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Electric scooter safety: An integrative review of evidence from transport and medical research domains

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A B S T R A C T

Safe mobility is a prerequisite in the paradigm shift toward sustainable cities and societies. Yet, the serious safety concerns associated with the practice of emerging modes such as electric scooters (e-scooters) are a major challenge for a smooth adoption of these transport modes. We have systematically reviewed peer-reviewed e-scooter safety papers with a primary focus on transport and a secondary focus on medical research domains. Our findings suggest a dire need for analysing interactions of e-scooters with other road users, and, subsequently, adopting surrogate safety measures for e-scooters. Also, it is determined that head and face injuries are the most common injury types for e-scooter riders involved in collisions. The absence of uniform regulations for the practice of e-scooters could potentially affect their safe adoption. The findings highlight the importance of providing uniform regulations for safety gears as well as the prevention of riding under the influence.

1. Introduction

Active and non-motorised modes of transport provide various benefits for users and society (Chibwe et al., 2021; Lu et al., 2018; Nikiforiadis & Basbas, 2019). This includes alleviating environmental concerns raised by motorised vehicles that operate with fossil fuels, decreasing the risk of obesity, and mitigating congestion (Hosseinzadeh et al., 2021; Hung & Lim, 2020; Olabarria, Pérez, Santamariña-Rubio, & Novoa, 2014). Therefore, governmental support for active mobility has been on the rise in the past few decades (Kazemzadeh & Koglin, 2021). Powered micro-mobility, including electric bikes (e-bikes) and electric scooters (e-scooters)[1], are novel types of mobility. The electrically-assisted riding experience of this mode increases the trip enjoyment for users (Plazier, Weitkamp, & van den Berg, 2017). As a result, the market of powered micro-mobility has been rapidly expanded across the globe (Fishman & Cherry, 2016; Hosseinzadeh et al., 2021).

E-scooters provide unique mobility deemed to primarily address the first-last-mile trip problems (Nikiforiadis et al., 2021). However, the lack of physical effort in riding e-scooters contributes to their potential impact on substituting and supplementing other modes of transport, such as public transport and cars, for even longer trips (Laa & Leth, 2020). Riding e-scooters has been considered an enjoyable activity. The relatively small size and high speed of the e-scooters increase their agility and facilitate their navigation in different infrastructures such as sidewalks and bike lanes. Regardless of their benefits, the operation of e-scooters in road facilities comes along with serious safety concerns. For instance, there is a high risk of conflict between e-scooters and pedestrians on sidewalks considering that their speed regime is considerably different (Che, Lum, & Wong, 2020). Also, the issue of miss-parked e-scooters across different types of urban infrastructure could pose problems to the safety and comfort of all road users (Brown, Klein, Thigpen, & Williams, 2020).

Along with their growing popularity within the transport market, safety issues relating to using e-scooters have also come to light. The current statistics show that the number of accidents related to e-scooters has been rapidly on the rise. For instance, the number of e-scooter accidents in Sweden has dramatically increased since the introduction of e-scooters in 2018 in Swedish cities (Stigson, Malakuti, & Klingegård, 2021). Emergency department admissions across the world also represent a similar trend of rising accidents. Several studies in the US have documented the increasing trend of e-scooter accidents through existing hospital records (Cicchino, Kulie, & McCarthy, 2021a; Vernon et al.,

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[1] An electric scooter also called an electric kick scooter or electric standing scooter (e-scooters), is a stand-up scooter equipped with an electric motor. The rider should stand up on the large deck positioned at the centre of the e-scooter for riding.

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2020).

From the perspective of transport policy-making, it stands to reason that one can assess the safety concerns of new technologies at the early stages of their introduction to the market, prior to full commercialisation/operationalisation. The evaluation of the e-scooter academic literature in the transport domain also demonstrates the lack of comprehensive studies on the safety concerns of e-scooting. The central theme of the previous e-scooter studies is the evaluation of usage patterns (De Ceunynck et al., 2021) and the supplement/substitution impact of e-scooters (Huo et al., 2021; Reck, Haitao, Guidon, & Axhausen, 2021), while safety research has been scarce. Hence, the overarching aim of this paper is to integrate the e-scooters transport literature with the empirical evidence from the medical research domain regarding the safety of e-scooters. The study discusses policy-making implications that can also shape future safety research agendas. We refer to *medical-based* studies as a research strand whose primary focus is on the typologies of e-scooter accidents. In this domain, the challenges associated with the practice of e-scooters from the transport perspective are less highlighted. However, *transport-based* studies mainly discuss e-scooter safety issues in light of traffic flow, infrastructure, and engineering treatments.

The e-scooter literature evaluation revealed a lack of comprehensive systemic literature review studies (Toofany et al., 2021). Most studies in the medical domain research provided evidence from reviews of emergency department cases rather than previous studies (Dibaj et al., 2021; Iroz-Elardo & Currans, 2021; Shichman et al., 2021; Shichman et al., 2022). In the transport domain, the previous review focused on usage patterns and substitution effects of e-scooters (Liao & Correia, 2022; Kazemzadeh & Sprei, 2022; Şengül & Mostofi, 2021; Wang et al., 2022). Hence, there is a dire need for a comprehensive literature review to provide evidence for researchers, planners, and policymakers.

The contributions of this study are threefold. First, a comprehensive overview of the e-scooter literature with a primary focus on transport and a supplementary focus on medical research domains is delivered (see Appendix for a summary of previous studies). Next, the research themes which could contribute to evaluating the safety of e-scooters, e.g. modal interaction analysis, are discoursed, and research directions within each theme are suggested. Finally, a concluding discussion to converge different research themes for shaping future research agendas is provided.

2. Methods

Several methods could be adopted to conduct a review study. Scoping, systematic, thematic and bibliographic reviews have been frequently used in previous research to review the literature (Haghani & Bliemer, 2022; Kutela et al., 2021; Mendiate et al., 2022). The systematic review method is adopted in this paper to elicit relevant literature.

