A Safe Infrastructure for Micromobility

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Major cities in Europe have seen a significant increase in micromobility infrastructure, including cycling infrastructure, with 42 European Metropolitan cities implementing 1421.54 km of cycling infrastructure in a year. However, the design principles for bikeways primarily rely on conventional road design for bicycles and lack consistency in accommodating emerging powered micromobility devices like e-scooters.

Keywords: micromobility ; cycling infrastructure ; scientometric analysis

1. Introduction

Micromobility (MM) and e-micromobility (eMM) are rapidly becoming popular as a new sustainable mobility solution. Their objectives are to increase mobility during urban congestion and address certain land use and environmental issues like parking space shortage, carbon emission, and sound pollution. In tourist destinations, they are deemed as a flexible, cheap transport solution for tourists and a way to bypass traffic. In addition, they are being promoted to facilitate modal shift from personal cars to personal lightweight Micromobility Devices (MDs) that are more energy efficient, require less space, and have no or less detrimental impact on the environment. The average inner-city trip range of these vehicles is considered short distance and mostly below 20 km range, wherein 70% of most daily trips in urban areas are taking place [1][2][3][4]. In addition, by completing first and last mile distances, they also contribute to more public transport use [5][6].

The European commission has prioritized bicycle usage promotion in the new Sustainable Urban Mobility Plans (SUMPs) [7][8][9]. In the United States, different transportation agencies have started to define specific visions for their bicycle network promotion plan. Massachusetts Department of Transportation, for example, declares "Massachusetts' integrated and multimodal transportation system will provide a safe and well-connected bicycle network that will increase access for both transportation and recreational purposes. The Plan will advance bicycling statewide as a viable travel option – particularly for short trips of three miles or less– to the broadest base of users and free of geographic inequities" [10].

This novel form of mobility has been proven to promote safety and accessibility in cities. In fact, in a dense urban area, the likelihood of a fatal crash occurrence is much higher for cars rather than micro-vehicles. Nevertheless, the new mobility also generates safety risks for its users and pedestrians, most of which are associated with cycleway placemaking and design. The International Traffic Forum (ITF) has published an extensive report about "Safe Micromobility" [11], where out of 10 safety recommendations, three are related to the infrastructure safety development and the rest can be classified to drivers' behavior, speed, regulation, user's training, vehicle design, and shared operation.

2. Micromobility Characterization

2.1. Micromobility Devices

Micromobility classification across the world is not consistent. In many countries, bicycles are considered as the smallest design vehicle and many other MD types like standing e-scooters, e-skateboards, and self-balancing vehicles are not defined or regulated.

In Europe, the L-category vehicles were introduced for powered two, three, and four-wheel vehicles, using six classification criteria of power, power source, speed, length, width, and height. Light two-wheel powered vehicles are categorized as L1e-A powered cycle and L1e-B two-wheel mopped. In type A, the net power of the electric bicycle is between 250 watts and 1000 watts, with a maximum speed of 25 km/h. For type B, the net power is up to 4000 watts and the design speed range is between 25 km/h to 45 km/h. Human-powered bicycles, kick scooters, skates, pedelecs (up to 250 watts), self-balancing vehicles with no seat, like standing e-scooters, are excluded from L1e category [12].

In the United States, e-scooters and e-bikes are distinguished from mopeds by various states to enable their operation on cycleways. However, the only thorough classification found in the literature was published by the Pedestrian and Bicycle Information Centre (PBIC) [13], where three categories of Electric standing or sitting scooters, electric bicycles, and other (i.e., skates, seaways, one-wheel hoverboards) are proposed. For electric bicycle category, three classes of pedalec, throttle assist, and pedalec at higher speed, are defined. In total 8 criteria of device type, brands, weight, occupants, power supply, speed, operating space, and regulation entity were considered.

The International Transport Forum (ITF) [11] has proposed a classification for Micromobility, based on the operational characteristics of MDs. In this definition, speed, and weight of the MDs, which directly correlate with the kinetic energy of a vehicle and thus determine the risk of fatality or serious injuries, are considered as the two main factors for determining their type.

2.2. Criteria Affecting Safety on Bikelane

A Bike Lane is defined by the National Association of City Transportation Officials (NACTO) as a portion of the roadway that has been designated by striping, signage, and pavement markings for the preferential or exclusive use of bicyclists [14]. Bike lanes enable bicyclists to ride at their preferred speed without interference from prevailing traffic conditions and facilitate predictable behavior and movements between bicyclists and motorists. A bike lane is distinguished from a cycle track in that it has no physical barrier (bollards, medians, raised curbs, etc.) that restricts the encroachment of motorized traffic. Conventional bike lanes run curbside when no parking is present, adjacent to parked cars on the right-hand side of the street or on the left-hand side of the street in specific situations. Bike lanes typically run in the same direction of traffic, though they may be configured in the contra-flow direction on low-traffic corridors necessary for the connectivity of a particular bicycle route [14].

