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Towards an electric scooter level of service: A review and framework

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ABSTRACT

Although electric scooters (e-scooters) are gaining ground rapidly, research on analysing their users' experience lags far behind practice. Level of Service (LOS) is a promising approach to bridge the gap between research and practice via quantifying e-scooter riders' experience. We reviewed the state-of-the-art literature of e-scooters concerning their users' experience and proposed a preliminary framework for developing e-scooter LOS (SLOS). The findings suggest a lack of studies to evaluate SLOS, and e-scooters are rarely considered in the LOS estimation of other transport modes. Considering the impact of e-scooters in both modal substitute and supplement calls for unique SLOS indices in each scenario to reflect their user's experience realistically. Future studies should analyse the interaction of e-scooters with other road users, particularly pedestrians. This study highlights the importance of treating e-scooter as a distinct transport mode and contributes to matching policy and practice to integrate e-scooters into transport planning.

1. Introduction

Micro-mobility[1] is a combination of transport modes that can substitute and supplement vehicles operated by fossil fuels, reducing the drawbacks of these vehicles (Leister et al., 2018; Smith et al., 2021). Bikes, electric bikes (e-bikes), and electric scooters (e-scooters) are different types of micro-mobility, operated in shared services (docked and dock-less) and in a privately owned manner (Caspi & Noland, 2019; Shaheen & Cohen, 2019).

E-scooter is a novel type of micro-mobility that has rapidly gained popularity since its introduction in 2017 (Caspi et al., 2020; Hosseinzadeh et al, 2021a). E-scooter has frequently been referred to as convenient mobility, specifically for short-distance trips, having playfulness and transport function (Christoforou et al., 2021; Glenn et al., 2020). However, the fast-growing usage of e-scooters and lack of consolidating planning strategies for their integration into mobility and urban planning have resulted in a mismatch of policy and practice and consequently caused discomfort for users (Anderson-Hall et al., 2019; Ma et al., 2021; Zou et al., 2020). Nevertheless, evaluation and improvement of e-scooter riding experience is a must for a smooth adoption of this mode of transport.

The assessment of users' experience related to various types of mobility leads to different results as each mobility type is associated with unique travel behaviour and driving/riding characteristics (HCM, 2016). For example, the speed regime, riding posture, and travel behaviour of e-scooters are different from (non)motorised vehicles (see 'Appendix 1' for more details). The distinct characteristics of e-scooters indicate that the evaluation of e-scooter riding experience requires an *ad hoc* framework, and a direct adaptation (without adjustment) of methods from other modes of transport would be questionable. Leveraging on a similar domain related to e-scooters, the overview of the last three decades' research on users' experience of cycling reveals a variety of methods to translate road users' comfort via indices such as suitability, friendliness, comfort, level-of-stress and Quality-of-Service (QOS) (Abadi & Hurwitz, 2018; Fitch et al., 2020; Lowry, et al., 2012; Maaza et al., 2012; Nikiforiadis et al., 2020). Among all, the concept of QOS has been well adapted for different modes of transport, e.g. cycling, personal cars, and public transport in the last few decades (HCM, 2016).

The QOS demonstrates how well the transport system operates from the users' point of view. More specifically, the representation of QOS is performed by the Level of Service (LOS) index, which quantifies the performance measures. The LOS indices are mainly providing the results via letter-based scales, which often range from A (best) to F (worst) scale (HCM, 2016). LOS is primarily reported based on each mode of transport, considering specific features of each mode. Since the emergence of the LOS idea in 1965 by the Highway Capacity Manual (HCM), a significant body of research has applied this concept to pedestrians, bikes, cars, and public transport (Botma, 1995; Dowling et al., 2008;

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[1] Micro-mobility refers to light weight vehicles (less than500 kg) which are devised for relatively short distance trips ~less than15km (Liao and Correia, 2022).

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Kazemzadeh et al., 2020; Nikiforiadis et al., 2021a, Nikiforiadis et al., 2021b). The development of LOS indices has various applications, such as assisting in planning, designing, and managing transport facilities (HCM, 2010). Therefore, the development of LOS indices is a vital metric for ex-ante and ex-post assessment of micro-mobility infrastructure, in this case, e-scooters. However, powered micro-mobility, including e-bikes LOS and e-scooters LOS (SLOS), has not been comprehensively studied. One of the prerequisites for the development of SLOS is to study performance measures of this mode of transport. In other words, the variables that contribute to e-scooter users' experience and (dis)comfort need to be explored and evaluated.

Few research and literature review studies have been conducted on e-scooters as this topic is still developing. As Table 1 shows, most review studies include e-scooters in an overall context of micro-mobility. The review of the previous studies (including literature articles) revealed a lack of research or even initial discussion on SLOS analysis. In response to this knowledge gap, the overarching aim of this study is to facilitate the development of SLOS via mapping the current literature on e-scooters against the concept of LOS. The review of the literature and the evaluation of previous studies provide insights from the state-of-the-art, influencing variables about users' experience, performance measures, and possible future research directions (Fishman & Cherry, 2016).

The contributions of this study are threefold. First, this study provides a systematic and comprehensive overview of the state-of-the-art in the e-scooter research domain. Next, each topic is discussed in light of the LOS concept (within each theme of the research) and challenges associated with the current studies are examined. Finally, a preliminary hypothetical framework is qualitatively proposed to facilitate the development of SLOS. It should be noted that throughout the paper, we systematically reviewed and discussed each topic (within each section) to maximise the takeaways from the studies.

Table 1
Previous review studies related to e-scooter.

Author(s) (Year)	Main focus	Included modes	Main conclusion(s) or recommendation(s)
Oeschger, Carroll, and Caulfield (2020)	Knowledge on the integration of micro-mobility and public transport	Micro-mobility and public transport	The effect of integrating micro-mobility and public transport on different elements of society, the environment, and the economy shape the primary knowledge gap.
Liao and Correia (2020)	Usage pattern, estimation, of demand & impacts	Shared e-mobility including electric vehicle, e-bike, e-scooter, & e-cargo bike	The shared e-mobility usage is mainly for short-distance trips. Users are primarily male, middle age, and well-educated with high income.
O'Hern and Estgfaeller (2020)	A summary of research status	Powered micro-mobility including e-bike, e-skateboard, & e-scooter	The findings demonstrate the increase in the trend of micro-mobility since 2012. Several topics such as users' behaviour, planning, policy and health were identified in the literature.
Abduljabbar, Liyanage, and Dia (2021)	Knowledge on micro-mobility from a sustainability standpoint	Micro-mobility including cycling, e-scooter & e-bike	The emerging micro-mobility could tackle mobility challenges such as congestion and accessibility discomfort in the next few years.
Şengül and Mostofi (2021)	Knowledge on micro-mobility from a sustainability standpoint	Micro-mobility, including e-bikes and e-scooters	An overview of micro-mobility is provided, and its impact is classified into four categories: energy consumption, travel behaviour, traffic safety, and environmental impacts.

2. Method

Different databases such as Scopus, Web of Science, and Google Scholar are available to retrieve the scientific literature. There are similarities among the coverage and function of these datasets, and they have been used as bibliographic resources in previous transport review studies (Bigazzi & Wong, 2020; Kazemzadeh and Ronchi, 2022). For example, Scopus has high coverage of publications and is a promising tool, especially in social sciences fields (Norris & Oppenheim, 2007).

Scopus (www.scopus.com) database is used as the primary search tool to retrieve extensive topic-related literature. The database was searched in June 2021, and keywords included: scoot, scooter, electric scooter, e-scooter, scooting, micro-mobility, and micromobility. These keywords were coupled with comfort, quality, service, satisfaction, 'quality-of-service', 'level-of-service', convenience, QOS and LOS. The previous queries were adjusted to search the title, abstract and keywords of the indexed articles. We performed some limited forward and backward searching in Google Scholar and Transport Research International Documentation (TRID)[2] databases to maximise the search's inclusivity. Also, citation search was applied as a supplementary searching strategy.

After that, the results of searching databases were merged, and the duplicates were removed. This strategy yielded 210 papers. We devised the following inclusion and exclusion criteria for screening the emerged literature. First, only peer-reviewed journal articles in English were included for further evaluation. Then, we included articles that elaborate on users' experience, usage patterns, comfort and satisfaction analysis, willingness to pay/use, and infrastructure assessment. Next, we excluded the articles on the users' safety concerns, life cycle assessment, manufacturing advancement, energy modelling, and environmental impacts. Finally, a total of 46 articles were qualified to be included in the review and subsequently individually reviewed. This screening strategy (see Fig. 1) is adopted based on the PRISMA framework (Moher et al., 2009). This number represents specific studies that met the searching criteria. To expand and motivate the discussion related to e-scooters, we also included and discussed some further studies within the context of micro-mobility.

3. Results of the reviewed literature

An analysis of the literature contributes to evaluating variables that could, directly and indirectly, depict the e-scooter users' experience. Adopting suitable themes to classify the variables of previous studies is challenging as one variable could be interpreted from different perspectives and, therefore, be placed in various categories. For example, we classified the trip purpose in the E-scooter (non)users' category as users evaluate the situation and eventually decide for their trips. However, this variable could also be classified as a subsection of Trip characteristics. Hence, the proposed category is deemed to help classify previous studies and could be reclassified differently. This analysis of the literature contains four sections: data collection methods, e-scooter (non)users, trip characteristics, and infrastructure characteristics.

