Towards an electric bike level of service

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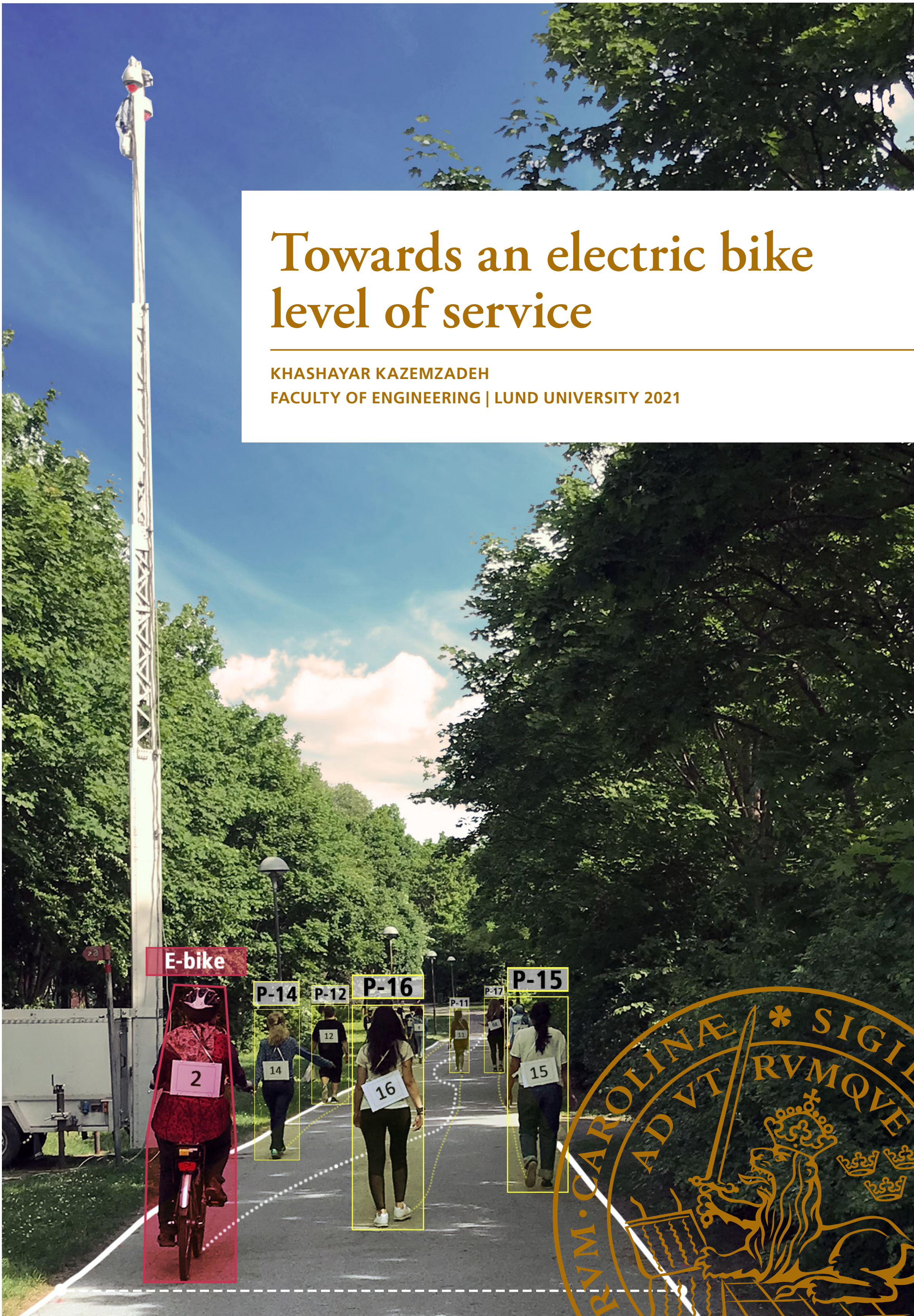

Towards an electric bike level of service

Khashayar Kazemzadeh

LUND UNIVERSITY

DOCTORAL DISSERTATION

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Abstract

The fast-growing market of electric bikes (e-bikes) has introduced a paradigm shift in mobility with a promise to enhance the sustainability agenda. An in-depth understanding of transport quality of service (QOS) from the e-bike rider's perspective is a promising approach to sustain the role of the e-bike in mobility. Level of service (LOS) is a method by which to quantify QOS for different transport modes. However, to date, the knowledge on e-bike LOS (ELOS) lags far behind that on other transport modes. Therefore, the central aim of this thesis is to provide fundamental knowledge related to the development of ELOS. To address the main aim of the thesis, the travel behaviour and riding characteristics associated with e-bikes were scrutinised. Both qualitative and quantitative methods were employed to provide knowledge on the travel behaviour (strategical level) and riding characteristics (tactical level) related to e-bikes.

From a strategic perspective, an extensive review of the literature was conducted to explore which transport mode LOS is applicable for developing ELOS. Based on the findings from the state of the art and the reviewed literature, bike LOS (BLOS) was deemed substantial for the development of ELOS. Thus, to move towards the development of ELOS, a set of studies was conducted to understand the comfort concerns of e-bike riders via the literature review, interviews and a field experiment. Based on the reviewed literature, it appears evident that research related to the travel behaviour of e-bike users is sparse and that the scale of e-bike substitution for other modes of transport is unclear. The findings of the aforementioned study led to the proposition of a preliminary theoretical framework for the development of ELOS and served as a roadmap for conducting the studies that followed. To provide a deeper understanding of the travel behaviour related to e-bikes, a qualitative study was conducted to explore e-bike users' (riders) and nonusers' comfort concerns. This study was extended to include the comfort and health concerns of e-bike users and nonusers in the unprecedented COVID-19 pandemic situation. The findings of this study provided a set of e-bike riding comfort variables, such as infrastructure facilities and e-bike performance in both pre- and peri-pandemic situations. This study also documented the potential effect of e-bike substitution for other transport modes such as public transport and cars.

