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E-Scooter Presence in Urban Areas: Are Consistent Rules, Paying Attention and Smooth Infrastructure Enough for Safety?

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Abstract: Electric micromobility represents a sustainable mobility option for specific classes of users and distance thresholds. Had this mobility solution been integrated into a comprehensive mobility framework from the beginning, it would have expanded the coverage and accessibility of urban transit services. Instead, slow and incoherent regulation has established a contrast between enthusiastic users (who consider electric micromobility vehicles "fun" and "easy to use") and recalcitrant public opinion (wherein electric micromobility vehicles are deemed "unsafe" and "dangerous"). Beyond the few attempts made by transport experts to assess the capability of e-scooters to become a sound mobility option (through mobility surveys, pattern analysis, fleet and routing problems), safety and infrastructure design should be developed in a consistent way in order to guarantee a balanced transport setting. With respect to this challenge, a methodology framework is proposed to address the increasing proliferation of micromobility in the context of a coherent transport system. Special attention is devoted to those aspects that have received less attention from the scientific community, namely infrastructure and safe interactions at intersections. The similarities and differences between e-scooters and bikes, chosen in this study as the representative of traditional soft mobility modes, have been taken into consideration. To support the proposed approach, tests investigating e-scooter performance and the perception of both the modes at safety-critical nodes (such as intersections) under different conditions are presented, and the methodology can be applied to a variety of urban scales. The results can be adopted by local authorities, transport companies and e-mobility providers to optimize infrastructure and increase the number and quality of available mobility options.

Keywords: e-scooter; safety; sustainable mobility; user behaviour; transportation

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1. Introduction

Despite all efforts undertaken towards sustainable mobility, people still mostly rely on the car for their urban mobility, and the average motorisation rate in Europe is still relevant (i.e., the EU-28 demonstrates an average of around 600 cars per 1000 inhabitants, with Italy ranking 2nd with 646, according to Eurostat, 2021) [1–4]. In response to these issues and to contribute to the reduction of the transport carbon footprint [5], governments have set challenging objectives for the reduction of climbing transport emissions and have promoted the concept of sustainable, inclusive and more liveable cities. Specifically, strong attention has been paid to the promotion of less intrusive modes of transport as well as to the balanced and integrated development of all transport options [6]. Researchers have been trying to understand the main determinants of modal choice in order to find strategies to promote the adoption of environmentally sustainable habits. One fascinating line of research attempted to categorise users in order to identify some peculiar characteristics on which to base interventions and develop persuasive actions [7–9]. One of the earliest attempts to investigate the mechanisms concerning modal choice from a sociological perspective (though only car, bike and public transport were included at that time) was proposed by [10], while the grouping of users into car owners (i.e., malcontent motorists, complacent car addicts, die-hard drivers, aspiring environmentalists) and non-car owners (i.e., car-less crusaders, reluctant riders) based on the Theory of Planned Behaviour (see [11]) was proposed by [12]. The outcomes of the two works were different: while the former concluded that ad hoc strategies to promote behavioural change for each identified group were unrealistic, the latter found the opposite. Users' travel behaviour was differentiated based on objective measures such as the weekly mileage of different transport modes by [13], showing that travel patterns could not be explained by socio-economic characteristics alone and that strong users of a given mode seemed more willing to balance their modal consumption. Similarly, [14] clustered road users based on their self-reported frequency of mode use and performed a latent class cluster analysis exploring the effects of socio-demographic and attitudinal dimensions towards each mode of transport. However, "the same behaviour can take place for different reasons and the same attitudes can lead to different behaviours" [11]. Indeed, a plethora of different factors influence modal choice: psychosocial ones such as values, attitudes and perceptions [15,16], environmental and spatial ones such as urban density, public transport accessibility or geographical aspects [17–19], behavioural ones such as habits or previous experience [20,21] as well as travel characteristics such as travel distance or time [22–24].

One of the main reasons for high car use is the low performance of public transport services in satisfying users' needs along complex trip chains (see the seminal works of [25]) due to shortcomings involving accessibility, attractiveness, integration and the level of service (i.e., punctuality and reliability), as explained recently by [26]. However, urban mobility analysis and data from Sustainable Urban Mobility Plans (SUMPs) show that the average daily displacement often has limited spatial extension and time horizons which would be well suited to sustainable transport habits such as mass transport or shared or light mobility solutions (i.e., pedestrian or cycling). The reliance on private cars contributes to road congestion, which damages liveability from the spatial (reduced accessibility, delays), social (a high risk of accidents, the reduced performance of collective transport services) and environmental (pollution) points of view. The concept of sustainable mobility encompasses solutions to reduce the external impact of private transport on the environment (but also on social and economic aspects), often with a focus on technological and innovative components. In recent years, shared micromobility options have become increasingly popular in many cities worldwide and have exhibited dramatic expansion compared to other sharing services of the past [27–29]. From an operational point of view, a typical company puts a fleet of vehicles at the disposal of its users, allowing rentals by means of a smartphone application and a per-minute fee within a service area [30]. The earliest bike-sharing services in Europe date back to the early 2000s, with recent figures claiming more than 1.5k cities involved and 1.8×10^7 vehicles deployed [31,32]. Shared e-bike services allow for higher speed and range, and include the elderly and people with poor athletic habits into the pool of potential users. Thanks to SUMPs and trip planning tools, bike sharing has been integrated into a mobility paradigm to reduce externalities, fight congestion, support healthy lifestyles and provide a low-carbon solution to the "last mile" issue (i.e., by bridging the gaps between existing transportation networks, which is also helpful for tourism-related activities [33,34]). Beyond the positive aspects, bike sharing services have failed in (i) fighting social exclusion; (ii) providing a feasible transport alternative due to the reduced size of the fleet; (iii) being transparent as far as purposes, benefits, economic sustainability and success metrics are concerned; and (iv) building a comprehensive integrated transport plan aiming at sustainability [35]. Infrastructure quality and the financial management of the service, that is, finding a balance between keeping fares low and high running costs, are two additional issues.

Individual electric micromobility is an even more recent solution involving short trips performed with small vehicles such as electric scooters (which are referred to in the literature as e-scooters or e-kickscooters; the latter option better underlines the fact that the motion of the vehicle is started by the leg of the driver), monowheels, etc., which are gaining a primary role in terms of diffusion both as a shared and individual mobility solution [36]. McKinsey data show that investments in micromobility were huge before (USD 7 billion between 2015–2019) and throughout (USD 2.9 billion in 2021) the pandemic, which also sets a turning point as far as investor type, vehicle type and geography are concerned: while in the pre-pandemic era, Asia was the leading market, Europe has taken the lead since 2020, likely due to the accelerated policy measures, as well as to the relevant growth of many European players. E-scooters attracted twice as much fundings as bicycles and ten times that of mopeds in the 2018–2022 period, and the gap is still widening. Institutional investors (banks, venture capitalists and private-equity firms) issued around 92% of the total $8.4 billion in the past, but now the cash flow from the bigger providers is rising, both in the field of supporting services (such as parking and charging solutions) and for strengthening their market position via mergers and acquisitions [37].

Although such systems cannot conceivably replace cars due to reduced comfort, perceived safety and different spatial and temporal scales of displacement (travel time/distance, partial network coverage), shaping their integration with existing transit from a policy point of view would help in satisfying users' displacement needs along their trip chain and contribute to the re-development of the urban space [38–40]. Many researchers have claimed that the combination of micromobility and transit possesses an interesting synergy and is likely to provide fast and accessible transit options while also increasing sustainability, efficiency, and equity [41–45]. The majority of studies discussing the potential of micromobility to replace car trips and to improve transit coverage are based on investigating mode choice behaviour [46–48]. Some surveys show that e-scooters often replace trips on foot [49,50] and more rarely trips by car. A large share of trips are undertaken for fun and leisure purposes [46], likely due to the novelty effect. Supporters of integration between micromobility and transit systems stress that the average distance travelled by micromobility users is consistent with first/last mile displacement [27,51]. Micromobility can have a positive effect on easing vehicular congestion on roads; on the other hand, illegal behaviour and space sharing issues in urban areas have been highlighted. One additional topic that has been widely investigated is fleet design and optimal positioning, also taking into account vehicles' features such as electric batteries, charging point location and maintenance. Guidelines on sustainable mobility encourage the new design of urban space, by prioritizing new or larger bike and pedestrian lanes and low speed zones, to reduce conflicts with private cars and other safety issues [6]. From the market side, e-scooter sharing services have similar issues to car- and bike-sharing services: an effective and successful plan must integrate planning, design, business, users' need and cooperative efforts between the public (regulator) and private (service provider and developer) sectors [52]. Contrary to that too much focus has been placed on (i) safety, (ii) surrogate safety measures such as reduced spacing, which may complicate interactions with other road users, and (iii) technological aspects to attract investment and advertising; on the other hand, mobility and transport science insights tend to be mostly disregarded [53]. This paper builds from the research of [53], which claims that electric micromobility is yet to find its place within the transport system framework: are e-scooters competitors of private cars, of mass transport or of active light mobility? In addition, how can e-micromobility be integrated in a profitable way into the urban mobility framework?

The methodology proposed is described in Figure 1 below.

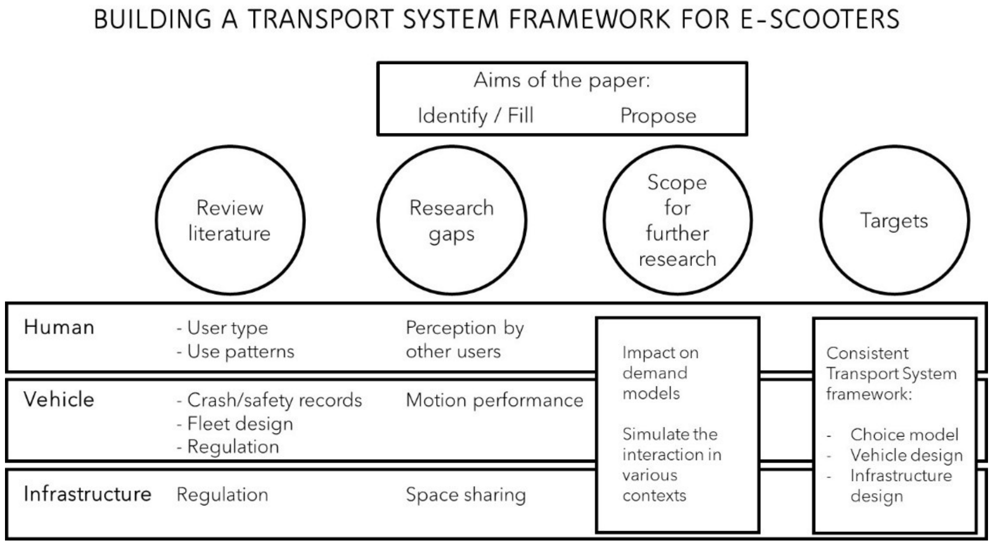

Figure 1. Methodology (authors' elaboration).

A summary and discussion of the existing body of literature is needed to clarify the boundaries of this paper and to identify the main research gaps. Section 2 of this paper will provide an extensive—although partial—overview of the topics dealt with and of the main findings highlighted by research teams worldwide, in order to identify commonalities and differences. What is missing is the holistic framework, in which transportation science insights are also included. The aim of this paper then is to identify and address some research gaps that appear overlooked by the existing body of literature and to outline a way forward for the research community towards the definition of the holistic framework mentioned above, which should identify to what extent and under which conditions electric micromobility vehicles—such as e-scooters—impact existing transport systems.

