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Review

A Safe Infrastructure for Micromobility: The Current State of Knowledge

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Abstract: 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. To address this research gap, this paper conducts a systematic review and scientometric analysis to explore safe bikeway infrastructure design. It identifies three overlooked topics (marking and signing, grading, and mode choice) and nine understudied areas (vibration, distress, skidding, alignment features, clearance, lateral control, connectivity, traffic composition, and intersection presence) that significantly impact micromobility safety. The study's comprehensive understanding and use of scientometric tools reveal patterns and relationships within the literature. It also highlights criteria influencing micromobility safety and the need for research on pavement and user behavior. The findings contribute to evidence-based decision-making for practitioners and researchers, emphasizing the importance of tailored infrastructure design to enhance micromobility safety and achieve cost-effective improvements.

Keywords: micromobility; cycling infrastructure; scientometric analysis; Reseacrh Gap; Safe Mobility; sustainable mobility

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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 [1–4]. 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) [7–9]. 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.

In this article, a compressive literature review is conducted to find gaps in the research area of safe Micromobility infrastructure. This is an initial attempt to address existing design and safety inconsistencies on bike lanes. In fact, the latest trends of MDs comprise physical dimensions and operating characteristics that differ those of a typical upright adult bicyclist, often considered as the design vehicle. Recognizing variables and necessities of the emerging MD users is vital for attaining a safe infrastructure for all users. This research is in fact useful for evidence-based decision-making of both practitioners and researchers. The principal aspect that distinguishes this review from similar studies are the focus of the literature review on a topic that is unique and not covered at this level to this date, and as well the novel scientometric methods used for visualization and analysis.

1.1. Micromobility Characterization

1.1.1. 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 (Figure 1). 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. As can be seen in Figure 1, two weight ranges of below 35 kg and between 35 kg to 350 kg, and speed range of up to 25 km/h and between 25 to 45 km/h are introduced that divide MDs to four distinct types: A, B, C, and D.

1.1.2. 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].

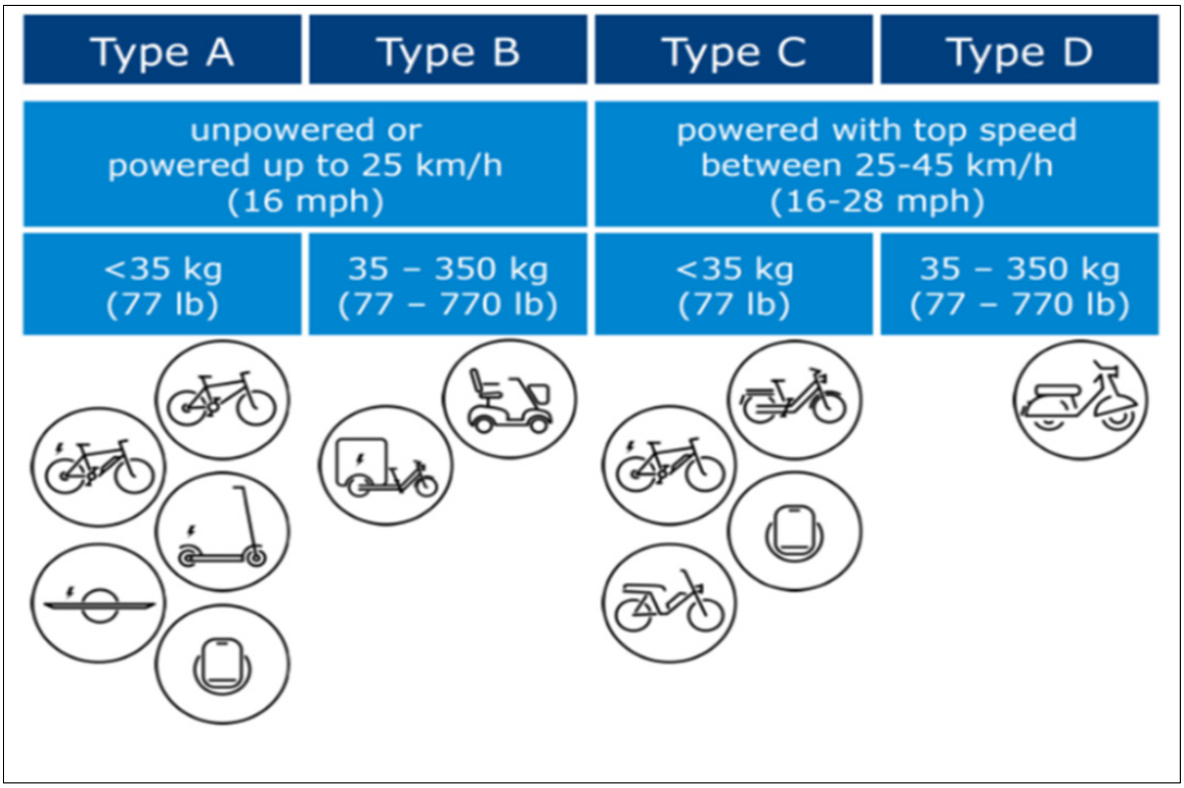
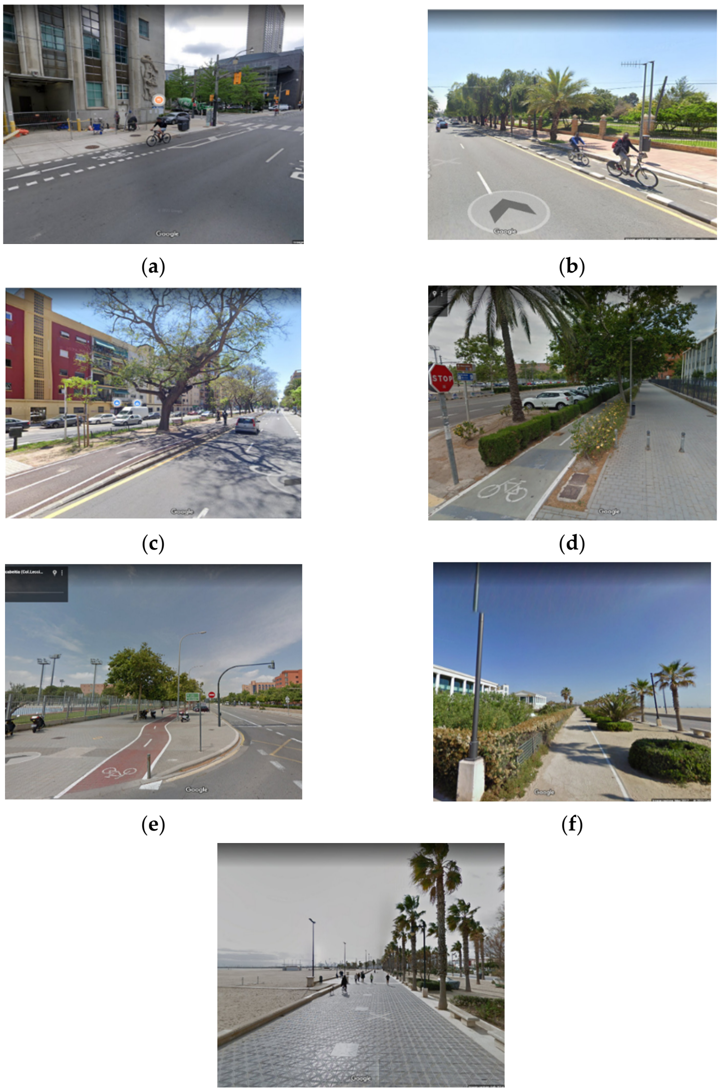