From a tactical level of analysis, there was a lack of studies to facilitate understanding the riding characteristics associated with e-bikes, specifically where vulnerable road users are involved. To address this knowledge gap, the interaction between e-bike users and pedestrians was studied in an off-road facility experiment. The study was designed to evaluate whether the traffic characteristics of passing (same-direction) and meeting (opposite-direction) encounters impose different difficulties for the navigation of the e-bike rider in pedestrian crowds. The results suggested that passing events cause the e-bike rider more hindrance compared to meeting events. This study was further extended to investigate the sociodemographic characteristics of e-bike riders along with their characteristics of riding in traffic and eventually model e-bike riders' comfort in pedestrian crowds.

In sum, this thesis addresses the knowledge gaps related to e-bike comfort concerns based on different study set-ups, which can be used substantially for developing ELOS. Along with exploring e-bike riders' comfort concerns, the thesis puts forward information related to e-bike nonusers in both pre- and peri-pandemic situations. The findings of the thesis are applicable for planners and policy-makers when integrating the role of e-bikes in mobility policies. At a general level, the findings of the studies presented in this thesis pave the way for developing future ELOS and highlight the dire need to develop the concept of ELOS based on different contexts. All in all, the thesis opens new avenues into the field of e-bike comfort modelling by rendering the importance of the subject as an independent mode of transport.

Key words: Level-of-service, LOS, quality-of-service, QOS, electric bike, e-bike, sustainable mobility, comfort

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MADE IN SWEDEN

To my parents

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Publications included in this thesis

I. **Kazemzadeh, K** & Ronchi, E. (2021). From bike to Electric Bike Level-of-service. Transport Reviews. 1-26.

II. **Kazemzadeh, K** & Koglin, T. (2021). Electric bike (non)users' health and comfort concerns pre and peri a world pandemic (COVID-19): A qualitative study. Transport & Health, 20: 101014.

III. **Kazemzadeh, K**., Laureshyn, A., Ronchi, E., D'Agostino, C., & Hiselius, L. W. (2020). Electric bike navigation behaviour in pedestrian crowds. Travel Behaviour and Society, 20, 114-121.

IV. **Kazemzadeh, K** & Bansal, P. (2021). Electric Bike Navigation Comfort in Pedestrian Crowds. Sustainable Cities and Society, 69:102841.

Contribution Statement

Khashayar Kazemzadeh is the main author of all the papers included in this thesis. Kazemzadeh was responsible for the research questions, the conceptualisation of the work, the data collection and the data processing as well as preparing the original drafts of all manuscripts. Dr Laureshyn and Dr Ronchi in Paper 3 and Dr Bansal in Paper 4 contributed to the conceptualisation of the works. Professor Hiselius was the principal supervisor and responsible for the funding acquisition for all works in this thesis. All co-authors provided critical feedback and helped shape the manuscripts.

Other publications during candidature

Kazemzadeh, K., Laureshyn, A., Winslott Hiselius, L., & Ronchi, E. (2020). Expanding the Scope of the Bicycle Level-of-Service Concept: A Review of the Literature. Sustainability, 12(7), 2944.

Kazemzadeh, K., Camporeale, R., D'Agostino, C., Laureshyn, A., & Winslott Hiselius, L. (2020). Same questions, different answers? A hierarchical comparison of cyclists' perceptions of comfort: in-traffic vs. online approach. Transportation Letters, 1-9.

Huang, W., **Kazemzadeh, K**., Mansourian, A., & Harrie, L. (2020). Towards Knowledge-Based Geospatial Data Integration and Visualization: A Case of Visualizing Urban Bicycling Suitability. IEEE Access, 8, 85473-85489.

Popular science summary

Electric bikes (e-bikes) are an environmentally friendly mode of transport which supports an active and healthy lifestyle. E-bikes assist pedalling via an electric motor. This feature enables an extensive range of users, including the elderly and people with a physical limitation, to use active mobility. Simultaneously, users can count on e-bikes for long-distance trips, and potentially, motorised vehicles can be replaced by e-bikes – consequently, e-bikes address some environmental issues, such as air pollution. As a result, e-bikes are receiving increased political support from governments across the world. However, the scientific literature related to the e-bike riding experience is sparse.

In this thesis, I explore the necessity of analysing e-bike riding comfort and provide fundamental knowledge for developing tools to assess the quality of e-bike riding. First, I discuss the specific travel behaviour of e-bike users (strategic level) which renders the importance of having a dedicated framework for analysing e-bike riding comfort. This is due to the fact that e-bike rider travel behaviour has some similarities with that of users of both motorised and non-motorised vehicles. For example, e-bikes require pedalling, similar to bikes, while they also enable riders to plan long-distance trips (due to the presence of an electric motor) akin to a car. As a result, neither motorised nor non-motorised transport modes' comfort assessment methods could accurately represent the comfort of e-bike riding. To further explore e-bike travel behaviour, I interviewed e-bike users and nonusers and explored their travel behaviour, modal choice and travel preferences. Based on the aforementioned information, I further studied the specific characteristics of e-bike riding.

To assess the riding characteristics related to e-bikes (tactical level), I designed an experiment and assessed e-bike riders' interactions with pedestrians. I extended this study and modelled e-bike riding comfort, which can be used as a dedicated procedure for the computation of e-bike riding comfort. In sum, I have proposed a preliminary theoretical framework that considers both the travel behaviour and riding characteristics associated with e-bikes. The proposed framework can be seen as an initial attempt towards an evaluation of e-bike riding comfort. The proposed framework and individual studies in the thesis have applications in both the theoretical and practical evaluation of e-bike riding comfort. From a theoretical standpoint, the thesis documents a dedicated assessment procedure for both the travel behaviour and riding characteristics related to e-bikes. From a practical point of view, the proposed framework is useful for planners and policy-makers when considering the specific travel behaviours and riding characteristics associated with

e-bikes in their assessment agendas. All in all, this thesis highlights the importance of considering the e-bike as a unique mode of transport and consequently the significance of using a dedicated procedure for the evaluation of e-bike riding comfort.