The main research gaps identified are reported in Figure 1 and can be summarized into: the descriptions of motion and mechanic performance, which have an impact on safety, regulations and the definitions of the transport framework; the conspicuity and perception assessment, to evaluate whether regulation is consistent with facts or adds a burden to the safety of road users; and the investigation of the interaction between different user groups at network nodes such as intersections. In Section 3, tests and surveys carried out will be presented, discussed and justified; the advances with reference to the existing literature are presented. In particular, the main research questions investigated are as follows. (i) Are bikes and e-scooters actually perceived as the same, in particular by car drivers with whom interactions frequently happen at crossings? Does the perception change depending upon varying external conditions? (ii) How is it possible to describe the e-scooter motion? Are acceleration, braking and vibrations transmitted by the infrastructure to the rider overlooked by non-experienced drivers?

In Section 4, the results and findings will be presented and discussed. Finally, in Section 5, the conclusion and shortcomings are presented and a way forward is proposed regarding how to use these research results in future discussion and research. The envisaged common goal is the definition of a consistent transport framework which keeps in mind the user (e.g., the need to modify choice models in the wake of the pandemic and ongoing discussion on the mobility of the future), the vehicle (e.g., can e-scooters be made safer than they are now?) and the infrastructure (e.g., the relationship between urban space, mobility and users should be adapted to the changing framework which has sustainability at its core).

2. Literature Review

The modern e-scooter is based on a motorized prototype dating back to 1915. Its present success is due to a skilful marketing focused on its alleged environmental sustainability made possible by electric propulsion [54]. On the other hand, lifecycle analyses (for example, [55,56]) show that e-scooters are still as polluting as cars (or even more so) and have a very short lifespan.

Recent data on e-scooter diffusion (1.8 million users in 85 cities in 2017; 350 active services and 86 million trips in 2019), operators and fleets are manifold [57–60], while there are no homogeneous data on their diffusion as private vehicles. If, on the one hand, the COVID-19 pandemic had the effect of reducing the use of all non-individual transport systems—due to the combined effects of the fear of contagion, restrictions on mobility and the spread of smart-working/distance learning—then on the other hand, measures and incentives to encourage sustainable mobility have produced a significant increase in the sales of pedal-assisted bikes and e-scooters in various countries, thus strongly affecting people's mobility habits. In Italy, the shared e-scooter fleet rose from 4650 to 27,850 samples in a very short time, overreaching the bike sharing free-float fleet, and the number of daily rentals in a city sample rose from 50 to 750 over a few months against flat figures for traditional shared mobility services (cars, bicycles) [61]. The reasons behind the modal choice are varied [62], encompassing the area of origin, the socio-economic context, the cultural background, the education and the degree of confidence with technology [63]. For example, [64] note that e-scooters are perceived as cheaper than private or shared cars; while [65] argue that the use of e-scooters is led by environmental concerns.

2.1. Classification of Individual Micromobility Vehicles

Attempts to classify individual micromobility vehicles (electric or not) are summarized in [66,67]. A comparison between e-scooters and bikes entails the following aspects: both have a longitudinal chassis, two wheels and a handlebar that acts directly on the steering wheel; on the other hand, e-scooters exhibit smaller wheels (as small as 10″, which make sudden steering and driving along irregular surfaces complicated), while bikes have longer axle spacing and greater spacing between the centre of gravity and the front axle. What is more, e-scooters are driven from a standing position which increase the chances of the loss of stability [68] both in acceleration, upon changing direction and while braking. Finally, e-bikes and e-scooters exhibit similar peak speeds, which is higher than that of traditional bikes; however, e-bikes are heavier. In conclusion, bikes are more stable both upon increasing speed and when braking, while e-scooters allow seamless motion due to their reduced dimensions.

2.2. Interaction with Infrastructure, Other Road Users and Collision Dynamics

The phases of an accident include the identification of danger, the collision and the evaluation of trauma. While the latter aspect relies on onboard passive safety systems, the former phases involve the driver's readiness, the quality and effectiveness of his manoeuvres and the active safety systems onboard [69]. With regard to road traffic, it is essential to guarantee safety at the highest degree for all users and in all conditions, regardless of assumptions of user behaviour; on the other hand, even negotiating a common space entails a potential risk source. The concepts of visibility and perception deeply affect the driver's choices. Perception is the outcome of a personal and subjective understanding, which is affected by emotions, knowledge and factors such as age, gender, culture, prudence and previous experience. A fairly recent contribution to this topic is provided by [70]. The concept of visibility is twofold, as it includes both if and how much an object is perceptible by an external observer and the ability of the observer to perceive their surroundings. It is explained in [71,72] that a driver tends to fix his gaze farther away with increasing speed, in order to take apparently motionless objects as a reference; thus reducing the amplitude of the visual field and excluding objects placed laterally.

The design of infrastructure and signage plays a fundamental role in perception, as demonstrated by [73], referring to how vegetation and road furniture affect the minimum visibility distance. Another fundamental aspect to be considered is the concept of "looked-but-failed-to-see" [74,75]. Furthermore, car drivers appear to grant greater gaps to approaching cyclists if there is also a car in their visual field, implying that the driver perceives the weak user approaching as less dangerous than a vehicle of similar size. Moreover, [76] suggest that motorists tend to develop aggressive behaviour towards potential sources of danger and disturbance; [77] concluded that cyclists' safety is harmed if they are seen as anomalous compared to ordinary circulation. It is argued in [78,79] that high infrastructure expenditure and a high percentage of drivers accustomed to soft mobility favours the adoption of respectful behaviour towards weak users and the reduction of accidentality. These studies investigate the car–bike relationship; to the authors' knowledge the car–e-scooter relationship is still poorly investigated. In general, an improvement in safety has been observed as the diffusion and acceptance of bikes has progressed. The transferability of this improvement to e-scooters is not ensured, considering the stigma, the high resonance attributed to the growing accidentality and the high growth rate of e-scooters with respect to pre-existing transport solutions.

A collision between a car and a weak user involves differing masses of about an order of magnitude; while the occupants of the car are protected by the chassis, the salvation of the weak user depends on their individual protective equipment (if mandatory) and on the external shape of the impacting vehicle. Pedestrians, cyclists and e-scooter users exhibit quite different impact dynamics: [80] observe that, in most pedestrian–vehicle accidents, the impact is frontal or front-lateral and the acceleration depends on the direction, structure, height and speed of the impacting vehicle. The literature classifies impact types by varying the impact speed and reports formulas computing projection distance as a function of impact speed, friction, the masses involved, the height of the centre of gravity, the slope of the road and the braking effect [81–83]. The 3D simulation of the impact allows for the evaluation of the lesions thanks to a biomechanical model of the human body and parameters such as the HIC (Head Injury Criterion), TTI (Thoracic Trauma Index) and maximum instantaneous force at the time of impact. The authors of [84] investigated impacts with SUVs or buses and their outcomes based on the impact being frontal or lateral, whereas [85] focused on cyclist–car lateral impacts under varying speeds. Additionally, [86] observed that the head–windscreen impact point is higher and takes place at a greater speed than for pedestrian. Impacts between cars and several weak users (pedestrians, cyclists and monowheel/scooter users) in terms of head damage are compared in [87], observing that the latter might suffer minor injuries, as the risk of being raised from the ground is mitigated by the vehicle absorbing part of the impact. Finally, the only study on the collision dynamics of e-scooters is by [88], although it is limited to four scenarios in which the e-scooter hits a standing car at various speeds: in front and side impacts, the driver impacts the car hood after dissipating part of the energy in flight; if the impact takes place against the car strut, head lesions are more severe; the main determinants are the erect/curled position and the position of the arms. In addition, the reduced friction increases the probability of damage to the lower limbs compared to incidents involving pedestrians and the different dynamic causes greater head-to-windscreen impact speed. Again, speeding makes it possible for impact scenarios to involve the entire perimeter of the car. Compared to the cyclist, the decoupling between an e-scooter and its driver after the impact is more likely. As for events caused by poor road surfaces, a recent study by [89] investigates the characteristics of the head–ground impact on varying the size of the pothole and the speed of the e-scooter, finding that (i) the probability of falling increases if the depth of the hole exceeds 3 cm, (ii) the impact force on the ground is higher than the threshold of cranium fracture and (iii) the impact speed on the ground is comparable to bike falls. Many studies compare bicycles and e-scooters in terms of kinematics and safety; Refs. [67,90,91] compare the vibrational events associated with the motion of e-scooters and bicycles on different surfaces under varying speeds, concluding that e-scooters undergo more and more intense vibrational events, which depend on the road surface (materials and regularity) and the lower diameter of the wheels, thus affecting motion comfort. The authors of [91] add that vehicles not equipped with shock absorbers are even less stable, as the vibrations induced by the potholes adds to those resulting from the longitudinal profile of the road. The braking performance is investigated in [92], concluding that the configuration with two levers on the handlebar acting separately on both wheels is more efficient, while the configuration with one lever and a pedal acting on the rear wheel is less efficient but safer against the rollover, which is a typical phenomenon of the e-scooter's motion due to the standing driving position, the distribution of weights during the braking and the consequent shift of the centre of gravity. The same authors report that many users would rather omit the showing of their intention to turn by raising one of two hands from the handlebar than lose control of either throttle or brake levers.

2.3. Research Topics

To the authors' knowledge, the scientific literature on e-scooters follows these main research lines:

Insertion into the urban context: vandalism [93] and incorrect behavior [94]—with particular reference to inappropriate parking [95] and the potential overcrowding of cycle paths [96]—are often mentioned. The fact that users have approximate knowledge of the rules is highlighted in [97]: 13% and 46% of users consider parking on sidewalks and in bike racks, respectively, to be lawful, and 17% would park against a construction. Three out of four interviewees have never seen an area reserved for e-scooter parking. Other violations include speeding, driving against the flow of traffic, carrying a passenger and driving along unallowed areas. Those conclusions are partly contradicted by [98], whose video footage demonstrates lesser violations, mainly of the driving against the flow of traffic and lack of helmet use types.

Choice paradigm and user behavior: studies about space–time use patterns are nourished by the data provided by local operators [99–103]. Furthermore, attributes of modal choice [104–106] and the integration with other means of transport [29,107–111] are investigated. Many studies focus on one or two cities: [97] ranks use motivation; [98] involves over 2000 users—both residents and tourists—exhibiting an average trip of 3.5 km for residents and 4.6 km for tourists and information on the replaced means of transport. The authors of [28] focus on data from 28,502 e-scooters between August 2018 and February 2019 in Austin, detecting an average of 11,358 trips/day (peak of 23,417) and more intense usage on the weekends. As for the spatial characterization, the denser use of e-scooters in areas with plenty of cycle infrastructure suggests a link between these two factors. Finally, the authors noted that user type (e.g., students) is more relevant than income in the choice paradigm. Studies carried out at the EU level show different results: [112] confute the hypothesis that e-scooters support eco-sustainable choices, as the replaced modal alternatives are mainly foot and public transport. The same paper provides interesting data on the average search time of an available vehicle (3–4 min, comparable with the search time of a free parking slot by car), the average use duration and motivation (mainly leisure trips, which justify the short duration of the rentals; however, for non-leisure movements, longer routes and a perception of saving time and money is reported). The low average trip length is confirmed by [51], in addition to the split 90% vs. 10% between trips undertaken with shared and owned e-scooters. In this study, the majority of the interviewees used an e-scooter at least once, exhibiting merit for its practicality compared to public transport or going on foot; in addition, 40% perceived positive effects regarding the reduction of pollution and traffic and considered e-scooters to be an effective remedy to the deficiencies of public transport. A further distinction in the paradigms of use between those who own the vehicle and those who rent it is highlighted by [100], according to which owners exhibit frequent use (several times a week), while rentals happen rarely (a few times per month), mainly replacing foot or public transport trips with the aim of saving time. The use of the e-scooter in routine trips over a period of 45 days is investigated in [113], discussing the average and total distance covered, and the main use motivations. The impacts of socio-demographics, car ownership, perception in terms of comfort and chaotic road circulation on the willingness to rent a micromobility vehicle were assessed with an ordered logit model in a case study in the south of Italy [114]. A classification tree model and a latent variable logit model were used to identify the characteristics of people attracted by e-scooters and the attributes explaining regular use [50]. An interesting line of research is proposed by [115,116] who include the gender perspective in sustainable mobility choices. Finally, a holistic approach on 30 European cities shows similar use patterns within the same country and mainly on the weekends, short trips (an average distance of 0.91–1.79 km and an average duration of 5.67–13.77 min), higher use frequency in northern Europe and a positive correlation between e-scooter density, the ratio of e-scooters to inhabitants and the intensity of use [117].

