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Kinematic performance of micro-mobility vehicles during braking: experimental analysis and comparison between e-kick scooters and bikes

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Abstract

According to the Italian legislation, e-kick scooters and bikes are considered a single category of vehicles and can travel on the same infrastructures with the same rules; however, their kinematic behavior is very different.
The adoption of a bike as a vehicle for covering short distances i.e., within 5 km is widely known both at the kinematic level and for its use by users. Conversely, e-kick scooters are "unknown" vehicles both for their kinematic characteristics and for their use by users. A handful of studies have shown how the behavior of e-kick scooters and bikes is very different; however, there are not many studies that analyze the different kinematic behavior of e-kick scooters and bikes. This study presents an experimental analysis that evaluates braking behavior by comparing e-kick scooters and traditional bikes according to several vehicle speeds.
These analyzes help build a probabilistic mathematical model for estimating the stopping space of e-kick scooters and bikes. The availability of this model is crucial for the design of safe intersections between cycle paths and roads intended for motor vehicle traffic. Moreover, this model may reveal insights that could challenge the recent European regulations that equated e-kick scooters as bikes.

Keywords: micromobility; e-kick scooters: e-bikes; safety; braking distance

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1. Introduction

Modalities linked to urban mobility in areas with high population density in recent years are changing rapidly and considerably in relation to numerous causes. Mainly the private car is considered an unsustainable means of transport due to many externalities produced, such as greenhouse emissions, noise emissions, traffic congestion and road accidents (e.g., Zagorskas and Burinskienè, 2020). For this reason, mobility experts and urban planners are trying to change people's choice of transport modes by studying ways towards a social and environmental sustainability direction with less energy-consuming modes of travel such as walking, cycling and micro mobility (personal) vehicles. In this context, a growing interest in electric-powered Personal Mobility Vehicles (e-PMV) is emerging. They are small vehicles equipped with low power electric motors powered by a rechargeable battery that include many devices such as electric scooters, e-bikes and self-balancing devices and are convenient especially for covering short distances i.e., within 5 km (Boglietti et al, 2021). Nevertheless, the large spread of e-PVMs in the United States since 2017, and in several large European cities (e.g., Barcelona, Milan, and Paris) later have triggered issues because of an increase of crashes where e-PVMs were involved and raised several concerns.

On the one hand, these vehicles can reduce the use of existing public transport systems and of public spaces (Gössling, 2020). On the other hand, e-PVMs raise issues regarding safety owing to a deficiency of specific regulations (Bloom et al., 2020). Therefore, some European countries have taken remedial actions by issuing specific regulations for the circulation of e-PVMs, especially for e-kick scooters being the most popular. Since these vehicles are quite compact, specific regulations (such as the Italian one) equated e-kick scooters as bikes and provided indications regarding their circulation on cycling paths and traditional roads. However, e-kick scooters and bikes present different characteristics and, thus, the consistency of the equation between both vehicles is not so obvious. For instance, the cyclists are seated on their vehicle, whereas the e-kick scooter users travel upright above the footboard. Hence, a different vehicle-rider system scheme and a different position of the center of mass occur. Also, bikes have large wheels and tires, which could dissipate the shocks induced by the pavement irregularities and generate a stabilizing gyroscopic effect. Conversely, e-kick scooters are generally equipped with small diameter wheels, often made of a rigid material, which may not be able to induce significant dissipative and stabilizing effects. Moreover, different braking systems could be employed (e.g., V-brakes, disc brakes, electric brakes, friction brakes, etc.). Therefore, the similarity between bikes and e-kick scooters could be somehow questionable and the equation between the two vehicles made from some regulations could adversely affect the circulation safety. This is even more concerning if it considered that comparisons between the two vehicles have rarely been experimentally investigated in literature, as far as the authors know. Indeed, only Boglietti et al. (2022) explored the vibrational response (which can affect users' comfort during a ride) of e-kick scooters and bikes at the pavement irregularities, but narrowly a small sample of real data was analyzed. According with the preliminary results of this research, the e-kick scooters appeared to be globally less comfortable than the e-bikes. Analysis performed on wider sample of experimental data expanded with Monte Carlo simulation confirmed the different response of the two vehicles (Ventura et al., preprint).