3.1. Data collection methods

Data collection is a critical part of each research project, and a

[2] https://trid.trb.org/.

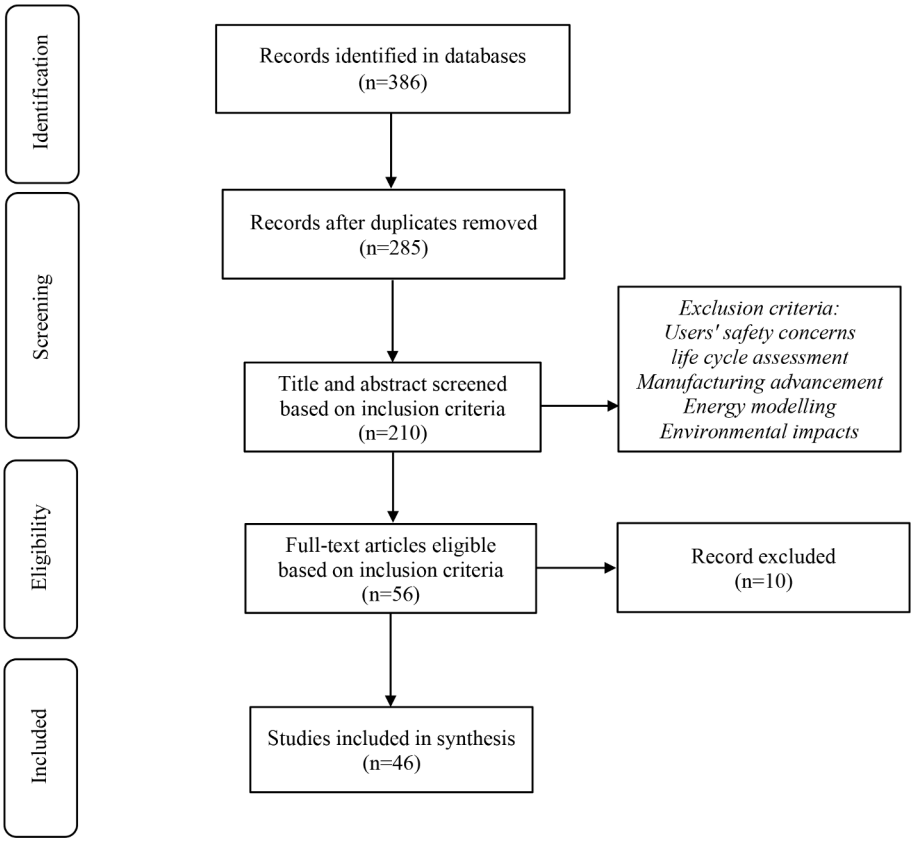

Fig. 1. The screening strategy based on the searching protocol.

precise administration procedure provides realistic information about users. Similar to other modes of transport, different data collection methods (i.e. stated- and revealed-preferences/settings) such as survey, naturalistic observation, and open source databases have been applied in the previous e-scooter research (see Appendix 3). This section briefly reviews and discusses the usage of open-source databases (from sharing e-scooter companies), observations and experiments, and surveys. The first two methods could be placed in revealed behaviour, while the last one is the stated-preference set-up.

3.1.1. *Open-source databases (shared e-scooter usage data)*

This data source has been widely used in previous shared micro-mobility research such as bikes and e-bikes (Guidon et al., 2019; Li et al., 2021). There are extensive databases available from different e-scooter companies that could be potentially used as a data source for e-scooter research considering the rapid popularity of e-scooter. This source of data is essential to understand a variety of behaviour concerning the shared e-scooter users. For example, this data usually contains the distribution of ridership, frequent paths, peak hours, pick up and drop off locations, and usage sensitivity to external factors such as weather conditions and gas prices (Huo et al., 2021; Noland, 2021; Younes et al., 2020). The number of trips is also a crucial part of this dataset type, which is different based on the study context and could range from a couple of thousand to millions of trips (Bai & Jiao, 2020a; Noland, 2021). Also, the interpretation of data involving different sets of variables such as weather conditions and trip purpose vary across previous research (Huo et al., 2021; McKenzie, 2019). The overall trend of this source of data usage, especially in the US, reinforces its applicability to reveal the behaviour of e-scooter riders in different facilities. However, more research is needed to evaluate the reliability of these datasets and evaluate their application in SLOS development.

3.1.2. *Experiment and observation*

Experimental set-ups and (quasi)naturalistic observation have been extensively applied in the field of micro-mobility, such as the analysis of bike-pedestrian, e-bike-pedestrian, and cyclist interactions (Botma, 1995; Kazemzadeh & Bansal, 2021; Yuan et al., 2018). It should be noted that designing and conducting this type of data collection (specifically experiments) require exhaustive work compared to other data sources such as shared e-scooter open-source data. Yet, experimental set-ups provide the most detailed mode data, and different scenarios could be tailored based on research questions to evaluate the road users' experience (Yuan et al., 2018). Few studies in the literature collected data based on observation and experiments. For example, Che et al., (2020) conducted a virtual reality experiment and explored the interaction of pedestrians and e-scooters in an off-road facility. Based on the designed experiment, different sets of data such as perceived safety, anger, and manoeuvre quality were collected via user manoeuvre rating scenarios. In the same context, experimentation, observation, and simulation were used to a limited extent to collect e-scooter data, such as speed, riding vibration, parking behaviour/violation, and riding characteristics (Brown et al., 2020; Cano-Moreno et al., 2021; James et al., 2019; Tuncer et al., 2020). In sum, more extensive research is needed to analyse the actual behaviour of e-scooter riders in different scenarios/contexts to understand their experience in urban settings better.

3.1.3. *Survey*

Along with using open-source data from e-scooter companies, different studies have been conducted in the literature based on stated-preference set-ups (see Appendix 3 for more details). This data collection method mainly depicts the users' experience of privately owned e-scooters (along with shared users). The evaluation of both owners' and renters' ridding experience provides a holistic view of the e-scooter usage for planners and policymakers. Subsequently, it could lead to the development of a comprehensive SLOS. Like for other modes of

transport, surveys have been conducted as one of the primary methods of data collection in this field – approximately 1/3rd of methods in the reviewed papers (Kopplin et al., 2021; Laa & Leth, 2020). This study stream has focused on willingness to use, usage patterns, perceived comfort and safety (De Ceunynck et al., 2021; Ko et al., 2021; Kopplin et al., 2021). Each of the variables mentioned above provides a partial image of the users' experience and contributes to the SLOS development.

As e-scooters have been advertised on various online platforms, social media platforms could also be considered a source of data collection. For example, the usage of e-scooters has been highlighted in different social media platforms such as Instagram and Twitter. These platforms provide an opportunity for users to express their travel experience and can be used as some self-reporting data collection method. In the literature, two studies used the data from these platforms to analyse the usage of e-scooters. For instance, the users' experience was retrieved via analyses of e-scooter app reviews, comments, and social media posts (Allem & Majmundar, 2019; Aman et al., 2021). Altogether, conducting stated-preference data collection is beneficial for evaluating e-scooter riders. More research should elaborate on different characteristics of e-scooter riders, such as users' experience in the presence of other road users and riding comfort in different urban contexts.

3.2. E-scooter (non)users

Leveraging the knowledge about the experience of users and non-users of e-scooting paves the way to the development of SLOS. Subsequently, this knowledge leads planners and policymakers to develop and adopt policies accordingly and improve the users' experience. This section includes three subsections: scooting experience, socio-demographic characteristics of users, and trip purpose. Each subsection provides a partial image related to the users' experience, and the entire section contributes to understanding the overarching aim of this study.

3.2.1. Scooting experience (comfort variables)

An in-depth understanding of the road users' experience leads to the development of realistic LOS indices. The usage of different types of micro-mobility is associated with various variables such as health condition, the flexibility of use, the flexibility of departure time, and lack of fuel expenses (Akar & Clifton, 2009; Fernández-Heredia et al., 2014). E-scooting is quite different from other types of micro-mobility (see Appendix 1). Therefore, there is a crucial need to evaluate how they are experienced. In general, the experience of using an e-scooter is associated with having fun for users (Bieliński & Ważna, 2020; Kopplin et al., 2021; Laa & Leth, 2020; Sanders et al., 2020). For example, e-scooting in short-distance trips (especially in hot weather) could be more enjoyable than walking (Christoforou et al., 2021; Sanders et al., 2020). This variable could also be seen in the usage of e-bikes (Leger et al., 2019; Popovich et al., 2014). This similarity might imply the enjoyment of electrically assisted riding of powered micro-mobility along with its mobility mission (Kazemzadeh and Ronchi, 2022). Other variables include saving money, convenience, environmental value, and health benefits related to e-scooters (Christoforou et al., 2021; Mitra & Hess, 2021; Sanders et al., 2020).

As e-scooters could also be operated in cycling facilities, the available infrastructure of cycling is deemed a critical factor for the e-scooting experience (Caspi et al., 2020; Zhang et al., 2021). In sum, the e-scooting experience has some similarities with other types of micro-mobility, specifically e-bikes. However, lack of physical effort, riding posture, and trip purpose/distance of e-scooter could result in different users' experiences.