- On changing geographical context, a survey on electric micromobility carried out in the Middle East reports that the greatest barriers to e-scooter usage are the deficiency of infrastructure, followed by the weather and poor safety. Most of the interviewees had never used an e-scooter (82%) or had used one once (10%; mainly abroad). Similar to the EU, the prevalent use motivation was leisure, replacing (if available) public transport or ride-hailing services (taxis, Uber, etc.) [60].
- Safety: the perception of low safety is one of the major barriers to e-scooter usage and in many cities an increase in accidents was evident after e-scooter pilot deployment took place [118]. Given that only events involving the police, medical teams, or insurance companies are registered, these figures could be strongly underestimated, as it already holds for accidents involving bikes. The most recurring accident type involves only the driver, mainly due to the lack of familiarity with the vehicle or to deficient instructions provided by the provider, following the adage "sell first, safety later" [119,120]. A recent study in New Zealand found that the total cost of e-scooter injuries over the course of 7 months was over GBP 650,000, with an average of GBP 850/injury [121]. The literature focuses mainly on accident databases (e.g., [122,123]), the type and location of lesions and the use of personal protection (although non-compulsory, helmets are used by less than 5% of users [91,124,125]). Other works surveyed access to emergency rooms following e-scooter events [126,127], showing that a relevant share of the events happened within the tenth trip and listing the main reported causes (i.e., irregular surface, followed by allegedly faulty vehicle, and collision with another vehicle or with fixed obstacles). The same sources emphasize that 40% injures involve non-residents and 16% of injuries follow a rule infringement (i.e., driving in a state of intoxication or carrying a passenger). The incidence of e-scooter events among hospitalization records of minors, people hit and people under the influence is investigated in [128]. In summary, the majority of the events involving e-scooters appear to be linked to the surprise effect/a lack of experience, dangerous behavior and poor infrastructure (extension and quality). Events on the road and involving frequent users are more severe, perhaps due to higher speeds.

The following table summarizes the main motivations referred to in the literature: relative to the negative aspects in Table 1, [90] claim that e-scooter users overjudge the vehicle's agility while being unaware of endangering other road users, while [98] claim that improper behaviour is usually due to misinformation about the rules and limitations. These results justify the reluctance to share the same infrastructure with different types of users; moreover, urgent decision-making should pursue homogeneous circulation rules and requirements (minimum age, the use of helmets, maximum speed, insurance, user punishment profiles, differences between personal and shared use, etc.). In some cases, extreme measures have been taken following safety-critical events: the pilot project in Miami was temporarily suspended in 2019 due to repeated cases of misuse and rising injury figures and then reactivated in 2022 on the condition that the police were allowed to issue fines. The Independent.co.uk reports that carrying e-scooters onboard public transport vehicles in London was forbidden in 2021 following the explosion of a lithium-ion battery.

Table 1. Summary of main pros and cons of e-scooters (authors' elaboration).

Pros	Cons
Easy to use and easy to park	Low-quality infrastructure
Low-cost solution	Misperception by other road users
Reduced travel time compared to car, public transport and foot/bike	Imprudent behaviour by individual users and towards weak users
Contributes to reduced urban congestion	Mistrust and sense of impunity

2.4. Regulation

In 2021 incentives to buy e-vehicles for individual micromobility purposes were issued, but the regulator took no action on making registration, side mirrors or plates compulsory, nor on how to deal with users' improper behaviour outside flagrant offences.

Innovations in the form of stricter guidelines other than those stated in Table 2 have been embedded in recent tenders, such as in Rome, where:

- Operators will decrease from 7 to 3: each successful bidder will be allowed to supply between 2500 and 3000 vehicles, with up to an additional 1500 vehicles per bidder allowed if a few supply and service criteria are satisfied in areas close to at least 20 railway and underground stations;
- The concession lasts for 3 years; the fee per vehicle to be paid to the municipality is EUR 1–4/month;
- A maximum of 3000 vehicles are allowed in the central areas, while the remainder will be split over a total area of 95 km^2;
- The location of vehicles will be monitored automatically every hour. In the event of repeated infringements, suspension and revocation are possible;
- Bidders must have already operated an authorized service inclusive of more than 1000 vehicles in cities bigger than 750,000 inhabitants;
- Both allowed or prohibited parking areas are defined by the municipality of Rome;
- Vehicles must be equipped with metal plate and QR code to allow immediate identification; speed will be adjusted automatically from 20 km/h to 6 km/h in pedestrian areas;
- Rental is permitted only to people over 18 after a compulsory registration with a valid identity card.

Choice criteria (with weights) include maintenance, fleet control and redistribution systems, customer relations, environmental sustainability, the possibility of offering season tickets and reductions/discounts for public transport users. The rationale of the tender—according to the mayor and the delegate for mobility—is to promote the sustainable use of this vehicle for "first/last mile" purpose, which includes trips between home and public transport stops or from public transport stops to a work–university–school destination; moreover, the reduction in the number of operators and the constraints on vehicles contribute to safety and a greater urban décor [129].

Table 2. Summary of Italian regulation on e-scooters (authors' elaboration).

Item	Rule
Classification	E-scooters are considered as similar to bikes, except when stated otherwise
Driving style	E-scooters must be driven in standing position; drivers must keep both hands on the handlebar except when showing intention to turn
Speed limit	20 km/h on road/bike lanes; 6 km/h in pedestrian areas
Setting	E-scooters are allowed on all pedestrian/cycle areas and along urban and extra-urban roads on bike lanes; circulation is prohibited on sidewalks and counterflow, except in two-lane roads
Power	Electric powertrain—Max 0.5 kW
Age-worthiness	Users must be aged over 14 and must wear a helmet if underage
Night rules	Both frontal and rear lights must be on; a rear cataphote must also be present; drivers must wear a high-visibility jacket
Other rules	It is forbidden to carry people/pets onboard and to be towed by other vehicles; rental and free-float services must have insurance
Parking	It is forbidden to park on sidewalks except when stated otherwise and parking is allowed in bike and motorcycle stalls; e-scooter operators must require a photo of the standing e-scooter at the release, from which the location is clearly identifiable
Fines	Vehicles whose equipment is different from the requirements are confiscated and owners will be fined EUR 100–400; improper parking is fined EUR 41–168, other infringements are fined EUR 50–250
Equipment	Starting 1 July 2022, new e-scooters must be equipped with turn indicators and brakes on both wheels; existing vehicles must comply prior to 1 January 2024

3. Materials and Methods

According to the law, e-scooters along cycle paths share the space with pedestrians and bikes and interact in singular points—such as intersections—with heavier vehicles (cars, motorcycles, mass transport vehicles and freight vans).

3.1. Interaction Study (IS)

The purpose of this test is to evaluate whether and to what extent bikes and e-scooters are actually perceived to be alike, even under variable environmental conditions (day/night). The comparison with bikes is justified on the basis of the vehicle's structure, the regulations in force and the fact that bikes are often replaced by e-scooters for short distances and leisure trips. The survey combines video recordings and a questionnaire that, in addition to user habits and familiarity with e-scooters, investigates the actual perception of typical car–bike–e-scooter interactions in urban areas according to the point of view of the car driver. The e-scooter user—as far as size and position are concerned—is more similar to a pedestrian, but in terms of speed is more similar to a bike. The study entails the following scenarios: a car is running along the way at fixed speed and crosses perpendicularly—in a signalized pedestrian crossing—the trajectory of the e-scooter/bike along a cycle path in daylight or artificial light conditions. This methodology is similar to that of [76] relative to the car–bike interaction. Alternative approaches found in the literature are the use of simulators [130–132], live footage observation [133] and Mobileye equipment [134]. The approach by [76] was chosen both for the ease of the dissemination of the questionnaire and to limit unnecessary physical contact, given the pandemic underway at the time of the investigation. The interviewee stops the video when he/she would start braking.

3.1.1. IS-Settings

Filming was carried out on an average weekday in the winter of 2021, far from relevant civil or religious holidays. The vehicles are detailed below:

- **Car** Ford Kuga 1.5 TDCI, 120 CV, diesel, manual gearbox, cruise control. Dimensions 454/184/170 cm; weight 1516 kg.
- **E-scooter** Aerlang h6 v2, e-engine 0.5 kW, max speed 40 km/h; lithium-ion battery 840 Wh, range 50–60 km. Tubeless tyres 10", disk brake on both tyres, ABS. Front and rear suspensions. Dimensions 119/20 cm, handlebar width 50 cm, adjustable height. Front and rear lights. Three modes. Max load 120 kg. Unladen weight 20 kg.
- **Bike** Medium size with tessellated tyres and skate brakes on both wheels. Reflective, front and rear lights. Wheels 26", height 106 cm, unladen weight 13 kg.

The team is composed of 4 persons, of which 3 drivers and 1 filming. Instruments used are as follows:

- **Mobile phone** Redmi Note 9 for filming onboard the car. Processor MTK Helio G85 freq 2,0 GHz, RAM 4 GB and 128 GB archive, quad-core camera 48 MP;
- **Selfie stick and strips** to secure the phone without hampering the driver;

Videos have been taken in vertical position, 1080 $\times$ 1920 px and 30 fps, and edited with DaVinci Resolve 17 | Blackmagic Design with the following specifications: 1280 $\times$ 720 px and 30 fps; zoom in ratio $\times$3.163; audio OFF; timecode in overlay.

The road segment is a straight and flat single carriage with one lane per direction (see Figure 2—note: the smaller westward lane with white arrows bending right serves a parking garage inside the building with the green roof; at the moment of the analysis construction works inside the building were being conducted and both the building and the lane were closed). The westward lane is shared and the eastward is for public transport and taxi only. The speed limit is 50 km/h. The pedestrian/bike crossing is 300 m from the preceding signalized junction. There are a few lateral roads with negligible flow. The bike/pedestrian crossing has a traffic island, correctly designed and placed. The road lanes are 4 m (down to 3 m close to the crossing marks) and 3 m wide, respectively. The crossing is 9.7 m wide overall, and red paint bitumen has been used. There is a building and there are a few small trees on the right side (see Figure 2 below) that partially hinder the car driver's sight with reference to the bike lane.

Figure 2. Setting (Aerial view).