Scopus (www.scopus.com) database was selected as the main portal for searching publications. The database was searched in July 2021 with the following keywords: 'scoot', 'scooter', 'electric scooter', 'e-scooter', 'scooting', coupled with the keywords 'micromobility', 'micro-mobility', 'accident', 'crash', 'safety', 'collision', 'conflict', 'quality of service'. Simultaneously, we performed limited forward and backward expansion searching on the Google Scholar database with the original queries. Also, we searched the reference list of each article to include

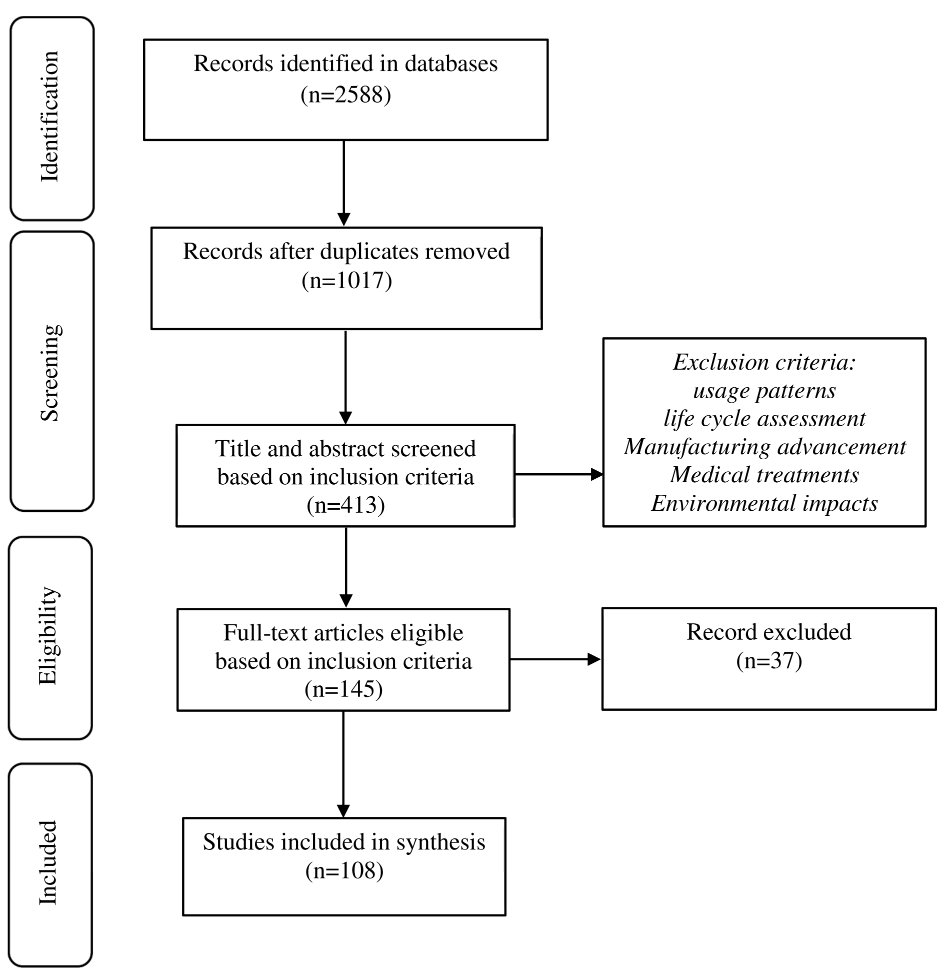

Fig. 1. The screening strategy based on the Prisma framework.

more topic-related studies. All searching strategies returned 2588 publications.

Based on the overarching aim of this paper (see the Introduction section), the following steps were designed to conduct a systematic literature review (see Fig. 1). In doing so, the Prisma framework was adopted as a guideline (Moher et al., 2009). First, publications were screened and classified based on their main focus. In the first stage, all papers with the primary focus on *transport* and *medical* research domains were included. Next, each individual paper was evaluated in the aforementioned domains. In the transport research domain, papers that had analysed e-scooters interaction, single and multiple collisions, and rules and regulations were included. The publications, which were mainly about usage patterns, riding comfort and the environmental impact of e-scooters were excluded based on title, abstract, and keywords. We picked publications from the medical research discipline that discussed the severity of collisions and safety gears. On the other hand, publications with a mere focus on medical treatments for e-scooters collisions were excluded.

All included publications are based on peer-reviewed English-language articles. After adopting all inclusion and exclusion criteria, 108 articles were fully reviewed. The reason for the large reduction of the included article is the strict criteria of inclusion and the specific scope of this article. We used publications from other fields (mainly other types of micro-mobility) to expand the discussion on each reviewed theme.

3. Findings from the reviewed research domains

To facilitate the navigation through the literature, we classified the findings of the literature (in both research domains) based on three following categories: safety concerns of e-scooting, accident patterns and issues, and traffic enforcement.

3.1. Safety concerns of e-scooting

The introduction of a new mode of transport induces a unique set of issues, such as compatibility challenges with other modes as well as a lack of adequate riding/driving experience for users. An in-depth understanding of e-scooting safety concerns could lead to developing risk mitigation plans and, consequently, a safer environment for riders. In this section, the safety concerns associated with e-scooters (mainly dockless) are first explored and discussed. Next, some interaction modelling procedures for e-scooters are discussed by using the literature of other types of micro-mobility. Finally, conflict-based measures and their applications for e-scooters are reviewed.

3.1.1. Sharing policies of e-scooters

The term *shared mobility* refers to transport services that are shared among users and includes several modes of transport, such as car-sharing and ride-sharing (Sprei, 2018). The development of sharing strategies for these modes dates back to a long time. For instance, car-sharing was established in Switzerland in 1948 (Shaheen, Sperling, & Wagner, 1999). In a similar vein, the notion of bike-sharing as a form of shared mobility has been around since 1965 (Shaheen, Guzman, & Zhang, 2010). Therefore, there is extensive knowledge regarding both car- and bike-sharing. In contrast, shared e-scooters were only operationalised in mass in 2017, while their usage rapidly increased after a short period of time (Younes, Zou, Wu, & Baiocchi, 2020). For instance, in 2019, 86 million e-scooter trips were reported in the US, which is about two times higher compared to 40 million trips on bike-shared trips (NACTO, 2019). The high demand for e-scooter usage highlights the importance of evaluating e-scooter sharing strategies.