Particularly, a key factor for the safety of a vehicle is its braking performance. Indeed, in an emergency scenario, such as the unexpected presence of an obstacle along the path, the driver must be able to stop his/her vehicle safely in a short distance, to avoid a potential and dangerous collision. On the one hand, the braking performance is a well know automotive research topic (e.g., Cho et al., 2006, Greibe, 2008). That literature has showed that the vehicle's braking distance depends on several factors pertaining to the vehicle, the road and the driver's behavior. The most important factors are the speed of the vehicle, the coefficient of friction between tires and roadway, the driver's braking behavior technique, the vehicle's braking system and condition, the tire pressure, the tire tread depth and road-holding capability, and the road's vertical grade (Greibe, 2007). The weather conditions have also proved to have a strong influence in the braking distance determination (Kordani et al., 2018). On the other hand, a handful of research investigated bicycle (e.g., Galanis et al, 2011, Rekilä et al, 2016) and e-kick scooter (Garman et al, 2020) braking performance separately. Nevertheless, as far as the authors know, no experimental studies have been carried out to compare bicycle and e-kick scooter braking behavior jointly. The proposed research aims to fill this gap.

2. Research objective

In the literature there are no models related to the quantification of the braking distance for vehicles intended for urban micro-mobility and the technical legislation only examines traditional vehicles, for this reason the objective of this research is modelling and experimental comparing the braking behavior of bikes and e-kick scooters, focusing on the factors that influence the braking distance, to investigate the safety of these vehicles. This analysis may reveal insights that could challenge the recent European regulations that equated e-kick scooters as bikes.

The approach was conducted with a direct experimental method, attempting to evaluate the variability of the phenomenon linked to the single braking maneuver and its systematic characteristics related to the type of vehicle and braking start speed. For the tests carried out, the effect of the different flooring was not considered and can be analyzed with further experimental tests.

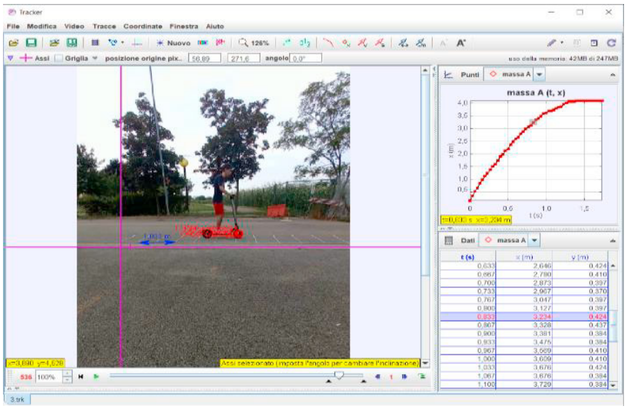
The work also intends to present a methodology that does not require scientific instruments but enables extremely accurate results to be achieved.

3. Methodological approach

Research tests involved several users of different weight and height, who were asked to drive an e-kick scooter and a e-bike on a dry (standard) paving with a good level of irregularity and under good climatic conditions. For carrying out the braking test, reference lines were traced on the pavement with chalk at 0.5 m from each other. Users drove at constant speed and began braking (without spinning the wheels) as the vehicle's front wheel reached the first reference line. The braking distance, i.e., the distance between the braking starting point and the point where the vehicle reached zero speed, was then measured with a tape. However, this measure was considered only for a preliminary assessment while the actual braking distance was assessed a posteriori with the procedure that will be highlighted, to obtain greater accuracy of the individual results.