Populärvetenskaplig sammanfattning

Elcykeln är ett av de miljövänliga transportsätten som stöder en aktiv och hälsosam livsstil. Elcyklar hjälper cyklisten att trampa via en elmotor. Denna funktion gör det möjligt för ett stort antal användare, inklusive äldre och personer med fysisk begränsning, att använda aktiv mobilitet. Samtidigt kan elcykeln användas för långväga resor och potentiellt ersätta motorfordon, vilket gör att elcykling kan adressera vissa miljöfrågor så som luftföroreningar. Som ett resultat får elcykeln ökat politiskt stöd från regeringar världen över. Emellertid är den vetenskapliga litteraturen relaterad till hur elcykling upplevs, begränsad.

I denna avhandling har jag undersökt behovet av analyser av elcyklistens komfort och tagit fram grundläggande kunskaper med syfte att utveckla ett ramverk för att bedöma elcyklingens kvalité. Först diskuterar jag det specifika resebeteendet som elcyklister har (strategisk nivå) och som gör det viktigt att använda ett särskilt ramverk för att analysera elcyklistens komfort. Detta beror på att elcyklistens resebeteende har vissa likheter med resebeteendet för både motoriserade och icke-motoriserade fordon. Exempelvis kräver elcyklar att användaren trampar på samma sätt som vid icke eldrivna cyklar, samtidigt som de gör det möjligt för användaren att planera långväga resor (på grund av elmotorn) vilket gör att den liknar en bil i det avseendet. Som ett resultat kan varken komfortbedömningsmetoder utvecklade för motoriserade eller icke-motoriserade transportsätt exakt representera elcyklistens komfort. För att ytterligare utforska resebeteendet hos elcyklister, intervjuade jag elcykelanvändare och icke-användare, undersökte deras resebeteende, val av färdsätt och preferenser. Baserat på denna information studerade jag specifika egenskaper hos elcyklingen.

För att bedöma elcykelns köregenskaper (taktisk nivå) utformade jag ett experiment och utvärderade elcyklisternas interaktion med fotgängare. Jag utökade denna studie och tog fram en modell som kan användas för beräkning av elcyklisters komfort. Sammantaget har jag tagit fram och föreslår ett preliminärt teoretiskt ramverk som inkluderar både elcyklistens resebeteende och elcykelns köregenskaper. Det föreslagna ramverket kan ses som ett första försök att skapa ett verktyg för att utvärdera elcyklisters körkomfort. Det föreslagna ramverket och avhandlingens olika studier har både teoretisk och praktisk tillämpning för utvärdering av elcyklisters körkomfort. Ur teoretisk synvinkel dokumenterar avhandlingen en särskild bedömningsprocedur för både resebeteende hos användare och köregenskaper hos elcyklar. Ur en praktisk synvinkel är det föreslagna ramverket användbart för planerare och beslutsfattare för att därigenom inkludera specifika resebeteenden och köregenskaper hos elcyklar i sitt arbete. Sammantaget betonar denna avhandling vikten av att betrakta elcykeln som ett unikt transportsätt och följaktligen betydelsen av att använda ett dedikerat förfarande för utvärdering av elcyklisters komfort.

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proudly dedicate my thesis to you. I would also like to extend my gratitude to my lovely siblings Mazda, Ashkan and Mitra. You have always been behind the scenes of my life kindly supporting me and never letting the last kid of the family get lost in this vicissitudinous life. Guys, you are awesome!

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Finally, my very special gratitude goes out to the Transport and Roads Division at Lund University for financial support for my PhD and for providing me with very pleasant conditions in which to conduct my painstaking yet joyful research process. I am grateful for the many networking opportunities, travels and help which let me grow as an independent researcher. Lund University is a fantastic place to carry out research and I am honoured and flattered to complete and conclude my education here.

I am blessed that I had such a great PhD journey at Lund and very grateful that another fruitful chapter of my life is to ensue. I love Albert Einstein and reading about his life, which always strengthened my enthusiasm for learning to be a researcher. I would like to close this chapter with one of his great quotes, which has been imprinted in my mind: '*Imagination is more important than knowledge. For knowledge is limited, whereas imagination embraces the entire world, stimulating progress, giving birth to evolution*'.

Khashayar, May 12

Glossary of terms

Bike: a two-wheeled vehicle that operates by human power and is usually ridden by one user.
Comfort: a situation in which a human and the environment are in harmony as a result of the adaptation of physical, psychological and sociological aspects. This notion can be conceptualised based on the context of each study in this thesis.
E-bike: an electric power-assisted bike that contributes to propulsion.
E-bike as referred to in this thesis: this type of e-bike assists the rider's pedal power, which contributes to the physical exertion of riding. The speed of this type is often limited to 25 km/h.
Event: in this thesis, an event is attributed to passing or meeting type of interactions.
Hindrance: the concept is mainly used to depict the comfort and convenience of bike riders. This concept can be used to derive level of service for bike facilities. Hindrance can also be used to quantify the interactions or manoeuvres of road users.
Interaction: situations where a road user modifies their speeds and positions because of their proximity to other road users.
Level of service: a method by which to quantify the quality of service.
Meeting: this entails opposite-direction encounters. The definition is related to the hindrance concept.
Moped: a type of small motorcycle that has a speed range between 25 and 45 km/h and a motor power of 1000–4000 W.
Navigation: the process of getting from one position to another, and in this thesis, it refers to the riding characteristics associated with e-bikes.
Off-road facility: a facility which is designed exclusively for bikes or bikes with non-motorised road users, such as sidewalks.
On-road facility: a facility shared between users of motorised vehicles and bikes, such as paved shoulders and buffered bike lanes.
Passing: this entails same-direction encounters. The definition is related to the hindrance concept.
Quality of service: the concept demonstrates how well a transport facility works from the user's perspective.
Service measures: the variables derive from different performance measures to reflect the quality of the facility.
Trajectory: series of x-y coordinates of road users at each moment.
Types of e-bikes: there are three types of e-bikes, including pure e-bikes, power-assisted e-bikes (i.e. pedelecs) and a combination of the first two types.