Two main sharing strategies (similar to other forms of shared micro-mobility), including docked and dockless systems, have been applied for e-scooters. In a docked system, an e-scooter should be picked up from a station and dropped off at any station, while in a dockless system, a user can pick up and drop off e-scooters at any location (Shaheen & Cohen, 2019). One of the critical benefits of a dockless sharing system compared to a docked one for users is the convenience of picking up and returning at any location. Although this system boosts the usage of e-scooters, this comes with several safety challenges in urban settings. For example, e-scooter parking violations (miss-parked e-scooters) cause serious problems in relation to cycling and pedestrian infrastructure (i.e. bike tracks and sidewalks). Illegal and miss-parked e-scooters on sidewalks affect both safety and comfort of road users (Brown et al., 2020; James, Swiderski, Hicks, Teoman, & Buehler, 2019).

Considering the agility and high speed of e-scooters, the conflicting interaction of e-scooters with miss-parked e-scooters in transport facilities will be inevitable. However, few studies have explored this issue. For instance, Gössling (2020) reviewed extensive media sources and suggested that irresponsible riding, safety and miss-parked e-scooters are the sources of concern regarding the usage of this means of mobility. James et al. (2019) evaluated the practice of e-scooters in the US and concluded that 16 per cent of the observed e-scooters are miss-parked, and six per cent of them blocked pedestrians' territory. Similarly, Brown et al. (2020) reported 1.7 per cent of parking violations for e-scooters based on an observational study in the US. Although the issue of miss-parked e-scooters has been discussed in a few research studies, the safety consequences of this behaviour are yet to be determined (Zuniga-Garcia, Ruiz Juri, Perrine, & Machemehl, 2021).

Furthermore, miss-parked e-scooters could potentially increase the chance of single collisions. This issue could be discussed from two perspectives. First, the relatively small size of e-scooters (compared to bikes) might reduce their visibility, specifically at night. This issue could cause safety concerns for all road users, particularly those using powered micro-mobility. Second, assuming that an e-scooter rider detects a miss-parked e-scooter at a transport facility, the navigation manoeuvre performed by the rider to avoid a potential collision at high speed might increase the chance of losing balance and, consequently, a single collision. The high speed and harsh weather conditions could potentially amplify the chance of single accidents, as shown in the cycling research domain (Olesen, Madsen, Hels, Hosseinpour, & Lahrmann, 2021). One possible solution to address the issue of the dockless sharing system could be the allocation of more precise virtual areas (e.g. geofence) for parking in different transport facilities (Cheng, Guo, Chen, & Qin, 2019). These efforts could be considered a type of *semi-dockless* system that could help plan safe infrastructure for e-scooters and other road users (Zou, Younes, Erdoğan, & Wu, 2020).

3.1.2. The interaction of e-scooters with other vulnerable road users

The interaction of e-scooters with vulnerable road users in transport facilities could range from a regular traffic interaction to a traffic conflict and, ultimately, a collision. Therefore, the assessment of road users' interaction involves various variables such as the spatiotemporal position of road users, speed regimes, infrastructure configurations, and the combination of road users (Arun, Haque, Washington, Sayed, & Mannering, 2021).

The rules and regulations related to the practice of e-scooters on infrastructure are unclear and could be varied based on geographical settings (Gössling, 2020). As a result, e-scooters could be operated in both on- and off-road facilities[2]. Therefore, evaluating safety concerns in all types of facilities is crucial for the safe adoption of e-scooters. The safety concerns of e-scooters could be discussed from the following perspectives. First, safety issues could vary based on the sharing policy of infrastructure (i.e. on- and off-road facilities). Second, unique safety concerns might be associated with different components of the infrastructure (i.e. node, link, and network). Also, other factors, such as the proration of road users, weather condition, and pavement distress, could

[2] In on-road facilities, the infrastructure is shared for both vulnerable road users and motorised vehicles. In contrast, off-road facilities are dedicated facilities for bikes, pedestrians and other road users, e.g. sidewalks (HCM, 2016).

contribute to modal interactions (Kazemzadeh & Bansal, 2021a).

The speed regimes of road users in transport facilities could be significantly different as each mode has unique characteristics (Nikiforiadis et al., 2020). For instance, e-scooters and pedestrians have the most different speed regimes in off-road facilities. These high differences between e-scooters and pedestrians increase the chance of interactions, conflict, and potential collisions. Also, sidewalks are relatively narrow, making road users move close to each other, which poses difficulties for making manoeuvres. For example, N. Haworth, Schramm, and Twisk (2021) conducted a study in Australia and reported that 40 per cent of e-scooters ride within 1 meter of at least one pedestrian. Therefore, both parties could be involved in a high risk of collisions in off-road facilities (Feng, Jiao, & Wang, 2020). Previous studies documented how pedestrians and cyclists were injured in the collisions of e-scooters (English et al., 2020; Toofany, Mohsenian, Shum, Chan, & Brubacher, 2021). Although both pedestrians and e-scooters are vulnerable in collisions, pedestrians may be the more vulnerable party in these scenarios compared to the rider, who may already be equipped with protections gears such as a helmet. More research is needed to explore the interaction/collision of e-scooters-pedestrians and possible collision avoidance mechanisms.

Regarding on-road facilities, beyond the speed differences between e-scooters and motorised vehicles, the vulnerability of e-scooters (e.g. a lack of a protective body) increases the possibility of severe collisions. The literature shows only a few studies that compared the accident rate and severity based on off- and on-road facilities, with contradictory results in some cases. For example, Bloom et al. (2021) reviewed the records of patients involved in e-scooter collisions and reported that 36% of injuries occurred on streets which is two times the percentage of injuries that occurred on sidewalks (17%). However, Cicchino, Kulie, and McCarthy (2021b) reported sidewalks as the most frequent location for e-scooter injuries. The crude comparison of studies on these facilities might introduce some biases as the representative sample, riding skill, and the severity of injuries could be different in these facilities. Thus, there is a need for more comprehensive research to analyse and compare the sharing policies of infrastructure from the safety perspective.

