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Development of a Criteria Framework for Micromobility Pathway Mapping towards Sustainable Urban Transport Integration

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ABSTRACT

Route mapping for micromobility vehicles aims to ensure user safety and reduce the risk of accidents that may arise from interactions between micromobility vehicles and other transport modes with different speeds. The purpose of this study is to identify and develop a framework of key criteria for micromobility vehicle routes to enable safer and more efficient route design for users. The selection of criteria for micromobility route mapping was analysed through a literature review. The review was conducted by examining academic journals, conference papers, government reports, and industry publications discussing micromobility infrastructure, usage patterns, and the challenges in developing route mapping. The search strategy involved gathering relevant data from multiple sources including SCOPUS, ScienceDirect, and open-access repositories using specific keywords to ensure comprehensive coverage of micromobility devices and their infrastructure. Four main criteria were analysed for developing micromobility route mapping: (i) user safety aspects, (ii) existing infrastructure conditions, (iii) compliance with local regulations, and (iv) the level of micromobility user accessibility. The findings from the literature review led to the formulation of primary and secondary criteria for proposed micromobility route selection, which must be considered with reference to all relevant guidelines. The development of a systematic route mapping criteria framework is a critical prerequisite to support the integration of micromobility vehicle operations into the urban transport ecosystem, thereby filling a gap in the literature. Based on the literature result, two main aspects were identified as critical in developing a more systematic mapping framework: the importance of clear criteria and the need for holistic data integration.

Keywords: micromobility; criteria mapping; routes; transport integration; safety

1. INTRODUCTION

Mapping routes for micromobility vehicles aims to ensure user safety and to reduce the risk of accidents that may arise from interactions between micromobility vehicles and other transport modes with different speeds. When the traffic flow between micromobility vehicles and other transport modes with different speeds mix together, often leads to the risk of accidents (Hishikawa & Iryo-Asano, 2022). Micromobility vehicles, which include electric scooters, electric bicycles, and human-powered vehicles with a maximum speed of up to 50 km/h, are increasingly becoming a primary choice in urban areas, particularly among city dwellers seeking fast, flexible, and sustainable alternatives (Comi & Polimeni, 2024; Zulkipli & Amir, 2024).

The use of micromobility vehicles has shown wider adoption in city centers and tourist hubs. Safety aspects of such vehicles need to be emphasized, considering that road accident cases involving micromobility vehicles and pedestrians have already resulted in fatalities, as has occurred in several other countries. Micromobility vehicles exist as one of the critical solutions to reduce dependence on conventional vehicles. Rapid developments in the urban transport sector have shown an increase in the use of micromobility vehicles as an alternative mode of transport (ITF, 2020). In Malaysia, accident data recorded by the Royal Malaysia Police (PDRM) shows that the number of deaths involving bicycles was 192 in 2010 and decreased to 107 in 2019 (as shown in Figure 1).

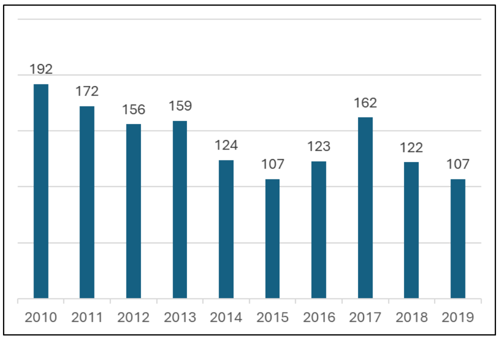

Figure 1. Total deaths involving bicycles from 2010-2019
Source : PDRM Accident Report 2019

Through an in-depth analysis of the specific requirements and criteria for micromobility vehicle routes, this study is expected to produce strategic guidelines that support more systematic, safe, and environmentally friendly urban infrastructure planning (Hossein Sabbaghian et al., 2023). Although numerous studies exist on micromobility vehicles, specific criteria for constructing micromobility route mapping have not yet been extensively discussed. How can safety, infrastructure, regulatory, and accessibility criteria systematically integrated in constructing a sustainable route mapping framework? The findings of this study are anticipated to make significant contributions toward strengthening the integration of micromobility as part of a sustainable urban transport ecosystem. By considering route categories and these elements, micromobility vehicle routes can be designed to be safer and more efficient for users. While many studies discuss on safety and usage trends, this study focus on develops a structured route-mapping framework based on four integrated criteria, safety, infrastructure conditions, regulatory compliance, and accessibility