Figure 1. Classification for MDs, Reprinted with permission from Ref. [11]. 2019, ITF.

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 2):

(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 2a).
(b) Protected bike track: a bike lane, physically separated from the road and sidewalk with lateral elements (Figure 2b).
(c) Sidepath: a bicycle route that is marked on the sidewalk or median island (Figure 2c), that can be with (Figure 2d) or without (Figure 2e) vegetated/physical curb.
(d) Bike track: a bike path with an independent layout that is completely segregated from motorized traffic (Figure 2f).
(e) Cycle path: dedicated path for both pedestrians and cycles, segregated from traffic (Figure 2g).



(**a**) (**b**) (**c**) (**d**) (**e**) (**f**) (**g**)

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].

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]. Other relative studies on vibration are summarized in Table 1.

Table 1. Articles that focus on the use criteria affecting safety on MM infrastructure.

#	Researcher/Year	Criteria	Sub-Criteria	MD Modes	Sample Size & Location
1	Wyman [23] (2022)	operating condition	crash & conflict	bike	300 h of video recording at 5 bike lanes (Portland, OR, USA)
2	M. Pérez-Zuriaga [24] (2022)	pavement, geometry	vibration, clearance	e-scooter	850 m of bike lane (Valencia, Spain)
3	Tian et al. [25] (2022)	operating condition	crash & conflict	e-scooter	worldwide (social media data)
4	Prencipe et al. [26] (2022)	operating condition	intersection, long.control, connectivity	e-scooter	336 buffers (Bari, Italy)
5	Dozza et al. [27] (2022)	operating condition	longitudinal control	e-scooter, segway, e-bike, bike	34 participants (Chalmers, Sweden)
6	Folco et al. [28] (2022)	traffic, operating condition	route planning, crash & conflict	bike, e-scooter	314 crashes in 2019, 40,694 trips (Turin, Italy)
7	Clewlow et al. [29] (2022)	traffic, operating condition	route planning, crash & conflict	e-scooter	22,022 crash data from 2014–2021 (4 cities, USA)
8	Anke et al. [30] (2022)	traffic, operating condition	route planning, connectivity	e-scooter	six sites/738 recording (Dresden & Berlin, Germany)
9	Gehrke et al. [31] (2022)	traffic, operating condition	route planning, crash & conflict	e-scooter	eight months (Brookline, MA, USA)
10	Cafiso et al. [22] (2022)	pavement	distress	bike, e-scooter	979 tests (Italy)
11	Chang F et al. [32] (2022)	operating condition	crash & conflict	e-bike	2222 crash records from 2014 to 2016 (Hunan, China)
12	Fonseca-Cabrera [33] (2021)	geometry	clearance	bike, e-scooter	80 km bicycle tracks/25 h video (Valencia, Spain)
13	Ma Q [20] (2021)	pavement, geometry	vibration, clearance	e-scooter	One road segment—vehicle lane & sidewalk (Norfolk, VA, USA)
14	Zuniga-Garcia N. et al. [34] (2021)	traffic	route planning	e-scooter	80,000 trips/11 million location points (Austin, TX, USA)
15	Hosseinzadeh A [35] (2021)	traffic	route planning	e-scooter	494,008 trips/159 route planning analysis zone (Louisville, KY, USA)
16	Hawa L et al. [36] (2021)	traffic	route planning	e-scooter	1671 geographic grid cells of 0.19 km^2 (Washington, DC, USA)
17	Ma Q [20] (2021)	operating condition	longitudinal control	e-scooter	NA
18	Bayoumi Kamel M & Sayed T [37] (2021)	operating condition	crash & conflict	bike	NA
19	Tan S. et al. [38] (2020)	operating condition	crash & conflict	multiple	1 case study (Washington, DC, USA)
20	Tomiyama K and Moriishi K [39] (2020)	pavement	vibration, skidding	e-scooter	10 different surfaces—grading &roughness (Saitama, Japan)
21	Carrignon D [40] (2020)	pavement	skidding, distress	e-scooter	Synthesis of literature (France & UK)
22	Gössling S. [41] (2020)	operating condition	crash & conflict, longitudinal control	e-scooter	173 news items (10 cities *)
23	He and Shin [42] (2020)	traffic	route planning	e-scooter	2,430,806 trips (Austin, TX, USA)

