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From bike to electric bike level-of-service

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ABSTRACT

The evaluation of electric bike (e-bike) riders' perception of comfort can lead to a better understanding of user requirements. This can be performed through Level-of-service (LOS) studies. To date, the e-bike LOS (ELOS) concept is scarcely developed and research concerning e-bike travel behaviour characteristics is relatively sparse. In this paper, we use bike LOS (BLOS) studies as a foundation to identify the knowledge gap for ELOS. Along with BLOS, e-bike riding comfort and the distinction between bikes and e-bikes characteristics were scrutinised. Travel behaviour, and e-bike modal substitution research were also reviewed to provide a better picture of e-bike riders' requirements. Based on these domains, we propose a preliminary conceptual framework for the development of ELOS. The results suggest that there is a limited number of studies that whether explicitly evaluate ELOS or consider the e-bike in the BLOS analysis. Also, the extent of substitution of cars, public transport, and bikes by e-bikes can range from partial to complete replacement, thus potentially affecting ELOS developments. The specification of this substitution contributes to a deeper understanding of the ELOS concept in relation to the adaptation of LOS indices used for other transport modes. Finally, it appears evident that ELOS developments would require further research on e-bike interaction analysis in shared mobility in which vulnerable road users are present. The findings of this study help researchers and policy-makers assessing the knowledge gap in ELOS and provide them a preliminary conceptual framework for ELOS development.

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Electric bike; e-bike; level-of-service; quality-of-service; LOS; BLOS

1. Introduction

Electric bike (e-bike) is considered a more environmentally friendly mode of transport compared to the vehicles that consume fossil fuels. However, e-bikes also generate greenhouse gas emissions to a certain degree (Hung & Lim, 2020). E-bikes can be considered as the fastest-growing means in the transport market in several regions of the world, e.g. China and Western Europe (Fishman & Cherry, 2016). For instance, over 40 million e-bikes were sold in 2015 worldwide and the selling trends are projected to keep

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increasing (Salmeron-Manzano & Manzano-Agugliaro, 2018). It was estimated that the e-bike sale would rise to 130 million by 2025 and 800 million by 2100 (Jamerson & Benjamin, 2012). More information regarding the trend of e-bike markets can be found in (Hung & Lim, 2020). E-bikes have the power to improve and develop the role of the bike mode in urban transport systems (Rose, 2012) given their higher speed compared to bikes. However, their fast development introduces some challenges concerning its compatibility with the urban transport system (Lin, He, Tan, & He, 2008).

The speed regime for an e-bike could range from an average speed of 21.86 km/h to a maximum speed of over 30 km/h (Cherry & Cervero, 2007; Lin et al., 2008). Recent studies have reported that there are 2–9 km/h average speed differences between an e-bike and a bike (Baptista et al., 2015; Schleinitz, Petzoldt, Franke-Bartholdt, Krems, & Gehlert, 2017). This needs specific considerations in mixed facilities where e-bikes, bikes, and pedestrians may be present (Bai, Liu, Chan, & Li, 2017).

The navigation of e-bikes in mixed traffic including pedestrians is challenging since the speed regimes they adopt are quite different. Potential risk of conflict is present when considering sidewalks as a place to accommodate both modes. E-bikes are mostly classified as bikes and sometimes they are ridden in bike and pedestrian infrastructures. For example, US regulations on the use of bikes and e-bike on urban sidewalks range from this being illegal (Dill & Rose, 2012; Kang, Xiong, & Mannering, 2013) to fully permitted across the country. The impact of bikes on pedestrians' comfort in shared facilities could be also addressed via pedestrian Level-of-Service (Jensen, 2007; Kang et al., 2013).

On one hand, the assessment of Quality of service (QOS) is a way to illustrate how well a transportation facility works from a user's perspective. On the other hand, a level-of-service (LOS) index is a quantitative way of assessing performance, and in turn, it represents QOS through a measure. Performance measures that are used to define LOS are called "Service Measures". The LOS index generally presents the results through a letter scale, from A (best) to F (worst) condition (HCM, 2016). The concept of LOS is mainly reported based on each mode of transport. This way of reporting contributes to the assessment of multimodal facilities as mentioned by HCM (2016): "[...] Reporting LOS separately by mode also assists in assessing multimodal trade-offs when design options are evaluated [...]". This concept has been adopted for the cycling mode via an index able to aggregate the factors affecting user experience (Beura, Manusha, Chellapilla, & Bhuyan, 2018; Botma, 1995; Dixon, 1996; Epperson, 1994; Jensen, 2007; Mekuria, Furth, & Nixon, 2012; Petritsch et al., 2007).

In practical terms, LOS is a useful tool for stakeholders and transport planners to evaluate and improve facilities and infrastructures (Griswold, Yu, Filingeri, Grembek, & Walker, 2018). Existing literature reviews related to bike LOS (BLOS) show that limited research has been dedicated to e-bikes (see Table 1) and no dedicated studies have been found on e-bike LOS (ELOS).

With the growth of e-bike use across the world, dedicated indices for ELOS could be proposed, and existing LOS indices may need to be updated to be useful for ELOS studies. The main purpose of this study is to identify the knowledge gap for ELOS and provide insights into the development of ELOS indices. To address this issue, we propose a preliminary conceptual framework (including a checklist) for developing ELOS. This has been performed through the mapping of e-bike literature against existing BLOS literature and using the insights from travel behaviour and e-bike substitution research domains. The results of the study provide a potential practice-ready framework

Table 1. Previous review studies related to BLOS and e-bike.

Author(s) (Year)	Main focus	General theme	No. of References	Main conclusion(s) or recommendation(s)
Turner, Shafer, and Stewart (1997)	Bike	Review and summary of bike suitability criteria	21 ^a	Suitability criteria have been employed in the literature interchangeably – largely in the urban context. There is a dire need to specify the definition of bike suitability.
Allen, Roupail, Hummer, and Milazzo (1998)	Bike	A literature review of bike facility analysis	27 ^a	The review shows that there is an absence of comprehensive methods to be applied for bike facility operational analysis.
Taylor and Davis (1999)	Bike	Review of traffic operations, and facility design	67 ^a	It is recommended to develop a methodology to analyse mixed-use features of off-street facilities.
Asadi-Shekari, Moeinaddini, and Zaly Shah (2013)	Bike	Review of effective indicators for pedestrian and bicycle LOS	151 ^a	Pedestrians and bike riders are considered equivalent to motorised vehicles and they use shared facilities. The evaluation process is most complex and time-consuming and it may be difficult to relate it to the design process.
Fishman and Cherry (2016)	E-bike	Review of research on e-bikes	63 ^a	Research on e-bikes is inadequate. E-bike usage continues to grow, and more research is needed to provide the essential data to inform policy-makers and industry.
Salmeron-Manzano and Manzano-Agugliaro (2018)	E-bike	Review of e-bike world research trends	59 ^a	Demonstrating worldwide research development on e-bikes, and identification of its scientific domains.
Bourne et al. (2018)	E-bike	Review of the health benefits of e-bike use	17 ^b	E-bike use contributes to physical activity recommendations and increasing physical fitness. Future research could evaluate the long-run health impacts of using e-bikes.
Hung and Lim (2020)	E-bike	Review of history and development of e-bike	128 ^a	Besides the benefits of e-bike use, it presents challenges related to limited travel distance, safety, charging the battery, and battery recycling. To tackle these obstacles, the development of modern technologies is essential for increasing capacity and reducing battery weight.
Kazemzadeh, Laureshyn, Hiselius, and Ronchi (2020)	Bike	Review of bicycle LOS, bicycle flow, and comfort research domains	195 ^b	The heterogeneity of separated facilities due to the presence of e-bike needs more in-depth studies. Network-based LOS analysis has been studied to a lesser extent compared to node and link.

^aNo. of references of the manuscript.^bNo. of studies reviewed.

for implementing a new ELOS. To the best of the authors' knowledge, this is the first study that systematically looked into ELOS and reviewed the research domains related to the development of the ELOS concept.