This study is systematically structured by analyzing four main criteria for developing micromobility vehicle route mapping: (i) user safety aspects, (ii) existing infrastructure conditions, (iii) compliance with local regulations, and (iv) the level of accessibility for micromobility users. From this study, the objective of this study is to identify a comprehensive assessment framework for micromobility route planning. In the subsequent section, a conceptual framework is constructed through critical synthesis of academic literature related to the selected criteria, thereby providing a theoretical foundation for data interpretation. Previous studies have examined the micromobility trends, safety issues, and policy implication, there still lack of systematic framework that prioritizes specific criteria for micromobility route mapping, especially in urban infrastructure planning. A detailed explanation of these criteria is presented regarding their relevance in constructing micromobility routes, along with the importance and considerations necessary for micromobility route mapping. Finally, the research findings will be concluded through integration of analytical results, presenting strategic recommendations based on discussions conducted throughout the study.

2. METHODOLOGY

2.1 Theoretical Framework Based on Literature Synthesis

The study's theoretical framework comprises three primary stages: search strategy, selection process, and criteria evaluation. The search strategy involves gathering relevant data from multiple sources including SCOPUS, ScienceDirect, and open-access repositories databases using specific keywords to ensure comprehensive coverage of micromobility devices and their infrastructure. The search was conducted through literature review, secondary data analysis, technical documents, and relevant policies, aiming to identify key criteria for micromobility routes.

The literature review was performed by examining academic journals, conference papers, government reports, and industry publications discussing micromobility infrastructure, usage patterns, and mapping challenges. A total of 17 articles were selected and reviewed in this study. These selected articles reflect a focused and criteria-specific review rather than a broad scoping review. Data and literature collected through the search strategy were filtered according to several selection criteria, including safety, infrastructure, regulations, and accessibility facilities. The reviewed studies were published between 2019 and 2024, ensuring that recent development and trends in micromobility research were captured. Only studies relevant to micromobility mapping, whether from technical, policy, or societal usage perspectives, were selected.

Based on the theoretical framework in Table 1, findings from studies related to route criteria for micromobility vehicle mapping have been systematically organized by country, source, and main criteria for route selection. Country-based analysis reveals that the most frequently referenced country in micromobility research is the United States (US) with 2,919 citations, followed by the United Kingdom (UK) (1,474 citations), Australia (1,291 citations), Netherlands (1,291 citations), and Canada (620 citations). Country citation data follows the country markers indicated in each journal article during publication (Abduljabbar et al., 2021). Figure 2 presents the micromobility route selection framework, which integrates by four keys criteria: safety, infrastructure conditions, regulatory compliance, and accessibility. This diagram framework shows interrelated factors guide the evaluation and selection on optimal route, ensuring the micromobility planning support safe, efficient, and sustainable urban transport development.

Table 1. Theoretical Framework of Key Criteria Based on Literature.

Theoretical Framework					
		Main Criteria			
Country	**Source**	**Safety**	**Infrastructure**	**Regulations**	**Accessibility**
Poland	(Bieliński & Ważna, 2020)	/	/	/	
Singapore	(Cao et al., 2021)	/			
Italy	(Comi & Polimeni, 2024)	/			/
Taiwan	(Hsu & Rodríguez, 2024)	/			
Malaysia	(Roslan & Naharudin, 2023)	/			/
United Stated	(Aman et al., 2021)		/	/	
	(Brown et al., 2020)		/		/
	(Glenn et al., 2020)		/		/
	(James et al., 2019)	/			
	(Hosseinzadeh et al., 2021)				/
Brazil	(de Jesus et al., 2021)	/	/		/
Washington D.C	(Hawa et al., 2021)		/	/	/
Korea	(Ko et al., 2021)			/	/
German	(Porojkow & Lißner, 2024)	/			
Europe	(Hossein Sabbaghian et al., 2023)	/	/		
Canada	(Jacobs & Dhaliwal, 2024)			/	/
Switzerland	(Reck & Axhausen, 2021)		/		/