3.2.2. Socio-demographic characteristics of users

A series of information regarding e-scooter users such as dominant gender, age group, and education level may profoundly contribute to the evaluation of e-scooter usage patterns, and consequently, their perceived experience. In the literature, an e-scooter is frequently referred to as a male-dominated mode of transport (Aman et al., 2021; Laa & Leth, 2020; Nikiforiadis et al., 2021a,b). The male over-representation of e-scooter usage needs to be further studied to explore its causes and remedies to maintain transport gender equity. The users' age distribution analysis revealed that e-scooter riders are mainly young adults (Almannaa et al., 2021a,b; Cao et al., 2021; Laa & Leth, 2020). This trend of usage by young adults, in general, could also be seen in *shared mobility* as its use is mainly correlated to young people (Bieliński & Ważna, 2020; Burghard & Dütschke, 2019; Reck & Axhausen, 2021). The prerequisite of using smartphones and working with apps (for renting) might strengthen the hypothesis of using shared mobility by younger adults as they could be more familiar with new technologies. Also, e-scooter users are reported (based on surveys) a well-educated group of society (Christoforou et al., 2021; Jiao & Bai, 2020; Laa & Leth, 2020). The same argument related to the young-age distribution of shared mobility usage could be extended for the education level of users. Plus, young adults (and possibly educated) are deemed to use more social media, and the new technology trends are extensively highlighted in these media platforms (Berryman, Ferguson, & Negy, 2018). In sum, the converged trend of the literature reveals a higher pattern of e-scooter usage among male, young, and high-educated users, which implies that a single SLOS index might not realistically depict all e-scooter users' experiences. Therefore, there is a need to consider the dominant variables in the SLOS and the possibility of the index adjustment based on different e-scooter riders' socio-demographic characteristics.

3.2.3. Trip purpose: Substitution or supplement?

Evaluation of trip purposes of e-scooter rides (e.g. recreational and commuting) could provide a clear picture of the user's requirements, such as trip-end facilities. Different trip purposes have been associated with the usage of e-scooter in previous studies. Recreational and leisure trip purposes are frequently reported as potentially the main applications of e-scooters (Bai et al., 2021; Glenn et al., 2020; McKenzie, 2019; Noland, 2021). However, lack of physical exertion for e-scooting provides mixed and multiple trip applications for e-scooters such as commuting, shopping, and other errands (Caspi et al., 2020; Lee et al., 2021a,b; Liao & Correia, 2020). Nevertheless, there is a need for further research to analyse explicit trip functions of e-scooters (e.g. substitute and/or supplement other modes of transport). In general, introducing a new mode of transport could affect the supply and demand management of mobility (e.g. generation of new demands and modal substitution), especially in shared mobility, as ownership is not required for use (Juschten et al.,2019). Therefore, the extension of supplement and substitution of new mobility approaches could be beneficial for the management of mobility (e.g. congestion management during rush hours), and subsequently, the user's experience in emerging types of motilities (Reck et al., 2021).

The literature evaluation yields nested applications of e-scooters that contain substitution and supplement of active and motorised vehicles (Caspi et al., 2020; Kopplin et al., 2021; Lee et al., 2021a, Lee et al., 2021b). Various causes have been discussed in the literature, such as trip purposes and trip distance, to discuss the usage of e-scooters in mobility (Caspi et al., 2020; Liao & Correia, 2020). For example, e-scooters have been frequently referred to as a remedy for the first-last mile trips (Baek et al., 2021; Crowe & Elkbuli, 2021; Gössling, 2020; Mathew et al., 2019; McKenzie, 2019). Also, On the other hand, e-scooters could partly/fully substitute motorised vehicles such as public transport and cars (Bai & Jiao, 2020a, 2020b; Laa & Leth, 2020). These results stem from the analysis of usage patterns and users' preferences. For example, the short distance and duration of trips of e-scooter suggested their application for first-last-mile trips. A similar unclear substitution scale of trips by e-scooters could be seen in the e-bike research domain (see Kazemzadeh and Ronchi, 2022 for more details). This might be due to the electrically assisted function of these vehicles, which reduces (for e-bikes) and removes (for e-scooters) the physical exertion and provide the

possibility to plan different trip purposes. To sum, e-scooters have applications to substitute and supplement both active and motorised modes of transport.

3.3. Trip characteristics

E-scooters could be operated in different urban contexts and infrastructure configurations. Evaluating e-scooter usage and trip distances aids planners and practitioners in designing and improving infrastructure and efficient management of travel demand. Moreover, the analysis of e-scooters interaction with other road users directly inputs the development of SLOS for off-road facilities[3]. This section contains three subsections: place and time of prevalence, trip distance, and navigation characteristics.

3.3.1. Place and time of prevalence

Understanding the hot spots and prevalence of e-scooter usage could be beneficial from different perspectives. First, planners discern high demand spots for e-scooter use, which contributes to evaluating and improving the quality of e-scooting. Moreover, the sites with increased exposure to e-scooting might also be related to unexpected events such as conflicts and collisions, which require special considerations to avoid. The literature evaluation reveals that the city centres are referred to as one of the main hot spots associated with the high percentage of e-scooter usage (Bai & Jiao, 2020b; Caspi et al., 2020; Hawa et al., 2021; Huo et al., 2021). This might be due to the application of e-scooter usage in short-distance trips, the difficulty of operating personal cars in crowded spaces, and the high cost of parking in city centres (McKenzie, 2020). Moreover, e-scooter usage is prevalent on university campuses (Bai & Jiao, 2020b; Caspi et al., 2020; Huo et al., 2021; Jiao & Bai, 2020; Zhu et al., 2020), which could be due to the popularity of e-scooters among young and well-educated people, as discussed in the 'socio-demographic characteristics of users' section. Also, this group might be more open to experience new emerging technologies such as e-scooters. More research could be conducted to understand the role of e-scooters in different urban and short-distance rural set-ups.

The usage of e-scooters based on different days (e.g. weekday and weekend) could be associated with several variables. First, it seems that the usage rate of e-scooters on weekends is different compared to weekdays (Bai & Jiao, 2020a; Hawa et al., 2021; Younes et al., 2020). Different trip purposes and consequently trip distances might be the reason for various usage and exposure of e-scooters based on weekday. Second, riding navigation of e-scooters (e.g. speed) is different based on the day of using e-scooters. For example, it was reported that e-scooter riders have higher speed on weekdays than on weekends (Almannaa et al., 2021a, Almannaa et al., 2021b; Zuniga-Garcia et al., 2021) which could be evaluated from different perspectives. For example, Zuniga-Garcia et al. (2021) found that the higher speed of weekdays than weekends is due to the higher number of e-scooters in the latter. In addition, other variables such as different trip purposes and paired riding might affect riders' speed on different days. However, more research is required to understand the e-scooter user's experience in various conditions such as weekdays and weekends.

3.3.2. Trip distance

Trip distance covered by e-scooter could be connected to various variables such as trip purposes, weather conditions and the availability of different modes of transport. Understanding the distribution of trip distances of e-scooter is crucial and could have impacts on the users' experience, and eventually, the development of SLOS. As an illustration, users have different needs (e.g. trip-end facilities) based on their trip distance which directly affects their riding experience. This could also be beneficial to assess and adopt comfort variables from other transport modes (with similar trip distances) for e-scooters, considering lack of extensive scientific knowledge for e-scooters. A great body of the e-scooter literature has extensively discussed trip distance in their study set-up (Gössling, 2020; Jiao & Bai, 2020; Liao and Correia, 2022). This is partly due to the wide application of open-source data from shared e-scooter companies and the availability of origin–destination information, enabling researchers to estimate trip distance. Two critical takeaways could be identified from analysing the trip's distance in previous studies. First, e-scooters have mainly been reported as a remedy for short-distance trips, the so-called first-last mile trips (Hosseinzadeh et al., 2021b). Second, the definition of a *short distance* trip could be different based on each study's assumption. In general, the trip distance for micro-mobility could be associated with less than 15 km (Liao and Correia, 2022). As a result, various trip distances from half km to over 10 km are reported. More specifically, the trip distance of e-scooting in the US is often reported to be about 2 km (Noland, 2021; Bai et al, 2021; Jiao & Bai, 2020). However, longer trip distances are reported in Asia, such as 13.7 km (Ko et al., 2021). Among different modes of micro-mobility, e-scooter trip distance is generally reported to be shorter than e-bikes and bikes trips (Liao and Correia, 2022; Noland, 2021), which might be due to higher cost of a shared e-scooter system than other micro-mobility types and/or more convenience of using e-bikes. In addition, the trip duration for e-scooters is mainly reported to be less than 30 min (McKenzie, 2019; Huo et al, 2021; Noland, 2021). As trip duration could be correlated with stress, fatigue, and comfort (De Vos et al., 2013; Morris & Guerra, 2015), the trip distance/duration evaluation could be helpful for the development of SLOS.