2. Literature search protocol

Research literature was retrieved from the Web of Science and the Transport Research International Documentation (TRID) databases (<http://trid.trb.org/>). The goal was to

perform an extensive review of the different research domains variables that affect ELOS. The TRID database includes both the Transportation Research Information Services database and the OECD's Joint Transport Research Centre's International Transport Research Documentation database.

The database search was performed in November and December 2019. The same process was conducted again in February 2020 to include newly published articles. The search protocol included using the following terms: *level-of-service*, *LOS*, *quality-of-service*, *QOS*, *flow*, *comfort*, *convenience*, *easiness*, *travel behaviour*, coupled with the keywords *bicycle*, *pedelecs*, *electric-bicycle*, *electric-bicycling*, *electric-bike*, and *e-bike*. In order to retrieve the literature related to BLOS, the most recent review study (BLOS) by Kazemzadeh, Laureshyn, et al. (2020) was used. Citation search was also performed as a complementary tool to detect more topic-related studies. The search resulted in 1108 papers from the databases along with 195 records from the review by Kazemzadeh, Laureshyn, et al. (2020). After removing the duplicates, a screening strategy based on the PRISMA methodology (see Figure 1) was performed to identify the relevant papers (Moher, Liberati, Tetzlaff, & Altman, 2009). Inclusion criteria were related to the relevance to the development of ELOS indices. The material included only peer-reviewed English-language articles and scientific reports. BLOS studies that considered e-bike in their LOS estimation process were included. Pure e-bike flow research and the combination of e-bike flow with vulnerable road users (cyclists and pedestrians) were included as deemed relevant for ELOS development. Exclusion criteria related to studies examining environmental

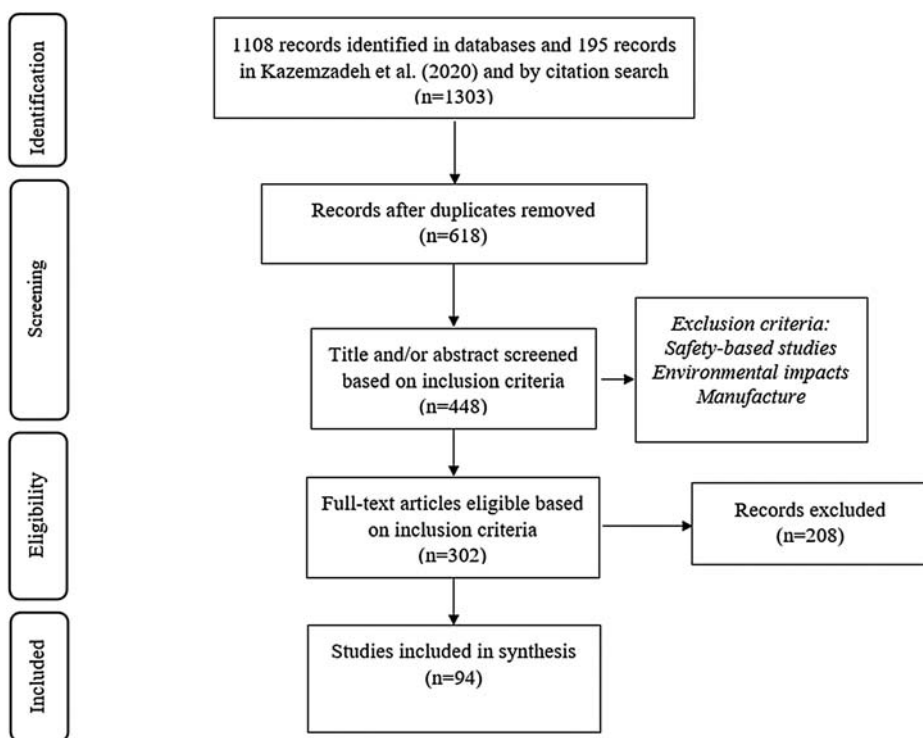


Figure 1. Protocol adopted for the database search and identification of relevant papers.

impact, manufacture, technical characteristics (e.g. e-bike batteries, motors, etc.), and safety of e-bikes. After screening the papers based on these criteria, the number of full papers reviewed was reduced to 94.

3. Workflow for ELOS development

In order to propose a preliminary conceptual ELOS framework, the BLOS studies are first explored. Then, e-bike comfort research is reviewed and thereafter, the differences between bike and e-bike characteristics are discussed. This set of studies were considered being the core research for ELOS development. Then, e-bike travel behaviour and modal substitution research were explored as performance and operation (complementary) domains to understand the characteristics of e-bike riders. Finally, based on the core and complementary domains, we proposed a conceptual ELOS framework. Figure 2 shows the workflow of the methodology.

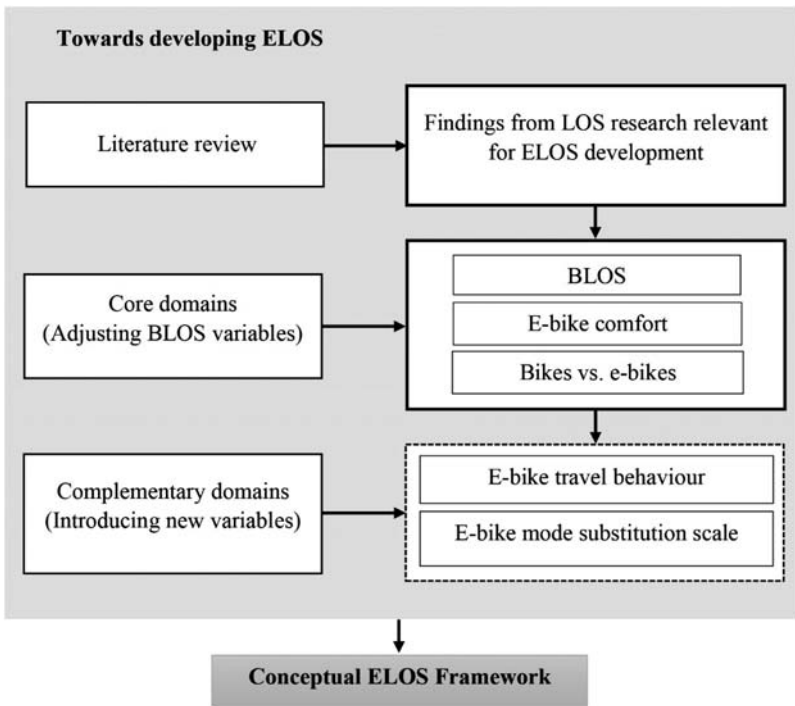


Figure 2. Workflow for the development of the ELOS conceptual framework.

4. Core domains for ELOS development

E-bikes and bikes have similar size and shape; however, the electric motor introduces differences in the e-bike performance function. An in-depth understanding of BLOS, reviewing existing literature on e-bike riding comfort, and exploring the distinction between bikes and e-bikes characteristics are the core step toward developing ELOS. In this section, different aspects of these core domains are discussed (Figure 2).

4.1 BLOS research

Over the last decades, the promotion of cycling and the identification of potential strategies to improve cycling infrastructure have been deeply investigated (Hong, Philip McArthur, & Stewart, 2020). After the first so-called systematic study on the evaluation of cyclist's facilities by (Davis, 1987), several other indices have been developed. The developed BLOS can be classified according to the transport component features they consider, such as:

- Link-based: bicycle stress level (Sorton & Walsh, 1994) and BLOS (Botma, 1995; Jensen, 2007), and BLOS for protected bike lanes (Foster, Monsere, Dill, & Clifton, 2015);
- Node-based: BLOS (Jensen, 2013), bicycle intersection safety index (Carter, Hunter, Zegeer, & Stewart, 2007), and QOS analysis for intersections (Beura, Kumar, Suman, & Bhuyan, 2020);
- Network-based: level of traffic stress (Mekuria et al., 2012), network evaluation for bike system (Klobucar & Fricker, 2007) and low-stress network connectivity (Lowry, Furth, & Hadden-Loh, 2016)

Another classification can represent BLOS based on sharing policy such as (HCM, 2016):

- On-street facilities: the facility is shared for motorised vehicles and cyclists. Examples of this facility are paved shoulders and buffered bike lanes.
- Off-street facilities: this includes an exclusive facility for cyclists, and a pathway where the facility is shared with pedestrians and other users (e.g. sidewalks).