The severity and rate of conflict and collision could also be related to the infrastructure component. Considering the similarity of different types of micro-mobility, the extensive research domain of cycling could be insightful for the assessment of e-scooter safety. For instance, intersections are common infrastructure components where collisions occur for cyclists (Schepers, Kroeze, Sweers, & Wüst, 2011; Wang & Nihan, 2004). The literature evaluation reveals a lack of a comprehensive study that evaluates the safety of e-scooter riders based on the component of infrastructure (Shah, Aryal, Wen, & Cherry, 2021). The records of hospitals in the medical transport domain could provide more details related to injuries and the respective components of the infrastructure. This information could potentially be used in the transport domain to guide planners comprehensively. More information related to the configuration of collision locations, type of transport component, and vicinity of collision locations to intersections/crossings could be beneficial for safety analysis.

3.1.3. Surrogate safety measures

Surrogate safety indicators are non accident-based metrics related to traffic safety. This concept is based on the assumption that traffic events which involve the nearness of road users could be relevant for safety (Johnsson, Laureshyn, & De Ceunynck, 2018). Leveraging on the safety concepts from other vulnerable road users, different indicators have been developed to evaluate the safety of road users. We classified indicators as pure safety-based and quasi safety-based indicators. In the first category, the spatiotemporal characteristics of road users are analysed (Johnsson et al., 2018). The next category is related to quasi safety-based indicators, which could potentially be based on hindrance-based approaches or stress (subjective safety) of road users (Kazemzadeh & Ronchi, 2021).

Since the e-scooter research domain is still at the early stages of development, this section primarily discusses literature from the related domains. In the above first category, time to collision, post-encroachment time, and deceleration metrics could be used as surrogate safety measures. Time to collision represents the potential time of collision if the two road users do not change their speed and direction (Hayward, 1972). Post-encroachment time refers to the time between the arrival and departure of two road users at one point or an area of conflict (Johnsson et al., 2018). The metrics mentioned above have been commonly applied to different domains of micro-mobility (Beitel, Stipancic, Manaugh, & Miranda-Moreno, 2018; Rasch et al., 2020). Thus, these safety metrics could similarly be potential indicators to be adopted for e-scooters.

In addition to the first category, there is a significant body of research related to quasi safety-based indicators (the second category). These indicators are mainly originated in the level-of-service (LOS) research domain and have been extensively applied in the analysis of bike and pedestrian interactions. Applications of these indicators in safety and comfort in many cases are mixed. For example, the first systematic LOS index for bikes was proposed by Davis in 1987, which is related to the safety evaluation of bike systems (Kazemzadeh, Camporeale, D'Agostino, Laureshyn, & Winslott Hiselius, 2020). Thereafter, many different indices, such as suitability, compatibility, level of stress, and psychological stress have come into circulation in this field (Asadi-Shekari, Moeinaddini, & Zaly Shah, 2013). One of the most relevant concepts which could be directly adopted for e-scooter safety analysis is the *hindrance* concept. This concept deals with measuring the degree to which a road user is restricted from manoeuvring. According to this concept, the interactions are classified based on the same-direction (passing) and opposite-direction (meeting) encounter. This concept has been commonly applied to the development of bike LOS methods based on (e)bike-pedestrian interactions (Botma, 1995; Kazemzadeh & Bansal, 2021b). The operation of e-scooters in off-road facilities and their similar interactions with other vulnerable road users reinforce the application of this method for the safety analysis of e-scooters. The analysis of the interaction of e-scooter riders provides useful information for conflict analysis.

Along with the aforementioned methods, microsimulation models have been frequently used in the literature on powered micro-mobility (Li, Ni, Sun, & Ma, 2020). This body of research primarily depicts the interaction of road users and mimics future scenarios. Different models, such as Cellular automata, psychological-physiological force, and car-following models have been applied in the field of active mobility (Xue, Jia, Jiang, Li, & Shan, 2017). Considering that the e-scooter research is at its early stage, the adoption of such models from the field of active mobility could be beneficial to assess future scenarios and planning for e-scooters.

It should be noted that accident records could also be considered as a way of safety evaluation for a transport mode. However, different limitations are associated with accident records. For example, accidents are random, and their typologies vary across locations and situations. Also, accidents are rare, and it would not be ethical to wait to gather enough records of accidents in order to evaluate safety of a system (Elvik, Vaa, Hoye, & Sorensen, 2009; Laureshyn, 2010). Therefore, there is a need for surrogate safety measures, which enable researchers to evaluate the events that could lead to accidents.

3.2. Accident patterns and issues

The evaluation of the previous accident characteristics provides valuable information for adopting safety mitigation plans for e-scooters. In some cases, the presence of new types of powered micro-mobility could change the epidemiology of accidents, and therefore, there is a need for respective adjustments in accident analysis and prevention methods (Botton, Takagi, Shlez, Yechiam, & Rosenbloom, 2021). This section discusses the socio-demographic characteristics of users involved in accidents, the frequent location and time, and the typology and severity of accidents.

3.2.1. Socio-demographic characteristics of users involved in accidents

The socio-demographic characteristics of e-scooter riders involved in collisions provide helpful information for planners and the health care system as they allow the risk groups to be identified, whereby respective policies could be adopted. This information is mainly recorded in the health care systems (i.e. emergency departments). The evaluation of the e-scooter literature revealed that men are more involved in such accidents (W. C. Kim & Campbell, 2021; Mukhtar, Ashraf, Frank, & Steenburg, 2021; Namiri et al., 2020). This result could be discussed from different perspectives. From the usage patterns distribution analysis, e-scooters have been frequently referred to as a "male-dominated" mode of transport (Nikiforiadis et al., 2021). This might partially describe the high rate of males involved in collisions. Another explanation for the high rate of male-related collisions could be due to the different riding behaviour of men and women. As an example, some similar studies in the field of micro-mobility reported that male riders more frequently show risky behaviour than female riders and are therefore more prone to collisions (Bai, Liu, Guo, & Yu, 2015; Hollingworth, Harper, & Hamer, 2015; Prati, Fraboni, De Angelis, & Pietrantoni, 2019).