Table 1. *Cont.*

#	Researcher/Year	Criteria	Sub-Criteria	MD Modes	Sample Size & Location
24	Zou et al. [43] (2020)	traffic	route planning	e-scooter	138,362 trips (Washington, DC, USA)
25	Almannaa et al. [44] (2020)	operating condition	longitudinal control	e-scooter	15,400 E-Scooters (Austin, TX, USA)
26	Caspi et al. [45] (2020)	traffic	route planning	e-scooter	11,358 trips per day (Austin, TX, USA)
27	Jiao and Bai [46] (2020)	traffic	route planning	e-scooter	158,208 trips per month (Austin, TX, USA)
28	Yang et al. [47] (2020)	operating condition	crash & conflict	e-scooter	169 news on E-Scooter-involved crashes
29	Bai and Jiao [48] (2020)	traffic	route planning	e-scooter	661,367 & 225,543 trips/month (Austin, TX, USA, Minneapolis, MN, USA)
30	Lazarus et al. [49] (2020)	traffic	route planning	bike, e-bike (shared)	124,980 trips per month (San Francisco, CA, USA)
31	Politis et al. [50] (2020)	operating condition	crash & conflict	bike	2 one-way & 1 two-way bike lane (Karditsa, Greece)
32	Wang K and Chen J [51] (2020)	traffic	route planning	bike (shared)	430,560 trips in September 2016 (New York, DC, USA)
33	Hu L et al. [52] (2020)	operating condition	crash & conflict, longitudinal control	e-bike	219 accidents—2014 to 2016 (6 cities, China)
34	Xing et al. [53] (2020)	traffic	route planning	bike (shared)	1,023,603 trips in August 2016 -Mobike (Shanghai, China)
35	AASHTO [54] (2019)	operating condition	crash & conflict	e-scooter	271 E-Scooter-related injuries (Austin, TX, USA)
36	McKenzie G [55] (2019)	traffic	route planning, composition	bike, e-scooter	1,414,055 bike & 937,590 e-scooter trips (Washington, DC, USA)
37	Voinov et al. [56] (2019)	operating condition	crash & conflict	scooter	10,811 scooter owners (Enschede Netherlands)
38	Chang et al. [57] (2019)	traffic, operating condition	route planning, longitudinal control	multiple	Synthesis of literature (Washington, DC, USA)
39	Du Y et al. [58] (2019)	traffic	route planning	bike	830,000 trips in September 2016 (Shanghai, China)
40	He Y et al. [59] (2019)	traffic	route planning	e-bike (shared)	7921 trips in 107 days-20 July to 3 November 2017 (Park City, UT, USA)
41	Guo Y et al. [60] (2019)	operating condition	crash & conflict	e-bike, e-scooter	310 e-bike collision records (Ningbo, China)
42	Zhang et al. [61] (2019)	traffic	route planning	bike (shared)	Approximately 48,000 trips per day (Shanghai, China)
43	Xu C and Yu X [62] (2018)	operating condition	crash & conflict	e-bike	1091 crashes records from 2015 to 2016 (Hangzhou, China)
44	Smith and Schwieterman [63] (2018)	traffic	route planning	e-scooter	10,000 trips per study area (Chicago, IL, USA)

Table 1. *Cont.*

#	Researcher/Year	Criteria	Sub-Criteria	MD Modes	Sample Size & Location
45	Wang T et al. [64] (2018)	operating condition	crash & conflict	e-bike	4000 crash records from 2008 to 2014 (Guilin, China)
46	Zhang X et al. [65] (2018)	operating condition	crash & conflict	e-bike	3200 e-bike owner participants (Jiangsu Province, China)
47	Zhang Y et al. [66] (2018)	traffic	route planning	bike (shared)	12,915 trips per day (Zhongshan, China)
48	Yuan Q et al. [67] (2017)	operating condition	crash & conflict	e-bike	150 serious crash samples from 2009 to 2015 (Beijing, China)
49	Greibe P [18] (2016)	geometry	alignment features	bike	8 one-way cycle tracks (Copenhagen, Denmark)
50	Park J & Abdel-Aty M [19] (2016)	geometry	alignment features	bike	6420 urban roadway segments with 2514.518 miles (FL)
51	Xu J. et al. [68] (2016)	operating condition	crash & conflict	ESS, bike	Synthesis of literature (Beijing, China)
52	Xu J. et al. [69] (2016)	operating condition	crash & conflict, longitudinal control	self-balancing ESS **	Accident simulation in MADYMO software (v.2010)
53	Bordagaray et al. [70] (2016)	operating condition	route planning, composition	bike	24,664 trips in July & August 2011 (Santander, Spain)
54	Greibe P [18] (2016)	operating condition	longitudinal control, lateral control	bike	Video observation of 8925 cyclists (Copenhagen, Denmark)
55	Garcia A. et al. [71] (2015)	operating condition	crash and conflict	bike	2928 motor vehicles pass (Valencia, Spain)
56	Corcoran et al. [72] (2014)	operating condition	route planning	bike (shared)	448 trips per day (Brisbane, Australia)
57	Ohri V [73] (2013)	pavement	skidding	e-scooter	4 different surfaces (Toronto, ON, Canada)
58	Blackman R. et al. [74] (2013)	operating condition	crash & conflict	e-scooter, moped	5 years crash data (Queensland, Australia)
59	Montella A et al. [75] (2012)	operating condition	crash & conflict	mopeds, motorcycles	254,575 PTW involved crashes from 2006 to 2008 (Italy)
60	Dondi G et al. [76] (2011)	geometry, pavement	alignment, clearance, skidding, distress	bike	1500 m bike lane (Rimini, Italy)

* Brisbane (Australia), Christchurch (New Zealand), Copenhagen (Denmark), Dallas & Los Angeles (USA), Malaga (Spain), Paris (France), Stockholm (Sweden), Vienna (Austria), Zurich (Switzerland) ** Electric Self-balancing Scooters.

Traffic patterns and distribution of micromobility users have been extensively studied. These studies that are listed in Table 1 have explored the usage distribution of e-scooters on sidewalks, bike lanes, and roadways, providing valuable data for the development of effective surrogate safety measures. 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 [77]. 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 [33]. 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 [27].

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 [69]. All studies that are classified under operating conditions, are included in Table 1.