Abbreviations/Acronyms

IA: Influence area

BLOS: Bike level of service

BN: Bayesian network

COVID-19: Coronavirus disease of 2019

E-bike: Electric bike

ELOS: Electric bike level of service

E-scooter: Electric scooter

HCM: Highway Capacity Manual

LOS: Level of service

Peri-pandemic: A period of time during the outbreak of COVID-19

PLOS: Pedestrian level-of-service

Post-pandemic: A period of time after the outbreak of COVID-19

Pre-pandemic: Normal situation (implies the situation before the COVID-19 pandemic)

QOS: Quality of service

1. Introduction

The transport system is an indispensable part of daily life which bridges different sectors of society. Social welfare and economic upswing have revolutionised the transport system over recent decades, and the complexity underlying travel behaviour has increased (Bifulco, Cartenì, & Papola, 2010). The need to accommodate various activities in multiple destinations shapes the travel demand carried out by both motorised and non-motorised modes of transport. Dependence on motorised vehicles is associated with various societal, environmental and health concerns (Sener, Eluru, & Bhat, 2009). For example, the physical inactivity of road users, which may stem from using motorised vehicles, contributes to adverse health consequences, such as obesity (Bell, Ge, & Popkin, 2002).

Active mobility (non-motorised modes) has alleviated the aforementioned disadvantages of motorised vehicles, and in turn, contributed to the mission of sustainable societies. Active mobility provides extensive sets of benefits, such as increasing the physical activity of users (health benefits), cost-effectiveness and enabling space-saving for infrastructure compared to other modes of transport (Markvica, Millonig, Haufe, & Leodolter, 2020). In addition, active mobility reduces greenhouse gas emissions and contributes to congestion management (Hung & Lim, 2020). Thus, different policies are focusing on improving and sustaining the role of active mobility ('Swedish law for e-bikes', 2018).

The political move towards the integration of active mobility in the transport system indeed facilitates the ridership of this mode of transport. However, there is a dire need for scientific analysis of this mode of transport to provide comfortable mobility for its users (Kazemzadeh, Laureshyn, Winslott Hiselius, & Ronchi, 2020). Each mode of transport has specific characteristics and consequently requires a dedicated analysis. For instance, cycling and walking are both categorised as active mobility, but their travel behaviours are extensively different. This argument can be extended to comparable modes, such as bikes and electric bikes (e-bikes), which have similar size and shape; however, their diverse operational characteristics (e.g. speed, acceleration and deceleration) impede the applicability of similar analyses for these modes. The unique characteristics of each mode of transport reinforce the crucial need for a specific set-up for the assessment of the user's experience and, consequently, comfort analysis (HCM, 2016). The evaluation and improvement of the user's experience in active mobility have several advantages for users, planners and society. From the user's perspective, more comfortable transport facilities lead to a more enjoyable trip. Moreover, understanding the user's experience facilitates the planning, evaluation and management of the transport system for planners. Consequently, serving transport facilities with high quality may contribute to increasing active mobility and improving the environmental issues caused by motorised vehicles. Thus, research on the user's experience is a current need specifically for certain transport modes, such as e-bikes. This is due to the rapid increase in e-bike ridership and the lack of comprehensive research regarding their users' experience (Fishman & Cherry, 2016). To address the aforementioned knowledge gap, this thesis provides scientific evidence for both the travel behaviour and riding characteristics associated with e-bikes, which could be considered as a foundation for the analysis of their users' experience and consequently their perceived comfort.

Road user's experience

The concept of the *user's experience* has been widely employed in various research domains, such as human-computer interaction, product design, social psychology, marketing and traffic engineering (Kazemzadeh, Camporeale, D'Agostino, Laureshyn, & Winslott Hiselius, 2020; Nicólas, Carlos, & Aurisicchio, 2011; Toms, Dufour, & Hesemeier, 2004). Each research domain has specific characteristics, and therefore, the evaluation of the user's experience is context dependent, dynamic and subjective (Law, Roto, Hassenzahl, Vermeeren, & Kort, 2009). The aforementioned characteristics of the user's experience increase the complexity underlying the assessment of the road user's experience.

An in-depth understanding of the user's experience would provide valuable information for each domain and enable the adoption of suitable policies accordingly. For instance, in marketing, knowledge on the user's experience with a specific product could help providers focus on specific aspects of goods, leading to increased user satisfaction and subsequent recommendations of the product. Similarly, in the transport domain, understanding road users' experience contributes to providing more comfortable mobility for users, increasing their travel satisfaction and consequently sustaining the ridership of the envisioned modes (Kazemzadeh et al., 2020). As mentioned earlier, understanding road users' experience in active mobility is crucial due to the importance of this mode in alleviating societal issues such as air pollution and health concerns. Therefore, there is a dire need to evaluate and, eventually, improve the user's experience of this mode of transport.

Within the realm of active mobility, different concepts such as safety, stress, comfort and various indices (e.g. friendliness and suitability) have been used to depict the road user's experience (Lowry, Callister, Gresham, & Moore, 2012). The following section provides a few examples of concepts related to the understanding of the road user's experience in active mobility.

Safety is a primary objective of all modes of transport and can be clustered into objective and subjective types. Objective safety demonstrates the number or risk of accidents or injuries; alternatively, subjective safety describes perceived (feelings of) safety (Sørensen & Mosslemi, 2009). A vast body of literature has been focused on the subjective and objective safety of cyclists (Pokorny & Pitera, 2019a, 2019b; Von Stülpnagel & Lucas, 2020). Moreover, an extensive body of research related to safety has been conducted for different vulnerable road users, such as bike riders, e-bike riders and pedestrians (Langford, Chen, & Cherry, 2015; Malin, Silla, & Mladenović, 2020). For instance, safety indicators such as time to collision and post encroachment time exclusively evaluate safety concerns for cyclists (Johnsson, Laureshyn, & De Ceunynck, 2018).