Furthermore, young adults have been associated with a higher rate of e-scooter riding, which might be due to the general popularity of powered micro-mobility among this age group. The evaluation of users' age involved in collisions varies among previous studies. The age group between 18 to 44 years is a consistent age range for users involved in collisions (W. C. Kim & Campbell, 2021; Moftakhar et al., 2020; Mukhtar et al., 2021). This result could be interpreted from several angles. First, little experience navigating a new mode of transport, especially for younger adults, might increase the chance of collisions. In addition, young adults might get more distracted by different types of phone activities, such as phone reading or writing texts while riding. This behaviour has been extensively observed among this age group while they were driving cars and riding bikes (Cook & Jones, 2011; Ichikawa & Nakahara, 2008). Also, the usage of an e-scooter (locking and unlocking the device) requires mainly the use of smartphones, and users might continue using their phones for navigation after that.

The overall socio-demographic characteristics of e-scooter riders represent male, young and educated users. The traffic safety improvement for this group has some advantages and challenges. For example, the fact that planners mainly deal with educated users in this context may facilitate the delivery of traffic education programs. However, young adults might ride e-scooters recklessly, and peer pressure might amplify their risky behaviour (Gheorghiu, Delhomme, & Felonneau, 2015). These challenges indeed could be connected to different transport modes, while some characteristics of e-scooters make them more cumbersome. For instance, using an e-scooter does not require a driving licence, the scooters could be easily picked up and dropped off in cities, and there are no strict rules or regulations to control users' age.

3.2.2. Frequent locations and time periods of collisions

The determination of frequent locations and times of conflicts and collisions contributes to safe planning and engineering solutions. Exploring previous research on e-scooter safety shows that information regarding the collision location is rarely provided in either research domain (transport and medical research domains)[3]. This could be expected in the medical research domain since the main theme of these studies is the type of injuries and respective medical treatments. This knowledge gap in both research domains is a disadvantage for accident analysis and prevention programs.

In order to assess the places with high exposure to e-scooters and potential risky spots, the literature related to the usage patterns of e-scooters was further explored. The results consistently suggest that e-scooters are highly appealing in the city centre and university campuses (Huo et al., 2021; Zhu, Zhang, Kondor, Santi, & Ratti, 2020). This could be due to the fact that e-scooters are appealing modes of transport for short-distance trips, and thus makes them a popular option to travel within city centres. Also, e-scooters are frequently used on university campuses which might be explained by the high usage of young and well-educated adults. The frequent sighting of e-scooters in the aforementioned places calls for more attention from the safety perspective for planners. This finding does not necessarily mean that locations with high exposure to e-scooter are associated with higher risks of accidents. Leveraging the concept of *safety in numbers,* the locations where more people walk and cycle have a lower likelihood of collisions in those modes (Jacobsen, 2015). This could be because when more drivers cycle, they have more cycling experience and be more aware of cyclists while driving (Johnson, Oxley, Newstead, & Charlton, 2014).

On the other hand, places with high exposure of vulnerable road users could pose an elevated risk of conflict/collisions, as different modes adopt various navigation characteristics, e.g. speed and acceleration/deceleration (see 'The interaction of e-scooters with other vulnerable road users' section for more details). Matching the accident typology and location (from medical and transport research domains) could provide useful information for the detection of unsafe spots and respective risk mitigation programs.

The time/date of collisions has been frequently reported in previous studies. More specifically, more collisions occur out of business time and over the weekend (Moftakhar et al., 2020; Vernon et al., 2020). This could be partly explained by the high rate of e-scooter usage over weekend days. Indeed, more research is needed to compare riding behaviour on weekdays and weekends (e.g., riding under the influence of alcohol over weekends). In sum, there is a lack of detailed e-scooter accident data in both medical and transport research domains. The evaluation of the frequent time of accidents is essential information for adopting strategies in both transport and medical domains. From the transport domain perspective, planners could further elaborate on the causal mechanism and contributing factors of the specific time of collisions. From the medical research domain, the management of the healthcare system would be more efficient and prepared for possible accidents

3.2.3. The typology and severity of injuries

Understanding the typology and severity of collisions contributes to assessing and eventually improving e-scooters safety. A general classification could be based on agents involved in an accident, i.e. single and non-single collisions. Single accidents could be referred to as obstacle collisions (or falling down from bikes or e-scooters). On the other hand, in non-single accidents, more than one vehicle (or a road user) is involved in collisions (e.g. rear-end and head-on collisions).

According to the medical research domain, single collision (falling from e-scooters) has been found to be the frequent type of collision for e-scooters (Bloom et al., 2021; Cicchino et al., 2021b; English et al., 2020). The loss of balance and falling from e-scooters could stem from different factors, such as the experience level of riders, modal interactions, pavement distress (e.g. pothole, uneven pavement) and weather conditions. Furthermore, colliding with other road users and vehicles is also pronounced as a common type of e-scooters collision (English et al., 2020; Hourston, Ngu, Hopkinson-Woolley, & Stöhr, 2021; Yang et al., 2020). Further studies are needed to investigate other e-scooter collisions, such as overtaking, rear-end, and door crashes. Moreover, contributing factors to collisions based on the typology of collisions (e.g. infrastructure configurations, safety gears, and weather conditions) could be recorded in the medical research domain and contribute to engineering treatments. In previous studies, the medical research field

[3] This argument could have some exceptions. For example, Strada is an extensive accident record database in Sweden which has details of accidents e.g. location, time, and agents' involved in accidents (www.transportstyrelsen.se).

mainly reported wearing a helmet and riding under the influence.

The severity of accidents could range from minor to fatal injuries. The severity of injuries could be correlated with the typology of collisions and the types of vehicles and road users involved. Head and face injuries are registered as the main types of injuries related to e-scooter collisions (Dhillon et al., 2020; English et al., 2020; Harbrecht et al., 2021; Mebert, Klukowska-Roetzler, Ziegenhorn, & Exadaktylos, 2018). These types of injuries are mainly reported in the medical research domain and are not reflected in transport studies. More details related to accident typology, severity and the possible contributing factors from the medical research domain could be beneficial for engineering treatment in the transport domain. In sum, single collision is one of the main typologies of e-scooter accidents. Plus, head and face injuries are the most common damages of e-scooter collisions.

3.3. Traffic enforcement

Traffic enforcement, along with engineering and education, paves the way for providing safe mobility. The influx of e-scooters and their rapid popularity has left planning behind the practice. Therefore, there is a need to evaluate and improve risky behaviour and safety issues related to using e-scooters and adopting necessary traffic rules and regulations. In this section, some general considerations regarding the usage of e-scooters are discussed, which are deemed necessary for a safe adaptation of e-scooters. This section covers the following issues: the regulations related to using e-scooters, helmet law and riding licence, and riding under the influence.