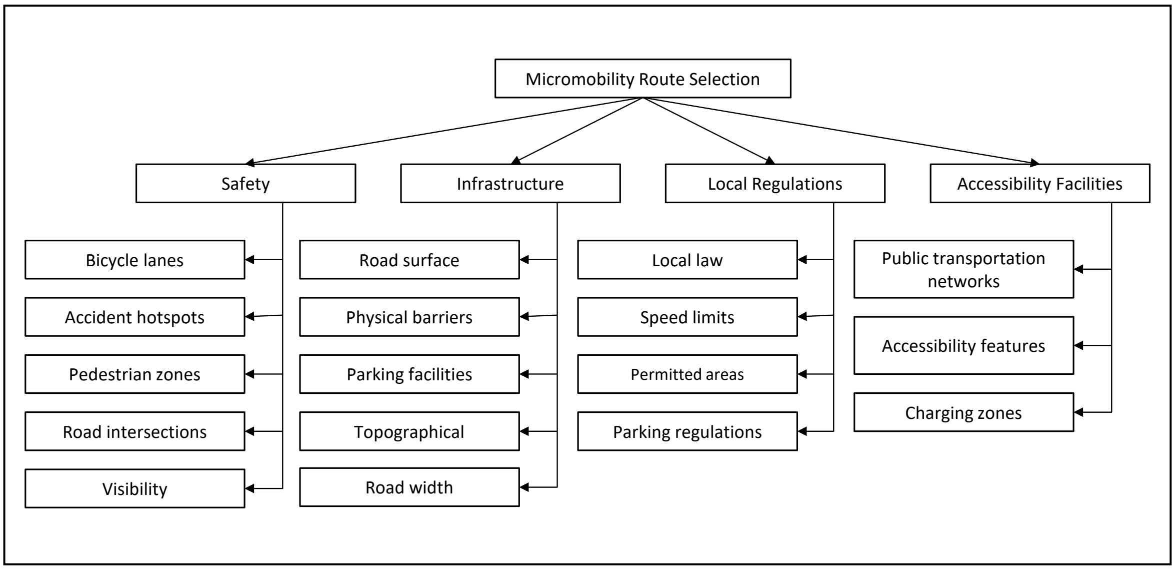

Figure 2. Schematic Diagram of the Micromobility Route Selection Framework.

3. DISCUSSION OF CRITERIA AND IMPLEMENTATION CONSIDERATIONS

Findings from the literature in Table 2 present the formulated main and secondary criteria for proposed micromobility vehicle route selection, which must be considered with reference to all relevant guidelines.

Table 2. Main and Sub-Criteria for Potential Micromobility Vehicle Routes Based on Literature Review.

Main Criteria	Sub-Criteria	Description
Safety	Bicycle lanes	Routes featuring dedicated bicycle lanes to prevent conflicts with motorized vehicles.
	Accident hotspots	Identify and avoid areas with high accident records.
	Pedestrian zones	Avoid routes through crowded pedestrian areas unless specifically permitted.
	Road intersections	Identify high-risk intersections and seek safer alternatives.
	Visibility	Routes with adequate lighting and elimination of visual obstacles such as billboards, trees, or structures that obstruct user sightlines.
Infrastructure	Road surface	Select routes with smooth pavement, free from potholes, cracks, or obstacles.
	Physical barriers	For shared lanes, ensure the presence of curbs, cones, barriers, or lane markings.
	Parking facilities	Ensure routes are located near designated parking areas or docking stations.
	Topographical	Avoid routes with excessively steep hills or challenging terrain.

