B.: experiment, visualization, data analysis. All authors have read and agreed to the published version of the manuscript.

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