3.3.1. The regulations related to using e-scooters

The literature on rules and regulations could contain a variety of topics, from economic to social concerns, including safety, privacy, security, and environmental issues (Button, Frye, & Reaves, 2020; Petersen, 2019). Safety issues related to e-scooters are critical for this mode of transport, and rules and regulations contribute to providing a safer environment for riders. Safety considerations such as speed limit, riding one person per device, and helmet use should be part of the regulations' agenda. However, there are no uniform and clear regulations for e-scooter riders regarding safety considerations. For example, in Scandinavian countries, rules and regulations related to riding e-scooters practice, such as riding for more than one person per device, the legal place of riding and helmet use are different. In Norway, e-scooters with more than one rider get 3,000 Norwegian kronor penalties (Norwaytoday, 2021). The newly adopted rule in Sweden from the first of September 2022 does not allow e-scooters to be ridden on sidewalks, and they should not be parked on sidewalks and bike lanes except for designed parking spaces (Regeringen,2022).

Furthermore, speeding could be considered a critical problem for different transport modes, and the assessment of possible inhibition approaches could benefit road users (Haglund & Åberg, 2000). For instance, speed contributes to the severity and frequency of collisions which is the primary safety concern for users (Tranter, 2010). Different approaches, such as education and enforcement, could be applied to increase the safety of road users, specifically vulnerable road users (Wegman, Zhang, & Dijkstra, 2012). Previous studies suggest the importance and applications of the speed limit for e-scooter practice (Field & Jon, 2021; Ma et al., 2021a,b). In practice, speed limits could be implemented in various ways. For instance, the maximum speed could be regulated by the operators in a way that the e-scooter is adjusted to the intended speed (Haworth & Schramm, 2019). Also, users who do not obey the rules could be observed via their registration information. However, handling personal data and using it for traffic enforcement requires legal authorisation.

Considering the high speed/acceleration of e-scooters, proposing a minimum (and possibly maximum) age range for users might help a safer practice of e-scooters. However, the legal age for riding e-scooters could be varied based on operators' decisions and the countries wherein e-scooters are operated. For instance, e-scooter riding is only allowed for riders who are at least 18 years old by some operators and countries (Gössling, 2020). Also, e-scooters from some companies/countries like Australia can be operated by riders who are 12 years old and supervised if they are under 16 years (Haworth & Schramm, 2019). In sum, the rules and regulations do not seem uniform (e.g. speed limit, minimum user's age) and are tailored mainly by each operator and city, which calls more attention worldwide to improve public health.

3.3.2. The helmet law and riding licence

Active mobility users do not have protective bodies like cars, so a helmet is the primary[4] safety gear to protect users from head injuries. Wearing a helmet has been confirmed as safety gear that could reduce the consequence of head injuries in cycling accidents (Cripton, Dressler, Stuart, Dennison, & Richards, 2014; Scuffham, Alsop, Cryer, & Langley, 2000). The usage of helmets for cycling and e-cycling still faces several challenges, and there is no uniform rule for the implementation of helmet use. The adoption of helmet use for e-scooters, especially shared could be expected to be even more cumbersome.

The review of the literature revealed that regulations related to the use of helmets differ based on the geographical distribution (Gössling, 2020; Harbrecht et al., 2021). For example, the use of helmets is different across the US, such as being mandatory for all ages, special age groups (usually <14), or being optional (Sikka, Vila, Stratton, Ghassemi, & Pourmand, 2019). Scrutinising the literature with the medical research focus revealed a very low helmet usage rate (about less than 5%) for users involved in collisions (Bloom et al., 2021; Cicchino et al., 2021b; English et al., 2020). The percentage of helmet usage and respective discussions related to head and face injuries have been mainly provided in the medical research domain. This could be due to the registration of patients in hospitals (mainly emergency departments) and reporting the overall conditions, including the usage of safety gears. The low percentage of using a helmet for users involved in collisions could have several takeaways for the transport sector. The aforementioned information should be widely used in traffic education, and consequently, users would be aware of the potential risks. Also, these statistics highlight the importance of immediate action from planners and policymakers to regulate the usage of safety gears for e-scooters.

The requirement for a riding license, license plates, and insurance could also be the case for a wide range of powered micro-mobility such as e-scooters, e-bikes, and e-boards. Similar to a helmet, the necessity of providing a riding license, license plates, and insurance is unclear for other types of micro-mobility, such as e-bikes. For instance, e-bike riders need to register license plates in China but have no requirement for riding licenses (Guo, Li, Wu, & Xu, 2018; Yao & Wu, 2012). The case of license plates might not be necessary for shared e-scooters as operator companies track riders for registration and cost estimation. Similarly, insurance could also be provided by e-scooter companies as part of the renting costs. The quick acceleration feature characteristics of e-scooter riding imply the requirement of the user's experience and knowledge about the device. Also, providing some mandatory risk courses[5] prior to the use of an e-scooter might increase the safety of riders as they would understand potential risks both in theory and practice. In sum, the usage of a helmet and having a driving licence for an e-scooter are not mandatory, and more research is needed to evaluate different scenarios to implement these policies for e-scooters.

[4] Different safety gears, such as elbow and knee protectors, and airbag head protection (Hövding), could also improve riders' safety.

[5] In Sweden, before the car driving test, the candidate needs to pass two courses (i.e., Risk One and Risk Two) in theory and practice. The lessons learned from these courses could be applied to e-scooters to make them aware of the potential risk of e-scooting.

3.3.3. Riding under the influence

As discussed in the previous sections, micro-mobility usage is less regulated than motorised vehicles, which might make it easier for some risky behaviour, such as riding under the influence. Riding under the influence could be considered a serious threat to micro-mobility users. For instance, alcohol use for cyclists is mainly associated with severe injury (Andersson & Bunketorp, 2002; Martínez-Ruiz et al., 2013). As a result, the use of alcohol could also be related to the use of more hospital resources and a high death rate (Sethi et al., 2016). This issue calls for the collaboration of medical, transport, and policy sectors to prevent such behaviour for micro-mobility users.