	Road width	Ensure existing road width meets established regulations and standards for safe micromobility operation.
Local Regulations	Local law	Ensure routes comply with local laws, such as bans on sidewalk usage or specific zones.
	Speed limits	Select routes that adhere to designated speed limits for micromobility vehicles.
	Permitted areas	Ensure routes pass through areas where micromobility vehicle use is authorized.
	Parking regulations	Ensure routes terminate in areas that permit micromobility vehicle parking.
Accessibility Facilities	Public transportation networks	Select routes located near bus stops, LRT stations, or other public transit hubs.
	Accessibility features	Ensure routes are accessible to all users, including those with disabilities.
	Charging zones	Select routes located near charging points for electric vehicles.

The review of selected shows several clear trends in micromobility research. Firstly, many focused-on safety especially accident risk and conflict between other road users. Safety aspects constitute one of the main criteria in selecting micromobility vehicle routes. Safety refers to the protection of micromobility users from accident risks and hazards while using their routes. Sub-criteria such as dedicated bicycle lane, identification of accident hotspots, establishment of pedestrian zones, safe intersection design, and enhanced visibility are crucial for reducing accident risks and user injuries. However, several challenges exist in ensuring comprehensive realization of every safety element within dense urban contexts where infrastructure planning often lacks uniformity. The study's critical approach requires continuous safety risk assessment through utilization of accident data and user feedback to ensure the relevance of implemented measures.

Then, there is growing attention to infrastructure, such as dedicated lanes and better integration with public transport, to improve safety and comfort for micromobility user. Infrastructure aspects similarly play an important role in determining potential routes for micromobility vehicles. Road surface quality, existence of physical barriers, parking facilities, considerations of topographic conditions and road width design are the factors contributing to travel comfort and efficiency. Nevertheless, infrastructure implementation cannot be achieved when issues of budget allocation, compatibility with existing development, and spatial constraints in urban areas exist.

However, more recent studies discuss regulations and policies to manage the rapid growth of micromobility in urban areas. The local regulations including legislation, speed limits, permitted areas, and parking regulations need alignment with infrastructure requirements. Consequently, insufficient coordination between policy and implementation can lead to confusion and suboptimal utilization of public space, ultimately negatively impacting user safety and comfort.

Therefore, accessibility facilities represent a critical aspect in ensuring the integration of micromobility vehicles within public transportation systems. Seamless connections with public transport, inclusive accessibility for users, and provision of charging zones constitute important elements for encouraging micromobility usage. Although this concept offers numerous advantages in terms of congestion and pollution reduction, the main challenge lies in accessibility and equitable resource distribution.

Most studies examine this aspect separately. There is still limited research that integrates safety, infrastructure, regulation and accessibility into one comprehensive route mapping framework. Additionally, integration between existing systems and new infrastructure requires strategic planning involving various stakeholders, including government authorities, developers and user communities, to ensure sustainable and effective implementation. These trends reflect the broader movement toward sustainable and integrated urban transport planning.

3.1 ANALYSIS OF MICROMOBILITY ROUTE CONSTRUCTION CRITERIA

3.1.1 User Safety

Safety in micromobility vehicle usage is a critical issue requiring serious attention due to several key reasons related to user safety, urban sustainability, and transport system integration. Empirical studies indicate a tendency for micromobility users to utilize pedestrian pathways stemming from perceived higher safety (James et al., 2019). However, this practice indirectly contradicts local authority guidelines prohibiting electric-powered vehicles in pedestrian spaces. A solution proposed by Porojkow & Lißner (2024) emphasizes the necessity of physical separation between micromobility corridors, motor vehicle lanes, and pedestrian zones. Protective measures for micromobility riders can include adequate space allocation with protective elements, rendering these routes impassable to other motorized vehicles. This approach aligns with hierarchical mobility design principles, which prioritize user-specific infrastructure adaptation to address speed differentials.