Videos (adopting the car driver's point of view) show the bike/e-scooter approaching from the right side; the speed is set to 36 km/h and 20 km/h for car and bike/e-scooter, respectively. The sequence of the videos is as follows: 1—bike crossing in daylight, 2—e-scooter crossing in daylight, 3—e-scooter crossing with artificial light, 4—bike crossing with artificial light.

3.1.2. IS-Survey Structure

The survey—16 questions in a Google Survey format—is split into three sections: the first investigates the general features of the interviewee (gender, age, city, driving licence's age, ownership/previous use of e-scooters, use frequency and motivation); the second reports the time in which the interviewee stops each video; the last investigates the subjective perception and tests whether the interviewee correctly recalls the location and sequence of the videos. The questions and variables are justified by similar studies in the scientific literature, which are summarized in Table 3 below (the list is non-exhaustive).

Table 3. Non-exhaustive literature review on mobility surveys (authors' elaboration).

Item	References
Gender	[31], [49], [50], [51], [58], [77], [85], [87], [90], [96], [97], [108], [111], [125], [126], [127], [128], [135]
Age	[31], [49], [51], [58], [59], [69], [77], [85], [90], [96], [98], [108], [111], [117], [125], [126], [127], [128], [135]
City size	[28], [49], [59], [87], [96], [112], [127], [135], [136]
Driving experience	[60], [77], [112], [136]
Previous experience with e-scooters	[49], [60], [87], [112], [128]
Use frequency of e-scooters	[28], [31], [51], [58], [77], [87], [96], [112], [113], [126], [135]
Main use motivation of e-scooters	[31], [51], [59], [60], [96], [97], [112], [116], [127], [136]
Safety perception	[49], [59], [60], [78], [85], [87], [88], [91], [96], [98], [109], [112], [120], [127], [128], [135]
Light condition perception	[127], [137]

The questions are here summarized:

- 1/2/3/4/5/6/7—see Table 4
- 8/9/10/11—look at the video and press stop when you would brake;
- 12—on comparing artificial and natural light condition, you braked . . . (earlier, later, the same);
- 13—location memory (yes–no);
- 14—sequence memory: is the third video about an e-scooter? (yes–no);
- 15—in natural light conditions, which is the most demanding interaction (overtaking an e-scooter, overtaking a bike, a bike crossing my path, an e-scooter crossing my path);
- 16—in artificial light conditions, the most demanding interactions are those . . . (involving e-scooters, involving bikes, the same as those in natural light).

Table 4. Summary of the answers to Section 1.

Question	Options	Answers	%Share
1—Gender	Female	101	44.9
	Male	123	54.7
	No answer	1	0.4
2—Age	<40	106	47.1
	>40	119	52.9
3—Living	City over 100,000 inhabitants	98	43.6
	City below 100,000 inhabitants	122	54.2
	No answer	5	2.2
4—Driving Licence Age	No + no answer	8	3.6
	Less than 3 years	11	4.9
	3 to 6 years	29	12.9
	6 to 10 years	28	12.4
	Over 10 years	149	66.2
5—Previous Experience with e-scooters	Yes	45	20.0
	No + no answer	181	80.0
6—Use frequency	Never + no answer	181	80.0
	Once per month	29	12.9
	2–3 times per month	3	1.7
	Once per week	4	1.8
	Regular use	8	3.6
7—Main use motivation (45 user = 100%)	Work/study	23	51.1
	Free time/leisure	20	44.4
	No answer	2	4.5

3.2. Vehicle Performance (VP)

Section 2.2 highlighted that their very structure and ride characteristics make e-scooters less comfortable and more susceptible to a greater risk of stability loss. Here, we will investigate three key milestone performances to characterize the vehicle motion: the ability to absorb the roughness of the road surface with wheels and shock absorbers, acceleration and braking phases, during which sudden jerks are recorded in short periods of time.

The capacity to come to a complete stop in the shortest space and time in case of a hazard is an important safety requirement. The aspects to be investigated are the braking power, the modulation and the braking system's technical time of activation. Braking tests are described by [58,138]. In the first case, four drivers travel a stretch of road at full throttle and then stop as quickly as possible from v_0 = 16 km/h. The second document compares the braking performance of various types of bicycles (city bikes, trekking bikes, mountain bikes, pedelecs) on dry and wet surfaces, evaluating the space and the technical time of the activation of the braking system. The results show that the performance on a dry surface is fairly uniform, while the distance increases by up to 30% on a wet surface, except for the pedelec, which—being equipped with ABS—exhibits a lower increase (less than 10%). In addition to the consolidated literature: (i) the test proposed below is carried out for e-scooters; (ii) the brake phase starts at $v_{0'}$ = 25 km/h, which is equal to the highest speed limit in force in the EU countries; and (iii) braking is carried out in emergency conditions, that is, blocking the rear wheel and braking with the front brake in safe conditions.

The testing of e-scooters' performance in acceleration is often overlooked, as more focus is placed on braking. However, the real capabilities of the vehicle are underestimated by inexperienced users due to the small size of the vehicle [139]. Moreover, the driving position is not very efficient in counterbalancing longitudinal accelerations, thus, driver stability is threatened. As no literature on the topic is available, in this paper an approach based on video footage is proposed to measure the acceleration profile over time: the vehicle travels along a dry, straight, flat and smooth stretch of asphalt track, whose length is such as to eliminate the effect of the transient due to the initial thrust given by the driver's foot.

Finally, the evaluation of the discomfort suffered by e-scooter drivers due to the low quality of the road surface in terms of transmitted vibrations is another advance compared to the existing literature, as the only references available are related to bicycles [140,141] and cars [142,143]. ISO standards distinguish between whole-body and hand-transmitted vibration, whose KPIs—however—cannot be easily transferred to e-scooters. The test described below, thus, constitutes another advance with respect to the state of the art. Three stretches of homogeneous length (35 m) made of different materials are travelled at constant speed (Figure 3 below); vibrations will be assessed by the accelerometer along the vertical axle: S1 (smooth asphalt), S2 (pavement) and S3 (worn asphalt).

Figure 3. Examples of S1 (**left**), S2 (**centre**), S3 (**right**) (authors' elaboration).

VP Settings

Filming was carried out on an average weekday in the winter of 2021, far from relevant civil or religious holidays. The vehicles are detailed below:

- **E-scooter Model #1** is the Aerlang h6 v2, detailed above.
- **E-scooter Model #2** is equipped with a 0.3 kW electric engine, lithium-ion battery. Tubeless wheels 8.5″. Electric brake with regeneration on the front wheel and an actuated disk brake on rear wheel. No ABS nor front/rear suspensions.

The team is composed of two persons, of which one is the driver (frequent user, weight 70 kg and 1.7 m tall) and one is present for measurement and videomaking. The instruments used are as follows:

- **Smartphone** Xiaomi Redmi 9S; mounted on the e-scooter footboard and with principal axles detailed as in Figure 4 below to evaluate the acceleration profiles (x = longitudinal; y = lateral; z = vertical)
- **Accelerometer** Analyzer version 16.11.27;
- **Video-camera** Action-cam Xiaomi Yi 4K;

Videos have been taken in the vertical position 1080 × 1920 px and 120 fps; audio OFF.

Figure 4. Orientation of principal axles (authors' elaboration).

4. Results

4.1. IS-Discussion

The survey was disseminated via web link and QR code, reaching a sample of interviewees varied by age, gender, city and daily habits. Answers were anonymized and treated statistically with Excel and SPSS. Of the 1000 users reached, 225 valid sets of answers were collected, of which 123 were male, 101 were of female gender and 1 was not declared. With regard to the municipality, the threshold of 100,000 inhabitants was introduced as e-scooter sharing services have been found to be greater in medium to large cities, which are also busier, which could in turn encourage the purchase of an e-scooter. In addition, bigger cities have more infrastructure supporting sustainable mobility, such as a wide network of cycle paths, low traffic and low speed zones, etc. The 45 users who declared some form of previous experience are again split by gender, age, city size and driving license ownership. These data are consistent with many findings from the scientific literature: a high share of users with limited knowledge of e-scooters, a high share of male people (two out of three users is a recurring value), people under 40 and those owning a driving license but not for too long (which confirms the fairly low age of the average e-scooter user). On the other hand, a clear distinction has not been found as far as the size of the city is concerned, meaning that either the chosen threshold (100,000 inhabitants) is wrong or that in Italy—thanks to the mobility bonus—the diffusion/knowledge of e-scooters is more homogeneous.

A high share of users living in cities of <100,000 inhabitants is a sign of a more homogeneous diffusion of e-scooters in Italy, due to the presence of cycle infrastructure and paths dedicated to sustainable mobility also along the arterials linking main cities and nearby centres (e-scooters are allowed if a separated cycle path is present).

The slight prevalence of necessity trips compared to those for leisure (23 vs. 20) could be motivated by the increased ownership of e-scooters induced by the incentives provided during the first waves of the COVID-19 pandemic. In particular, those who make regular use of e-scooters declared work/study as their main motivation, while those who use them rarely tend to be leisure-oriented.

Relative to Section 2, answers have been anonymized and processed as follows:

- The outliers have been discarded (i.e., the stated time precedes the appearance of the weak user in the video);
- If the stated time is greater than the video duration, it is labelled "99";
- The instant of the appearance of the weak user in the video is subtracted from the stated time.

Table 4 summarizes the answers to the first section of the survey; as for the second section, Table 5 details the relative positions and the settings of the videos, while Table 6 summarizes the answers.

Table 5. Video description.

Video n°		**1**	**2**	**3**	**4**
Setting	Light [D = daylight; A = artificial]	D	D	A	A
	Weak user involved	cyclist	e-scooter	e-scooter	cyclist
When the weak user appears . . .	Dist. Car—Crosswalk [m]	20.00	20.00	20.00	20.00
	Dist. User—Crosswalk [m]	5.50	5.50	2.52	2.52
When the braking occurs . . .	Time [s]	1.00	1.20	0.88	0.86
	Dist. Car—Crosswalk [m]	10.00	10.50	9.90	10.10
	Dist. User—Crosswalk [m].	2.70	2.70	0.15	0.15

Table 6. Summary of the answers to Section 2.

Video	**99**		**Outliers**		**No Answer**		**Valid Answers**		**Avg. Time**	**Std. Dev.**
	N°	**%**	**N°**	**%**	**N°**	**%**	**N°**	**%**	**[s]**	**[s^2]**
1	70	31	34	15	5	2	116	52	1.00	0.684
2	45	20	8	4	4	2	168	75	1.20	0.797
3	37	16	18	8	3	1	167	74	0.88	0.616
4	21	9	25	11	5	2	174	77	0.86	0.607

From Table 5, it is possible to see that in natural light conditions, braking occurs on average 0.2 s earlier for the bike (Video 1) than for the e-scooter (Video 2), but the car is 0.5 m closer to the crossing line. In artificial light conditions, braking occurs 0.02 s earlier for the bike (Video 4) than for the e-scooter (Video 3), but the car is 0.2 m farther away from the crossing line. By comparing the videos involving either the bike or the e-scooter, in artificial light conditions braking occurs earlier on average (0.12 s for the bike, which is −12%; 0.34 s for the e-scooter, which is −28.33%), which indicates more cautionary behaviour (on other hand, the interviewee might have become accustomed to the survey structure and reacted faster) and an increased effectiveness of onboard lights for e-scooters, thus highlighting how important it is that lights are in place and working properly.