3.3.3. Navigation characteristics

The presence of different transport modes with various navigation characteristics (e.g. speed regime and acceleration) increases the chance of users' interaction in shared facilities (e.g. passing, same-direction and meeting, opposite-direction encounters). In the literature of micro-mobility, the interaction of pedestrians and bikes has been extensively discussed (Botma, 1995; Griswold et al.,2018; Yuan et al., 2018). As an example, the so-called concept of *hindrance* has been adopted in the field of bikes and e-bikes to evaluate the degree of manoeuvring, which is limited by slower road users (HCM, 2016; Kazemzadeh and Bansal, 2021a,b). Considering different speed regimes of e-scooter and other vulnerable road users (e.g. pedestrians and bikes), there is a dire need to understand the navigation of e-scooting in different facilities. This analysis would be helpful for comfort analysis (i.e. the development of SLOS) and the safety evaluation of facilities. However, a limited number of studies have been conducted to analyse the interaction of e-scooters in on– and off-road facilities (Che et al. (2020). More research in this area is needed to assess the modal interactions specifically for vulnerable road users. In a similar vein, the fundamental relationship between traffic flow variables of e-scooters (i.e. speed, flow, and density) is a required step toward an in-depth understanding of the macroscopic behaviour of e-scooting (Reck et al., 2021). The distribution, impact, and interaction of e-scooter traffic flow variables are also beneficial for understanding users' experiences. For instance, Almannaa, Ashqar, et al. (2021) explored the speed distribution of e-bikes and e-scooters in the US. They concluded that e-bike and e-scooter have a different distribution pattern in their average speed, and e-scooter has a lower speed average than e-bikes. Furthermore, there are limited studies to assess speed characteristics of e-scooting based on the type of infrastructure (Tuncer et al., 2020; Zuniga-Garcia et al., 2021). Different combinations of road users and configuration of infrastructure could affect the speed regimes of e-scooter riders. For instance, the lower speed regime of e-scooter on sidewalks could be due to the presence of pedestrians and the necessity of precautionary behaviour of e-scooter riders to avoid conflict and collisions. This implies that a variety of studies based on different infrastructure settings are needed to evaluate a precise e-scooter users'

[3] Off-road facilities refer to facilities which is dedicated for active mobility such as sidewalks and bike lanes. In contrast, on-road facilities provide a shared usage facility for both active and motorised vehicles e.g. paved shoulders.

experience. Furthermore, imposing speed limit is discussed in different studies, which requires further investigation to evaluate its impact on users' experience (Gössling, 2020; Lo et al., 2020). In line with (dis) comfort consequence of the speed variable, the vibrations transmitted to the rider (due to speed and pavement types) could be a source of riding discomfort, which needs further study. For example, Cano-Moreno et al. (2021) conducted an experiment to analyse the vibration impact of road pavement on e-scooter users' experiences. They concluded that for a common e-scooter and on good pavement, 16 km/h speed is the threshold of discomfort, and 23 km/h speed is harmful to the user in short-distance trips. This finding needs further exploration and could be discussed within the importance of speed limit and dedicated facilities for e-scooters. All in all, the navigation characteristics of e-scooters have not been extensively studied in the literature. Indeed, analysing the precise interaction of e-scooters need dedicated experiments and/or observations.

3.4. Infrastructure characteristics

The precise design, operation, and management of infrastructure are crucial to providing comfortable and safe mobility (Pucher et al., 2010). From the economic point of view, the cost-benefit analysis of active mobility infrastructure reveals positive benefits compared to the costs (Cavill et al., 2008). E-scooters could be operated in different transport facilities, and therefore, it is crucial to understand their riding experience in various settings. Three main categories are discussed in this section to assist the analysis of the users' experience, namely: transport components, sharing policy of infrastructure, and trip-end facilities.

3.4.1. Transport components

The transport component consists of links (the stretch of roads), node (end-points of links), and network (combination of links/segments and nodes). LOS for active mobility is mainly reported based on each component of transport. For instance, assessing cycling experiences such as comfort and safety could have different variables based on the road components (see Kazemzadeh et al. (2020) for more information related to BLOS studies). Different riding tasks (e.g. manoeuvring, acceleration, deceleration and stopping) are required based on transport component types. Consequently, users have unique travel experiences in different transport components (HCM, 2016). A similar logic could be extended for e-scooters as they are also operated in various transport components, and thus the scooting task and experience would be different.

A significant body of the literature has focused on the different infrastructure characteristics for e-scooter riders, such as the preference of riders for cycling infrastructure, speed profile on infrastructure, and capacity issues (Caspi et al., 2020; Laa & Leth, 2020; Zhang et al., 2021; Zuniga-Garcia et al., 2021). The open-source datasets (mainly from shared e-scooters) provide valuable information related to the network level of analysis. The quality of e-scooting at the network level could be associated with infrastructure shortcomings (e.g. discontinuity) which could be further explored in future studies. Moreover, the evaluation of e-scooting in links and nodes is yet to be studied. As a case in point, the riding experience of e-scooters needs to be further explored on signalised intersections, crossing, and roundabouts. This category could contain the delay analysis, modal interaction, and travel time, affecting comfort and safety.

3.4.2. Infrastructure sharing policy

Sharing policies for infrastructure could be classified based upon off- and on-road facilities. Vulnerable road users (e.g. cyclists) share the facilities with motorised vehicles (e.g. private cars and buses) in on-road facilities. However, off-road facilities are specifically dedicated to vulnerable road users (HCM, 2016; Kazemzadeh et al., 2020). Off-road facilities have frequently been reported as the preferred type of infrastructure for cyclists (Fernández-Heredia et al., 2014; Wardman et al., 2007). A similar trend could be expected for e-scooters considering riders' vulnerability in interaction with motorised vehicles (Zhang et al., 2021). Regarding off-road facilities, few studies in the literature discussed the challenges in off-road facilities for e-scooters, e.g. the interaction of e-scooters, cyclists and pedestrians (Che et al., 2020; Tuncer et al., 2020).

In a similar vein, the rules and regulations of sharing infrastructure for operating e-scooters are not evident, and they are operating in both on– and off-road facilities (Gössling, 2020). Therefore, more research is needed in each type of facility to evaluate the users' experience and subsequently apply it to develop SLOS. First, the interaction of e-scooters based on the presence of bikes, e-bikes, and pedestrians provides valuable information to manage off-road facilities. Next, the evaluation of road markings and the speed limit on the perceived comfort and subjective safety of e-scooter users in on-road facilities could be beneficial for the development of SLOS in on-road facilities. Altogether, the experience of e-scooter riders in link and nodes needs more considerations and developing dedicated SLOS indices would assist planners in managing and improving these facilities.

3.4.3. Trip-end facilities

Trip-end facilities have not been considered a main component in previous micro-mobility LOS studies, such as the BLOS research domain (Kazemzadeh et al., 2020). However, their importance (e.g. safe parking) for cyclists, especially commuters and e-bike riders, has been discussed in the literature (Heinen et al., 2010; Kazemzadeh and Ronchi, 2022). This fact can be extended for e-scooters as they also share the same facilities. As a case in point, lack of regulations and availability of trip-end facilities (e.g. parking) for e-scooters could cause discomfort for other road users (Brown et al., 2020; Gössling, 2020). This issue leads to miss-parked e-scooters in sidewalks, which impedes the access of road users and consequently negatively affects their comfort and safety. This issue might be more related to renters as owners are expected to be more careful about their e-scooter and find secure and proper parking. Also, privately owned e-scooters are foldable and lighter than renting scooters, and users could carry them to their destinations. Leveraging on the cycling research, it has been suggested that improvement in cycling facilities (e.g. secure parking) is associated with increased cycling comfort and ridership (Titze et al., 2007; Yuan et al., 2017). This finding could be expected to be valid and even more critical in the case of powered micro-mobility, considering their higher initial investment. In using shared e-scooters, the freedom of returning dockless e-scooters at any location introduces different challenges in the urban area (Moran et al., 2020; Zou et al., 2020). As the users do not own e-scooters, they might not be careful to park them properly and impede both on– and off-road facilities. More traffic engineering solutions, traffic education, enforcement could be helpful to tackle the challenge of e-scooter miss-parking, which requires extensive research.

4. Overall challenges in the current literature

In this section, we identify key challenges associated with the reviewed themes of the literature, including data collection, e-scooter (non)users, trip and infrastructure characteristics. The open-source databases of shared e-scooters have been frequently used in previous studies as they are time- and cost-efficient. However, these datasets fail to depict the travel behaviour of privately owned users and nonusers. Furthermore, even in similar cities, the sample size of these datasets varies significantly. Consequently, there could be issues of representative sample size and reliability of findings within different studies. In addition, the privacy considerations associated with the use of these data sources have not been well examined in the literature. Moreover, the existing e-scooter literature lacks specific experiments and observation data sources, which are critical tools for assessing e-scooter interactions with other road users.

In a similar vein, few studies discussed the e-scooter nonusers' experience. Developing comprehensive SLOS and, consequently, holistic

policy tools require a wide range of knowledge related to nonusers who could be potential users in the future. In addition, the young male overrepresentation of e-scooter usage is reported in previous studies. However, the underlying reasons for this finding and its potential impact on travel demand and future mobility equity have not been discussed in the available literature. Also, more dedicated studies are needed to evaluate the role of e-scooters in modal substitution and supplement. This fact is critical in identifying and implementing relevant policies from similar modes that contribute to the development of SLOS based on similar road user experiences.