In line with previous research, the concept of stress has been employed in cycling research to investigate the user's experience. For instance, Sorton and Walsh (1994) suggested that motorised vehicle traffic volume, motorised vehicle speed and curb lane width are important variables to assess cyclists' level of stress, the so-called Bicycle Stress Level index. Mekuria et al. (2012) proposed an index for the evaluation of cycling stress based on variables such as number of lanes, speed limit and bike lane width.

Furthermore, the concept of comfort has been introduced in the cycling field to evaluate the road user's experience. As a case in point, Abadi and Hurwitz (2018) conceptualised cyclists' perceived level of comfort based on different variables such as traffic flow, pavement markings and traffic signs. Li, Wang, Liu, Schneider and Ragland (2012) considered a different set of variables, including the width of the cycling path, the presence of a bus stop and the flow rate of cyclists. Along with the aforementioned concepts, different indices such as suitability and friendliness have been used to assess the road user's experience and, consequently, the comfortability of the cycling mode (Lowry et al., 2012).

As a result, a variety of concepts and indices have been introduced and implemented over the last three decades in the field of cycling to measure the road user's experience and the performance of transport systems (Kazemzadeh, Laureshyn et al., 2020). One crucial fact in this area is that the choice of concept by which to evaluate the road user's experience could be context-based and that one index may not necessarily be suitable in similar cases. This point is also highlighted within the Highway Capacity Manual (HCM, 2016):

"There are many ways to measure the performance of a transportation facility or service – and many points of view that can be considered in deciding which measurements to make. The agency operating a roadway, automobile drivers, pedestrians, bicyclists, bus passengers, decision makers, and the community at large all have their own perspectives on how a roadway or service should perform and what constitutes "good" performance. As a result, there is no one right way to measure and interpret performance".

Consequently, researchers, planners and decision-makers have the freedom to select a method by which to evaluate the road user's experience based on the context of their projects.

Level of service as a tool to understand road users' comfort

An in-depth understanding of the quality of service (QOS) provided by the transport system from the user's perspective is a needed step towards the analysis of the road user's experience and, subsequently, the user's comfort. Level of service (LOS) is a method through which to quantify the performance measure which represents the QOS (HCM, 2016). The concept of LOS has been used in the transport field since 1965 (HCM, 2010). The mission of LOS could be described as methods by which to illustrate the user's experience based on different transport modes (e.g. by car, on foot and using bikes) and transport infrastructure components (e.g. link and node). Therefore, LOS is often reported based on each mode of transport (HCM, 2016). In early versions of the HCM (e.g. 1965), the manual's focus was mainly on motorised vehicles. However, the rapid increase in the usage of active mobility across the world has highlighted the importance of considering bike riders and pedestrians in the LOS procedure. The more recent versions of the HCM (e.g. 2016) provide a dedicated process for evaluating bike and pedestrian LOS (PLOS) studies. However, active electromobility, such as e-bikes and electric scooters (e-scooters), is neither considered in the modelling procedures of other forms of active mobility nor regarded as a separate mode of transport. The lack of considering modes such as e-bikes risks underestimating their users' requirements and may affect their ridership in the long run.

Moreover, within a similar concept of LOS, different variables and study set-ups can be selected based on the researcher's opinion and the project's features. For instance, the interaction of road users could be considered a fundamental part of the methodology for the assessment of bike LOS (BLOS; Botma, 1995). However, other variables such as roadside landscape and on-street parking have also been used in the modelling procedure of BLOS (Jensen, 2007). Among all the aforementioned concepts, LOS is a well-established concept within the field of active mobility and has been successfully applied in the BLOS research domain to measure road users' comfort.

LOS has several applications in different domains. First, the retrieved variables and the association among them (based on each transport mode) can be useful for designing facilities. Second, it provides useful information for roadway agencies in controlling the QOS of different transport infrastructures. Third, the delivered information can be used to prioritise maintenance programmes based on the estimated LOS for different facilities. It is worth noting that in the bigger picture, LOS addresses three types of analysis based on its applications, namely planning and preliminary engineering analysis, design analysis and operational analysis (HCM, 2016). Altogether, LOS has different applications based on the predefined study set-up and the context of the research. The set-ups can be used for QOS evaluations of either new or existing facilities. The applications of LOS suggest that this index is a promising tool to reflect the road user's experience for different modes of transport. Therefore, there is a need to pave the way for developing a dedicated LOS index for e-bikes due to their rapid adaptation in mobility.

E-bike as a mode of transport

An e-bike is equipped with an electric motor and thus requires less physical exertion compared to bikes. The initial version of the e-bike was introduced in the 1890s in the US (Hung & Lim, 2020). Since then, different models and commercial designs have been proposed and used across the world. E-bikes can be categorised according to three types of power source, including pure e-bikes, power-assisted e-bikes (i.e. pedelecs) and a mixture of the first two types (Hung & Lim, 2020). The type of e-bike referred to in all the studies included in this thesis, is the second type (pedelec). This is due to the prevalence of this type across the world and its functionality as an active mode of transport. More information related to the different types of e-bikes and their characteristics is provided in section 4.3, 'Bike vs. e-bike', of Paper 1.

E-bikes are recognised as one of the fastest-growing transport modes across the globe. As an example, in 2015, over 40 million e-bikes were sold throughout the world, and the trend is expected to increase (Salmeron-Manzano & Manzano-Agugliaro, 2018). The fast-growing trends of e-bike usage call for more extensive research to evaluate its users' experience. This is due to the fact that e-bikes provide different sets of advantages, which work to sustain its ridership in the long run.

E-bikes have revolutionised mobility across the globe with promises to support the sustainability agenda. Indeed, similar to other modes of transport, e-bikes could also have some disadvantages, such as their heavy weight, high initial investment and limited battery range (Van Cauwenberg, De Bourdeaudhuij, Clarys, de Geus, & Deforche, 2019). However, the e-bike's advantages compared to vehicles that operate with fossil fuels render the advantage and importance of this transport mode. Understanding the merits of e-bikes highlights the dire need to study different aspects of this mode of transport. As mentioned earlier, e-bikes provide varied sets of benefits which can motivate dedicated studies to scrutinise the different aspects of this transport mode.