In Table 6, the number of "99" labels decreases between Video 1 and Video 4, showing a better understanding of the survey mechanism (the label "99" also indicates that the interviewee would not brake). The share of "no answer" is <3%, which is fine. A greater number of outliers is present for Videos 1 and 4, involving the bike, while the share is <10% for Videos 2 and 3, involving the e-scooter; the likely motivation in the absence of specific reasons may be:

- In Video 1, a pedestrian wearing red appears right before the bike, which might be confusing;
- The front wheel of bikes is more prominent than that of e-scooters', so bikers appear later;

Section 3 of the survey starts with two "test" questions relating to the setting and the sequence of the observed videos: one question asserted the truth, the other the false answer. Finally, three questions required a subjective evaluation from the interviewee regarding overall safety under varying light conditions and depending upon the light vehicle involved. Tables 7 and 8 below summarize the findings from Section 3: in Table 7, a general overview is provided, while in Table 8 the results are split by gender, age and driving licence ownership.

Table 7. Summary of the answers to Section 3—general overview.

Item	Option	N°	%
Location	Correct answer	126	56
	Wrong answer	96	43
Sequence	Correct answer	150	67
	Wrong answer	73	32
By comparing artificial and natural light conditions, you brake . . .	The same	110	49
	Earlier	64	28
	Later	50	22
In natural light conditions, which is the most demanding interaction	E-scooter crossing	106	47
	Overtaking an e-scooter	61	27
	Overtaking a bike	30	13
	Bike crossing	28	12
In artificial light conditions, the most demanding interaction is . . .	Involving an e-scooter	127	56
	Involving a bike	22	10
	The same as in daylight.	76	34

Table 8. Summary of the answers to Section 3—split overview.

Item	Option	Gender		Age		Driving License [year]				
		F	M	<40	>40	>10	10	6	3	No
Location	Correct answer	62	64	71	55	74	20	21	7	3
	Wrong answer	39	59	35	64	75	8	8	4	4
Sequence	Correct answer	70	79	77	73	96	21	18	8	6
	Wrong answer	31	44	29	46	53	7	11	3	1
By comparing artificial and natural light conditions, you brake . . .	The same	45	66	51	60	74	15	9	6	5
	Earlier	36	28	24	40	49	3	9	1	2
	Later	20	29	31	19	26	10	11	4	0
In natural light conditions which is the most demanding interaction	E-scooter crossing	42	64	55	51	63	17	16	6	4
	Overtaking an e-scooter	30	30	27	34	42	6	6	3	3
	Overtaking a bike	16	14	12	18	23	3	2	2	0
	Bike crossing	13	15	12	16	21	2	5	0	0
In artificial light conditions, the most demanding interaction is . . .	Involving an e-scooter	55	72	58	69	84	18	19	4	2
	Involving a bike	10	12	7	15	16	2	1	0	3
	The same as in daylight	36	39	41	35	49	8	9	7	2
Total		101	123	106	119	149	28	29	11	7

From Table 8 we infer that:

- In terms of gender, even if the percentages for location and sequence tests are comparable, the perception of behaving more prudently (i.e., braking earlier) in artificial light conditions is greater among females. Both genders deem e-scooter manoeuvres to be more dangerous (with crossing more dangerous than overtaking). The male gender considers bike crossing slightly more dangerous than bike overtaking, unlike the female gender, which indicates the opposite (i.e., the bike turning left is perceived as less predictable). In artificial light conditions, both pay more attention to e-scooter manoeuvres (perceived as 5.5 times more dangerous), while about one in three declare that they does not perceive a difference.
- In terms of age, respondents < 40 years have better identified location and sequence, while people > 40 believe they adopt more prudent behaviour in artificial light con-

ditions. The two groups agree in attributing a greater perceived danger to e-scooter crossing and overtaking; people > 40 perceive bike overtaking to be more dangerous than bike crossing (i.e., a bike turning left is perceived as less predictable). In artificial light conditions, both agree upon paying greater attention to e-scooters (which are perceived to be from 4.5 to 8 times more dangerous), while about one in three sees no difference.

- In terms of driving license ownership, both those owning a license for less than 10 years and those not owning one at all performed better in the two test questions. On the other hand, people with greater driving experience exhibit more prudent behaviour in artificial light conditions. All licence owners agree in attributing e-scooter crossing and overtaking to be a greater perceived danger. In artificial light conditions, those owning a driving license for more than 3 years pay more attention to e-scooters, while those who do not have a license would pay more attention to bikes.

All in all, tests on the recognition of location and sequence are satisfied in 56% and 67% of the cases, respectively. Half of the interviewees (49%) claim to maintain a homogeneous braking style irrespective of light conditions, while the remainder are equally split in the belief of slowing down sooner or later. E-scooter crossing and e-scooter overtaking are perceived as more dangerous, even in artificial light conditions.

To gain even deeper insight, the statistical analysis software SPSS was used to perform Hypothesis Testing Analysis (*t*-test). Indeed, *t*-test can be used to determine whether a single group differs from a known value (*t*-test single sample), if two groups differ from each other (*t*-test with two independent samples) or if there is a significant difference between paired samples (*t*-test with paired samples). To evaluate a possible difference in perception between e-scooters and bikes, a paired sample *t*-test is needed. We compare answers to videos (Questions 8–11), user type (Questions 1–7) and subjective opinions (Questions 12–16). The null hypothesis is tested according to the *p*-value: the higher the *p*-value, the higher the probability of making mistakes by refusing the null hypothesis; that is, the null hypothesis is nothing to be accepted. The null hypothesis is the following: "the interviewee perceives bikes and e-scooters in the same way" and the threshold value used is 0.05. For each pair of sets, only valid answers (i.e., the time instant in which the interviewee stops the video) are considered and outliers of "99" are discarded. The following Tables 9–20 summarize the tests carried out and the findings.

Bike vs. e-scooter—Artificial light

The *t*-test (Table 9) suggests that the null hypothesis should be accepted; so, cyclists and e-scooter riders are perceived alike in artificial light conditions.

Table 9. *t*-test paired sample results: Video 4 (bike) vs. Video 3 (e-scooter).

Mean	Dev std	Err Std Mean	Min	Max	T	DF	Sig (2-Code)
−0.056	1.114	0.082	−0.218	0.106	−0.684	184	0.495
V4	Mean = 5.307; N = 185; Std dev = 1.225; Err std mean = 0.090						
V3	Mean = 5.363; N = 185; Std dev = 1.221; Err std mean = 0.090						

Bike vs. e-scooter—Natural light

The *t*-test (Table 10) suggests that the null hypothesis should be refused; therefore, cyclists and e-scooter riders are perceived differently in natural light. It is worth noting that interviewees mostly perceive e-scooter riders as more dangerous in artificial light conditions (56.5%), while 33.77% see no difference.

Table 10. *t*-test paired sample results: Video 1 (bike) vs. Video 2 (e-scooter).

Mean	Dev std	Err Std Mean	Min	Max	T	DF	Sig (2-Code)
−1.15	1.284	0.104	−0.356	−0.944	−11.009	150	0.000
V1	Mean = 5.116; N = 151; Std dev = 1.629; Err std mean = 0.132						
V2	Mean = 6.266; N = 151; Std dev = 1.443; Err std mean = 0.117						

Bike vs. e-scooter—Natural light and gender

The *t*-test (Table 11) suggests that the null hypothesis should be refused; therefore, the samples are significantly different: cyclists and riders are perceived differently in daytime both by male and female people.

Table 11. *t*-test paired sample results: Video 1 (bike) vs. Video 2 (e-scooter).

Gender	Mean	Dev std	Err Std Mean	Min	Max	T	DF	Sig (2-Code)
Female	−0.852	1.098	0.137	−1.126	−0.578	−6.205	63	0.000
Male	−1.363	1.376	0.025	−1.658	−1.068	−9.186	85	0.000
V1	Female: Mean = 5.41, N = 64, Std dev = 1.59, Err std mean = 0.198 Male: Mean = 4.91; N = 86; Std dev = 1.64; Err std mean = 0.177							
V2	Female: Mean = 6.26, N = 64, Std dev = 1.54, Err std mean = 0.193 Male: Mean = 6.27, N = 86, Std dev = 1.38, Err std mean = 0.149							

Bike vs. e-scooter—Artificial light and gender

The *t*-test (Table 12) suggests that the null hypothesis should be accepted for both genders. As a matter of fact, for the female gender the similarity is stronger, while for male gender the *t*-test is more slightly satisfied, thus the two vehicles could also be confused. These data can be read under two perspectives: from a positive point of view, female people—tendentially more careful and prudent while driving, as noted in numerous scientific works on naturalistic driving behaviour coupled with gender topics—are able to recognize the two types of danger as similar. From a negative point of view, however, it could be assumed that female people find it more difficult to distinguish between cyclists and e-scooter riders in artificial light conditions compared to male people.

Table 12. *t*-test paired sample results: Video 4 (bike) vs. Video 3 (e-scooter).

Gender	Mean	Dev std	Err Std Mean	Min	Max	T	DF	Sig (2-Code)
Female	−0.093	1.255	0.139	−0.369	0.183	−0.672	81	0.503
Male	0.174	0.983	0.097	−0.019	0.367	1.784	101	0.077
V3	Female: Mean = 5.38, N = 82, Std dev = 1.50, Err std mean = 0.165 Male: Mean = 5.35; N = 102; Std dev = 0.96; Err std mean = 0.095							
V4	Female: Mean = 5.47, N = 82, Std dev = 1.20, Err std mean = 1.132 Male: Mean = 5.17, N = 102, Std dev = 1.24, Err std mean = 0.123							

Bike vs. e-scooter—Artificial light and age

The two samples exhibit different outcomes after the *t*-test (Table 13). For younger people (<40 years) the T-test suggests that the null hypothesis should be accepted; therefore, cyclists and e-scooter riders are perceived in the same way in artificial light. This is consistent with younger people being more accustomed to newer individual mobility vehicles and therefore reacting without showing a surprise effect. Instead, for older people ($\geq$40 years) the *t*-test suggests that the null hypothesis should be rejected (albeit slightly) and, therefore, cyclists and riders are perceived quite differently.

An interesting point for further research would be to repeat the analysis after narrowing the "young" range to people 0–30 years old or, conversely, widening it to people 0–50 years old. In general, this result apparently supports the literature claiming that young people are preferential users of individual electrical mobility systems and that the users with more experience and greater age need to be the target of education and awareness campaigns on new mobility solution topics.

Table 13. *t*-test paired sample results: Video 4 (bike) vs. Video 3 (e-scooter).

Age	Mean	Dev std	Err Std Mean	Min	Max	T	DF	Sig (2-Code)
<40	0.132	1.132	0.112	−0.370	0.107	−1.098	88	0.275
>40	0.230	1.075	1.110	0.012	0.448	2.098	95	0.039
V3	<40: Mean = 5.170; N = 89; Std dev = 1.340; Err std mean = 0.142							
	>40: Mean = 5.542; N = 96; Std dev = 1.075; Err std mean = 1.110							
V4	<40: Mean = 5.302; N = 89; Std dev = 1.146; Err std mean = 1.122							
	>40: Mean = 5.312; N = 96; Std dev = 1.300; Err std mean = 0.133							

Bike vs. e-scooter—Natural light and age

The *t*-test (Table 14) suggests that the null hypothesis should be refused; therefore, cyclists and e-scooter riders are perceived differently in daylight, regardless of the age category. This result is in contrast to what happens in artificial light conditions. As a consequence, it is possible to infer that, regardless of age, night driving mobilizes a greater attention to detail in car drivers.

Table 14. *t*-test paired sample results: Video 1 (bike) vs. Video 2 (e-scooter).