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. However, there is a need for more comprehensive and reliable crash data to further enhance our understanding of micromobility safety and develop effective safety measures.

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 [54]. The relative diagram is demonstrated in Figure 3. 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 of this research, and to avoid missing any research that may lack sufficient relative keywords to be selected through the scientometric review.

1.2. 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. [78] 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 [79–81].

Two bibliographic analysis studies focused on the impact of micromobility on sustainability of transportation in cities. The study conducted by Abduljabbar et al. [82] visualized the transforming landscape of micromobility research, whereas Sengul & Mostofi [83] 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 [84] 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.

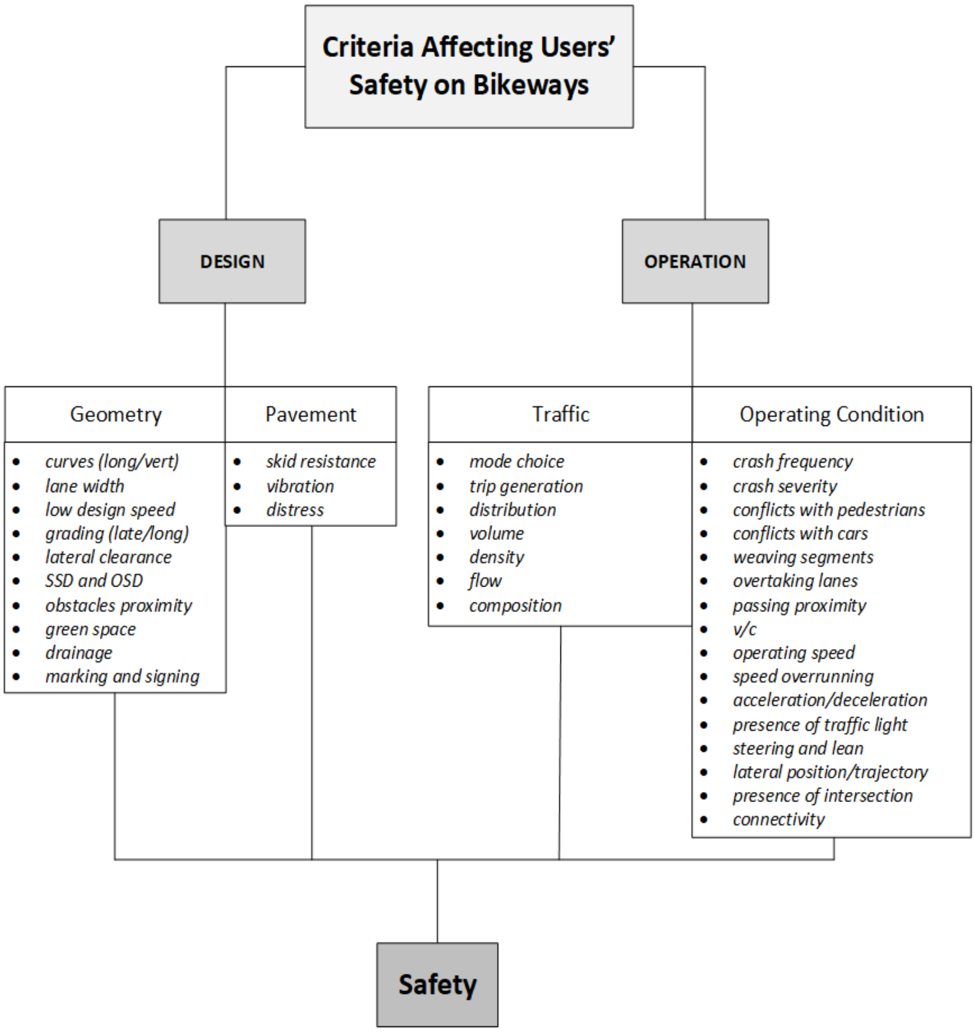


Figure 3. Classification of criteria affecting safe infrastructure for Micromobility.

Elmashhara et al. [85] 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 [86]. 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. In this study, 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 [87].

A comprehensive scientometric review on powered micromobility was conducted by O'Hern and Estgfaeller [88]. 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 in this study (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 (Section 3) 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 of this research 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.

This research is in fact useful for evidence-based decision-making of both practitioners and researchers. The principal aspect that distinguishes this review from similar studies are the focus of the literature review on a topic that is unique and not covered at this level to this date, and as well the novel scientometric methods used for visualization and analysis.

1.3. Objective

The objective of this study is to develop a literature map that helps identify gaps in the literature focused on planning, designing, and safety assessment of micromobility infrastructure. The result of this study is intended to allow micromobility designers and operators better understand the safety criteria and considerations for each recent modes of micro-vehicles and their mixed use on cycle paths, providing best practices for improving safety on this infrastructure.

2. Methodology

The scope of this literature review includes the keywords and criteria related to safety on bikeways that correlate with their geometry, pavement, traffic, and operational condition. The following pillars and sub-pillars are covered in the literature analysis:

- Geometry: curves (horizontal/vertical), lane width, low design speed, grading (lateral/longitudinal), lateral clearance, Stopping Sight Distance (SSD) and Overtaking Sight Distance (OSD), obstacle proximity, green space, drainage, and marking and signing.
- Pavement: skid resistance, vibration, distress.
- Traffic: mode choice, trip generation, distribution, volume, density, flow, and composition.
- Operating condition: crash frequency, crash severity, conflicts with pedestrians, conflicts with cars, weaving segments, overtaking lanes, passing proximity, v/c, operating speed, speed overrunning, acceleration/deceleration, presence of traffic light, steering and lean, lateral position/trajectory, presence of intersection, and connectivity.

To effectively collect and synthesize relative literature, a systematic literature review method was used, that had been adapted in similar studies from Thomas and Harden [89] method. The method has four steps: (i) designing the research process; (ii) conducting the research; (iii) analyzing and extracting information; and (iv) reviewing the findings.