The measurement procedure implemented involves evaluating the entire law of motion of the vehicle under braking through an image processing method. The goal is to evaluate with adequate accuracy the following parameters:

- speed of the vehicle at the start of the braking maneuver.
- spatial coordinate of the braking start point (being the reference mark on the ground only functional to a qualitative indication to the driver).
- instantaneous acceleration acting during the whole maneuver.
- spatial coordinate of the stopping point, and therefore the braking distance by difference.



t (s)	x (m)	y (m)
0,633	2,646	0,424
0,667	2,780	0,410
0,700	2,873	0,397
0,733	2,967	0,370
0,767	3,047	0,397
0,800	3,127	0,397
0,833	3,234	0,424
0,867	3,328	0,437
0,900	3,381	0,384
0,933	3,475	0,384
0,967	3,569	0,410
1,000	3,609	0,410
1,033	3,676	0,424
1,067	3,676	0,384
1,100	3,720	0,384

Fig. 1. Example of automatic estimation of the position of a reference point (target) during a braking maneuver (software "Tracker").

For this reason, the measurement procedure requires that each test is filmed using a fixed camera positioned on a tripod with a frequency of 30 fps.

Each vehicle examined is provided with a reference marker fixed on the front wheel center and on the steering head for the e-kick scooter and for the bicycle, respectively.

The videos were then analyzed with the free “Tracker” software that enables to associate the marker position with each time frame and with this it is possible to define the entire law of motion as a function of time.

An appropriate calibration operation of the software was carried out using the references marked on the ground every 0.5 m previously traced.

From the experimentally acquired data, a kinematic model of the braking maneuver was created. Evidence from the data showed that the braking action is very uniform and therefore a suitable model is that described by the uniformly accelerated motion of a rigid body.

Figure 2 shows the fitting on the experimental data for a kinematic model with constant acceleration (braking). The position data acquired through the movie shows an excellent representation by the model of the results obtained. The characteristics of the acquired movie and its calibration show a resolution of the measurement of the order of 0.018 m, while the linear regression model superimposed on the acquired values shows a residual standard deviation (σ_0) of 0.024 m. The two values are broadly compatible, and, for these purposes, it is reasonable to assume a category B (uniform distribution) standard uncertainty of 0.025 m. This reference value can be considered when evaluating the uncertainty associated with the braking distance.

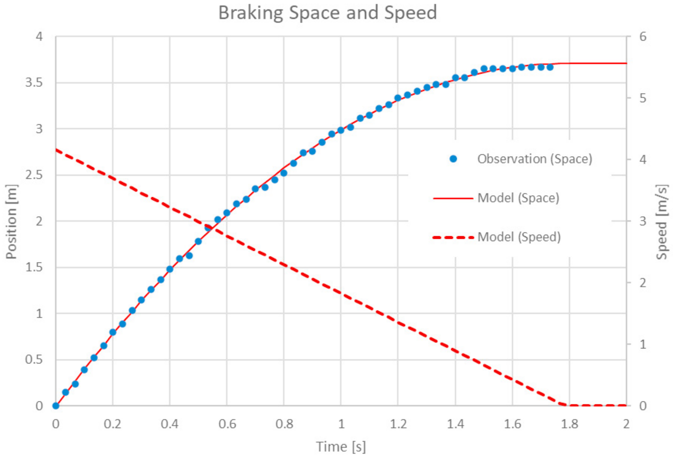


Fig. 2. Kinematic model of braking (experimental data and numerical model)

The model that was superimposed on the experimental data is:

$$x(t) = \sum_{i=1}^{3} \alpha_i \cdot \varphi_i(t) = \alpha_o \cdot 1 + \alpha_1 \cdot t + \alpha_2 \cdot t^2 \tag{1}$$

where α_o indicates the position, with respect to the spatial abscissa, of the braking start point, α_1 indicates the initial speed of the maneuver (i.e., V_i,), α_2 and indicates half of the braking acceleration (negative) (i.e., *acc*)

$$x(t) = x_o + V_i \cdot t + \frac{1}{2} acc \cdot t^2 \tag{2}$$

The kinematic parameters for braking distance, initial speed and braking acceleration are estimated by the linear regression method including their measurement uncertainty.