Age	Mean	Dev Std	Err Std Mean	Min	Max	T	DF	Sig (2-Code)
<40	−1.078	0.971	0.114	−1.305	0.851	−9.479	72	0.000
>40	−1.217	1.522	0.172	−1.561	−0.874	−7.063	77	0.000
V1	<40: Mean = 5.020; N = 73; Std dev = 1.547; Err std mean = 0.181							
	>40: Mean = 5.206; N = 78; Std dev = 1.708; Err std mean = 0.193							
V2	<40: Mean = 6.098; N = 73; Std dev = 1.570; Err std mean = 1.184							
	>40: Mean = 6.423; N = 78; Std dev = 1.304; Err std mean = 0.148							

Bike vs. e-scooter—Natural light and location

On the 149 valid answers obtained, the percentage of incorrect answers is almost 47%. This is not good in terms of interviewees' concentration. However, it is legitimate to assume that the formulation of the survey itself—which invites the interviewee to stop the video in the event of danger—may have an influence in focusing the interviewees' attention on likely danger rather than on the observation of the context.

Despite that, the *t*-test (Table 15) suggests that the null hypothesis should be refused and therefore the perception of the vehicle and the reaction time are not affected by the correct identification of the place in natural light conditions. This is positive and confirms the studies on vision claiming that, at lower speeds, the driver's attention is concentrated on his/her surroundings. Furthermore, the hypothesis that an object suddenly intruding the visual field of the driver catches the attention of the human eye by stimulating analysis and reaction is also supported by this result.

Table 15. *t*-test paired sample results: Video 1 (bike) vs. Video 2 (e-scooter).

Guess	Mean	Dev Std	Err Std Mean	Min	Max	T	DF	Sig (2-Code)
Wrong	−1.218	1.367	0.163	−1.544	−0.892	−7.457	69	0.000
Correct	−1.119	1.215	0.137	−1.391	−0.847	−8.186	78	0.000
V1	Wrong: Mean = 5.121; N = 70; Std dev = 1.595							
	Correct: Mean = 5.161; N = 79; Std dev = 1.581							
V2	Wrong: Mean = 6.334; N = 70; Std dev = 1.342							
	Correct: Mean = 6.280; N = 79; Std dev = 1.380							

Bike vs. e-scooter—Artificial light and location

On the 183 valid answers obtained, the percentage of incorrect answers is just over 45%. This is not good in terms of interviewees' concentration. However, it is legitimate to assume that the formulation of the survey itself—which invites the interviewee to stop the video in the event of danger—may have an influence in focusing the interviewees' attention on likely danger rather than on the observation of the context.

The *t*-test (Table 16) suggests that the null hypothesis should be accepted. In artificial light conditions, therefore, a generic danger is identified but it is more difficult to correctly distinguish the cyclist from the e-scooter rider, or in other words, the two cases are perceived as equally dangerous. By adopting the first point of view, policy action is needed (e.g., through the improvement of the lighting at road crossings) to encourage the correct perception, as shown by [134,144]. By adopting the second point of view, it is possible to conclude that the interviewees at night focus more on the identification of a generic danger rather than on the details, whether they relate to the context or the type of danger.

Table 16. *t*-test paired sample results: Video 4 (bike) vs. Video 3 (e-scooter).

Guess	Mean	Dev Std	Err Std Mean	Min	Max	T	DF	Sig (2-Code)
Wrong	0.171	1.132	0.124	−0.076	0.418	1.377	82	0.172
Correct	−0.030	1.104	0.110	−0.249	0.189	−0.274	99	0.785
V3	Wrong: Mean = 5.42; N = 83; Std dev = 1.00; Err std mean = 0.11							
	Correct: Mean = 5.37; N = 100; Std dev = 1.3; Err std mean = 0.13							
V4	Wrong: Mean = 5.25; N = 83; Std dev = 1.01; Err std mean = 0.11							
	Correct: Mean = 5.40; N = 100; Std dev = 1.3; Err std mean = 0.13							

By adding gender and age variables to the correct perception of the location (see Table 17 below), it is evident that location is correctly identified mostly by female interviewees (58.6% vs. 54.2%) and by interviewees younger than 40 years of age (60% vs. 52.6%). The *t*-test suggests that the null hypothesis should be accepted; so, cyclists and e-scooter riders are perceived to be alike in artificial light conditions.

Table 17. Correct perception of the location, split by gender (left) and age (right).

Gender		Freq	%	Age		Freq	%
Female	Wrong	41	41.4	<40	Wrong	42	40.0
	Correct	58	58.6		Correct	63	60.0
Male	Wrong	55	45.8	≥40	Wrong	54	47.4
	Correct	65	54.2		Correct	60	52.6

Bike vs. e-scooter—Natural light and sequence

Of the 150 valid answers obtained, incorrect answers made up 32% (the exact answer was "no"). This can be explained in the same way as the previous test. The *t*-test (Table 18) suggests that the null hypothesis should be refused. Therefore, in daylight conditions the two vehicles are perceived as distinct regardless of the correct identification.

Table 18. *t*-test paired sample results: Video 1 (bike) vs. Video 2 (e-scooter).

Guess	Mean	Dev Std	Err Std Mean	Min	Max	T	DF	Sig (2-Code)
Wrong	−1.163	1.222	0.176	−1.517	−0.808	−6.591	47	0.000
Correct	−1.146	1.323	0.131	−1.406	−0.886	−8.743	101	0.000
V1	Wrong: Mean = 5.31; N = 48; Std dev = 1.33; Err std mean = 0.19							
	Correct: Mean = 5.0; N = 102; Std dev = 1.76; Err std mean = 0.17							
V2	Wrong: Mean = 6.47; N = 48; Std dev = 0.75; Err std mean = 0.11							
	Correct: Mean = 6.2; N = 102; Std dev = 1.67; Err std mean = 0.17							

Bike vs. e-scooter—Artificial light and sequence

Of the 184 valid answers obtained, the percentage of incorrect answers was 32% (the exact answer to the question was "no"). It is reiterated that the relevant share of incorrect answers can be due both to the low general concentration of the interviewees and due to the formulation of the survey itself, which invites the interviewee to stop the video in the event of a perceived danger. The *t*-test (Table 19) suggests that the null hypothesis should be accepted and therefore in artificial night conditions, cyclists and e-scooter riders tend to be confused or perceived in a similar way.

Table 19. *t*-test paired sample results: Video 4 (bike) vs. Video 3 (e-scooter).

Guess	Mean	Dev Std	Err Std Mean	Min	Max	T	DF	Sig (2-Code)
Wrong	−0.065	1.326	0.173	−0.411	0.281	−0.377	58	0.708
Correct	−0.113	1.005	0.090	−0.064	0.291	1.260	124	0.210
V3	Wrong: Mean = 5.43; N = 59; Std dev = 0.87; Err std mean = 0.11							
	Correct: Mean = 5.33; N = 125; Std dev = 1.4; Err std mean = 0.12							
V4	Wrong: Mean = 5.50; N = 59; Std dev = 0.99; Err std mean = 0.13							
	Correct: Mean = 5.22; N = 125; Std dev = 1.3; Err std mean = 0.12							

By adding gender and age variables to the correct perception of the sequence (see Table 20 below), it is highlighted that the correct sequence is identified mostly by male people (69.2% vs. 64.6%) and by interviewees younger than 40 years of age (68.6% vs. 65.8%). By comparing Tables 17 and 20, the sequence identification is more successful than that of the location.

Table 20. Correct perception of the sequence, split by gender (left) and age (right).

Gender		Freq	%	Age		Freq	%
Female	Wrong	35	35.4	<40	Wrong	33	31.4
	Correct	64	64.6		Correct	72	68.6
Male	Wrong	37	30.8	≥40	Wrong	39	34.2
	Correct	83	69.2		Correct	75	65.8

4.2. VP Discussion

In the following subsections, the results regarding vehicle performance—namely acceleration, brake and vibration—are discussed.

4.2.1. Acceleration

The accelerometer has been calibrated and graphs have been derived accordingly over the duration of each test carried out. For the acceleration test, 20 iterations have been carried out for each e-scooter involved. From the video analysis, given the frames/second and the length of the test bed, a motion law can be derived (Equation (1)):

$$s = at^3 + bt^2 + ct + d \tag{1}$$

where t = time and s = space. The motion law expresses the linear decreasing acceleration and constant (negative) jerk from which—with a double derivative over time at a given dt = 0.2 s—instant acceleration values can be calculated. Coefficients are calibrated as follows (Table 21).

Table 21. Acceleration performance.

	a	b	c	d
Model #1	−0.046	0.976	−0.154	0.008
Model #2	−0.041	0.778	0.231	0.012

In Figure 5 below we see the acceleration profiles of e-scooter models #1 and #2 in reference to one of the iterations carried out. It is easy to identify the driver's kick to start the motion of the vehicle (first peak) and the start of the electric engine (second peak). T = 0 is set when the longitudinal acceleration is different from 0. The profile typically decreases for both e-scooters. The two vertical segments mark the time instant in which the two vehicles reached the end of the test bed (s = 14 m). On average, both vehicles exhibited similar acceleration values and Model #1 was always slightly better than Model #2; Model #1 exhibits a short 3 m/s^2 first peak while Model #2 has a smoother profile. The interpolating lines clearly describe the vehicle motion after the driver kick and the ignition of the electric engine up to the point of maximum speed, wherein the acceleration goes to zero.

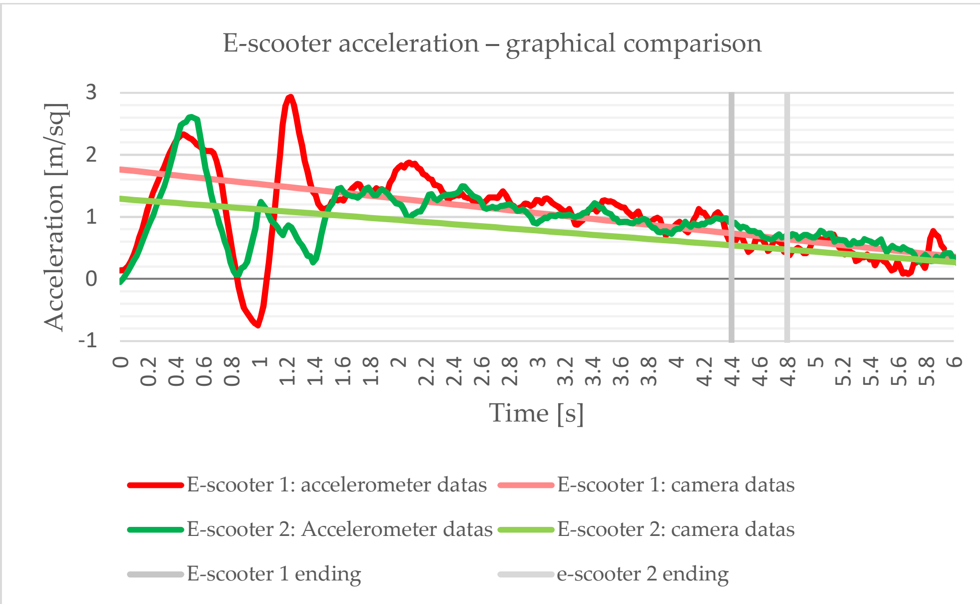

Figure 5. Acceleration profiles (authors' elaboration).