Previous research has reported on e-scooter trip characteristics such as distance, duration, and place and time of prevalence. However, these findings could be more useful in practice if they were linked to user experiences in various circumstances such as peak hour, time and location of usage, and socio-demographic characteristics of non-users (users). Such information could be obtained by conducting dedicated surveys as well as taking into account usage patterns by open-source databases. This shortcoming in the literature could be connected to data collection approaches. Future research should be more focused on surveys, experiments, and observation to provide detailed user experience information that could be linked to trip characteristics.

The operation of e-scooter in each type of infrastructure, i.e. on– and off-road facilities, presents unique challenges for riders and future research to assess e-scooting experience is needed. Miss-parked e-scooters have affected the safety and comfort of road users in off-road facilities. However, little research has addressed this issue in relation to the use of e-scooters. Hence, more studies are needed to determine the reasons and solutions for e-scooter miss-parking behaviour. Furthermore, this issue is more serious for shared e-scooters because private ones are lighter and foldable, and users may carry them with them, minimizing the need for suitable parking facilities. Future studies should investigate how e-scooter (non)users behave differently depending on their ownership and membership status. All of which could help planners and policymakers for a smooth adaptation of e-scooters.

5. Towards a preliminary framework for developing SLOS

Theoretical and psychological frameworks are crucial bases for analysing travel behaviour and developing LOS indices (Heinen et al., 2011). Few theoretical frameworks such as technology acceptance theory and theory of planned behaviour have been applied in the previous research to analyse adaptation/acceptance of e-scooter usage considering the nascent stage of research on e-scooter (Eccarius & Lu, 2020; Kopplin et al., 2021). Yet, more fundamental knowledge and subsequently frameworks are needed to analyse e-scooter riding as a mode of transport. In this paper, we discuss the LOS and hierarchical level of driving/riding task frameworks to pave the way for the development of SLOS (HCM, 2010; Michon, 1985). A similar strategy has been suggested in the literature to develop e-bike LOS (Kazemzadeh and Ronchi, 2022). Fig. 2 presents the suggested workflow for developing a preliminary framework for SLOS.

In this section, we walk through each step of the workflow and briefly discuss how these steps lead to developing SLOS.

5.1. Step 1: Dimensions of the LOS concept

As discussed in the introduction section, LOS is a method to translate users' experience to planners and policymakers and contribute to adopting policies accordingly. Different dimensions could be derived from LOS and here possible dimensions that are useful for developing SLOS are discussed:

5.1.1. Level of analysis

Three levels of analysis are defined for LOS: planning and preliminary engineering analysis, design analysis, and operational analysis. The planning level mainly concentrates on future scenarios and sets of alternatives that should be rapidly assessed. In the design phase, the established procedures (by HCM) are applied to determine the necessary characteristics of transport facilities. The operational level primarily deals with current or near-term situations (HCM, 2010). Furthermore, these steps could be associated with the strategic, tactical, and operational driving/riding task framework levels, respectively (Michon, 1985). The distinction of these levels is vital for developing respective indices. Also, an index can be developed depending on several factors such as the research purposes, availability of data, and development of literature for the underlying mode.

5.1.2. Transport components

The experience of road users is different when they travel through a different component of infrastructure (e.g. link and node) as they need various navigation behaviour, mental demand and consequently travel experience. For example, the rider/driver tasks are unique on an intersection (e.g. stop and go) compared to a link (e.g. maintaining speed, overtaking). Hence, previous LOS indices are specified based on the type of transport component to depict the user's experience in different transport facilities realistically.

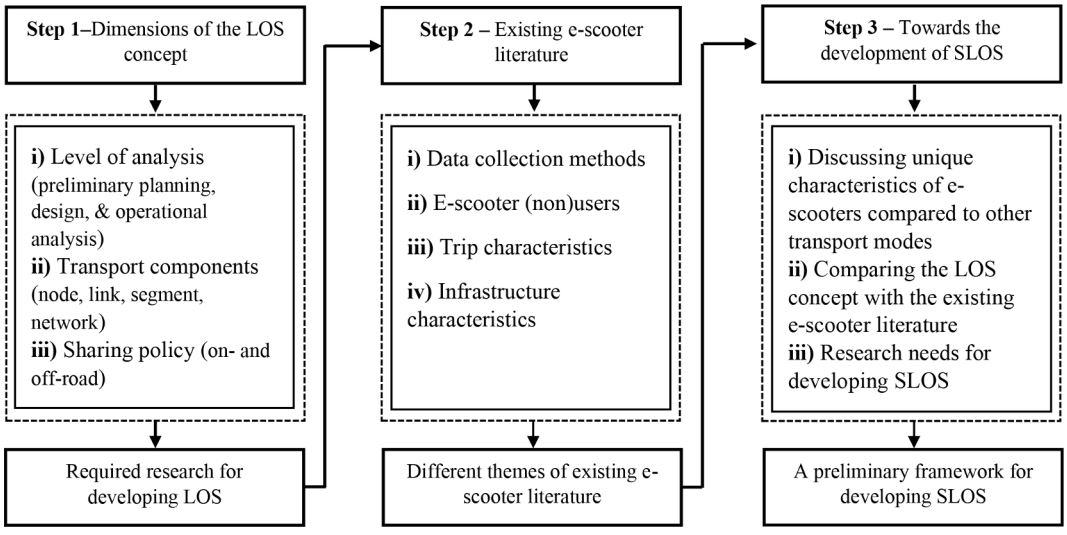

Fig. 2. Workflow for developing the preliminary SLOS framework.

5.1.3. Sharing policy

Active modes (e.g. cycling) are operated in both on– and off-road facilities. Several variables such as the types of road users, infrastructure characteristics, and traffic regulations (e.g. speed limit) are different in on– and off-road facilities. Therefore, the experience of road users is different in these facilities. This means that based on the sharing policy of infrastructure, specific variables are representative of the user's experience. Reporting LOS based on sharing policy of infrastructure has a long history in the transport community, especially for active mobility. For example, different studies separately estimated bike LOS for off-road (Botma, 1995) and on-road (Sorton and Walsh, 1994) facilities. This argument applies to developing SLOS as they operate in both on– and off-road facilities.

5.2. Step 2 – Existing e-scooter literature

In this section, we discuss the existing themes of the literature based on the aforementioned dimensions of the LOS concept.

5.2.1. Data collection methods

The shared e-scooter usage data has been extensively used in the previous studies as the shared service could be considered a dominant type of using e-scooters. However, surveys, observations, and experimentation have been conducted to a fewer extent. Leveraging on the knowledge of similar LOS studies, surveys and observations have been used to develop bike LOS indices. Also, for emerging modes such as e-bikes, experimentation and simulation models have been suggested in the literature to depict road users' experiences (Kazemzadeh and Bansal, 2021a,b).

5.2.2. E-scooter (non)users

E-scooting experience, users' socio-demographic characteristics, and trip purposes partly describe the type of e-scooter users. Having fun and enjoyable trip of electrically-assisted riding have been highlighted as reasons to use e-scooters, which is similar to e-bikes (Kazemzadeh and Ronchi, 2022). Previous studies specified the frequent type of e-scooter users (e.g. male and well-educated). Also, e-scooter both substitute and supplement other transport modes.

5.2.3. Trip characteristics

This category includes place and time of prevalence, trip distance, and navigation characteristics of e-scooters. The first two topics have been extensively reported in the literature as several studies are based on the data of shared e-scooters, and this information could be retrieved from such data. However, few studies elaborated on the navigation characteristics of e-scooters (e.g. analysing passing and meeting events). Considering developed LOS indices in similar fields, the quality of (e) bike-pedestrian interactions have been used as a basis for developing LOS indices.

5.2.4. Infrastructure characteristics

The development of a LOS index could be based on transport components and infrastructure sharing policy (see Step 1). Different types of information, such as the preference of e-scooter riders for cycling infrastructure and speed profile on infrastructures, have been studied in the literature. The issues related to trip-end facilities (e.g. parking) have also been discussed in the literature. For example, the miss-parked e-scooters could affect the QOS for all road users in a transport facility.

5.3. Step 3 – Towards the development of SLOS

In order to propose a preliminary framework for developing SLOS, we first briefly compare the unique characteristics of e-scooters with other transport modes. Next, we map the existing e-scooter literature (Step 2) against the concept of LOS (Step 1) to identify knowledge gaps and research needs for future SLOS studies, all of which shape a preliminary framework for developing SLOS.

5.3.1. Unique characteristics of e-scooters

Due to their specific characteristics, it might be challenging to classify e-scooters as active or motorised transport modes. First, the rider needs to stand up to operate e-scooters which is a sort of active behaviour. However, e-scooter riders do not need any other physical activity for riding (except a few kicks to start the trip), which is similar to motorised vehicles. This feature makes e-scooters different from even similar modes such as e-bikes (pedelec) which the riders still need pedalling effort to ride an e-bike. Second, the size and shape of e-scooters are different from both active and motorised mobility. It is similar to (e)bikes as it does not have a protection body and makes it a vulnerable transport mode. However, the riding posture of e-scooting is different from both cycling and using cars. Third, riding characteristics of e-scooters such as speed, acceleration, and deceleration are unique compared to other transport modes. This means that e-scooter riders would have a different navigation experience than other transport modes. Forth, LOS is historically reported based on each mode of transport and this way of estimating LOS is recommended by HCM (HCM, 2016). All in all, the unique characteristics of e-scooters call for an *ad hoc* framework for developing SLOS.