From the regression model it is possible to define the value of constant acceleration along the entire maneuver that in the indicated case is equal to 2.330 m/s^2, while the standard uncertainty value is equal to 0.030 m/s^2, less than 1.5% of the value.

4. Experimental data collection

The tests were conducted on the same bituminous road surface, with different vehicles (one bicycle and one electric scooter) and with different subjects (3 different drivers) repeating the tests several times and at different vehicle speeds for a total of 75 tests.

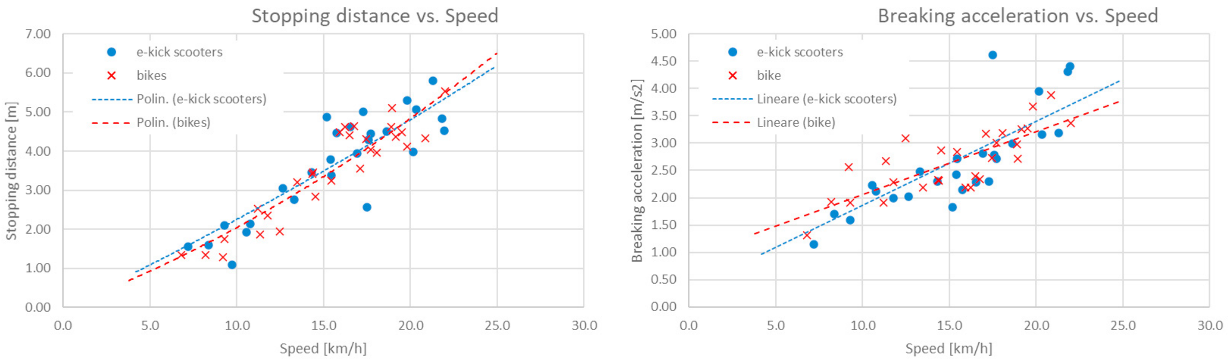


Fig. 3. Stopping distance Vs. Speed (a) and Breaking acceleration Vs. Speed (b) for e-kick scooters and bikes

Figure 3(a) shows the overall results for e-kick scooters and bikes. From the equation of motion (1), it is possible to also estimate the value of the average acceleration and it emerges that not only the distribution of this is random, but there is a dependence between the initial speed of the vehicle and the intensity of braking (value of acceleration), as shown in figure 3(b). The experimental tests show that there is no significant difference, at least graphically, between the two types of vehicles. On the evaluation of the average braking acceleration, therefore common to all tests and therefore comparable, both the T-test to see the dependence on the type of vehicle, and the one-way ANOVA analysis were performed to verify the dependence of the acceleration of vehicle braked by the vehicle type and by the driver.

The results of the T-test show that, for the type of vehicle, there is no significant difference (P-Value = 0.472). Analogous result for the one-way ANOVA (significance equal to 0.945≫0.05). This evidence suggests that e-kick scooters and bikes exhibit a similar behavior in terms of braking performance.

For the dependence on the single driver (3 different people) the one-way ANOVA showed a limited dependence (significance equal to 0.235> 0.05), indicating that the intensity of the maneuver is moderately correlated to the driving confidence of the single individual.

Finally, two-way ANOVA with replication was conducted which confirmed the results obtained previously.

Table 1. Two-way ANOVA results

Parameter	SQ	MQ	F	P-Value (α)	F crit
Vehicle (e- kick scooters and bikes)	0.3619	0.1809	0.5056	0.6067	3.21994
Test	0.0235	0.0235	0.0658	0.7987	4.07265
Driver (D_1, D_2, D_3)	1.4705	0.7352	2.0543	0.1409	3.21994

5. Discussion

Experimental tests have shown that, in general, during individual braking maneuvers the acceleration is constant (Fig. 3), however this is highly variable for each individual test (Fig.4). This not only varies for each individual case, but it is also strongly correlated with the initial speed of the vehicle. It clearly emerges that the intensity of braking (acceleration) increases with increasing vehicle speed.