The average values for acceleration from both video and accelerometer have been 1.3–1.4 m/s^2 and 1.0–1.1 m/s^2 for Model #1 and #2, respectively. The videos show clearly that e-scooter Model #1 has a sharper starting peak and the driver must counterbalance this to avoid losing stability. The second conclusion is that a more powerful engine does not guarantee higher acceleration in absolute terms, as the green line (Model #2) is seldom over the red line (Model #1).

4.2.2. Braking

The braking test allows the computation of the brakes' technical time (defined as the time interval between the driver acting on the lever and the blockage of the wheel) and the maximum deceleration available. For both e-scooter models, which are equipped with a disc brake on the rear tyre and a braking light, and whose status is commanded by the brake lever situated on the handlebar, the times (i) between the action on the lever and the brake light ignition and (ii) between the brake light ignition and the blockage of the rear tyres (brake technical time) are computed from the analysis of the videos and from the accelerometer. In this last case, the brake is assumed as activated when the acceleration becomes negative. Again, 20 iterations have been carried out for each e-scooter involved.

E-scooters have a mechanical brake system, which is notably slower than hydraulic ones (which are equipped on cars), and this is apparent from Table 22, below.

Table 22. Braking performance.

	Video			Accelerometer
	Mean Rear Light Activ. Time [s]	**Mean Rear Light-to-Wheel Lost Time [s]**	**Mean Total Braking System Activ. Time [s]**	**Mean Braking System Activ. Time [s]**
Model #1	0.25	0.15	0.4	0.4
Model #2	0.15	0.35	0.5	0.5

In addition, models #1 and #2 differ in terms of brake system structure: while Model #1 has disc brakes acting on both wheels, Model #2 has an electronic brake acting on the front tyre which is activated from the control unit after the brake lever on the handlebar is used, which makes the reaching of maximum braking capability slower so that when the rear tyre blocks, the maximum braking available has not yet been reached. As a consequence, in Figure 6 below (which refers to one of the iterations carried out), we have a flex for Model #2 at around t = 0.4″ when the electronic brake on the front tyre is activated from the control unit, which is not present for Model #1. On the other hand, Model #1 exhibits a wave profile due to the presence of the rear suspension, which is absent in Model #2.

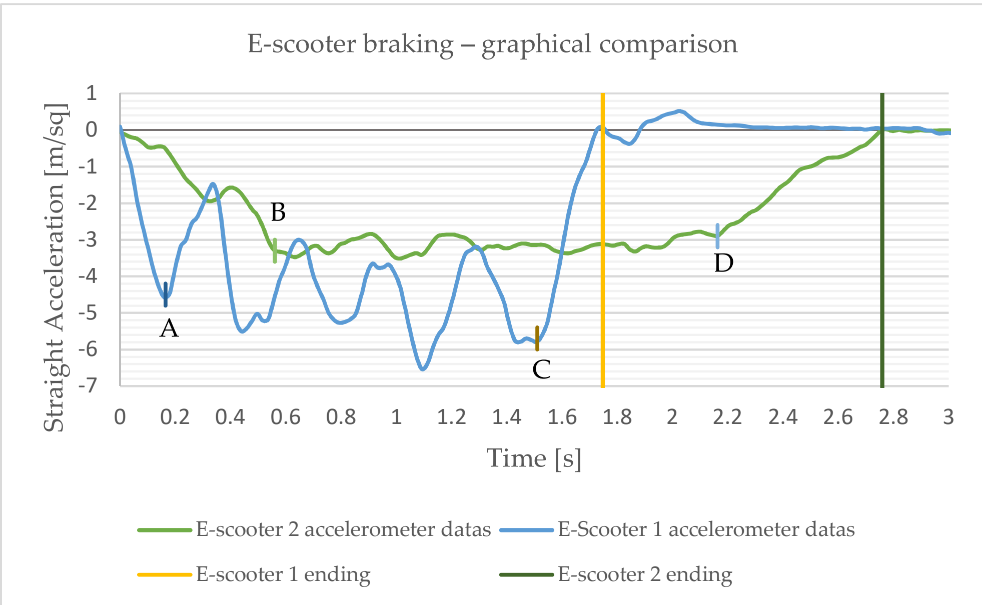

Figure 6. Braking profiles (authors' elaboration).

To compute the maximum deceleration available, the Technical Time Instant (A and B for Model #1 and #2, respectively) and the time instant after which acceleration climbs back to a = 0 value (C and D for Model #1 and #2, respectively) are marked in the accelerometer profile of Figure 6 below, so that the time windows AC and BD refer to models #1 and #2, respectively. For each iteration carried out, the distance "S_i" covered by the wheel while braking from a starting speed v_0 = 6.94 m/s (25 km/h) and the deceleration are computed; the results are summarized in Table 23.

Table 23. Average deceleration available.

	Accelerometer [m/s²]	**On-Field Measure [m/s²]**
Model #1	4.10	4.15
Model #2	3.10	3.20

The small deviation between the accelerometer and the on-field measure is due to the fact that the brakes are activated "around the marker point" along the path and not actually where the marker point is located. In addition, these values are obtained with all brakes activated to their maximum capacity by an expert driver, which is not always the case in real scenarios where the users might be distracted or have scarce knowledge of the vehicle, thus leading to a slower reaction [92]. Finally, the disc brakes on Model #1 allow the rider to brake harder than the coupling disc and electronic brake on Model #2. This fact is to be handled with care: as e-scooters have small tyres and short spacing between wheels, an increased risk of triggering the overturn of the vehicle following the blockage of the front wheel (due to excessive braking) and the lifting of the rear tyre (as the driver's load shifts forward) is present, if not compensated by the driver either releasing the front brake or using also the rear brake. The tests showed that the overturn becomes likely with a deceleration of $a = -1.6$ m/s^2, which is nearly half the deceleration available for Model #2 and nearly 40% of that available for Model #1. This situation can become even worse upon low friction pavement. In summary, the capability of the braking system itself does not necessarily increase safety, as the experience of drivers in the event of emergency braking also makes a relevant contribution.

4.2.3. Comfort and Vibration

Comfort while in motion is assessed by means of indicators such as the Dynamic Comfort Index—DCI [140], and the International Roughness Index—IRI [141,145] in terms of acceleration along the vertical z axis.

The IRI is a standardized, a-dimensional and positive index which is equal to zero for smooth surfaces and increases with irregular surfaces, according to Equation (2), while the DCI = [0; ∞] expresses the road quality on the basis of the vibration, according to Equation (3):

$$\mathrm{IRI} = \frac{\iint_{t1}^{t2} |a_z| \mathrm{d}t\mathrm{d}t}{s} \quad (2)$$

$$\mathrm{DCI} = \left(\sqrt{\frac{1}{N} \sum_{k=1}^{N} a_{z,k}^2} \right)^{-1} \quad (3)$$

where N = measure/s, $a_{z,k}$ = vertical acceleration values.

Again, 20 iterations have been carried out for each e-scooter involved and for each pavement type by the same experienced driver at the speed of 20 km/h; in this way, the wheel radius and the presence of suspension are the two factors which most influence the indexes (small wheels and the absence of suspension translate into increased vibrations). The average values of the DCI and IRI for S1-S2-S3 pavement types are summarized in Table 24.

Table 24. Average values of comfort and vibration index for the three pavement types.

	Smooth Asphalt S1		Paved Asphalt S2		Worn Asphalt S3	
	DCI	**IRI**	**DCI**	**IRI**	**DCI**	**IRI**
Model #1	0.98	8.4	0.38	31	0.27	40
Model #2	0.96	19.61	0.32	46	0.22	55

On increasing the DCI, higher comfort and fewer vibrations are present. Conversely, on increasing the IRI, vibrations also increase. Thus, both indexes agree in ranking S1 as the best surface type, S3 as the worst and S2 as the intermediate situation.

Figure 7 below shows the vertical acceleration profiles for the three pavement types proposed.

- For S1, vertical acceleration spans between $[-0.5; 0.5]$ m/s^2.
- For S2, vertical acceleration spans between $[-1; 1]$ m/s^2.
- For S3, vertical acceleration spans between $[-3.5; 3.5]$ m/s^2.

The equipment (two suspensions and 10″ wheels) make Model 1 more capable of dampening vibrations; in fact, larger wheels are more suitable for rough and uneven surfaces, and less sensitive to holes, thus providing greater driving stability. The accelerations measured on the S3 pavement by Model 2 make it unfit for worn-out pavement conditions.

Finally, the e-scooter swings vertically due to the pavement not being perfectly smooth. If we model the rambling pavement profile with a sinusoid function, the stresses due to the presence of uneven flooring can be modelled with Equation (4):

$$H = \pm H_z \sin^D(2\,\pi\, s/\lambda) \tag{4}$$

where λ = wavelength, H_z = measure of the uneven flooring on the z-axis and D = coefficient related to the shape of the obstacle. If D = 1, H = 2 and ω^* = 63 rad/s which is the critical value of the pulsation that causes the car wheels to detach from the ground (values from [146]), then (Equation (5)):

$$\omega = \omega^* = \frac{2\,\pi\, v_m}{\lambda} = 63 \text{ rad/s} \tag{5}$$

Additionally, given the relationship between the pulsation, wavelength, period and frequency known from the wave theory, it is possible to derive λ (which is the characteristic dimension of the pavement material) on varying e-scooter speed v_m. Conversely, based on the allowed speed of the e-scooter, it is possible to define which pavement material fits best the vehicle or, on the other hand, should be avoided to reduce the risk of resonance and, thus, detachment between the road and the e-scooter's wheels on irregular surfaces (see Table 25 below).

Table 25. Relationship between e-scooter speed and critical dimension of the pavement material.

λ [cm]	v_m [km/h]
70	25
55	20
41	15
27	10
14	5
11	4
5.5	2

For example, on a typical porphyry brick pavement (where cubic bricks can be 12 × 12 cm or 6 × 6 cm, which is λ = 12 or 6, respectively), the resonance speed for e-scooters is 2–4 km/h, and thus right after the vehicle has been started. Again, for the flagstones pavement (λ = 50–60 cm), the critical resonance speed is around 20–25 km/h (which is the maximum speed allowed in most countries).