In the first step, the research database, terms, and criteria were determined. This was performed by reviewing recent publications and relative guidelines (e.g., AASHTO green book [54]). Common academic search portals were used that include Science-Direct/Scopus, Taylor & Francis online, OneSearch, and other sources such as Google Scholar, TRID, Web of Science, JSTOR, and SAGE. After the initial review of terms, the criteria that could impact on user's safety on bikeways were classified (Figure 2) and were used as the base for the next step. The criteria were grouped into two main pillars of design and operation and four subcategories of geometry, pavement, traffic, and operating condition.

Secondly, the literature data collection was conducted on selected portals online, and then stored in a classified manner based on associated terms and criteria. Next, the classified literature was visualized in the form of tables, literature map, and cartogram. This was to identify gaps that existed in the literature in terms of defined criteria, location, and Micromibility modes. The findings were discussed and presented in Section 4.

3. Results

The results of the systematic literature review are presented in this section. Primarily, the adapted criteria from the literature are grouped into different main keyword categories, selected from the common relative keywords in the literature and the knowledge of the author. After that, four scientometric cluster maps are developed and presented (Figures 4–7). Overall, 60 selected articles are reviewed according to the studied criteria, sub-criteria, modes, sample size, and location (Table 1).

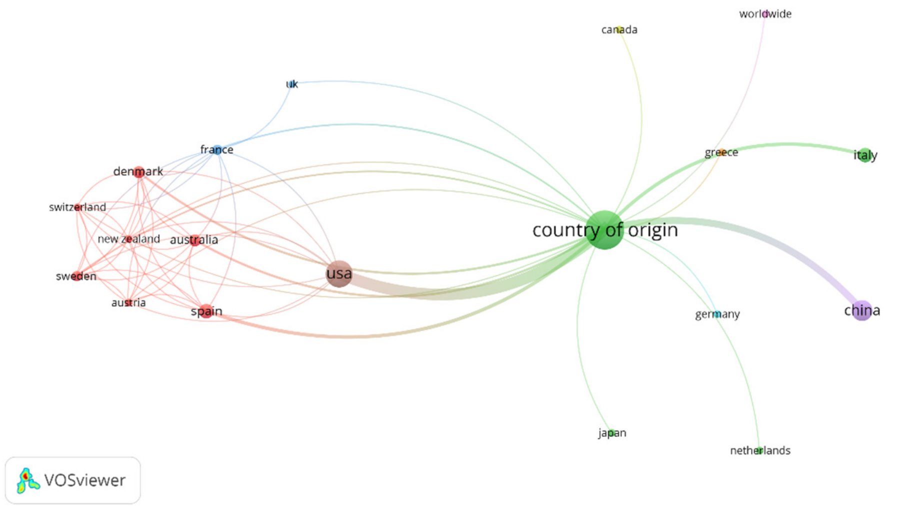


Figure 4. Geographical clusters.

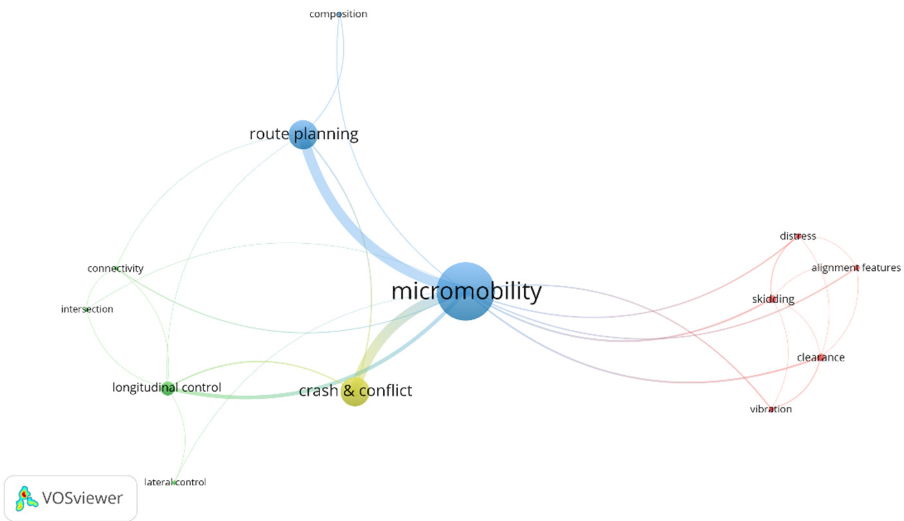


Figure 5. Criteria clusters for selected studies.

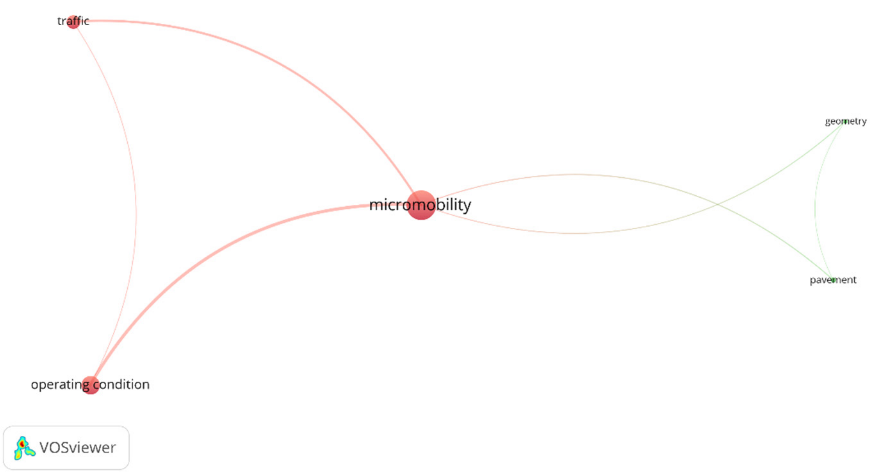


Figure 6. The clusters of the four main pillars.