5.3.2. Comparing the LOS concept with the existing e-scooter literature

The existing literature is compared with the concept of LOS via the aforementioned LOS dimensions (this argument is detailed in Appendix 2). Most studies have been conducted in the first two phases (planning, design, and operational analysis, respectively). These analyses include modal substitution analysis, understanding socio-demographic characteristics of riders, and trip distance. Regarding the analysis based on the transport components, few studies analysed the riding characteristics of e-scooters in different infrastructures such as sidewalks and bike lanes. Furthermore, few studies specifically discussed the e-scooter users experience based on the sharing policy of infrastructure. For example, trajectory data was used in a study to compare the mean speed and prevalence of e-scooters on off- and on-road facilities. Yet, the existing literature suffers from a lack of a consolidated framework to systematically evaluate the e-scooter riding experience in different infrastructures.

5.3.3. Research needs for developing SLOS

Based on the previous steps, we suggest some research directions for developing a possible SLOS index (see Fig. 3). In the first step (left column), we suggest different approaches adopted from other LOS research domains with applications for developing SLOS. For instance, the concept of hindrance has been successfully applied to evaluate the interaction of bikes with pedestrians. We suggest that this method be adopted for the evaluation of e-scooter and pedestrian interactions. This argument is extended for other examples, such as behavioural approaches and capacity analysis. Next, we summarise the unique characteristics of e-scooters (the middle column). These unique characteristics of e-scooters should be considered in developing future SLOS indices. Finally, we present the possible research strands towards the development of SLOS. In the first scenario, the previous framework analysis of the hindrance concept for bike-pedestrian interaction should be repeated, calibrated, and validated for e-scooters. This is because that e-scooters adopt different riding characteristics (e.g. speed, acceleration, and deceleration) compared to bikes and e-bikes. This process is useful for assessing how the well-established literature of cycling research could evolve to develop future SLOS indices. In the second scenario, we envision that capacity analysis of bike lanes, sidewalks, and curb lanes should be performed in the presence of e-scooters. This is due to the fact that the size, shape, and riding characteristics of e-scooters are different from other transport modes. These factors affect the capacity of infrastructure and, eventually, the riding experience for all road users. In the last phase, we emphasise that the socio-demographic characteristics of

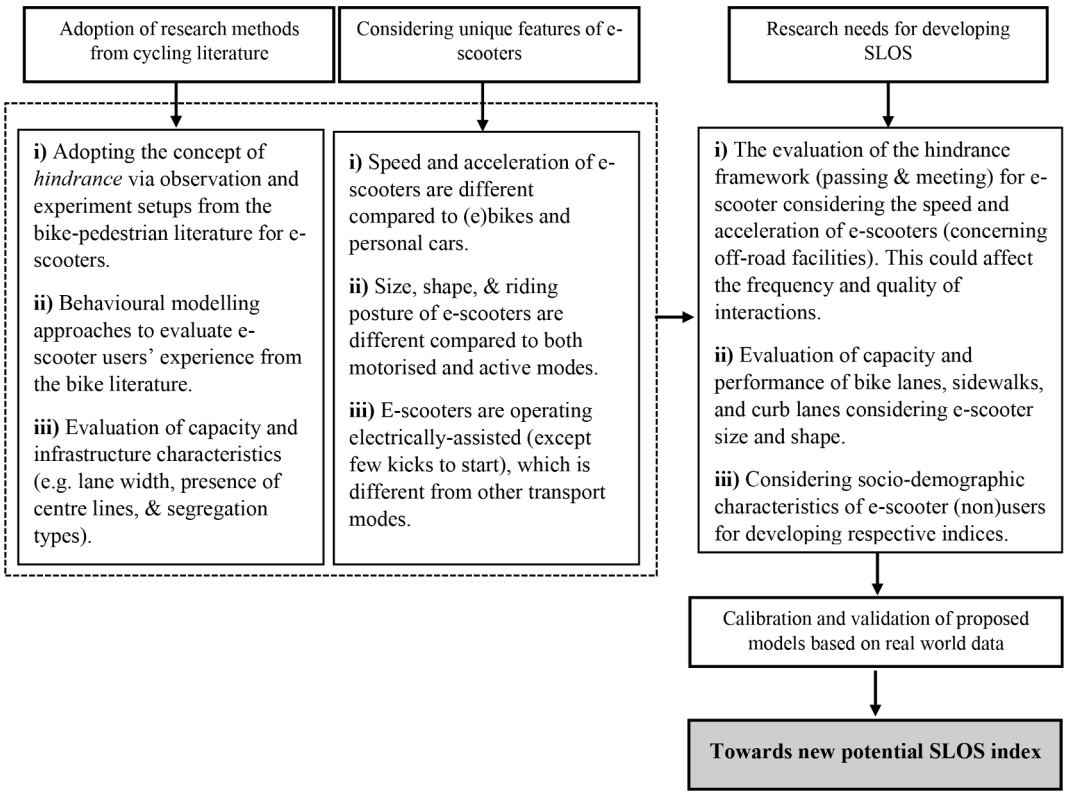

Fig. 3. Hypothetical framework towards the development of SLOS.

e-scooters should be considered in the development of future SLOS. For example, several studies reported that e-scooters are a male-dominated transport mode and are mainly used by young and well-educated people. This point is essential as the SLOS index should reflect both characteristics of users and nonusers. If only the existing literature considered for developing indices, minority groups would be neglected, and the developed SLOS would not be representative for all spectrums of society. Hence, it is crucial to consider the socio-demographic characteristics of (non)users in the SLOS indices.

Fig. 3 represents a summary of the suggested steps towards the development of SLOS. We exclude the details and description of steps (e.g. levels of the LOS analysis) in Fig. 3 for brevity, and the details of the steps are positioned in Appendix 2. It should be noted that both Fig. 3 and Appendix 2 are hypothetically suggested, and future research could help to make it a more practice-ready framework.

6. Concluding discussion and outlook

The rapid usage of powered micro-mobility (e.g. e-bikes and e-scooters) worldwide has highlighted the importance of systematic approaches to managing the demand of these new mobility approaches. E-bikes have been suggested as one of the fast-growing markets in the transport domain over the last decades (Fishman & Cherry, 2016). In a similar vein, e-scooters have bloomed since their introduction in 2017. For example, in 2018, 38.5 million trips were conducted by e-scooters in the US, which is the highest among all types of micro-mobility (Younes et al., 2020). In addition, the unprecedented COVID-19 pandemic and the restriction to the use of public transport could increase the ridership of both e-bikes and e-scooters in peri- and post-pandemic situations (Jenelius & Cebecauer, 2020; Kazemzadeh & Koglin, 2021). Hence, there is a dire need to scrutinise the user's experience of this type of mobility.

The assessment of the literature provides evidence that the number of publications in the e-scooter research is increasing. The usage pattern, trip distance, trip purpose of e-scooters were the predominant themes of the previous research. Open-access databases from companies that operate shared mobility have been widely used in the literature to analyse the pattern of usage and travel characteristics of e-scooters.

Analysing previous literature suggests that e-scooter is a male-dominated mode of transport, and users are relatively young and well-educated. These results need further investigation to assess the underlying reasons and eventually improve the usage of e-scooter for a broader range of users to improve transport equity across the gender. Also, several studies in the literature are based on shared e-scooters data (renter), and few studies (based on surveys) have discussed the e-scooter owners' preference. More research is needed to evaluate the users' experience of privately-owned e-scooters considering e-scooter as a mode of transport.

Based on the findings of this study, several research gaps remain to be addressed. First, it is essential to study e-scooter travel demand, specifically its impact on modal substitution and supplement. This body of research would contribute to the multi-modal management of mobility. Next, the practice of e-scooters in existing infrastructure requires more in-depth analysis. For instance, the capacity of sidewalks and bike lanes alters by the presence of e-scooters, and therefore, it affects all road users' experience. Thus, there is a need to evaluate the existing infrastructure functionality and rethink innovative solutions to improve the e-scooting experience.

Furthermore, traffic characteristics of e-scooter riding need to be taken into account. This series of analyses could range from analysing the fundamental relationship of e-scooter traffic flow to the analysis of e-scooter interaction with other road users. Considering the different speed regimes of e-scooters and pedestrians in off-road facilities (among other types of micro-mobility), the analysis of e-scooter-pedestrian interaction seems to have a high priority. Moreover, sharing policy of e-scooters needs to be further studied. For instance, different issues such as miss-parked dockless e-scooters have caused inconvenience for road users and consequently influenced their trip experience. This issue could

be reflected and addressed in future SLOS studies (e.g. tactical level) by allocating proper trip-end facilities for e-scooters. Also, the geographical spread of research calls for more e-scooter research in Asia, and Western Europe, specifically in Scandinavian countries (considering their high e-scooter ridership) to ease the adoption of e-scooters in these regions.

The bottom line is that e-scooters should be treated as a unique mode of transport considering their unique travel behaviour and ridership impact on mobility. This requires political movement (e.g. financial supports and regulations) and extensive consideration from the research community to converge research and practice to evaluate and improve e-scooter users' experience.