Based on the aforementioned classifications, different variables are needed as input for BLOS (Fernández-Heredia, Monzón, & Jara-Díaz, 2014). The BLOS index with a precise set of variables reflects the complexity underlying the user's perception of comfort in bike facilities. As the concept of LOS is linked to transport comfort from the *user's perspective*, the range of the adopted variables is different based on the context of evaluation. On-street facilities (mostly link-based) were primarily evaluated in the BLOS field. For example, Sorton and Walsh (1994) developed the Bicycle Stress Level (BSL) for on-street facilities. They considered motor vehicle traffic volume, motor vehicle speed, and curb lane width as a proxy for BSL. Landis (1994) included the proportion of heavy vehicles, speed limit, pavement conditions, the frequency of access points, the intensity of land use, motorised traffic, number of lanes, and usable width of outside lane to evaluate perceived hazard risk. Off-street facilities have received more attention later in the BLOS field. Botma (1995) developed the Bicycle Level of Service (BLOS) for off-street facilities. The BLOS method is based on path width, user proportion (cyclists and pedestrians), user volume, and user speed.

Jensen (2013) developed a study to quantify cyclists and pedestrians' comfort in relation to different types of node features such as roundabouts, intersections, and crossings. He employed different variables e.g. length of crossing, traffic volume, waiting time for facilities, and width of roadways. Mekuria et al. (2012) developed a network-based index to evaluate the stress level of riding. The main variables in this model are the number of lanes, speed limit, and bike lane width (including other variables such as

the appearance of the centreline, etc.). More details on BLOS variables are provided by Kazemzadeh, Laureshyn, et al. (2020).

The motorised vehicle traffic characteristics are crucial variables in BLOS for on-street facilities. In contrast, the BLOS in off-street facilities is mostly based on variables related to the interaction of users given the absence of motorised vehicles (HCM, 2016). Chapters 16, 18, and 19 of HCM (volume 3, interrupted flow) discuss the BLOS for on-street facilities, while chapter 24 explores the characteristics of BLOS in off-street facilities. We have summarised the BLOS estimation process in different chapters of HCM based on the type of facilities *per se* (see Appendix 1). For instance, HCM (2016) introduced three main criteria in the methodology for estimation of BLOS in off-street facilities:

- The capability of keeping the optimum speed
- The frequency of passing (same-direction encounters) and meeting (opposite-direction encounters)
- The bike rider's freedom of manoeuvring

The methodology considered five variables for BLOS including active passing and meeting per minute, the width of the path, the presence of centreline, and delayed passing. The HCM methodology considers the effect of pedestrians, runners, inline skaters, cyclists (including children), and does not consider e-bikes (HCM, 2016). Also, there is no methodological process mentioned in HCM concerning level-of-service estimation exclusively dedicated to e-bikes. This fact also renders the lack of e-bikes consideration in the BLOS estimation process.

4.2 E-bike comfort research

The research into BLOS indices which consider e-bikes in the estimation process is quite limited. To date, no study was found that comprehensively and exclusively evaluates ELOS in any transport component. It might be because of the fact that in most cases finding a pure e-bikes flow is difficult. In contrast, two studies consider the mixed flow of e-bikes and other transport modes. Bai et al. (2017) carried out a study on a separated bike lane in China. The factors that significantly affect cyclists comfort were reported as the age of riders, the type and volume of two-wheeled vehicles, the width of mid-block bike lanes, the percentage of e-bikes and e-scooters in two-wheeled vehicles, the physical separation, the slope of bike lanes, the roadside access points, and the land use. They concluded that the e-bike and e-scooter riders compared to bike riders perceive poor comfort level. Also, the average level of perceived comfort by e-bike riders was lower than e-scooters. Liu and Suzuki (2019) developed the concept of e-bike applicability, based on the change of convenience due to the introduction of e-bikes. They compared the convenience of e-bikes with bikes and public transport from the perspective of travel time and physical energy expenditure. They defined the index in two spatial scales: community-wide scale and city-wide scale. They concluded that on a steeper road or with geographical obstacles, the e-bike is more applicable than bikes. Compared to public transport, in the area with a deficiency of public transport, the e-bike is applicable in large cities or local cities.

In addition to the LOS indices which consider e-bikes, some factors are associated with e-bike riding comfort and comfort in relation to other modes such as the inconvenience of

the public transport system and the convenience of using a car. In general, the specification of these variables' role is not clear, and most studies reported mixed results. In this section, the results are classified based on e-bike comfort variables, and the variables related to the (in)convenience of other transport modes.

4.2.1 E-bike riding comfort variables

The association of comfort variables with e-bike use was highlighted in the body of literature. For example, Ye, Xin, and Wei (2014) reported that the main boosting variables to use e-bikes are saving time, comfort, saving money, convenience and bus inconvenience. Plazier, Weitkamp, and van den Berg (2017b) conducted a study in the Netherlands and reported that participants are interested in certain features of e-bikes such as e-bike speed, ease of use, the enjoyable experience of assisted cycling, and being independent of public transport schedules. Wild and Woodward (2019) reported that e-bike could facilitate the situation in daily trips in which certain variables could influence the time reliability of cyclists (in presence of adverse weather e.g. wind or tiredness). They emphasised that e-bikes may contribute to providing higher satisfaction among users who generally travel by bike. MacArthur, Dill, and Person (2014) reported that an e-bike enables users to bike more often, perform long-distance trips, and increase the possibility of carrying more cargo with them.

Simsekoglu and Klöckner (2019) reported three contributing factors toward the use of e-bikes including self-image, health, and ease-of-use. These approximately correspond to the same effects regarding the user attitude, since e-bike usage leads to increasing health, improving self-image and function in lifestyle. Haustein and Møller (2016) grouped e-bike users into three different categories. First, enthusiastic e-bikers showed the most positive attitudes regarding e-bikes and mainly bought an e-bike to increase cycling. Second, utilitarian e-bikers used the e-bike particularly for practical purposes and travel time reduction. And thirdly, recreational e-bike riders were very positive about e-bike use but used it less regularly and mostly for long-distance recreational trips. Fyhri, Heinen, Fearnley, and Sundfør (2017) reported that those who cycle less are most interested in buying an e-bike. Prior knowledge of the e-bike (assessed by six questions) contributes to a higher chance of buying an e-bike. Also, the stimulus of using e-bike increases after having experience of an e-bike.

The importance of e-bike usage variables can be different based on the rider's age group. For instance, Van Cauwenberg, De Bourdeaudhuij, Clarys, de Geus, and Deforche (2019) investigated the reason for purchasing an e-bike among the elderly. They reported that the most common reason for using an e-bike was the lower physical effort required compared to a bike. They also indicated that travelling longer journeys is one of the significant effects of using an e-bike. Leger, Dean, Edge, and Casello (2019) focused on the potential characteristics of using e-bike as an independent means of transport among the older adult population. They indicated individual and structural factors that have a potential impact on e-bike adaptation, namely: increase of convenience, reduction of physical exertion, a decrease of reliance on a vehicle, and fun.

4.2.2 E-bike riding comfort variables in relation to other transport modes

The feature of being both human-powered and having electrical supports make e-bikes a transport mode which can compete with public transport. As an example, Wei, Xin, An,

and Ye (2013) emphasised that the over-standard e-bike (the speed and weight index exceed the standard value of China) is competing with the bike and public transport, and users are eager to cover longer travel distances with an e-bike. Xin, Chen, and Wang (2017) evaluated the travel behaviour of e-bike users based on prospect theory. They concluded that e-bike riders prefer to use the subway in long travel distances rather than e-bikes. Subway was reported to be more attractive for e-bike riders due to the low bus QOS. Weinert, Ma, Yang, and Cherry (2007) conducted a study to examine the effect of e-bike on travel behaviour, public transit, and safety. They concluded that an e-bike is a so-called remedy for users who are not well-served by public transport. Weinert, Ogden, Sperling, and Burke (2008) studied the future vision of electric two-wheelers and electric vehicles in China. Their reported crucial factors for the development of this market are improvement in battery technology, gasoline-powered motorcycle bans, decrease in the enforcement of these vehicle standards, and decreasing public transport quality-of-service. Fitch and Handy (2019) evaluated the possibility of using e-bikes among employees currently driving or carpooling to the university. They reported that the possibility of theft and the cost of an e-bike are the two important barriers for those who have used an e-bike.