E-bike level-of-service research domain

Regardless of the long history of the usage of e-bikes, the scientific evidence regarding the e-bike riding experience is meagre. This issue might stem from the fact that the similar size and shape of e-bikes and bikes imply the applicability of BLOS for the e-bike LOS (ELOS) research. However, the different travel behaviours and riding characteristics associated with bikes and with e-bikes make the transition of BLOS to ELOS questionable. Therefore, ELOS requires a dedicated modelling procedure to depict a realistic picture of the e-bike user's experience.

To date, there is no research that comprehensively addresses ELOS. Based on a recent literature review in the field of BLOS, e-bikes are considered in only a few BLOS modelling studies (Kazemzadeh, Laureshyn et al., 2020) For instance, Bai, Liu, Chan and Li (2017) estimated BLOS for dedicated bike facilities. It was claimed that e-bike and e-scooter riders experience more discomfort compared to bike riders. The different riding characteristics related to bikes and to e-bikes, such as speed regimes, could impose discomfort for both parties, and the consideration of e-bikes in the BLOS indices could yield a more realistic picture of bike riders' experience. Simultaneously, few studies have elaborated on the travel behaviour of e-bike riders to advance comfort or ELOS indices. As an example, Liu and Suzuki (2019) presented the concept of e-bike applicability. The concept is defined based on the change regarding comfort in relation to the introduction of e-bikes. Section 4.2, 'E-bike comfort research', of Paper 1 discusses in detail the e-bike research comfort domain. Nevertheless, there is a dire need to evaluate ELOS based on the different configurations of transport networks.

Knowledge gaps

An in-depth understanding of the comfort provided by transport facilities from the user's perspective – the user's experience – is a key part of the evaluation, analysis and management of transport systems. The concept of LOS is a powerful tool for quantifying the level of comfort provided by transport facilities from the user's perspective (HCM, 2010).

The initial focus of the LOS concept was on motorised vehicles, followed by active mobility. Active mobility, including cycling, movement on foot, e-bikes and e-scooters, is an essential part of the transport system. BLOS and PLOS are the primary adaptation of the LOS concept in the active mobility realm. For example, BLOS has been widely studied over the last three decades since the first study by Davis (1987). The stream of research in BLOS has scrutinised different aspects of transport facilities from the bike rider's perspective, including on- and off-road facilities. The applications of BLOS can also be classified base on transport components (i.e. node, link and network).

The comfort provided by active electromobility has revolutionised the different aspects of mobility and has converted this mode of transport to an indispensable part of active mobility. Simultaneously, the unprecedented COVID-19 pandemic and restriction on the use of public transport contributed to highlighting the potential applications of e-bikes for long-distance trips. However, to date, the research stream related to the understanding of e-bike comfort and consequently ELOS is sparse. The lack of this knowledge might affect the role of e-bikes in mobility and influence the user's experience. The aforementioned situation highlights the importance of understanding e-bike users' comfort to integrate this transport mode into mobility.

The different characteristics of e-bike riding compared to other active mobility modes (e.g. bikes and pedestrians) are outlined in this section, which limits a direct adoption of BLOS or PLOS for ELOS. For example, the speed regime of e-bikes is quite different compared to that of bikes. These speed differences can range from 2 to 9 km/h (Kazemzadeh & Ronchi, 2021). Moreover, the speed regime of an e-bike is different to the case of pedestrians. Thus, BLOS and PLOS are potentially not directly applicable to e-bikes. Consequently, the high-speed differences between e-bike users and pedestrians can be expected to impose the highest level of discomfort for e-bike riders and pedestrians in off-street facilities, which calls for an exclusive modelling procedure. Furthermore, the riding characteristics associated with e-bikes, such as acceleration and deceleration, are different from those related to bikes. This implies that e-bike riders experience different levels of comfort compared to bike riders.

In addition, the power-assisted riding system of e-bikes enables riders to plan for long-distance trips. The experienced comfort of riding can be different based on short- and long-distance trips. Also, the e-bike has a strong application in utilitarian trips (along with recreation). Different trip purposes imply specific considerations for the quantification of riders' comfort.

Despite the aforementioned differences in travel behaviour and riding characteristics associated with e-bikes compared to those of other vulnerable road users (e.g. bike riders and pedestrians), there is no comprehensive tool to quantify the comfort, or lack thereof, provided by transport facilities from the e-bike rider's perspective. The usage of the developed methodologies for BLOS or PLOS risks underestimating the riding characteristics related to e-bikes.

The lack of tools (i.e. ELOS) for the quantification of perceived comfort from the e-bike rider's perspective challenges both users and planners. From the rider's point of view, users may experience riding with a lower intended QOS. The absence of ELOS limits the ability of planners to have a clear picture of e-bike riders' comfort and, consequently, their requirements. The aforementioned shortcomings in the assessments of e-bike riding comfort may result in providing low-quality service for users and consequently decrease the ridership of this mode of transport.

As mentioned in previous sections, a review of the literature both in the bike and e-bike research domains suggests that there is limited research in this field that has either considered e-bikes in BLOS methodology or has developed a dedicated ELOS concept (Kazemzadeh & Ronchi, 2021). Nevertheless, a major challenge in the evaluation of active mobility QOS is the lack of consideration of e-bikes and e-scooters in the estimation process.

Purpose, aims and objectives

The principal goal of this thesis is to provide knowledge related to the importance of research on e-bike users' experience and pave the way for research on the comfort of this mode of transport. Thus, the overarching aim of the thesis is to provide knowledge of how ELOS could be developed. To fulfil the aforementioned aim of the thesis, four specific objectives are defined as follows:

Objective 1: to explore e-bike travel behaviour and e-bike riding characteristics and the applicability of LOS indices from other modes of transport for e-bikes

Objective 2: to explore e-bike users' and nonusers' comfort concerns

Objective 3: to investigate the interaction of the e-bike with pedestrians in off-road facilities (e.g. sidewalks)

Objective 4: to evaluate the imposed discomfort of e-bike users due to the presence of pedestrians

Structure of the thesis

This thesis contains eight chapters and one appendix. The appendix consists of four articles. Each chapter of the thesis, along with the appended articles, provides information on how ELOS could be developed. The chapters provide a summary of information on the development of ELOS, while a detailed procedure and analysis is presented in each appended paper, respectively.