The review of the e-scooter literature (mainly on the medical domain) revealed that in many cases of e-scooters collisions, there was evidence of riding under the influence (Bekhit, Le Fevre, & Bergin, 2020; Harbrecht et al., 2021; Kobayashi et al., 2019; Puzio et al., 2020). In the previous studies, alcohol consumption was measured legitimately or self-reported (Cicchino et al., 2021b; Harbrecht et al., 2021). Other intoxication and drug, such as marijuana, were also documented via self-reports in some cases (Bloom et al., 2021). These findings reinforce the importance of a systematic approach to controlling riders under the influence. The linkage between the usage of e-scooters on weekends and drinking on such days could be taken into account for special considerations of e-scooter safety. In general, alcohol consumption is higher on weekends compared to weekdays (Pridemore, 2004; Sieri et al., 2002). Therefore, it is expected that e-scooter riders might be under the influence of alcohol, mainly on weekends which are associated with more injuries.

Also, city centres and university campuses have a high rate of e-scooter usage, and more caution is needed in these places to avoid riding under the influence. Moreover, riding under the influence and the severity of injuries were discussed in a few previous studies. For example, it was claimed that traumatic brain injury was associated with alcohol consumption (Uluk et al., 2021). Information regarding the frequent percentage of alcohol usage, collision typology, and time and date of collisions could be useful to have a comprehensive overview of collisions, which could be provided from the medical research domain.

4. Discussion and outlook

Safety issues of transport systems are a multi-faceted problem. In this paper, we considered the safety concerns of e-scooting from the transport and medical research domains. The results of the review revealed that safety-related research in the transport field is far more limited than in the medical research domain. Injury patterns have been discussed in both domains; however, the characteristics of injuries have mainly been highlighted in the medical research domain. The aggregation of findings from both research domains could contribute to safer transport planning and better management of hospital resources.

The competition of different transport modes for taking the best out of the existing infrastructure could provide a unique set of problems. For example, e-scooters need to be operated on sidewalks and bike lanes. The presence of e-scooters has not been considered in the design of this infrastructure in terms of speed regime, capacity and LOS analysis. The different speed regimes of e-scooters compared to pedestrians and cyclists lead to overtaking and possible conflicts. The evaluation of the literature demonstrates a lack of comprehensive studies that analyse the interaction of e-scooters with other vulnerable road users. This research gap could be addressed by designing dedicated experiments and microsimulation models in future studies to assess the interaction of road users in different scenarios. The research background of the surrogate safety measures of cycling could also be insightful for developing future tools for the safety evaluation of e-scooters.

Single accidents such as losing balance are commonly reported as the main type of e-scooter accidents in the medical research domain. Different explanations could be associated with this finding. First, the lack of experience in using a new type of mobility, young adult users, and possible risky behaviour could lead to losing balance and, consequently, single collisions. Next, the high speed/acceleration and agile characteristics of e-scooters could make the navigation of e-scooting cumbersome, especially in harsh weather conditions.

In terms of accident characteristics, head and face injuries are the most frequently reported. Also, patients were mainly without helmets and often rode under the influence. This issue has been highlighted in the medical research domain as the respective treatments were discussed in this research domain. The essential takeaway from this finding to the transport field is the importance of wearing helmets for riders to decrease the consequences of accidents. Also, enforcement of legal consequences for riding under the influence could be considered a mechanism for accident prevention.

All in all, the safety issues for e-scooters could be demonstrated as a sequence of events. First, the e-scooter, a novel technology, is introduced without a profound theoretical consideration of safety consequences, and therefore, safety issues will emerge in practice. Then, traffic enforcement for e-scooters (e.g. wearing a helmet and prohibition of riding under the influence) is not fully considered, which leads to a pattern of accidents where users lack safety gears and may be intoxicated. Hence, the evaluation of safety literature in transport and medical research domains reveals a dire need for further research into the safety characteristics of e-scooters. More specifically, further research is needed in some areas of research, such as the safety consequences of sharing policies in terms of e-scooters and infrastructure, user characteristics, and typology of accidents. Plus, developing and applying surrogate safety measures for e-scooters could provide useful knowledge for the practice of e-scooter in different scenarios.

Declaration of Competing Interest

There are no conflicts to declare.

Data availability

No data was used for the research described in the article.