Sharing patterns could lead to improve the use of e-bikes and reveal more details about the user's perception of comfort. Ji, Cherry, Han, and Jordan (2014) simulated (Monte Carlo simulation) the user demand and system availability for an e-bike sharing system. They considered three main variables, namely distributions of trip rates, trip lengths, and trip durations with consideration of supply parameters such as e-bikes numbers, number of swappable batteries, and battery recharging profiles. They concluded that trip duration is the most critical factor for e-bike and battery availability, trip rate, and then trip length, respectively. Campbell, Cherry, Ryerson, and Yang (2016) reported that the choice of the e-bike share is positively related to the need to cover long distances, high temperatures, and poor air quality while precipitation is reported as a negative factor. He, Song, Liu, and Sze (2019) conducted a study to evaluate user characteristics and travel behaviour factors associated with an e-bike sharing system. They reported the variables that affect demand for e-bikes such as weekends, summer periods, high pollution density, and proximity to public transport hubs, recreational centres, and bike trails positively. They also indicated that weather-related factors such as temperature and wind speed strongly affect e-bike share usage (e.g. high temperature and low-speed wind lead to higher expected e-bike's ridership)

4.3 Bike vs. e-bike

E-bikes can be classified based on different criteria such as power, speed, and design. The provided power of e-bikes can be classified into three types including pure e-bikes, power-assisted e-bikes (pedelecs), and the combination of the pure and power-assisted types. In the pure type, the rider does not need the pedalling and the power is transferred from the battery to the motor by the user controls of the handlebar throttle. Power-assisted e-bikes (pedelec) are a human-electric hybrid type that helps the rider when pedalling. This type is equipped with a sensor to measure the pedalling speed and force or both of them (Muetze & Tan, 2007). The combination of pure and power-assisted types is considered as the third type. In this type, the driving power of the e-bike can be

controlled either through the handlebar throttle (for the pure type) or it is a combination of rider and motor power (for pedelecs) (Hung & Lim, 2020). The European Commission also classified e-bikes based on speed and motor power including powered bikes and moped as the two main categories of throttle-controlled e-bikes. The powered bike has speed <25 km/h, and the motor power <1000 W, while moped has a speed range between 25 and 45 km/h and motor power of 1000–4000 W. The *Speed-pedelecs* (S-Pedelecs) require pedalling and can reach speeds over 32 km/h. S-Pedelecs are also classified as mopeds. Also, there is a wide range of commercial design of e-bikes in the market. They mainly range from bike-style e-bikes to scooter-style e-bikes (Fishman & Cherry, 2016).

The embedded battery and motor make e-bikes frame heavier than bikes. The provided power of e-bikes enables riders to reach higher speed. As e-bikes require less pedalling effort compared to bikes, the riding characteristics differ from bikes. For instance, e-bike riders can more easily plan for long-distance trips as they need less physical effort. In fact, as one of the crucial differences between bike and e-bike trips regard the case of the utilitarian trip purposes. This feature places e-bikes as a transport mode for commuting purposes which can compete with the motorised vehicle (e.g. public transport). These differences render the importance of complementary research domains such as travel behaviour and modal substitution for providing more insight into the development of ELOS. Simultaneously, the ability to change and regulate the provided power of e-bikes and switching from an e-bike to a bike can make it attractive for recreational trip purposes. These e-bike characteristics which easily can be adopted for different trip purposes make the evaluation process of riding comfort complex. Speed has been considered as a main indicator in previous BLOS studies and an in-depth understanding of the influence of speed in riding comfort is crucial for ELOS development.

Different speed regimes of vulnerable road users reinforce the importance of understanding the microscopic characteristics of riding (Alsaleh & Sayed, 2020; Zheng, Sayed, & Guo, 2020). However, there is limited knowledge about the microscopic navigation of bike and e-bike traffic. This knowledge deficiency leads to a lack of tools to design and evaluate the cycling system (Hoogendoorn & Daamen, 2016; Mohamed & Bigazzi, 2019). Most methods and theoretical frameworks in the flow of active transport modes are borrowed from motor vehicle flow and pedestrian dynamics (Zhang et al., 2014). Bike flow is different from motor vehicle flow, as characteristics such as speed, acceleration, and deceleration are imposed by the rider's physical characteristics (Twaddle, Schendzielorz, & Fakler, 2014). LOS discussions are often considered in the basic flow studies (Botma & Papendrecht, 1991; Navin, 1994). For example, Botma and Papendrecht (1991) stated that the mean speed evidences the QOS only when the mean speed alters with volume. Navin (1994) carried out an experimental study on single-file bikes to evaluate bike performance and claimed that the BLOS should be defined by considering the space around a bike.

After the early flow studies, Botma (1995) introduced the *hindrance* concept as a new method to estimate BLOS in off-street facilities. The hindrance concept can be used to quantify interactions or manoeuvres of road users and consequently estimate BLOS. This concept is important as it can be used as a proxy of interactions among different modes (with different speed regimes) in shared mobility. More details and references on hindrance (including the adoption of the hindrance concept as a proxy for

interactions), bike flow, and associated overtaking mechanisms can be found in Kazemzadeh, Laureshyn, et al. (2020). It is also worth pointing out that flow data can be collected in different manners (e.g. under laboratory or naturalistic conditions), thus the comparison of data should consider this issue while evaluating their validity and use (Lipinski & Nelson, 1974).

In heterogeneous traffic, overtaking chances increase in relation to the increase in the proportion of e-bikes, taking into account that the higher speed requirement should be satisfied by overtaking. Chen, Yue, and Han (2018) reported that widening the bike lane and applying a speed limit could lead to a lower frequency of overtaking issues on mixed moped and bike shared facilities. Li, Zhou, Nan, Wang, and Chen (2017) conducted a study in China and concluded that e-bike riders in mixed flow need more lateral space for safe riding. Mohammed, Bigazzi, and Sayed (2019) conducted a study to evaluate the cyclists' manoeuvres based on the following and overtaking interactions. They classified overtaking into initiation, merging, and post-overtaking states. Schleinitz et al. (2017) compared the speed of bikes, pedelecs, and S-pedelecs through a naturalistic study. They documented that e-bikes reach higher speeds than bikes and participants aged over 65 years rode significantly more slowly than younger participants. Kazemzadeh, Laureshyn, Ronchi, D'Agostino, and Hiselius (2020) conducted a controlled field experiment and applied the hindrance concept to quantify e-bike navigation in pedestrian crowds. They reported that passing resulted in more changes in speed and lateral positions for the e-biker compared to the case of meeting. All of the aforementioned hindrance findings, which partly overlap with LOS studies, can be used as an indicator for understanding the users' characteristics in LOS studies.

5. Complementary domains for ELOS development

Different performance and operation characteristics between bikes and e-bikes (e.g. speed regimes) introduce different travel behaviour demands. This impedes the direct application of BLOS for ELOS. The LOS concept, in general, quantifies user's perception of comfort in transport facilities and an in-depth understanding of user behaviour plays a crucial role in developing LOS indices. In order to fill this knowledge gap, the following sections provide insights into travel behaviour characteristics along with the modal substitution of e-bike riders for developing ELOS. The summary of this research domain can be found in [Appendix 2](#).

5.1 E-bike travel behaviour research

E-bike travel behaviour could be different based on the purpose of trips such as utilitarian or recreation. The assisted electric motor makes e-bike use more appealing for a wider range of users such as older adults and people with (limited) physical functional limitations. In order to have a clear picture of the user's perception of comfort, age, and gender aspects should be considered as well.