Chapter 1 (Introduction) presents a brief background of active mobility and identifies the research problem. Then, knowledge gaps, research aim, objectives and delimitations are summarised. The structure of the thesis is presented in Chapter 1.

Chapter 2 (Background) documents general information related to the adopted theoretical framework and the concept of LOS. The chapter continues by providing information related to BLOS. Then, the chapter provides the workflow for the development of ELOS.

Chapter 3 (Methodology) provides the motivations related to the employed methods. The chapter presents a summary of the data collection, data processing and data analysis for each paper.

Chapter 4 (Results) deals with the general results of the studies for each paper.

Chapter 5 (Discussion) presents the linkages of the articles towards developing ELOS. The provided discussions link all findings of the thesis.

Chapter 6 (Applications) includes the main applications of the thesis related to the development of ELOS.

Chapter 7 (Future Research Directions) includes the author's reflections on the content of the research and the topic of ELOS and advances some research directions for future studies in this field.

Chapter 8 (Conclusion) concludes the thesis and provides a general picture of the thesis.

Delimitations of the thesis

The central focus of the thesis (on the tactical level of analysis) is on the imposed discomfort of e-bike users due to the presence of pedestrians in off-road facilities. E-bikes and pedestrians have the most different of the speed regimes in off-road facilities, and understanding the underlying discomfort was deemed the most relevant analysis of comfort from the e-bike rider's perspective. For this reason, an evaluation of the interaction between e-bikes and other vulnerable road users (e.g. bikes and e-scooters) is excluded from this thesis. Providing a holistic view of the e-bike rider's (dis)comfort requires an evaluation of the different types of road users. Moreover, all studies included in this thesis are based on the Swedish context. This point should be considered while analysing the findings of the work given the infrastructural, economic, climate, weather conditions, sociodemographic and cycling culture variables of the country. This is deemed to impact the generalisability and transferability of the findings of this thesis.

2. Background

An in-depth understanding of the user's experience is a main component of planning, design and management of transport systems. As a result, different theoretical frameworks, such as customer satisfaction theory, the theory of planned behaviour, perceived QOS and hierarchical road users' tasks and behavioural intentions, have been employed in previous transport studies (Ajzen, 1991; de Oña, Machado, & de Oña, 2015; Fu & Juan, 2017). As an example, the main idea of the theory of planned behaviour is that the actual behaviour of a person is determined by their behavioural intention. This behaviour is a function of attitude, subjective norm and perceived behavioural control (Ajzen, 1991). This theory has been applied to different modes of transport, such as public transport and active mobility (Fu & Juan, 2017). Moreover, various components of the user's behaviour have been studied in previous cycling research (Gatersleben & Appleton, 2007; Gatersleben & Uzzell, 2007).

Psychological attitudinal theories could also advance the conceptual foundations for analysing road users' travel behaviour (Heinen, Maat, & Wee, 2011). In a holistic picture, the intention of transport system users is influenced by the quality of the transport system (Fu & Juan, 2017). This feature motivates the study of different concepts such as comfort, stress and safety to understand road users' behaviour and reveal their intentions and attitudes. As a result, different behavioural and psychological models and frameworks have been developed to explore road users' driving and riding behaviours. For instance, the road user's task and behaviour could be classified into three categories consisting of strategical (planning), tactical (manoeuvring) and operational (control) levels (Michon, 1985). The strategical level deals with long term-variables such as trip purpose, route choice, trip cost and modal choice. This level of behaviour also contains some considerations related to aesthetic satisfaction and comfort of mobility. Tactical behaviour is placed on the next level of the model. At this level, manoeuvres take place, which include tasks such as obstacle avoidance, overtaking (passing), turning, etc. The most refined level is the operational level of behaviour and includes automatic action patterns. This level includes actions with the shortest time span compared to those in the previous levels. Investigating road users' strategical and tactical behaviour contributes to understanding their intention (Kircher, Ahlstrom, Palmqvist, & Adell, 2015), which is a valuable input for planners and policy-makers. This type of framework has been widely applied in different disciplines, such as the pedestrian dynamic, cycling comfort and risk analysis (Hoogendoorn &

Bovy, 2004; Van Der Molen & Bötticher, 1988; Kazemzadeh et al., 2020). As the research on ELOS is in its nascent stage, an in-depth understanding of the strategical and tactical levels opens new avenues of research on different aspects of this mode of transport.

This thesis aims to investigate both the strategical behaviour (travel behaviour) and tactical behaviour (riding characteristics) of e-bike riders. From the strategic perspective, the main purpose is to understand trip purposes, modal choices and variables that are associated with e-bike riding comfort (see Paper 1 and Paper 2). This level of analysis also highlights the importance of ELOS development and provides an overview of the research topic. From the tactical standpoint, the manoeuvring characteristics of e-bike riders in pedestrian crowds are analysed (see Paper 3 and Paper 4). The analysis is performed to quantify e-bike riders' interactions and comfort based on the concept of hindrance (i.e. passing and meeting events). The following sections provide a brief background regarding the state of the art of the e-bike and BLOS research domains.

LOS for each mode of transport

Research into the understanding of the road user's experience requires dedicated analysis based on the specific characteristics of the underlying mode. This is due to the fact that the operational characteristics of each mode are different (HCM, 2016). For instance, cycling requires physical exertion, which is not the case for motorised transport modes. As a result, the same variable (e.g. delay) can lead to different LOS results for different transport modes. The assessment of LOS based on each transport mode contributes to evaluating multimodal comparisons of designing options. This fact is crucial as the use of a mixed LOS risks overlooking QOS deficiencies that deter the use of active mobility, especially if the mixed LOS is weighted by the number of modal travellers (HCM, 2016). Therefore, there is a need to define LOS based on each transport mode. Furthermore, different methods can lead to measuring the performance of facilities and the assessment of QOS from different perspectives. This means that the methods can be selected based on the project context, policy-makers' opinions and road agency needs. Thus, a single widely accepted method to evaluate and interpret QOS does not exist (HCM, 2016).