The configuration of a bike lane requires a thorough consideration of existing traffic levels and behaviors, adequate safety buffers to protect bicyclists and other MDs from parked and moving vehicles, and enforcement to prohibit motorized vehicle encroachment and double-parking. Bike Lanes may be distinguished using color, lane markings, signage, and intersection treatments.

This research covers a variety of bikeways that were defined by guidelines and researchers. The ministry of interior in Spain [15] has distinguished five types of cycle lanes according to their placement, boundary features, and traffic mixture (**Figure 1**):

Figure 2. Types of bike lanes: (**a**) bicycle lane, (**b**) protected bike lane, (**c**) sidepath on median, (**d**) sidepath with vegetated curb, (**e**) sidepath without curb, (**f**) bike track, and (**g**) cycle path [16][17].

(a)Bicycle lane: a bicycle path adjacent to a road, that can be in the same direction of motor vehicle circulation or a two-way lane (**Figure 1**a).

(b)Protected bike track: a bike lane, physically separated from the road and sidewalk with lateral elements (**Figure 1**b).

(c)Sidepath: a bicycle route that is marked on the sidewalk or median island (**Figure 1**c), that can be with (**Figure 1**d) or without (**Figure 1**e) vegetated/physical curb.

(d)Bike track: a bike path with an independent layout that is completely segregated from motorized traffic (**Figure 1**f).

(e)Cycle path: dedicated path for both pedestrians and cycles, segregated from traffic (**Figure 1**g).

Research in the field of micromobility safety has focused on various aspects, including infrastructure, pavement conditions, traffic patterns, and operating conditions. When it comes to geometry, studies have shown that narrow lane widths pose higher risks for micromobility users, as they increase the likelihood of collisions with curbs, other cyclists, and conflicts with cars during overtaking maneuvers [18][19]. Additionally, research has examined the proximity of obstacles to e-scooter riders, highlighting the importance of considering the surrounding environment to ensure user safety [20].

Pavement conditions also play a significant role in micromobility safety. Studies have found that the type of pavement surface can affect skid resistance, which is particularly crucial for lightweight devices like e-scooters. For example, painted cobble and smooth painted tile pavements have been found to have lower skid resistance compared to asphalt and concrete surfaces [21]. Monitoring methods using smartphone sensors have been proposed to assess pavement conditions and determine key performance indicators for user comfort and safety [22]. Vibrations experienced by e-scooter riders have also been investigated, with concrete pavements found to impose higher vibrations on riders compared to Hot Mix Asphalt (HMA) [20].

Traffic patterns and distribution of micromobility users have been extensively studied. Factors such as comfort and convenience have been found to influence e-scooter riders' behavior, including instances of sidewalk riding violations. Correlations between trip generation, crash frequency, and the promotion of shared micromobility services through safer infrastructure have also been identified.

Operating conditions, including network characteristics and interactions between different micromobility users, have been investigated. Accordingly, Street network characteristics correlate with road safety outcomes, emphasizing the importance of considering the design of the network [23]. Studies have examined conflicts between different modes, such as cyclists and e-scooter riders, and highlighted the impact of bike lane positioning on conflict frequency [24]. Risk factors for e-scooter-related crashes (injury and non-injuries) have been developed [25]. Additionally, Acceleration and deceleration performance between cyclist, e-scooter, and Segway riders are different [26].

While there is a growing body of research in the field of micromobility safety, there are some limitations. Reliable crash data for e-scooters from traffic management agencies are lacking, with most studies relying on data provided by shared micromobility companies. However, studies on bikes and mopeds have shown satisfactory accessibility to reliable crash data. Simulation studies have also been conducted to explore the risks associated with electric self-balancing scooters (ESS) and their impact on head injury intensity [27].

In conclusion, research in micromobility safety has provided valuable insights into the impact of infrastructure design, pavement conditions, traffic patterns, and operating conditions on user safety. These findings can help inform the development of safer micromobility networks and improve the design and maintenance of infrastructure to ensure the well-being of micromobility users.

Assuming the homogeneity of fundamental aspects of infrastructures used for motor vehicles and those of the micromobility users, the criteria affecting users' safety on bikeways were adapted from ASSHTO Green Book 2011 [28]. The relative diagram is demonstrated in **Figure 2**. This diagram will be the base for further literature synthesis and analysis. These adapted criteria are useful to better filter relative studies to the topic, and to avoid missing any research that may lack sufficient relative keywords to be selected through the scientometric review.