A regression model was constructed to calculate acceleration as a function of speed and vehicle type. The model provides good significance ($R^2 = 0.972$); however, there is no significance for vehicle type dependence (P-Value>0.6). Conversely, the dependence on speed has a significant influence on the intensity of braking (P-Value<0.05), as showed in Table 2. Hence, the residual plots were analyzed, and the validity of the proposed regression model was endorsed since normality and homoscedasticity assumptions were confirmed.

Moreover, Analysis of Variance (ANOVA) confirmed that for braking acceleration there is no significant difference when varying user and vehicle type.

Therefore, the model that is proposed turns out following:

$$acc = \alpha_o + \alpha_1 V_i \tag{3}$$

while the stopping space is

$$S_0 = \frac{1}{2} \cdot \frac{{V_i}^2}{acc} \tag{4}$$

From the acquired data it results that the model is

Table 2. Regression model for breaking acceleration (eq. 3).

Parameter	Value	Standard Deviation	P-Value (α)
α_0 [m/s^2]	0.759.	0.255	0.0043
α_1 [1/s]	0.445	0.057	<0.0001

with $\sigma_0 = 0.478\ m/s^2$ and $R^2 = 0.971$.

This model considers both the velocity dependence of the braking intensity (Eq. 3) and the intrinsic variability of the phenomenon (σ_0) and enables to predict, in a statistical way, the stopping distance for the vehicle.

Equation (4) deterministically predicts stopping distance based on a kinematic model of motion (uniformly accelerated rectilinear motion), but the value of the braking acceleration must be considered a random variable with a component of dependence on vehicle speed (equation 3) and a random component independent of vehicle type and individual driver. The random component was described as a normal (gauss) distribution with zero mean and standard deviation equal to σ_0.

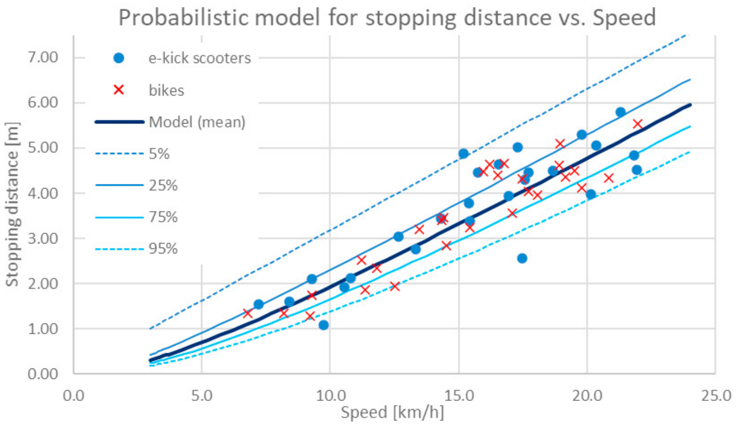


Fig. 4. Stopping distance Vs. Speed for e-kick scooters and bikes

The model thus created allows estimating the stopping distance as a function of vehicle speed. It is probabilistic and considers both the systematic component (speed dependence) and the random component (variability of the single maneuver), but the evidence of the acquired data shows that there is no dependence of the type of vehicle (e-kick scooters and bikes).

Figure 4 shows the performance of the model in terms of mean (thick blue line) and probabilistic at 5%-25%-75%-95% (dashed lines), superimposed on the experimental observations.