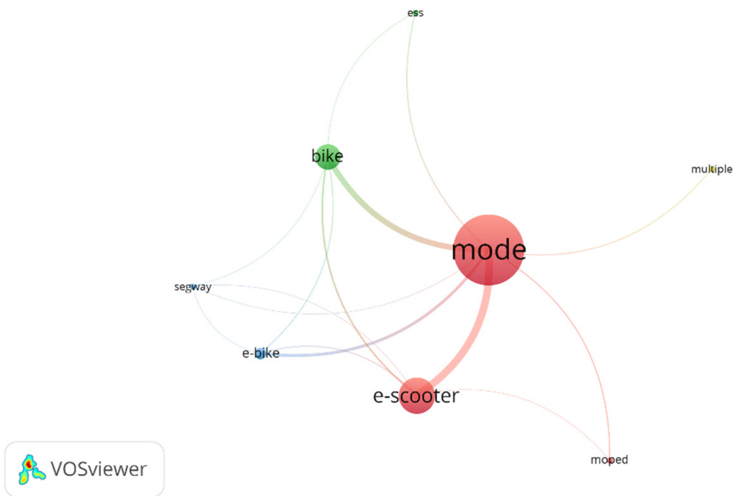


Figure 7. Mode clusters.

Of the 36 criteria adapted in the introduction (Figure 2), 27 were categorized into six relative groups. As the result, the number of criteria were reduced to 15, shown in Figure 8. This was to reduce the complexity of the cluster maps shown in Figures 4–7.

The associated subcategories and criteria for the selected articles were clustered with VOSviewer. Accordingly, from the four main pillars, and their subset 12 criteria, two maps were developed that shows their cluster and interconnection. The visualized map (Figure 5) clearly shows three main cluster groups. Primarily, "route planning" and "crash and conflict" are both equally the largest cluster, that are interconnected and have links to two and one other criteria, respectively. The second cluster is "longitudinal control" with a major link to crash and conflict, and other links to route planning, lateral control, connectivity, and intersection. In the third cluster "skidding" and "clearance" are positioned with three other keywords of alignment features, distress, and vibration centered around them.

For having a clearer scientometric view of the safety for micromobility infrastructure, another map was developed using only the major four pillars of the adopted map. This map (Figure 6) illustrates how geometry and pavement are overlooked in the literature for improving safety of micromobility users.

In terms of modes, the cluster analysis map (Figure 7) shows that e-scooters have been the center of attention in the selected studies, with links to four other modes of bike, e-bike, moped, and segway. Next are bikes surrounded by four modes of e-scooter, e-bike, segway, and ESS. E-bike is the third cluster, with three links to bike, e-scooter, and segway. The map clearly shows that there are limited studies that include multiple modes, ESS, segway, and moped.

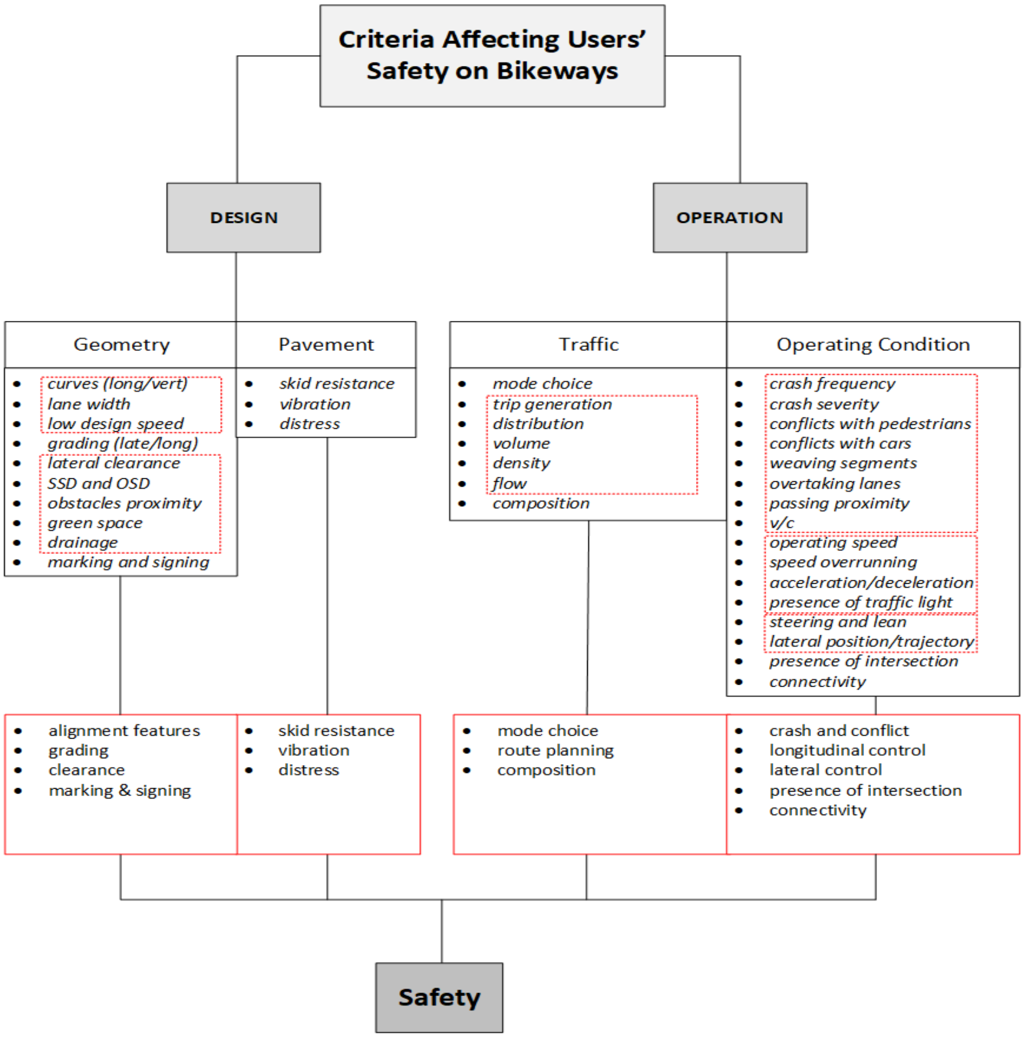


Figure 8. Categorization of adapted criteria.