The application of e-bikes in utilitarian trips such as usage for work and commuting purposes has been explored in different studies. For example, Edge, Dean, Cuomo, and Keshav (2018) conducted a qualitative study in Canada and indicated that participants substantially used e-bikes for utilitarian trip purposes rather than leisure activities. Ling,

Cherry, MacArthur, and Weinert (2017) emphasised the importance of e-bikes in utilitarian travels, such as commuting and running errands, compared to bikes. Also, they reported that bike-owning respondents use their bikes more frequently for recreation and exercise. Wolf and Seebauer (2014) indicated that the supportive social environment and personal ecological norms have an effect on e-bike usage on work and shopping trips, whereas leisure trips are the consequence of physical activity purposes. Ye et al. (2014) conducted a study in China and documented that e-bikes are often used for commuting trip purposes. Johnson and Rose (2015) conducted an online survey among elderly people in Australia. They concluded that for all trip purposes, replacing a car by an e-bike is the dominant mode of change.

The impact of gender on trip purposes is also investigated. Van Cauwenberg, De Bourdeaudhuij, Clarys, de Geus, and Deforche (2018) compared different characteristics of e-bike users vs non-users among older adults. They reported that e-bike use for women was associated with 57% more minutes of cycling for recreation for those who have cycled in the past week. However, for men, there was no significant relationship between e-bike users and the volume of cycling for recreation among users that have cycled for recreation. Van Cauwenberg et al. (2019) reported that for older adults, men use an e-bike more for recreation whereas women use an e-bike for social activities to a greater extent.

The impact of gender on different characteristics of travelling with an e-bike is also discussed in the literature. Fyhri and Fearnley (2015) conducted an experiment in which they provided an e-bike to randomly selected participants (test users) to investigate its usage. They reported that the use of the e-bike was greater for women than men, and no differences were found in terms of age. Campbell et al. (2016) investigated the factors that influence the choice of both bike share and e-bike share systems. They reported that unlike bike share, e-bike share is attractive for young to middle age males who tend to have low income and education levels.

5.2 Substitution scale

The extent of substitution of cars, public transport, and bikes by e-bikes can play a key role in the development of new ELOS indices. In fact, the specification of this substitution contributes to choose the appropriate mode characteristics (for ELOS) and understand specific users' requirements. Influencing variables in this body of research mostly include ownership, distance abilities, and user experience (Campbell et al., 2016; Plazier et al., 2017b). The scale of substitution of other modes by e-bikes is sometimes unclear. The user's preference in rural and urban contexts is crucial to develop a suitable ELOS. In some cases, there are mixed preferences between cars and bike benefits which should be considered when assessing the use of e-bikes.

Plazier et al. (2017b) conducted a study in the Netherlands to assess the benefits and limitations of using e-bikes among students. They indicated that public transport can be potentially replaced by e-bikes. Bourne et al. (2018) reviewed seventeen studies related to the health benefits of electrically-assisted cycling. They concluded that e-bikes can help to perform physical activity, and they have a potential ability to be an alternative to bikes. Sun, Feng, Kemperman, and Spahn (2020) examined the e-bike rider travel changes in relation to owning an e-bike. They found that after the adoption of e-bike use, bike

usage decreases whereas car usage decreases to a lower extent. They stated that e-bike users tend to drive less in rural area compared to the urban context once e-bike use is introduced. Winslott Hiselius and Svensson (2017) explored the use of e-bikes by focusing on travel behaviour changes in Sweden. They stated that e-bikes could potentially be indicated as an alternative for car trips in rural areas similar to the case of urban areas.

Travel comfort and satisfaction can also change based on substitution decisions. For example, de Kruijf, Ettema, and Dijst (2019) showed that switching from car to e-bike trips will increase travel satisfaction. They indicated that the level of satisfaction by using an e-bike increased gradually – after a period of a month and even increased in the following period of half a year. Popovich et al. (2014) reported that the several positive aspects of using e-bikes. This includes reaching a higher speed and acceleration with more ease compared to a normal bike, enabling more people to bike, generating more trips by bike and fun. In addition, those users of e-bikes reported overall less driving and in some cases stop using the car. Jones, Harms, and Heinen (2016) reported that e-bikes provide an opportunity for riders who would not use the bike. They indicated the barriers to usage of an e-bike being e-bike weight, battery life, cost of the e-bike, infrastructure limitation, and social stigma. Cherry and Cervero (2007) reported that e-bike users travel significantly more than bike users do, and most e-bike users would travel by bus if the e-bikes were unavailable. They indicated that e-bikes are a transitional mode between human-powered bikes and automobile ownership to a lower extent. They concluded that an e-bike is a cheaper and a higher quality mobility option compared to public transport.

Lin, Wells, and Sovacool (2017) concluded that a car could not be considerably replaced by an e-bike, and the e-bike usage helps replacing other transport means such as walking, cycling, and bus. Cherry, Yang, Jones, and He (2016) investigated the use of e-bikes over 6 years in China. They reported that there is a decreasing trend in bike and bus popularity and an increasing trend in car and taxi popularity. However, they emphasised the role of e-bikes as an interruption of this shift to motorised vehicles. They stated that e-bikes are efficiently replacing many urban car trips. Kroesen (2017) indicated that e-bike ownership could crucially reduce the usage of bikes; however, to a limited extent, an e-bike can reduce public transport and car usage. Also, an e-bike can be a replacement for bikes not cars. Ding, Cao, Dong, Zhang, and Yang (2019) investigated the relation between built environment variables and e-bike ownership in China. They reported that almost all associations between built environment characteristics and e-bike ownership are non-linear. However, distance to transit, employment density, and land use mix are positively connected to e-bike ownership. Also, residential density has a negative association with e-bike ownership.

6. The conceptual framework for ELOS development

The study of the state-of-the-art of the core and complementary domains under consideration aid the development of ELOS. The proposed preliminary conceptual framework can be used as a practice-ready checklist for the ELOS development in that researchers and planners could easily navigate the potential variables and differences between bikes and e-bikes (see Figure 3). More information regarding different variables for BLOS can be found in Appendix 1 (based on HCM, 2016). In this section, we describe the different steps of the proposed conceptual framework. The case specification is placed

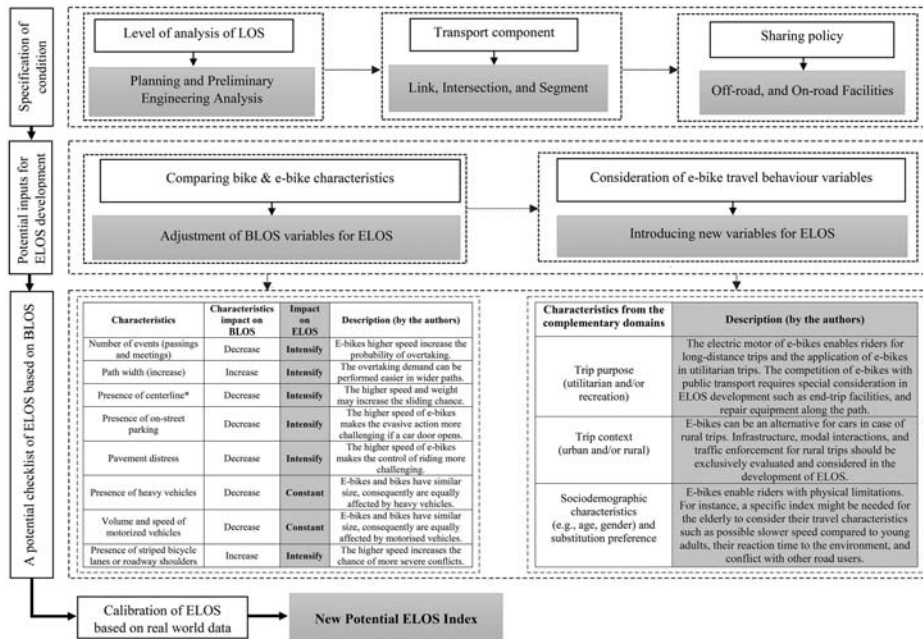


Figure 3. Hypothetical framework towards the development of ELOS. * The user should evaluate whether the centreline contributes to a better split of the mixed-flow conditions.