This research inevitably has a couple of (de)limitations. First, we have not explicitly discussed the methodological limitations of the reviewed studies. Also, we excluded the traffic safety issues of e-scooters which could also be related to users' experience. This (de)limitation is due to extensive safety literature of e-scooters which makes it impractical to be included in one paper. Besides, traffic safety is historically excluded from the previous micro-mobility LOS analysis. The presented number of publications and most referred journals are bases on literature search protocol, and the findings do not represent the status of the entire e-scooter research domain. The arguments through this paper mainly support the role of e-scooter in the transport domain, and the challenges facing the environment are not discussed. The arguments mentioned above may drastically impact future decisions towards the adaptation of e-scooters and should be exclusively studied. Moreover, the lack of quantitative data and considering the nature of systematic review studies limit us to provide a more practice-ready framework. This limitation opens new avenues for future research in the e-scooter research domain.

Finally, we envision two avenues for future review studies. First, safety concerns of e-scooting should be exclusively reviewed and discussed. This research theme is rapidly progressing, and a review study to converge literature contributes to improving riders' safety. Second, the methodological limitations of the previous studies should be further assessed and discussed. This theme could elaborate on the applied data collection and data analysis methods to demonstrate the strengths and weaknesses of the used methods in the literature.

CRediT authorship contribution statement

Khashayar Kazemzadeh: Conceptualization, Methodology, Investigation, Writing – review & editing. **Frances Sprei:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition, Supervision.

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Appendix

Appendix 1 A summary of the characteristics of micro-mobility.

Features	Bikes	E-bikes	Moped	E-scooter (rental and private)	E-wheels & E-boards
Schematic view[1]					
Average speed (km/h)	15	25	25–45	25	NA
Mandatory driving licence	NA	NA	x	NA	NA
Riding facilities	On– & off-roads	On– & off-roads	On-road	On– & off-roads	On– & off-roads
Riding posture	Sitting	Sitting	Sitting	Standing up	Standing up
Physical effort	x	x	NA	NA	NA
The availability of LOS indices	x	x	x	NA	NA

Note: Information provided in this table, such as average speed and the usage of different types of facilities (i.e. on- and off-road facilities), could be different based on geographical settings and applied rules and regulations. NA (not available or not applicable).

[1]Sources of pictures: bike, e-bike, moped, e-board, and private e-scooter (https://www.biltema.se), rental e-scooter (https://www.voiscooters.com), e-wheel (https://www.robotexperten.se).

Appendix 2. Towards the development of SLOS

Table A1 represents the required information for the development of SLOS. In the first stage, the level of analysis is discussed. More specifically, three levels of analysis, namely: strategic, tactical, and operational phases, shape the framework's structure (HCM, 2010). These levels could also be seen both as time-, scope- and task-based levels. For instance, the planning and preliminary engineering analysis phase refer to the strategic level of analysis. This level is laid out at the first level. It deals with strategic and long-term themes - *initial problem identification* – which potentially deals with travel demand management, assessment of policies, and future LOS. The second level (third column) contains design analysis associated with mid- to long-term analysis. This level includes tasks analysis such as estimating the required width of sidewalks, lanes, auxiliary lanes. The required data is

mainly detailed at this level and could be allocated for design purposes. The operational level of analysis is positioned in the last column of the framework. This level of analysis is based on a current situation and is related to near and short-term analysis. This level analysis is deemed to feed analysis to decide the need to improve existing facilities such as signal timing, lane configuration, and evaluation of bike lanes.

The comparison of the LOS concept and existing literature yields the required information for the development of SLOS based on different levels. Considering the relatively new existence of e-scooters, all levels of analysis require further research. More specifically, the travel demand of e-scooters considering their substitution and supplement scale for other mobility types requires more attention and detailed analysis (strategic level). The unprecedented COVID-19 *peri*-pandemic and its impact on travel demand could be beneficial to be considered in this level of analysis. Moreover, more research is needed to analyse policies related to the smooth adoption and integration of e-scooters into transport planning. Lack of uniform policies/regulations and the relatively easy navigation of e-scooters allow them to be operated in both on– and off-road facilities. This consideration needs to be reflected in the design level of analysis (tactical level). For instance, the capability of bike lanes to accommodate e-scooters should be reanalysed, and possible alternative design solutions could be proposed to meet the high demand for e-scooters. Also, the interaction of e-scooter with other road users (e.g. pedestrians and cyclists) has not been extensively studied in the literature. The analysis of the frequency and quality of passing and meeting is needed specifically to develop SLOS in off-street facilities. It would provide information related to the user's experience and fundamental traffic relationships.

Furthermore, developing methodologies to assess the SLOS based on the existing facilities could be insightful to prioritise facilities with immediate improvement. Compared to strategic and tactical-level of analysis, there has been no research on the operational level of analysis for e-scooters. In sum, more comprehensive research in the tactical and operational levels is needed to develop SLOS. The adopted methods such as the concept of *hindrance* for the analysis (e)bikes and pedestrians could be used as a foundation for further developing future SLOS indices, specifically in the tactical level of analysis.

Table A1. The comparison of the existing literature with the required information for the development of SLOS.

Research themes/status	**Level of analysis**		
	Preliminary engineering analysis	**Design analysis**	**Operational analysis**
Time/task level	-Strategic level -Long-term analysis	-Tactical level -Mid/long-term analysis	-Operational level -Short-term analysis
LOS & Driving/riding task analysis	-Initial problem identification -Future conditions -The general planning stage of a trip -Modal choice -Trip cost	-Lane width -Sidewalk width -Passing & meeting -Obstacle avoidance	-Controlling oversaturation -Controlling LOS -Automatic action patterns
Existing literature	-Modal substitution analysis -Socio-demographic characteristics of users -Usage patterns & hot spots -Trip distance	-E-scooter interaction with pedestrians -Navigation characteristics based on infrastructure types	-NA
Research needs	-Understanding the future ridership and its impact on travel demand -How e-scooters could assist the mission of sustainability -How to consider e-scooters in the planning of infrastructure -A precise analysis of modal substitute/supplement by e-scooters	-Comfortability analysis of infrastructure for e-scooters -Sidewalk/bike lanes capacity analysis for the accommodation of e-scooters -Analysis of e-scooter interaction with other vulnerable road users -Understanding the impact of trip-end facilities	-Controlling the SLOS for on- and off-road facilities -Controlling the capacity of infrastructure -Controlling SLOS based on the combination of road users
Applications	-Support planning decisions -Propose systemic policies -Demand management	-Design or modify a facility for an envisioned SLOS	-Aiding practitioners to manage e-scooter facilities -Analysis of alternative solutions

Note: the LOS and driving/riding task information is retrieved from HCM, 2010 and Michon, 1985. Please note that the information provided in the framework does not reflect all details of the frameworks mentioned above, and it is mainly tailored for the development of SLOS.

Appendix 3. Summary of previous e-scooter studies

Author(s) (Year)	Geography	Central theme	Data/collection	Data analysis	Main conclusions or recommendations
Noland (2021)	The US	Usage pattern (focuses on weather conditions)	Open-source databases	Prais-Winsten, Negative Binomial regressions, and Random Forest model	The findings suggest that all types of micro-mobility are sensitive to adverse weather conditions, which cause a decrease in their ridership. However, among all types of micro-mobility, e-scooter usage is less sensitive to poor weather conditions.
Huo et al. (2021)	The US	Usage pattern (focuses on built environment)	Open-source databases	Multilevel Negative Binomial regression	The findings show that university campuses and central business districts are the areas with high e-scooter ridership.
De Ceunynck et al. (2021)	Four European countries	Usage pattern (focuses on willingness to use)	Survey	Logit model	The usage of personal mobility (including e-scooter) could be related to cycling facilities. As an example, cyclists who perceive obstacles (e.g. physical effort, sloppy road) in cycling are more prone to use e-personal mobility.
Reck et al. (2021)	Switzerland	Usage pattern (focuses on modal choice)	Open-source databases	Choice modelling	The results suggest that the users prefer dockless e-scooter during off-peak hours while they choose docked e-bikes during peak hours. Also, the modal choice is complex and influenced by distance and time of day.
Kopplin et al. (2021)	Germany	Usage pattern (focuses on consumer acceptance)	Survey	Structural equation modelling	E-scooter is mainly considered an entertainment device. The substitution of cars by e-scooters is weakly supported by this study and can only be supported for short-distance trips.
Cano-Moreno et al. (2021)	Spain	Usage discomfort (vibration analysis)	Simulation	Multiple regression	The findings suggest that a speed of 16 km/h is a threshold of being uncomfortable for a regular e-scooter rider in a very good pavement condition, while 23 km/h speed is harmful to riders in a similar situation (short-distance trips).
Almannaa, Ashqar, et al. (2021)	The US	Usage pattern (focuses on modal speed)	Open-source databases	Multi-objective clustering algorithm	The average speed of e-scooters is less than e-bikes. Also, e-scooters and e-bikes have a similar and different average speed pattern over the days of the week and the hours of the day, respectively.
Ko et al. (2021)	Korea	Usage pattern (focuses on usage intention)	Survey	Logistic regression	For shared mobility (including e-scooters), socio-demographic characteristics of users such as gender, car ownership, and education impact the usage intention.
M. Lee et al. (2021)	The US	Usage pattern (focuses on modal substitution)	Open-source databases (survey)	Regression model	The results show that e-scooter could substitute carpools, cycling, taxi trips, and trips to access public transport. Carpool trips have the highest potential to be replaced by e-scooters.
Aman et al. (2021)	The US	Satisfaction analysis	Review of apps	Topic modelling & logistic regression	E-scooter is a male dominate mobility. Females seem to be more satisfied by services and show a more positive impression of the e-scooter usage compared to males.
Hawa et al. (2021)	The US	Usage pattern	Open-source databases	Regression models	The presence of bike lanes and bike-share stations increase the probability of e-scooter usage. Also, areas with high density and activities are associated with more use of e-scooters.
H. Lee et al. (2021)	Korea	Usage pattern (focuses on willingness to use)	Survey	Logit models	The findings could be clustered based on commuters and fist-last-mile trip users. The findings suggest that the trip purpose and preference could be varied based on the socio-demographic characteristics of users and the quality-of-service of public transport.
Christoforou et al. (2021)	France	Usage pattern	Survey	Logit models	The usage of e-scooter is mainly associated with male, young, and well-educated people. The main contributing factor to the use of e-scooter are saving travel time, money and playfulness of travelling by e-scooters.
Almannaa, Alsahhaf, et al. (2021)	Saudi Arabia	Usage pattern	Survey	Regression Models	The study suggests that the lack of proper infrastructure is the main barrier to adopting e-scooters. Also, weather conditions and safety concerns are reported as obstacles to the usage of e-scooters.