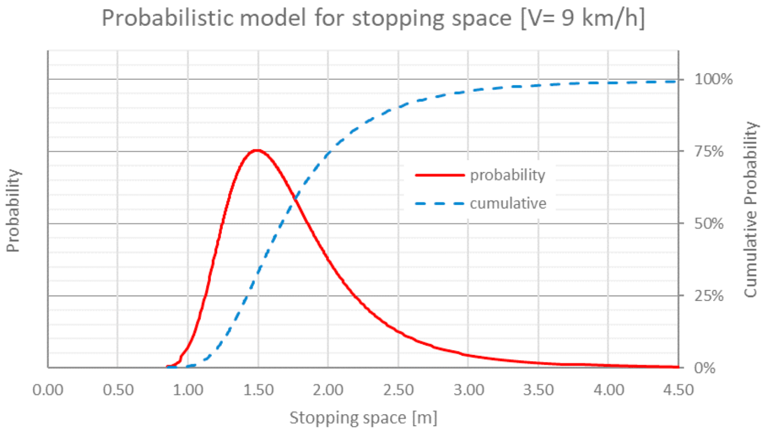


Fig. 5. Stopping distance Vs. Speed – probabilistic model

The graph in Figure 5 depicts the trend set at an approach speed (9 km/h in this case) with the confidence level where a certain percentage of the vehicles considered are expected to stop.

The model shows, as an example, that the stopping distance of 1.42 m, 1.67 m, and 2.02 m are expected to be not overcome in the 25%, 50%, and 75% of braking maneuvers, respectively.

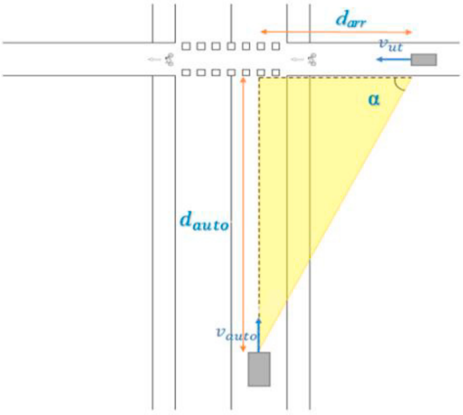


Fig. 6. Angle of view for intersections between roads and cycle paths

The determination of this stopping distance is of paramount importance in defining the required sight cones at bicycle crossings to ensure the safety of all road users, as shown in Figure 6. The proposed model allows to determine this distance also in a probabilistic way, thus considering the subjectivity of individual drivers of two-wheeled vehicles and has been calibrated on experimental observations.

6. Conclusion

This study work examines the braking and stopping maneuver for two-wheeled alleys and in particular e-kick scooters and conventional bicycles. Recently the legislator has equalized in Italy these two types of vehicles, however there are no comparative analyses in literature on the kinematic behavior of the two vehicles. The work presents a quantitative experimental methodology for the evaluation of the braking and stopping maneuver based on the processing of video footage. The experimental tests have shown that there is no significant difference for the evaluation of the maximum braking acceleration for the two types of vehicles, as well as there is no significant dependence of variability between the different users. These results are confirmed both by the ANOVA analysis and by the linear regression performed on the experimental data. Therefore, while Boglietti et al. (2022) objected the equation between e-kick sooters and e-bikes made by some European regulations by showing that the formers are globally less comfortable than the latter in terms of vibrational response at pavement irregularities, e-kick sooters and bikes appeared to have a similar behavior when braking performance is concerned.

Conversely, the experimental tests have shown a strong dependence of the braking acceleration value (maneuver effectiveness) on the vehicle speed. The higher the approach speed, the greater the braking intensity. Finally, the residual variability of the observations with respect to a central trend model is rather large and cannot be neglected. Therefore, a probabilistic mathematical model has been developed which considers, for the evaluation of the stopping space, both the functional dependence on the speed and the random component linked to the single replication of the maneuver. The proposed model, in addition to having been experimentally calibrated, can be successfully used to predict visual cones in the design of cycle crossings.

However, some limitations remain, for example: a) only a dry (standard) paving under good climatic conditions. was investigated; b) only two vehicles (i.e., one bicycle and one electric scooter) and 3 different drivers were considered. Further analyzes will be carried out in a real-world city context, using the same experimental approach, to investigate how surfaces with different levels of irregularity (e.g., uneven cobblestones, bituminous conglomerate, metal ventilation grids, smooth stone pavement. dirt road, etc.) under various climatic conditions (e.g., rain, ice, etc.) could influence braking performance. Moreover, different models of bicycles and electric scooter will be considered to accounting for different vehicular features and wider group of drivers chosen among habitual users will be involved.

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