in the first step of the framework. As mentioned, the scope of the framework is only for planning and preliminary engineering analyses (this is mainly due to the lack of extensive quantitative research in the field of e-bikes). Then, the transport component (e.g. link, and node) and sharing policy (i.e. on- or off-road facilities) should be defined to specify the context under consideration. The next step of the framework is the adjustment and modification of BLOS variables for ELOS (based on the listed core domains). This is performed in parallel with the introduction of a new set of variables based on the complementary domains. Two subsections belonging to the domains are listed to provide more details regarding the adoption and use of the introduced variables. For instance, concerning the evaluation of off-road facilities, when the frequency of the event increases, the BLOS decreases (hindrance concept). This variable is indeed valid for e-bikes as in shared mobility the higher speed of e-bikes increases the frequency of events. Consequently, this variable decreases the ELOS to a greater extent compared to BLOS, i.e. users would experience higher speed differences. This approach is adopted for all the variables in this subsection. In contrast, the different riding characteristics of e-bikes (compared to bike) may influence ELOS. This is also described in this subsection. For example, e-bikes facilitate utilitarian trips as the riding distance potentially increases. Riding on a long-distance trip may need more preparation for the infrastructure e.g. repairing facilities and appropriate traffic signs for a smooth transition to e-bikes for cycling facilities (considering the high speed of e-bikes). It is worth mentioning that the proposed conceptual framework does not consider safety concerns explicitly in order to be consistent with the methodology adopted by HCM. For instance, the presence of

heavy and motorised vehicles can present safety issues for e-bike riders which are not considered in the framework.

7. Discussion

E-bikes are gaining ground rapidly, which calls for more extensive research evaluating different aspects of this transport mode. The overall world trend of e-bike usage can lead to a paradigm shift in mobility patterns which could result in a massive modal substitution. Simultaneously, the unprecedented pandemic of COVID-19 and the social distancing recommendations may affect the use of public transport. For instance, Jenelius and Cebecauer (2020) evaluated travel pattern variations due to the COVID-19 pandemic in three populated areas of Sweden. They claimed that public transport ridership had dropped by 40% to 60% in different regions. E-bikes potentially can compete with public transport (as discussed in the substitution section) and this may lead to increase e-bike ridership in the peri- and post-pandemic situations. Understanding and evaluating the e-bike rider's perspective enable policy-makers to be prepared for investment in the programs and infrastructure.

E-bikes require less physical energy (compared to the bike) while they can enhance ride health with low maintenance costs. This feature makes the e-bike a solution adopted by many governments and policy-makers across the world to improve active transport. However, policy-makers are still struggling with the development of strategies for encouraging e-bike usage since there is limited knowledge about users, reasons behind demand, and influencing factors (Cherry & Cervero, 2007). In Europe, the financial contributions of the government may lead to a boosted presence of e-bikes. For instance, in Sweden, each e-bike purchaser got a 25% subsidy of the cost of an e-bike purchased in 2018 ("Swedish Law for e-bikes", 2018). The significant role of e-bikes as a promising substitute for motorised vehicles may trigger governments of countries with relatively low ridership of e-bikes (e.g. North America) to invest more in this sustainable mode of transport. These policies are crucial toward encouraging active transport while there are few studies evaluating the outcome of these policies and e-bike user's perception of comfort.

LOS is a beneficial tool to enable planners and policy-makers to evaluate and improve cycling systems. Different variables have been employed in BLOS studies. However, there is no systematic study assessing the applicability of those variables in ELOS. Selection of influencing variables and, eventually, data collection is a costly and time-consuming process. It is crucial to itemise and assess the ability of BLOS variables and the possibility of the adaptation for ELOS. E-bikes are mostly ridden in cycling infrastructure and evaluating the effect of e-bikes in these facilities could have benefits for both bike and e-bike riders. However, the results suggest that there have been a few BLOS studies that include e-bikes in their estimation process. This knowledge deficiency could lead to comfort concerns for vulnerable road users. It is still not clear how much cycling infrastructures in different countries are capable to accommodate e-bikes in different cycling facilities.

In the BLOS literature, different terms have been used interchangeably to quantify the rider's comfort. For example, *bikeability*, *bicycle friendliness*, *Bicycle suitability*, *stress level* (Fitch, Sharpnack, & Handy, 2020; Harkey, Reinfurt, & Knuiman, 1998; Lowry, Callister, Gresham, & Moore, 2012; Majumdar & Mitra, 2018). Inconsistent terms in different facilities may lead to confusion in the range of indices applications. Early adopters of ELOS should

consider using consistent terminology based on sharing policy and transport component classifications to avoid conflicts in the applicability of the developed indices.

The hindrance concept plays a crucial role in understanding and estimation of BLOS. E-bikes adopt different speed regimes compared to bikes which require special consideration for developing ELOS. This diversity in the operating characteristics of e-bikes and bikes calls for more comprehensive research assessing bike-pedestrians vs e-bike-pedestrian interaction rules. The higher speed also increases the chance of overtaking considering mixed flow, which in turn may become more complex and consequently decreases LOS. Defining the extent of the impact of e-bikes in mixed flow conditions contributes to the need for an ELOS. Equivalent units for e-bikes can be considered as a needed step and powerful tool for the planning, design, operation, and management of mixed-flow facilities (Jin et al., 2015).

Concerning the limited literature on e-bike comfort characteristics for adoption in ELOS, the travel behaviour and substitutional scale domains provide insights towards the development of ELOS. E-bikes can be a substitution for cars and public transport. However, the scale of this substitution is limited and partly contradictory (Haustein & Møller, 2016). Some studies in the literature acknowledged that e-bikes can substantially substitute car usage in specific conditions (Johnson & Rose, 2015; Plazier, Weitkamp, & van den Berg, 2017a); however, the e-bike is discussed as a replacement of other modes to a lesser extent (Kroesen, 2017; Lin et al., 2017). This subject is vital since if an e-bike can be considered as a substantial replacement for a car, those studies for car LOS can have a strong application for ELOS studies; otherwise, this may lead to evaluating and improving the system in a wrong direction.

The reviewed literature suggests that e-bikes have a strong application in utilitarian trips such as commuting and work. This result can be expected as e-bikes enable riders to long-distance trips with relatively less effort compared to bikes. The scale of this result is mixed in the literature by sociodemographic characteristics of users (Van Cauwenberg et al., 2018). The current methodology of HCM for BLOS in off-street (which does not consider e-bikes) facilities has applications for both commuter and recreational trip purposes (HCM, 2016). The specification of trip purpose contributes to developing an ELOS to be distinctive based on trip purposes or weighted based on trip purposes.

Understanding the socio-demographic characteristics of e-bike users contribute to planning this transport mode for a wide user range. Several studies stated that e-bikes are beneficial among older adults, however, no studies elaborated on the possible and potential comfort concerns of this mode for the older adults. For instance, an e-bike facilitates cycling, however, it may be difficult for older adults to control and navigate the e-bike in some circumstances. Some studies emphasised the importance of gender differences (Fyhri & Fearnley, 2015; Van Cauwenberg et al., 2019). However, it is not still clear the effect of gender in relation to the age of e-bike users.