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Appendix

Previous studies related to the e-scooter safety

Author(s) (Year)	Geography	Central theme	Data/collection	Data analysis	Main conclusions or recommendations
N. Haworth et al. (2021)	Australia	Risky behaviours	Observation	Chi-square	The illegal riding behaviour of shared and privately owned e-scooters was different. For example, riding without a helmet, riding with more than one passenger, and riding on the road was more common for shared e-scooters than privately owned ones.
Moftakhar et al. (2020)	Austria	Incidence and severity of injuries	Hospital databases	t-test and Chi-square test	The average age of people involved in the collision was 34.4 years. Older adults (over 40 years old) reported having a higher injury severity score than young adults. During late afternoon and evening, injuries associated with e-scooters increased, plateauing around 8 p.m.
Siebert et al. (2021)	Germany	Ergonomics and users' knowledge	Field observation & survey	Fisher's exact test with Bonferroni correction	A high percentage of illegal behaviour was documented by users. Also, one-third of users precisely knew the braking system of shared e-scooters.
Kopplin, Brand, and Reichenberger (2021)	Germany	Usage pattern	Survey	Structural equation modelling	E-scooters are regarded as a fun mode of transport, and subjective safety is an obstacle to the usage of e-scooters.
Harbrecht et al. (2021)	Germany	Injury patterns	Prospectively collected data	Chi-square	The average age of users was 30.03 years. None of the users involved in collisions wore a helmet. Riding under the influence was also reported in some cases of collisions (15.25%).
Botton et al. (2021)	Israel	Injury patterns	Prospectively collected data	Chi-squared test & t-test	In terms of injury severity score, light electric vehicles result in more severe injuries for children compared to light non-electric vehicles. Light electric vehicles introduce changes in the epidemiology of collisions, and the road safety mitigation framework should be adapted accordingly.
Lee, Yun, and Yun (2021)	Korea	Risk factors	Survey	Clustering	The findings of this study provide some inputs for the design stage of e-scooters.
McGuinness, Tiong, and Bhagvan (2021)	New Zealand	Injury Patterns	Hospital databases	Fisher's exact test	E-scooting is less safe than cycling as the data revealed a high rate of e-scooter hospitalisation. The possible strategies to improve e-scooting safety could be the prohibition of riding under the influence, mandator helmets, and restriction of the operation time of e-scooters.
Beck, Barker, Chan, and Stanbridge (2020)	New Zealand	Hospital admissions changes due to e-scooter injuries	Hospital databases	Descriptive statistics, Fisher's exact test	With the introduction of e-scooters, emergency department admission increased.
Almannaa et al. (2021)	Saudi Arabia	Usage concerns	Survey	Regression Models	The safety concerns of e-scooters, weather conditions and lack of proper infrastructure are the main barriers to the adoption of e-scooters.
S.-H. Kim, Lim, and Kim (2021)	South Korea	Countermeasures of collisions	Questionnaire	Structural equation modelling	According to the survey results (for powered micro-mobility), many respondents felt that safety equipment and systems are needed, and the current system is insufficiently safe, resulting in an increased accident risk.
J. Y. Kim et al. (2021)	South Korea	Characteristics of injuries	Emergency department-based Injury	Descriptive statistic	The participants involved in the collision were male, and their age range was between 19 and 59 years. The head was the most frequently damaged body component, accounting for 58.1 per cent of e-scooter collisions.
Mebert et al. (2018)	Switzerland	Injury patterns	Hospital databases	Descriptive statistic	The majority of the accident were classified as unspecified types. 12.73% of patients wore a helmet.
Yang et al. (2020)	The USA	Injury patterns	News sources	Descriptive and cross-tabulation analysis	The trend of e-scooters involved in a collision is unproportionally increased among states
Dhillon et al., (2020)	The USA	Hospital admissions changes due to e-scooter injuries	Hospital databases	Descriptive statistic	The average age of participants was 35.1 years, and the majority of them were male. The head and face were the most injured parts.
Namiri et al. (2020)	The USA	Trend of injuries	The National Electronic Injury Surveillance System	Linear regression	The majority of injured participants were male and urban hospitals were more loaded with injured patients than rural and children's hospitals.
Nellamattathil and Amber (2020)	The USA	Injury patterns	Hospital databases	Descriptive statistic	Injuries were mainly related to the upper musculoskeletal system.
Lavoie-Gagne, Siow, Harkin, Flores, Girard, et al. (2021)	The USA	Characterisation of injuries	Institutional electronic medical record database	Multivariable logistic regression	The helmet usage rate for patients at the hospital was 2.5%, and 3% needed intensive care. Major trauma occurs half as often for those with facial injuries as those with orthopaedic injuries. Contributing factors to hospital admission: age > 40 years, alcohol and other intoxication, loss of consciousness, and being transferred by ambulance to the hospital.
Mukhtar et al. (2021)	The USA	Injury incidence and patterns	Hospital databases	Descriptive statistic	Patients were mostly male and averaged 28 years of age. E-scooter accidents often lead to injuries to the face and extremities.
W. C. Kim and Campbell (2021)	The USA	Injury Patterns	Healthcare system records	Review	Users involved in collisions are young males, ranging from 20 to 40 years (at night). Head and extremities are the frequent types of reported injuries. Riding under

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Author(s) (Year)	Geography	Central theme	Data/collection	Data analysis	Main conclusions or recommendations
					the influence (intoxication) is the primary contributing factor to injuries that lead to hospital admission and surgical interventions.
Cicchino et al. (2021b)	The USA	Severity of injuries	Interview and injury data	Logistic regression	Sidewalks (58%) and roads (23%) are the most frequent places where most e-scooter collisions occur. The severity of injuries is higher on roads which could be related to the higher speeds of vehicles in these facilities.
Lavoie-Gagne, Siow, Harkin, Flores, Politzer, et al. (2021)	The USA	A review of injuries	A retrospective review of patients	Bivariate analysis, Kruskal-Wallis tests	The average age of participants involved in collisions was 40.19. Facial injuries were the highest type of e-scooter collisions (48%), followed by orthopaedic and cranial injuries, respectively.
Kappagantu, Yaremchuk, and Tam (2021)	The USA	Injury patterns	National Electronic Injury Surveillance System	Logistic regression	The introduction of shared e-scooters rapidly increased the rate of injuries, specifically for the age between 18 to 44 years old. Head and neck injuries are the main types of injuries for e-scooter injuries.
Cicchino et al. (2021a)	The USA	Injury patterns	Hospital databases	Logistic regression	The injuries related to electric scooters and bike use were discussed. The rate of head injuries was similar for these vehicles; however, e-scooter riders involved in accidents were more experienced concussions with loss of consciousness.
Shah et al. (2021)	The USA	Crash typologies	Traffic database	Fisher's Exact test	E-scooter and bicycle collisions with motorized vehicles mainly happen in daylight, while e-scooter collisions (the second-highest proportion) occur during the night. The e-scooter riders involved in vehicle collisions were younger than cyclists.
Bloom et al. (2021)	The USA	Injury, mechanism, and cost	Hospital databases	Descriptive statistics, ANOVA	Loss of balance is a common reason for e-scooter accidents. 3% of riders wore a helmet.
English et al. (2020)	The USA	Injury patterns	City's public health syndromic surveillance system	Descriptive statistic	The median age of people involved in injuries was 30, and the majority of them were male. Loss of balance is a common reason for e-scooter accidents.
Vernon et al. (2020)	The USA	Injury patterns	Hospital databases	Descriptive statistics, analysis of variance	Emergency department visits due to e-scooter injuries are increasing. Evenings and weekends have different patterns.
Allem and Majmundar (2019)	The USA	The safety aspect of e-scooter practices	News sources	Descriptive statistic	The majority of road users have not worn protective gear. Photos of customers posted in the Bird's account were rarely featured with safety gears
Yavuz, Temel, Satilmis, Güven, and Çolak (2021)	Turkey	Injury patterns	Hospital databases	Descriptive statistic	Head and soft tissue trauma were the main reasons for the emergency department records. The fraction of users who wore helmets were 4.3%, and 2.9% of people involved in collisions were under the influence of alcohol.

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