Several findings identify road intersections as high-risk zones due to interactions between micromobility vehicles, motor vehicles, and pedestrians (Hossein Sabbaghian et al., 2023; Mura et al., 2022; Pérez-Zuriaga et al., 2023). Consequently, intersection designs incorporating priority hierarchy, geometric scaling, and universal accessibility are required to support an inclusive and safe transport ecosystem. Fabriek et al. (2012) emphasize that enhanced visibility constitutes a critical criterion in micromobility route planning, particularly within the context of ensuring user safety. Research by Vidal-Tortosa & Lovelace (2024) corroborates this, demonstrating that adequate lighting on micromobility routes can reduce nighttime risks while facilitating prediction of other users' movements and enabling faster responses. However, researchers including Li et al. (2021), Stone (2017), and Pothukuchi (2021) contest this criterion, citing high costs and light pollution that may disrupt local ecosystems. As an alternative, motion-sensor lighting implementation could be considered to achieve operational cost reduction while controlling light pollution (Levin et al., 2020). Therefore, integrating these innovative technological solutions holds potential for long-term cost optimization without compromising route user safety among micromobility user.

3.1.2 Adequate Infrastructure

Well-maintained infrastructure is crucial for micromobility route mapping to ensure safety of the user. Multiple studies indicate that most injuries among micromobility users are associated with non-collision incidents, particularly those involving static objects or falls caused by poor road surfaces and exceeding designated speed limits (Badeau et al., 2019; Blomberg et al., 2019; Trivedi et al., 2019). The impact of poor road infrastructure such as potholes, cracks, or uneven surfaces increases accident and injury risks (ITF, 2020; Moosavi et al., 2022). The condition of micromobility infrastructure not only affects transport network effectiveness but also serves as a primary criterion for injury prevention.

Strategic planning of vehicle parking locations near micromobility routes represents a crucial measure for enhancing user effectiveness in reaching intended destinations (Berg Wincent et al., 2023). Intermodal integration potentially generates positive impacts on transit system connectivity through effective last-mile service provision. However, such planning requires holistic consideration given existing risks of spatial overlap with pedestrians regarding safety aspects, movement flow, and design requirements (Zhang et al., 2023). Consequently, road width must also be prioritized as critical design parameter that aligned with regulatory standards to facilitate effective planning. According to Furth et al. (2023), extreme topographic gradients present operational challenges for micromobility vehicles while indirectly compromising user safety. These findings are further reinforced by Fang (2022), who discovered that steep gradients increase the probability of slipping or falling accidents due to high momentum that can trigger loss of control in small-wheeled vehicles. Routes with good road surfaces and adequate parking facilities are believed to enhance micromobility user adoption rates.

3.1.3 Compliance with Local Regulations

Adherence to local regulations can reduce conflicts with authorities and enhance public acceptance. Market penetration of micromobility remains limited, potentially due to infrastructure deficiencies and insufficient policy establishment (Esztergár-Kiss et al., 2022). In this context, it is crucial to understand micromobility acceptance behavior among communities and investigate influencing factors to inform infrastructure investments and policy decisions that can promote micromobility adoption. Research by James et al. (2019) indicates that micromobility regulations remain poorly understood by the public. Both users and non-users of micromobility require more direct education, along with regulations that are more comprehensible and coordinated.

Limited regulations and inadequate awareness of micromobility transport risks have raised various safety concerns. According to Glenn et al. (2020), assessments of planned policy impacts and interventions are necessary to reduce micromobility-related injuries. A study by Bresler et al. (2019) utilizing U.S. national database data demonstrates that facial and head injuries caused by micromobility vehicles tripled over the past decade. The research indicates accident numbers increased from 2,325 in 2008 to 6,957 in 2018. Among these cases, 66% of treated victims were found not wearing helmets, which may increase serious injury risks during micromobility use. Kopplin et al. (2021) found risk perceptions were relatively low, suggesting policymakers need to clarify dangers associated with micromobility riding and potentially enforce protective gear usage during operation.

Several criteria have been identified for regulating urban micromobility usage, including speed limits, permitted operational zones, and parking regulations as criteria for ensuring system safety and effectiveness (Aman et al., 2021; Brown et al., 2020; Gössling, 2020). A systematic review by Abduljabbar et al. (2021) linking micromobility development with sustainable urban development is further supported by Allem & Majmundar (2019) emphasizing micromobility's role in carbon footprint reduction, and Dormanesh et al. (2020) focusing on safety design integration as prerequisite for social acceptance. This approach demands policy coordination among government agencies, policymakers, and communities to achieve sustainable development objectives.