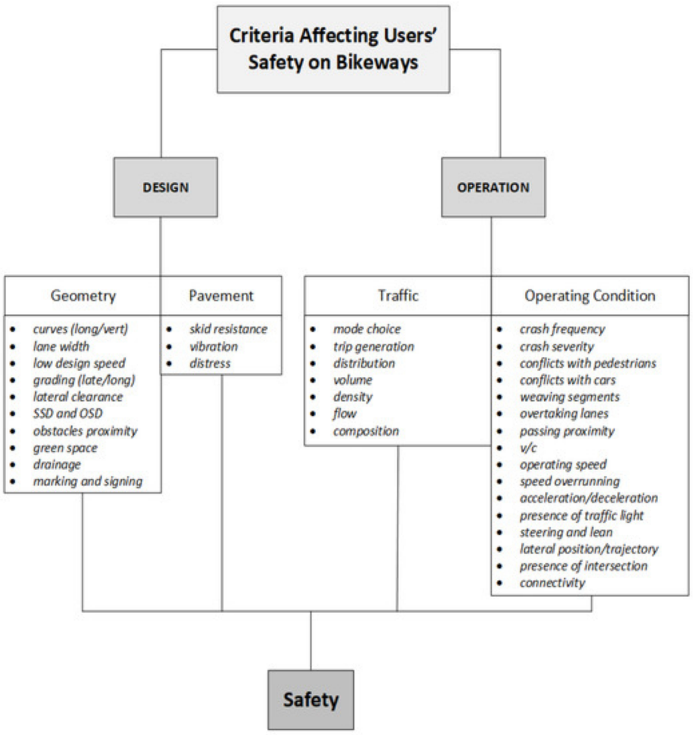

Figure 2. Classification of criteria affecting safe infrastructure for Micromobility.

3. Literature Review Studies on Micromobility

Previous review studies on micromobility have successfully identified gaps and directed subsequent research efforts. The focus was on the integration of micromobility with the public transport, sustainability, users' behavior, and usage pattern. For instance, Oeschager et al. [29] conducted a systematic literature review on micromobility and public transportation integration in 2020. The gaps identified in that study, such as spatiotemporal analysis of e-scooters and transit systems, sustainable parking for micromobility, and mode shift potential, later became focal points for researchers [30][31][32].

Two bibliographic analysis studies focused on the impact of micromobility on sustainability of transportation in cities. The study conducted by Abduljabbar et al. [33] visualized the transforming landscape of micromobility research, whereas Sengul & Mostofi [34] used the PRISMA method (Preferred Reporting Items for Systematic Reviews) to compare literature worldwide in terms of their findings about the future role of micromobility in urban transportation. In neither of the two studies was a gap analysis involved. Lia and Correia [35] performed a similar study that contained all shared e-mobility modes: electric car sharing, e-bike sharing, and e-scooter sharing. The results presented a comprehensive review of their usage pattern, demand estimation, and potential impacts on the transportation system.

Elmashhara et al. [36] conducted a SLR study to find the factors driving behavior of micromobility users. The study found 25 driving factors and offered directions for future studies. The factors were grouped into three categories: (i) temporal, spatial, and weather-related factors; (ii) system-related factors, and (iii) user-related factors. Kaths (2022) conducted a comprehensive literature review on conflicts between cyclists, pedestrians, motorists, heavy-duty vehicles, and buses in urban areas. The study found that researchers were more focused on dangerous interactions that are classified on top of the Hyden's Safety Pyramids rather than normal encounters [37]. The USA National Academies of Sciences, Engineering, and Medicine (NASEM) has recently published a comprehensive report that reveals the relationship between e-scooter crashes, injuries, and fatalities and contributing factors: behavioral and environmental. The emerging behavioral safety issues of e-scooter users are discussed. Moreover, a summary of all safety solutions attempted by cities are presented, providing real case studies [38].

A comprehensive scientometric review on powered micromobility was conducted by O'Hern and Estgfaeller [39]. The study reviewed 474 publications from 1991 to 2020 in a wide range of topics including user behavior, vehicle technology, planning, policy, health, and safety for powered micromobility. The result shows e-bikes user behavior studies were ranked first with 55 related studies, while keywords like safety, road safety, accident, and crashes were in the bottom of the ranking (9th and 10th).

However, to the knowledge of the authors, no studies have yet found synthesized the literature for identification of the research gaps on the micromobility infrastructure. A systematic and compressive review on a new trending topic like micromobility can in fact provide a comprehensive understanding of the current state of knowledge on the topic. The scientometric analysis tools integrated within journals search platforms can only provide limited insights about their own publication. Therefore, such review studies where relevant studies are carefully selected, evaluated and synthesized are contributing extensively to the advancements of the topic in the right direction. Moreover, the scientometric tool used here (VOSviewer) allows unique visualization and analysis of the existing literature, identifying gaps and potential areas for future research. This approach goes beyond traditional literature review methods and provides a data-driven perspective to uncover patterns, trends, and relationships within the studied literature.

The identification, classification, and cluster analysis of criteria that impact micromobility safety can lead to a clear insight on areas that micromobility researchers can direct their studies to have the most impact on this field. Although there are aspects of infrastructure for motor vehicles and micromobility that are similar, however, they are never identical. The main motivation and potential future impact could be directing studies on micromobility pavement (skid resistance, vibration, distress), and micromobility naturalistic traffic behavior (longitudinal control, lateral control, impact of geometry or alignment). These important areas, if elaborated, can have significant impact on cost-beneficial safety improvements.

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