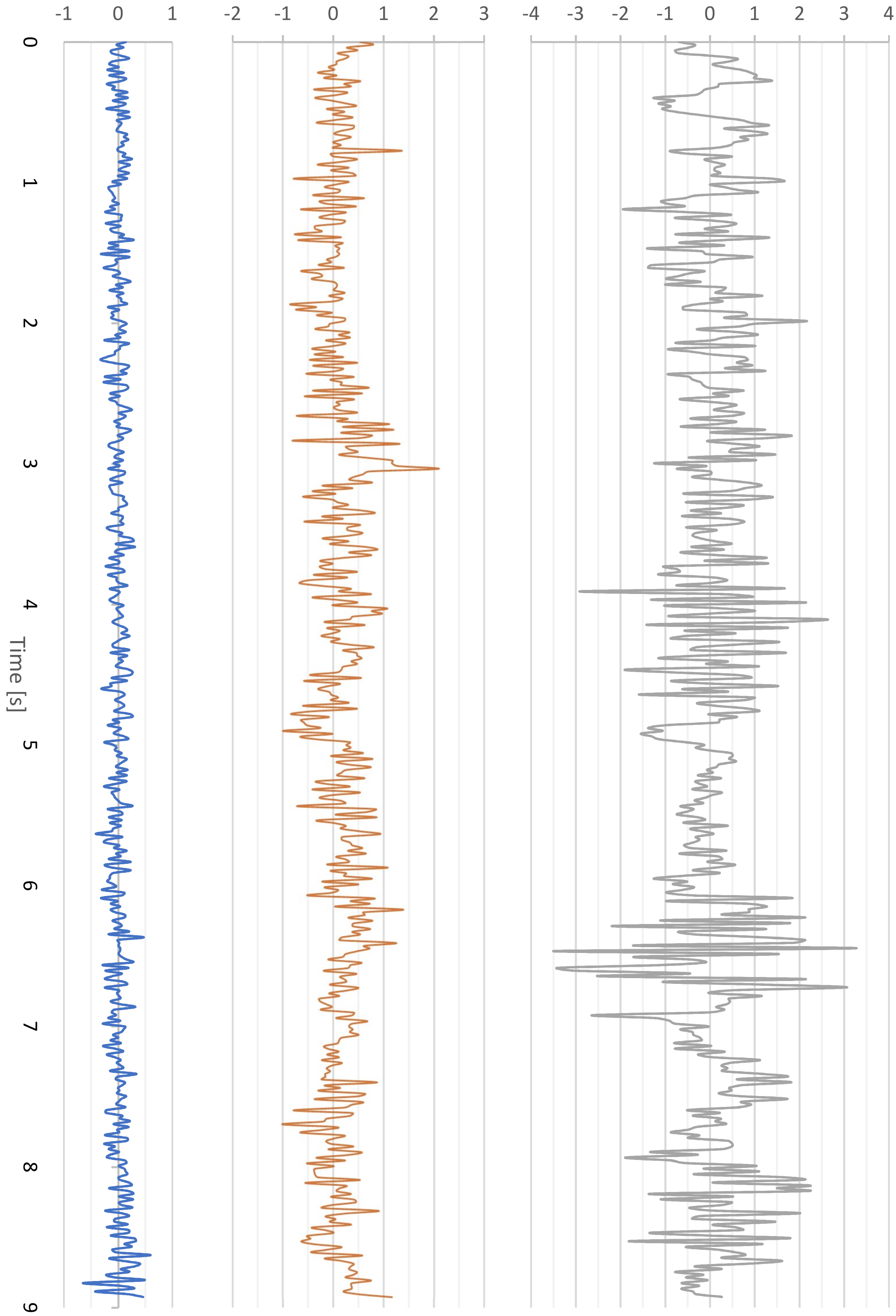

Figure 7. Vertical acceleration profiles for S1 (left), S2 (centre) and S3 (right) (authors' elaboration).

To summarize, vibrations caused by the infrastructure (material and pavement quality) affect vehicle motion based on several features (e-scooter type, presence and stiffness of suspensions, tyre radius and type). The combination of the IRI and DCI describes the quality of the pavement and is a good proxy for the presence of vibration for e-scooter riders; low-quality pavement induces higher vibrations, lower comfort and an increased likelihood of stability loss, which is in turn also influenced by the characteristic dimensions of the material. The presence of suspension on both wheels and a higher wheel radius is more effective than wheels alone in dampening vibration, thus allowing higher speed and stability on irregular/steep surfaces.

5. Scope for Further Research and Conclusions

The current state of research on e-scooters follows an approach based upon several parallel lines of research, which are difficult to integrate into an organic framework. This paper was conceived with the intention of closing the framework, investigating or providing references to some aspects that have remained marginal in the scientific literature on the subject, and to find a point of convergence between safety, the paradigms of user choice, social and gender equity and the characteristics of supply and demand, with a transport system approach and the traditional paradigm of mobility as a reference. To ensure safety, which seems to be the top priority for users, regulators, and the greater public, a huge effort is needed: it is necessary to take into account (i) e-scooter users, (ii) other road users, (iii) the infrastructures on which the motion act is carried out, (iv) the characteristics of the modes of transport investigated. In this study, we wanted to investigate whether or not cyclists and e-scooter riders (both classified as weak users, even if relevant differences exist in terms of structure, speed, driving position, etc.) were perceived the same by a car driver through the use of video footage and an online survey. In this way both active (i.e., the vision of the car driver) and passive visibility (i.e., how the cyclists and e-scooter riders are perceived) have been investigated in a sample intersection in an urban setting and under different conditions.

To answer to the first research question, a summary of the cases analysed (see Table 26) leads to the conclusion that in natural light conditions the e-scooter is perceived, in all cases, as distinct from the bike. Opposite to that, in artificial light contexts, the results tend to be more varied.

Table 26. *p*-value tests with SPSS—Summary.

		***p*-Value Tests**	
		Natural Light	**Artificial Light**
Total sample		0.000	0.495
Gender	Female	0.000	0.503
	Male	0.000	0.077
Age	<40	0.000	0.275
	> 40	0.000	0.039
Location	Wrong	0.000	0.172
	Correct	0.000	0.785
Sequence	Wrong	0.000	0.708
	Correct	0.000	0.210

Younger subjects (people under 40 years old) demonstrate a greater awareness of contemporary means of individual mobility. This consideration is supported by the fact that young people are also preferential users. On the other hand, education and awareness campaigns should target people with greater driving experience and those over 40 years old, who—in turn—tend to perceive the difference.

The questions investigating interviewees' attention to the location and sequence of videos suggest that the interviewees showed more attentiveness to impending danger in their surroundings rather than to the context, which is in agreement with studies in the literature investigating the linkage between speed and vision.

The population sample reached by the survey can be considered satisfactory, as no major differences relating to socio-economic factors prevail (gender, age, origin). The candidate sample is instead unbalanced in relation to driving experience, with most users (66%) owning a driving licence for longer than 10 years. The data relating to the use of the e-scooter are consistent with the body of literature, as a large part of the sample (80%) has no previous experience. In terms of age, those who have some form of previous experience with e-scooters are generally younger than 40 years old (32 vs. 13 over 40 years old).

In addition, among the 45 interviewees classified as "users", only 6 belonged to the cohort of "people under 40 years old, owning a driving license for more than 10 years"; this is consistent with the greater familiarity and adaptation capability of youngsters towards technological development and modern individual e-mobility vehicles. In particular, in artificial light conditions, there was no surprise effects among young candidates, who perceive e-scooters as equal to bikes.

As for the motivation behind e-scooter choice, the survey reports a balance between necessity and leisure users, also in terms of gender, age and driving license ownership. With regard to city size, most of the "necessity" users live in urban areas of > 100,000 inhabitants (15 vs. 7), while most "leisure" users (13 vs. 7) live in smaller settings. This indicates that for "necessity" trip chains—usually longer—those who live in smaller areas perceive other means of transport as faster and more reliable. In addition, all users who regularly use the vehicle (8) have also indicated "necessity" as the main use motivation, while those who use e-scooters rarely appear more oriented to the leisure motivation.

Finally, the survey also confirms to a certain extent the fears relating to the perceived danger of e-scooters, both for crossing and overtaking manoeuvres. However, this subjective opinion finds only partial confirmation from the videos; users react quicker to the appearance of the biker, but this happens closer to the crossing line. In artificial light conditions, instead, the reaction is almost identical. In addition, the analysis with SPSS highlights how the distinction between the bike and the e-scooter actually holds in daytime and high visibility conditions but is only partially met in artificial light conditions (and only by males aged over 40). The varying light conditions, therefore, are a key factor, and furthermore, the one on which the interviewees exhibited contradictory opinions. As already observed, the artificial light conditions make the differences smoother. This conclusion is supported both by the analysis on SPSS and from the survey, which shows a difference in the times of (virtual) braking of only 0.02 s; on the other hand, the majority of the users (71%) claimed to brake after or at the same time compared to daytime conditions. Finally, in terms of which manoeuvre is perceived as more dangerous by comparing natural and artificial light conditions, 34% of interviewees claimed that nothing changed and 56% argued that e-scooters require more attention in artificial light conditions.

To answer to the second research question, a deep investigation of the components related to the infrastructure and the vehicle that can lead to an accident has been carried out. The in-depth knowledge of the mechanical characteristics and performance of e-scooters can contribute to the design of suitable and safe vehicles and infrastructure, highlight the topics and the users for which preventive education is required and pinpoint the characteristics to be embedded into simulators to investigate space negotiation topics in detail. The performance of two e-scooter models with regard to acceleration, brake and vibration were analysed and compared, together with the influence of the pavement status on motion and stability. Accelerations are short but sharp, thus forcing drivers to compensate for the inertia and the induced vibrations with the body. On braking, the brake system plays a role too; the presence of a less powerful front brake favours less experienced users (as it prevents blockage and overturn), even if it requires greater space and time; on the other hand, only shock absorbers on both tyres ensure good performance on wet surfaces. Furthermore, the very structure of the vehicle influences adherence (tubeless and high radius wheels perform better than full and small ones, as greater rolling resistance and the absorption of road roughness is produced, regardless of the pavement type). Finally, the instability due to vibration resonance is possible in (i) historical pavement settings in pedestrian areas (where a lower speed limit is usually enforced) but only when the motion starts, and (ii) on brick pavement of 50–60 cm dimension at 20 km/h speed; this should influence the design and definition of eligible paths.

These are the underlying causes of the e-scooters' trajectory not being straight, which makes it difficult for other road users to read riders' intentions properly in addition to unpredictable behaviour such as mounting/dismounting the e-scooter—switching from rider to pedestrian and back again in order to take advantage of the pedestrian right of way where present—or marching zigzag between the car lane and the cycle path to avoid the longitudinal deflections of the latter. On the other hand, equipping e-scooters with lights and turn indicators will avoid the rider to losing grip on the handlebar even for short time periods and will allow quick communication in case of space negotiation, thus enhancing riders' confidence. This—together with stricter education campaigns and the possibility of coupling users and vehicles in the case of law infringement—will reduce examples of inconsistent behaviour and enhance safety and street décor.

The unpredictable motion of e-scooters and their drivers, as well as interaction and space negotiation phenomena, are not yet implemented in microsimulation tools as far as flow, level of service and network simulations are concerned, which makes these tools not yet fully reliable as unsafe interactions are very complex to model. To this scope, promising approaches are being proposed which may also become useful for the evaluation of the transport systems of the future (i.e., interactions between autonomous vehicles and human road users) [147,148].

This study aims to contribute to the definition of a holistic policy framework for e-scooters in order to insert them into a reliable, consistent, social and gender-neutral transport system context. For this reason, tests have been developed to determine their performance in relation to acceleration, braking, comfort and space negotiation in defined conditions. Performing further tests (i.e., varying the input conditions or the test fields) can help in achieving greater transferability and robustness (i.e., investigating the combined effects of vibrations and slope, the speed of the vehicles, speed limits, surface type, lighting condition, wet roads, etc.).

This study is affected by limitations relating to the instrumentation and methodologies for the realization of the tests, and last but not least, the pandemic affected the way in which the survey was made available to the audience. However, the main goal was to contribute to the discussion from a policy point of view and encourage discussion and cooperation at the scientific level.

The results are generally consistent with the body of literature and provide some notable advances in the comprehension of vehicle motion and on how e-scooters are perceived by other road users. In particular, as far as the transferability of the results is concerned, different pavement types or design criteria adopted in other countries are not seen as able to belie the findings of the paper. Drivers from countries in which light mobility and sustainable and healthy lifestyles are given higher priority might actually exhibit more careful attitudes towards both e-scooter users and cyclists. On the other hand, since e-scooters and bikes are quite widespread in those countries, there are higher odds that the two vehicles are perceived as similar; however, this hypothesis warrants further investigation.

By increasing the audience and repeating the analysis in different contexts and/or when the e-scooter becomes a "mature" modal alternative, increased reliability can be reached.

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