3.1.4 Accessibility for Micromobility Vehicles

Research by Huo et al. (2021) indicates that individuals residing in densely populated areas with high employment rates, mixed land use, numerous bus stops, and high intersection density demonstrate greater propensity for adopting micromobility vehicles for short-distance travel. Similar findings were reported by Bai & Jiao (2020), who analyzed individual trip record data and established higher micromobility usage in city centers and university districts compared to other areas. In another investigation, Sanders et al. (2020) conducted a survey among university staff examining user characteristics and revealed 76% of respondents preferred micromobility over walking during hot weather conditions.

The general population exhibits increased inclination toward micromobility usage when reliant on public transport services, with this tendency escalating as home-to-nearest-bus-stop distance increases (Ko et al., 2021). These findings warrant particular attention as public micromobility adoption correlates strongly with existing public transport facility locations. The Road Safety Plan 2022-2030 outlines how suboptimal connectivity between urban and rural public transport systems continues to drive private vehicle dependency (cars, motorcycles) (Ministry of Transport Malaysia, 2022). In response, the plan emphasizes universal accessibility-based infrastructure development to bridge transport access disparities while shifting public paradigm toward more efficient and sustainable public transport systems.

The Road Safety Plan 2022-2030 further identifies persistent issues regarding inadequate inter-urban and rural-urban public transport connectivity, which reinforces personal vehicle preference. The plan consequently prioritizes infrastructure development to expand accessibility and enhance public transport network integration. Substantial investment in charging infrastructure development by government and urban planners is essential to overcome barriers in micromobility adoption (Lo et al., 2020). This includes strategic placement of charging stations in urban areas, along frequently traveled routes, and at major destinations (Cui et al., 2019). Enhanced accessibility provisions can significantly contribute to micromobility growth and public acceptance. However, charging station density and vehicle travel range remain critical usage determinants (Cordera et al., 2019; Haustein & Jensen, 2018; Liu & Lin, 2017; She et al., 2017). Researchers must develop specialized models to determine optimal micromobility vehicle locations and charging station quantities based on charging duration parameters (Masoud et al., 2019; Wang, 2007).

4. CONCLUSION

Comprehensive selection of micromobility vehicle routes requires the integration of safety, infrastructure, regulatory, and accessibility criteria as illustrated in Figure 2. Through the development of this theoretical framework, a comprehensive model can be produced for micromobility vehicle route mapping that will optimize safety, infrastructure effectiveness, regulatory compliance, and accessibility. Based on these criteria, the selected routes will not only be safe and comfortable for users but also contribute to sustainable and inclusive urban development. The framework provided by this study aims to assist urban planners, micromobility operators, and local authorities in making improved decisions. The research findings are expected to provide preliminary exposure for other researchers in establishing development frameworks for micromobility vehicle mapping. The policymakers and urban planner can use the proposed framework as structured decision support tool in design safer micromobility route, ensuring that infrastructure investments, regulatory measure, and accessibility improvements are aligned with sustainable urban transport goal. Criteria selection requires deeper analysis to determine the relative importance of each criterion in route mapping. The development of a systematic mapping criteria framework serves as a critical prerequisite for supporting the integration of micromobility vehicle operations into the urban transport ecosystem, thereby addressing a gap in the literature. Therefore, this study focuseses on developing a theoretical framework for micromobility route mapping which has not been fully tested in real urban development which will affect it effectiveness based on local condition and data availability. Based on the developed scientific literature review, two main aspects have been identified requiring deeper investigation for developing more effective mapping:

- Criterion prioritization in mapping: In-depth analysis is required to determine which criteria are most critical in shaping micromobility infrastructure mapping.
- Holistic data integration: Development of mapping frameworks that incorporate diverse requirements to understand how mapping can balance environmental needs and user practicality.

Both aspects are crucial for ensuring that micromobility infrastructure mapping is not only technically accurate but also responsive to community needs within the environmental context. Future studies should test and validate this framework using real-world data and spatial analysis methods to evaluate its practicality and suitability in urban design.

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