Different types of data collection, analysis, and modelling can be used for BLOS and ELOS development and analyses e.g. observations, experiments, and simulations. One of the potential challenges associated with an e-bike in an observational study is that the cameras may not be able to capture a clear picture of the bike. This issue can make it difficult to distinguish e-bikes from bikes. Previous research, e.g. Botma and Papendrecht (1991) clustered bikes and mopeds with respect to different speed regimes. However, in mixed traffic, some e-bikes may keep the same average speed as bikes

which introduce some bias to the process. This issue can be managed by conducting a laboratory experiment. The number of simulation tools for bikes is growing (Twaddle et al., 2014). Nevertheless, it is not possible to comprehensively simulate with them the interactions of road users in shared facilities (HCM, 2016). However, simulation is a powerful tool that can have an application in the development of ELOS to model the interaction of vulnerable road users. This is especially important once empirical data will be available. In terms of survey data collection, (online or in-traffic) questionnaires seem to be a frequent method to understand e-bike riders' behaviour. This type of studies is useful and relatively easy to conduct; however, there is a limited number of studies to address the challenges connected to this approach. More research needs to elaborate on these subjects since this can affect the result and the accuracy of ELOS development (Kazemzadeh, Camporeale, D'Agostino, Laureshyn, & Winslott Hiselius, 2020).

At present, Asia (China) is the world's leader in the e-bike market and the key existing studies related to ELOS were conducted in Asia (Bai et al., 2017; Liu & Suzuki, 2019). More studies are required to get insights in this field in the rest of the world. For instance, considering studies in the US regarding BLOS, and from studies that were conducted in Asia for ELOS to be applicable in different contexts such as the US and Europe. In terms of transport components, there is no study evaluating ELOS in nodes (intersections/crossings and roundabouts). Also, there is a dire need for a comprehensive understanding of e-bikes and their role in the transport network (Bjørnarå et al., 2017). Appendix 3 summarizes research needs, challenges, and suggestions for future ELOS development.

The present review presents a set of limitations. First, the proposed conceptual framework is based on HCM BLOS variables. However, different studies (with a wide range of variables) can be used for ELOS development. Second, scarce literature on ELOS and limited real-world data on e-bike navigation behaviour makes it difficult to propose a quantitative- or simulation-based framework. This challenge places the proposed framework for ELOS at a conceptual stage for planning and engineering purposes rather than a fully ready-to-use tool. Furthermore, an in-depth understanding of the road performance is not feasible by a single ELOS index, as mentioned by HCM (2016): "[...] *Neither LOS nor any other single performance measure tells the full story of roadway performance [...]*". Thus, the proposed framework can be applied along with other road performance evaluations such as BLOS, and pedestrian LOS to depict a realistic picture of the user's experience. It is acknowledged that the relevance of ELOS may be undermined by the relatively low ridership of e-bikes in certain regions (e.g. the US). Nevertheless, research on ELOS is deemed to feed the discussion on modal substitution towards more sustainable transport modes and in turn highlights the need for the preparation for future travel demands. Finally, the description of the "adjusted" and "introduced" variables (suggested by the authors) related to BLOS may need to be modified based on specific conditions under consideration.

Future research should include laboratory experiments to analyse hindrance characteristics of e-bikes and use the findings for ELOS index development. Since pure e-bike flow may not be common, mixed-flow conditions (including bikes, pedestrians, and e-scooters) have priority. Studies for e-bikes may contribute to the understanding of the e-scooter mode as well. As e-bikes are often classified as bikes, the study of ELOS in heterogeneous traffic is a concern. Most of the findings for the adoption of the e-bike are related to urban areas, while the substitution scale is relevant also for rural areas (e.g. those close to the city

where commuters work). Research is particularly needed to study how users perceive e-bike as a substitution of car, public transport, or bike. This is a substantial point in terms of developing ELOS indices based on users' attitudes towards this mode of transport. Future research can also evaluate the applicability of traffic signs and signals for bikes and verify if they are applicable for e-bikes. The higher speed on e-bikes may introduce some difficulties for reading traffic signs and necessary stops at intersections. Also, understating the scale of substitutions of public transport by e-bikes in the peri-pandemic situation may contribute to the management of travel demand for future pandemics.

8. Conclusion

Limited knowledge is available about ELOS and this issue affects the evaluation of the e-bike riding comfort and, in general, the identification of improvements in cycling infrastructure. This study investigates the prerequisites and requirements for the development of a dedicated ELOS index and highlights the knowledge gaps in the field. BLOS, e-bike comfort, e-bike travel behaviour, and modal substitution were reviewed to propose a conceptual framework for ELOS development.

Disclosure statement

No potential conflict of interest was reported by the authors.

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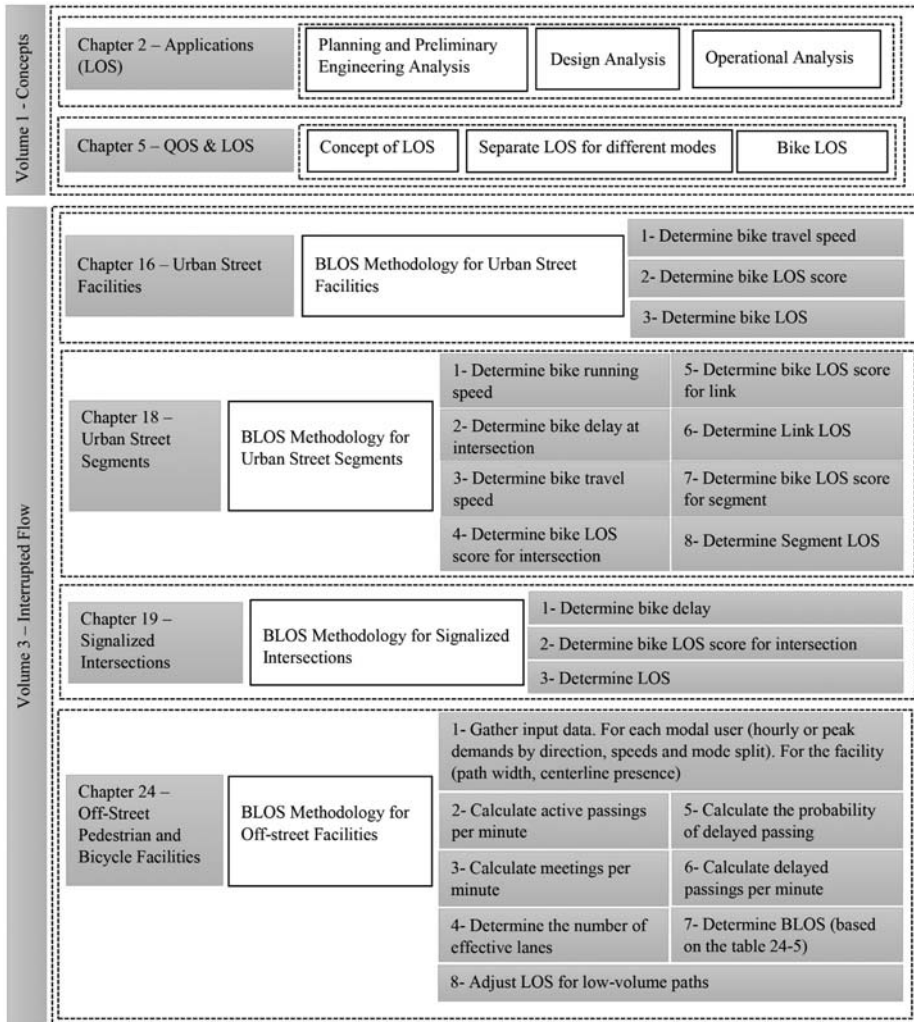
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Appendices

Appendix 1. Summary of HCM methodology for BLOS (HCM 6th edition, 2016)



Appendix 2. Summary of e-bike travel behaviour studies (alphabetical order by country)

Author(s) (Year)	Data collection	Territory	Main conclusion(s) or recommendation(s)
Johnson and Rose (2015)	Online survey	Australia	Substituting e-bike for car is the dominant mode change across all trip purposes. Also, respondents usually feel safer riding an e-bike than a pedal bike.
Wolf and Seebauer (2014)	Questionnaire	Austria	The supportive social environment and personal ecological norms have an effect on e-bike usage on work and shopping trips,

(Continued)

Appendix 2. Continued.