Geographically, the studied literature can be divided into three major clusters, as are shown in Figure 4. USA and China contain the largest cluster of research on micromobility infrastructure, with USA being on the top. Nine European countries were also involved in the sampled cities for micromobility studies linked to safety, that are usually interconnected and have links to some other countries like Australia, New Zealand, and UK. In Europe, Spain and Italy have the largest share. The map also shows that relative studies that include a wide variety of geographical locations are rare.

4. Discussion

In this section, the findings of the systematic and scientometric literature review of safe micromobility infrastructure are presented. The research is aimed to summarize academic research to date about the topic and identify gaps, trends, and present directions and demand-based recommendation for future studies.

A pie chart (Figure 9) is developed from the cluster analysis data presented in Section 3. In this way, most studies related to safe infrastructure for micromobility are focused on two criteria of "crash and conflict" and "route planning". For each of these criteria, 24 relative academic research were found, that together accounts for 60% of all the existing literature. After that, longitudinal control was studied the most, with nine related research (approximately 11%). The 30% of the rest is shared between nine other criteria (see Figure 9).

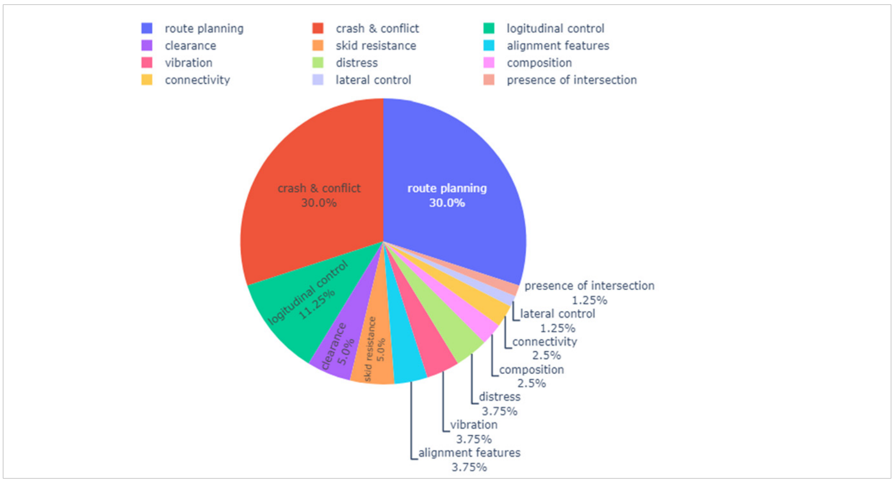


Figure 9. Pie chart of the criteria distribution.

The observed cluster of academic research on only two factors impacting safety for micromobility can suggest that regardless of the growing research interest on safety for micromobility, the research trend may be misdirected and clustered on areas that amount for only 13% of the real demands. Consequently, major areas of research such as geometry and pavement still lack attention, and so potential safety concerns in those areas have remained unanswered. For example, concerning geometry, there are no studies yet conducted on two aspects of "grading" and "marking and signing", even though they both are key elements of safety development for the MM users.

Some other important criteria like lateral control, presence of intersection, connectivity, and composition have seen limited attention, with one or two dedicated research work to each. It is believed that to eliminate all the existing safety concerns and increase public acceptance for micromobility, that could increase ridership, the future research should be directed towards the understudied identified in this research.

Existing studies lack multi modes in their analysis. Consequently, in some areas, the results offered may not be extendable to other modes because of the major physical and maneuvering differences, and thus remain unverified for the use of city planners.

A categorized bar chart (Figure 10) was developed to clearly illustrate the studied mode of micromobility for each area of the research on safe infrastructure. The horizontal axle is divided for each area and shows six different micromobility mode for each criterion, and the vertical axle shows the number of studies existed for each mode. Accordingly, in most criteria groups, there are only one or two modes included in the studies.

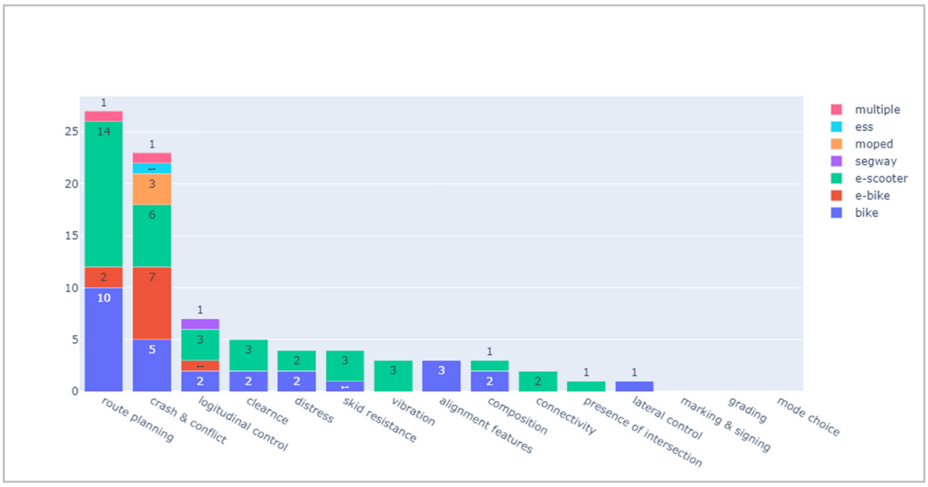


Figure 10. Distribution of modes studies for each area of research.

There are only three areas where the studies have covered more than two modes of micromobility. In the area of crash and conflict, five modes of bike, e-bike, e-scooter, electric self-balancing scooter (ESS), and moped were studied. The two areas of longitudinal control and route planning contained four and three modes, respectively.

Overall, Figures 9 and 10 clearly show traffic and operation are the areas where most research on micromobility are centered over the past decades, whereas for the two major areas of geometry and pavement, few studies were observed in comparison despite their essential role in safety. Therefore, they are suggested to be the focus of future studies related to safety for micromobility users. Specifically, three areas of marking and signing, grading, mode choice that are missing from the literature.