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Author(s) (Year)	Geography	Central theme	Data/collection	Data analysis	Main conclusions or recommendations
Zhang et al. (2021)	The US	Usage pattern (focuses on infrastructure charactristics)	GPS (installed on e-scooters)	Recursive Logit (RL) model	E-scooter riders prefer short-distance and simple paths. Also, bikeways, on-way paths, multi-use paths, and tertiary roads are preferable paths for longer distance trips for e-scooter riders.
Baek et al. (2021)	Korea	Usage pattern (focuses on willingness to use)	Stated preference experiment	Logit models	E-scooter is a reliable mode of transport for the last-mile trip problem. Also, there are variations to choose the last-mile trip mode based on past experience with e-scooter and income.
Bai et al. (2021)	The US	Usage pattern (focuses on daily leisure activities)	Open-source databases	Difference-in-Differences regression modelling	The usage of e-scooters is mainly associated with dining/drinking, shopping, and leisure trip purposes. Also, there is high exposure of e-scooters in university campuses and downtowns.
Mitra and Hess (2021)	Canada	Usage pattern (focuses on the user's demand)	Survey	Logistic regression	Most participants would substitute walking and public transport trips with shared e-scooters. Also, the quality of walking and biking along with the street safety increase the probability of considering travels by e-scooters.
Reck and Axhausen (2021)	Switzerland	Usage pattern	Survey	Probit model	The users of shared e-scooters are mainly young, male and well-educated. The findings suggest that more females use shared e-scoters compared to shared bikes.
Riggs et al. (2021)	The US	Ridership policy	Online e-scooters policy documents	Descriptive statistics	The study suggests that equity policy should be considered as a requirement in the practice of e-scooters, and the efficiency of this policy should be monitored. Also, pilot programs of e-scooter practices are suggested to match goals and objectives.
Nikiforiadis, Paschalidis, et al. (2021)	Greece	Usage pattern (focuses on the user's attitudes)	Survey	Logit model	The e-scooter mainly substitute walking and public transport trips. Moreover, e-scooter is more attractive for males compared to females. Also, downtown has a high exposure of e-scooters.
Ma et al. (2021)	The US	Ridership policy	Online e-scooters policy documents	Chi-square test, principal component analysis and K-means clustering	The study suggests that more practical guidelines (quantitatively) should be introduced by municipalities that depict the performance of the e-scooter practice.
Zuniga-Garcia et al. (2021)	The US	Infrastructure characteristics	Trajectory data & infrastructure geographic information	Analysis of variance	The average speed of e-scooter riders on sidewalks is lower than other infrastructure types (e.g. bike lanes, and roadways).
Cao et al. (2021)	Singapore	Usage pattern (focuses on the efficiency of the short-distance trip)	Stated preference survey	Logit model	Based on various levels of transit inconvenience, the use of e-scooters is more likely when there is a higher level of transport indirectness, more connections, and more access-egress walking.
Moran et al. (2020)	Austria	Spatial variance in scooter geofences & Parking issues	Spatial distribution of geofences	Spatial analysis	The results indicate that the areas lack parking: close to parks, pedestrian corridors, and cultural institutions.
Zhu et al. (2020)	Singapore	Usage pattern (focuses on the Spatio-temporal heterogeneity of usage)	Shared e-scooter spatial information	Spatio-temporal analysis	The high demand for shared e-scooters is related to the place of attractions, metro, and university campuses. The sharing efficiency of e-scooter is reported better than the bike-sharing system.
Che et al. (2020)	Singapore	Users' attitudes	Experiment	Rating scenarios	E-scooter riders feel safer compared to pedestrians in mutual interactions. This could describe that pedestrians are more vulnerable compared to e-scooter riders in the case of interactions.
Bai and Jiao (2020b)	The US	Parking issues	Parking violation reports	Analysis of variance	Public spaces and sidewalks were the two primary places that violations were reported. Also, smartphone apps were the main method of reporting violence.
Laa and Leth (2020)	Austria	Usage pattern (focuses on owners and renters)	Survey	Descriptive statistics	Being young, male and well-educated are the three main socio-demographic characteristics that are associated with the predominant e-scooter users. Both e-scooter renters and owners could replace walking and public transport with e-scooter, while car trips could also be substituted by the latter.
Zou et al. (2020)	The US	Travel patterns	Web-scraping data	Descriptive statistics and exploratory analysis	The scooter riders are more interested in streets that are equipped with bike facilities (i.e. bike lanes). Also, e-scooters are reliable mobility for leisure trips.

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Author(s) (Year)	Geography	Central theme	Data/collection	Data analysis	Main conclusions or recommendations
Glenn et al. (2020)	The US	E-scooter users behavioural analysis	Survey	Descriptive statistics and chi-squared analysis	E-scooter could replace walking and public transport. The usage of e-scooter could have both positive (e.g. air pollution reduction) and negative (e.g. injuries) consequences.
Brown et al. (2020)	The US	Parking issues	Observation	Descriptive statistics	E-scooter and bike riders use the parking facilities when they are available. Providing additional parking facilities could contribute to the reduction of violations and safer sidewalks.
Gössling (2020)	Ten cities in the USA, Europe and Australia/New Zealand	Policy and regulations	News content	Qualitative content analysis	The practice of e-scooters in many cities has been done by trial and error process to explore the best practice. The study suggests some policy avenues for planners such as speed limit, the necessity of cycling infrastructure, and parking facilities
Tuncer et al. (2020)	France	Riding behaviour	Observation	Ethnomethodology and multimodal conversation analysis	This study shows the interaction of e-scooters with pedestrians. Also, different practices of e-scooters in crowded areas (e.g. how the rider dismount and walk) is discussed in this study.
Younes et al. (2020)	The US	Sharing system	Open-source databases	Negative-binomial regression	This study examines differences between the usage of dockless scooter-share and station-based bike-share systems, and e-scooters could substantially contribute to the mission of low-carbon mobility.
Sanders et al. (2020)	The US	Usage pattern	Survey	Chi2 and Kruskal Wallis tests	E-scooter is an appealing mode of transport for both males and females with a variety of socio-demographic characteristics. Also, the e-scooter is a convenient mode of transport to get to a destination faster than walking (and not driving).
Bieliński and Ważna (2020)	Poland	Usage pattern	Survey	Descriptive statistics	E-scooters are mainly used for leisure trip purposes. E-scooter riders are also younger than e-bike riders.
Caspi et al. (2020)	The US	Usage pattern	Open-source databases	Descriptive statistics & spatial econometrics	The usage of e-scooters is higher in the presence of cycling facilities and areas with high rates of employment. Also, commuting is not the primary trip purpose of e-scooter users.
Eccarius and Lu (2020)	Taiwan	Usage pattern	Survey	Factor analysis &Structural Equation Modelling	Understanding the sharing system of e-scooters and environmental values could indirectly affect the user's intention towards e-scooters.
Bai and Jiao (2020a)	The US	Usage pattern	Open-source databases	Negative binomial regression	City centre, proper transit accessibility, and higher diversity of land use could lead to the higher exposure of e-scooters.
McKenzie (2020)	The US	Shared mobility services	Open data websites	Watson's non-parametric	The usage of micro-mobility in specific conditions (e.g. peak hours, and in urban settings) is a faster mobility option than automobile trips.
McKenzie (2019)	The US	Usage pattern	Operator datasets	Cosine similarity	Bike-sharing systems have a substantial role in facilitating commuting trip purposes which is not the case for e-scooters.
James et al. (2019)	The US	Parking issues	Survey, Observation	Descriptive statistics	The issues regarding miss-parked e-scooters (e.g. blocking sidewalks) are analysed in this study. Also, the substitution impact of e-scooters (for a taxi, foot, bike, car and public transport) are discussed.

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