Author(s) (Year)	Data collection	Territory	Main conclusion(s) or recommendation(s)
Van Cauwenberg et al. (2018)	Questionnaire	Belgium	whereas leisure trips are the consequence of physical activity purposes. Women with a higher BMI and with one motorised vehicle in the household were more likely to be an e-biker.
Van Cauwenberg et al. (2019)	Questionnaire	Belgium	The most dominant reason for using e-bike across genders was to bike with less effort.
Leger et al. (2019)	Interview	Canada	The discussed variables for e-bike adoption were convenience increment, physical exertion. reduction, reducing reliance on a vehicle and fun. In addition, cycling infrastructure and road safety, regulation, and stigmatisation barriers were counted as barriers.
Ye et al. (2014)	Questionnaire	China	E-bikes are mostly used for commuting. Saving time, bus inconvenience, comfort, saving money and convenience are the most important variables to use e-bikes.
Cherry and Cervero (2007)	Intercept surveys	China	E-bike users travel significantly more than bike users and most e-bike users would travel by bus if the e-bikes were unavailable.
Wei et al. (2013)	Survey	China	The over-standard e-bikes are strongly competing with bikes and public transport and users are eager to have longer travel distance with e-bikes.
Campbell et al. (2016)	Survey	China	The e-bike share choice is also affected by the trip distance, high temperatures and poor air quality while precipitation is also a negative factor.
Weinert et al. (2008)	Force field analysis	China	The crucial factors for the future development of this mode are improvements in battery technology, gasoline-powered motorcycle bans, decrease enforcement of these vehicles' standards, and decreasing public transport QOS.
Weinert et al. (2007)	Intercept survey	China	E-bikes are capable to facilitate longer travel distance by being energy efficient for riders, accessibility, and urban expansion of cities.
Cherry et al. (2016)	Survey	China	E-bikes play a role as an intermediate mode, interrupting the transition from bicycle to bus and from bus to car.
Xin et al. (2017)	Survey	China	E-bike riders prefer to use subway in long travel distance rather than e-bikes.
Ding et al. (2019)	Survey	China	There is non-linear relationship between built environment characteristics and e-bike ownership.
Lin et al. (2017)	Intercept survey	China	E-bikes are not necessarily substituting cars on a considerable scale, but replacing the other modes such as walking, traditional bicycling, and bus.
Haustein and Møller (2016)	Online survey	Denmark	Access to an e-bike reduced age differences in self-reported cycling frequency; however, it increased differences in self-reported distances.
Wild and Woodward (2019)	Interview	New Zealand	E-bikes could facilitate the situation in daily trips in case of wind or rider's tiredness which could influence time reliability of cyclists.
Fyhri et al. (2017)	Questionnaire	Norway	Those who cycle less are most interested in buying an e-bike. Motivation of using e-

(Continued)

Appendix 2. Continued.

Author(s) (Year)	Data collection	Territory	Main conclusion(s) or recommendation(s)
Bjørnarå et al. (2017)	Questionnaire-interview	Norway	bike increases after having experience of an e-bike (prior knowledge of the e-bike). Highlighting the importance of research on the influence of e-bikes and long tail bikes on travel behaviour and physical activity levels.
Simsekoglu and Klöckner (2019)	Online survey	Norway	There is a negative relation between usage of e-bike and bike; however, a positive relation was found between car and e-bike use.
Fyhri and Fearnley (2015)	Questionnaire	Norway	Cycling among test users (compared to the control group) crucially increased in terms of number of trips, distance cycled and as cycling shares.
Winslott Hiselius and Svensson (2017)	Survey	Sweden	E-bikes could potentially be indicated as an alternative for car trips in the rural area similar to the urban area.
Sun et al. (2020)	Longitudinal dataset from the Netherlands Mobility Panel survey	The Netherlands	After the adaptation of e-bike use, car usage decreases.
de Kruijf et al. (2019)	Questionnaire	The Netherlands	Switching from car to e-bike trip will increase travel satisfaction.
Plazier et al. (2017a)	GPS-tracking and interviews	The Netherlands	A car can be replaced by an e-bike for users on distances perceived to be too long to cover by bike.
Plazier et al. (2017b)	Survey and Interview	The Netherlands	Users are interested to some features of using e-bikes such as e-bike speed, easiness of using, the enjoyable experience of assisted cycling and independency from public transport schedules.
Kroesen (2017)	Database of national mobility surveys in the Netherlands	The Netherlands	E-bike ownership could crucially reduce the usage of bikes; however, to a limited extent, e-bikes can reduce public transport and car usage.
Ling et al. (2017)	Online survey	US	E-bikes are more important in utilitarian travel, such as commuting and running errands, compared to a bikes.
He et al. (2019)	Historical trip data of Summit Bike Share	US	Weather factors including temperature and wind speed, considerably affect e-bike share usage.
Ji et al. (2014)	Simulation	US	High demand scenarios require multiple swappable batteries per e-bike to meet the maximum demand. Trip duration has the most influence on e-bike and battery availability, followed by trip rate, and then trip length.
Fitch and Handy (2019)	Survey	US	The possibility of theft and the cost of e-bikes are the two important barriers for those who have experienced an e-bike.
Popovich et al. (2014)	Interviews	US	Several positive aspects of using e-bikes including higher speed and acceleration than normal bike with more easiness, enable more people to bike, generating more trips by bike and fun.
MacArthur et al. (2014)	Online Survey	US	E-bikes enable users to bike more often, longer distance trip and increase the possibility of carrying more cargo with them.
Dill and Rose (2012)	Interview	US	Most of the e-bike owners use their e-bikes to substitute for travel by either bikes or traditional motor vehicles.

Appendix 3. Summary of research needs, challenges, and suggestions for ELOS development

Research phase	Needs	Challenges (knowledge gap)	Suggestions (recommendations)
Conceptualisation	Evaluation of the impacts of the policies that governments are applying to improve e-bike mode.	It is already admirable to promote active transportation and less tendency to evaluate the impacts and consequences of the implemented policies.	Mapping the current strategies in relationship to the early adopters and quantify/itemise advantages and disadvantages of different policies.
	Developing an ELOS index.	A few research studies have been conducted concerning flow to support e-bike studies. Few studies about the capability of the adoption of BLOS variables to use for ELOS. Little knowledge of variables that should be proposed beyond BLOS variables.	Flow laboratory experiments could provide a detailed theoretical framework for e-bikes. Basic flow assumption of BLOS should be repeated in presence of e-bikes in different conditions. Concerning e-bike higher speed and weight compared to bike, comfort variables may seem to be different from BLOS. Considering e-bike travel behaviour characteristics and BLOS simultaneously is needed to understand more e-bike user's perception of comfort.
	Specification of substitution of public transport, cars and bikes by e-bikes.	E-bike is a mode between human-powered and fully motorised vehicle, and this makes it difficult to analyse this mode.	E-bikes should be either exclusively looked at as bike or public transport. This stream of research would reveal more details about the user's perception of comfort.
	Understanding of infrastructures (in)capability to accommodate the e-bikes.	E-bikes are mostly ridden in bikes and pedestrians' facilities and these facilities have not been analysed in the presence of e-bikes.	Off-street facilities should be analysed in the presence of e-bikes. Specifically, different studies on various infrastructure can provide a guideline for ELOS studies.
Data collection	Detection of e-bikes in mixed flow.	Due to the privacy regulations (mostly for cameras), it is difficult to capture e-bikes in naturalistic studies (mixed flow).	In laboratory experiments, e-bikes can be captured in the data analysis process (trajectory extraction).
	Adopting density calculation in the presence of bikes and pedestrians.	Different speed regimes introduce difficulties to estimate density for mixed flow.	Defining different interactive influence area and estimate the e-bike interaction distance in different conditions in relation to different modes (pedestrians and bikes).
	Understanding of perceptions of comfort for elderly and users with a disability.	Elderly could have difficulty to answer online questionnaires (technology adoption).	In person and phone interviews would be beneficial to collect data for this group.
ELOS index development	Understanding of e-bike user's perception of comfort in different transport component.	Lack of comprehensive studies on e-bike flow and travel characteristics.	Testing and verifying the basic assumption of BLOS studies. These studies could be in line with studies to test the application of new variables for ELOS.