Tableau (version 2022.3) was used to create a cartogram of the studies (Figure 11). The findings demonstrate that US cities were among the largest sampled locations. China was next with 12 studies that was almost half of the samples in USA. After that, Spain, and Italy each have 5 studies sampled their cities, more than France and Denmark with only 3 studies. However, overall, the nine European countries have a large of the literature, with 23 studies that is the same as USA share.

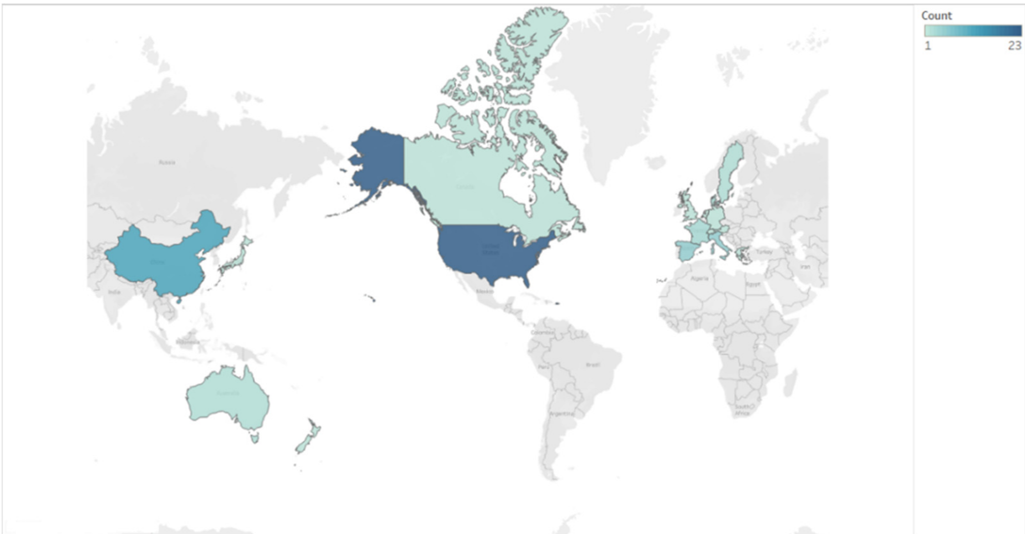


Figure 11. Cartogram of the geographical distribution of literature studies.

The Cartogram clearly shows that the studies are only centered in developed nations, and so many developing countries that have initiated the use of micromobility are still missing from the literature.

All studies reviewed are summarized in Table 1 in descending order of publication year. Various classification criteria were considered, that included the researcher, studied criteria and sub-criteria studied, mode, sample size, and location.

4.1. Recommendations for Future Studies

Based on the findings of this study, several recommendations can be made to guide future research and improve micromobility infrastructure design. Firstly, there is a need to develop a consistent and inclusive design approach that considers the diverse characteristics and safety requirements of emerging powered micromobility devices, including e-scooters. This approach should go beyond conventional road design principles tailored for bicycles.

Additionally, future research should prioritize the examination of specific areas within micromobility infrastructure, such as micromobility pavement characteristics (e.g., skid resistance, vibration, distress) and naturalistic traffic behavior (e.g., longitudinal control, lateral control, impact of geometry or alignment). Elaborating on these aspects can contribute to the development of cost-effective safety improvements.

Moreover, it is recommended to further explore the integration of micromobility with other transportation modes, particularly public transportation systems. Understanding the spatiotemporal dynamics, mode shift potential, and sustainable parking solutions for micromobility can enhance its integration and overall effectiveness within urban environments.

4.2. Limitations of the Review Study

It is important to acknowledge the limitations of this study. Firstly, the research focuses on the current state of knowledge up until a specific cutoff date, and new studies may have been published since then, potentially impacting the identified research gaps. Additionally, the systematic review process relies on the inclusion and exclusion criteria set by the researchers, which may introduce some subjectivity.

Furthermore, while scientometric analysis provides valuable insights, it has its own limitations in terms of coverage and the biases inherent in citation patterns. The study's reliance on scientometric analysis within the available literature may overlook relevant research published outside the included sources.

Lastly, the recommendations provided in this study should be considered as starting points for further investigation, as their implementation and effectiveness may vary depending on the specific context and local conditions of different cities or regions.

Despite these limitations, this study provides a comprehensive foundation for future research efforts and underscores the importance of addressing the identified research gaps to enhance the safety and development of micromobility infrastructure.

5. Conclusions

In this study, the status of knowledge of a safe micromobility infrastructure was evaluated through a systematic literature review. Overall, 76 articles that were focused on this topic have been selected and analyzed. The objective was to determine the main criteria, modes, and geographical location of the selected literature, while identifying the gaps that exist and should be addressed in future studies to improve the development and safety of micromobility. Accordingly, cluster maps and distribution charts were developed to fulfil the main goal of this research and illustrate areas where the literature has overlooked.

The results revealed that three areas of marking and signing, grading, mode choice are overlooked in the literature that focus on addressing safety on micromobility infrastructure. There are also nine other areas identified as understudied. They include vibration, distress, skidding, alignment features, clearance, lateral control, connectivity, traffic composition, and presence of intersection. Due to major differences between motor vehicles and micro devices in terms of the dimensions, weight and driving characteristics, future studies that focus on these identified areas can be effective in improving the infrastructure and operation of micromobility.

Geographically, most relative studies have been conducted for cities in US and China, and between the recent years of 2020 to 2022. E-scooter was the most studied mode (over 40%) for the topic of this research, and then bike, and e-bike had the rest of the attentions. Some rare studies were also found to include other modes like mopeds, and ESS. This shows that there is still a lack of information about the operational characteristics and safety requirements of some recently developed micro devices that need to be addressed in the future. Especially, for the recently trending self-balancing devices that have specific steering, and physical characteristics.

Finally, from the four pillars adapted for this study, the most share of the literature was allocated to the two pillars of traffic and operating condition, suggesting lack of attention to pavement and geometry studies for the safety of micromobility users that needs to be addressed in future studies related to this topic.

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