Over the last three decades, research into BLOS has been comprehensively conducted (Kazemzadeh, Laureshyn et al., 2020). The well-established BLOS research domain is particularly useful for developing ELOS in off-road facilities due to the presence of similar road users. Indeed, the different travel behaviours and riding characteristics associated with e-bikes compared to bikes, such as trip purpose, speed regime and acceleration/declaration, limit the direct adaptation of BLOS for ELOS. The series of differences between bikes and e-bikes requires adjusting the BLOS variables for ELOS development and introducing new sets of variables to depict a realistic picture of the travel behaviour with e-bikes and consequently the user's experience.

Different approaches can be followed for the development of ELOS. For instance, an in-depth understanding of travel behaviour with e-bikes can be used for considering (*introducing*) new variables/insights for developing ELOS. Furthermore, the procedure of *adopting* BLOS modelling approaches (e.g. selection of variables and modelling procedure) can be considered as addressing the specific riding characteristics related to e-bikes in the development of ELOS (see Paper 1).

Different modelling approaches, such as psychological, theoretical, hypothetical and simulation-based types, can also contribute to the development of ELOS. However, simulation-based studies require extensive datasets for calibration and validation to provide a reliable result. Proposing a theoretical framework (as suggested by this thesis) could facilitate the usage of other methodological approaches (e.g. including simulation-based approaches) for developing ELOS. In this chapter, specific travel behaviours related to the use of e-bikes, such as trip purpose and modal choice, are discussed, which contribute to introducing new sets of variables for developing ELOS. This level of information can feed the discussion on the strategical level of travel behaviour analysis with e-bikes. Moreover, at the tactical level, one of the most frequent methods of BLOS modelling (i.e. the concept of hindrance) is discussed, which can serve as a step towards adjusting method/variables for developing ELOS. Thus, both tactical and strategical levels of analysis provide relevant information for the development of ELOS.

Travel behaviour and riding characteristics related to the e-bike

Research into the travel behaviour associated with e-bikes lags far behind that of the bike field. An in-depth understanding of the travel behaviour and riding characteristics related to e-bikes paves the way to analyse e-bike riders' experience. In this section, the different aspects of the travel behaviour and riding characteristics associated with e-bikes that are deemed to facilitate the development of ELOS are discussed. The main topics covered in this section are as follows:

- Trip purposes of e-bike riders
- The scale of e-bike substitution for other transport modes
- Riding characteristics related to e-bikes

Trip purposes of e-bike riders

The choice of transport modes could be closely related to trip purposes. As discussed earlier, this type of decision belongs to the strategical behaviour of road users. At this level of behaviour, a different set of variables plays a role in the modal choice. As an illustration, the choice of using shared e-bikes for different trip purposes can be different based on diverse variables such as age group, weather conditions and available infrastructures (Campbell, Cherry, Ryerson, & Yang, 2016; Kazemzadeh & Ronchi, 2021). E-bikes have applications for both recreation and utilitarian trip purposes, but the primary use of e-bikes can be associated with utilitarian trip purposes (Bourne et al., 2020). The proposed methodology of BLOS in the HCM considers both commuter and recreational cyclists; however, the methodology does not include e-bikes (HCM, 2016). The ease of riding provided by e-bikes can trigger riders to plan long-distance trips. Understanding users' concerns and requirements based on their trip purposes is significant knowledge for improving the ridership of e-bikes. For instance, if riders plan a long-distance trip for utilitarian purposes (e.g. commute to work), they may have different expectations for end-of-trip facilities (e.g. shower facilities and lockers) and for roadway infrastructure (e.g. secure parking) compared to the case of recreational trip purposes. As an example, Edge, Dean, Cuomo and Keshav (2018) performed a study in Canada and claimed that e-bikes are significantly more often used for utilitarian trip purposes in contrast to leisure trip purposes. Ling, Cherry, MacArthur and Weinert (2017) reported that e-bikes (compared to bikes) are substantially more often used for utilitarian trip purposes, including commuting and running errands. More information related to the trip purposes of e-bike users is provided in section 5.1, 'E-bike travel behaviour research', in Paper 1. The choice of an e-bike (with consideration of the trip purposes) may also be related to the convenience of using other available modes of transport (Weinert, Ma, Yang, & Cherry, 2007). The extent of substituting e-bikes for other transport modes (e.g. public transport, cars, and bikes) provides useful information in relation to the comfort characteristics of using e-bike as one of the main transport modes (Kazemzadeh & Ronchi, 2021).

The scale of e-bike substitution for other transport modes

Several variables are important for a user to shift from one mode to another, such as relative convenience, comfort, and cost of a mode of transport (see Paper 1). As a result, a mode of transport that has the high QOS could be the choice of users (Fu & Juan, 2017). This fact renders the importance of considering features of similar modes of transport in behavioural studies. As a case in point, the ease of travelling by e-bikes position this transport mode to compete with other transport modes such as public transport, cars, and bikes. On the one hand, e-bike riding requires pedalling, which makes e-bikes as active mobility. On the other hand, the electrically-assisted motor of e-bikes facilitates pedalling, which enable e-bikes to compete with motorised vehicles for long-distance trips. The specification of the modal substitution helps to understand the user's requirements and attitudes.

A vast body of literature has discussed the scale of e-bike substitution for different modes of transport (see section 5.2, 'Substitution scale', Paper 1). For example, it appears evident that the e-bike is a promising mode to substitute for bike and private car journeys (see Paper 1 and Paper 2). A review of the literature suggests that e-bikes can be used as a replacement for public transport as well (Bourne et al., 2020). This scale of substitution could be changed and possibly amplified as the unprecedented COVID-19 pandemic and restriction on the use of public transport has significantly dropped the ridership of public transport (Jenelius & Cebecauer, 2020). The recommendations related to social distancing in the peri-pandemic situation may have a long impact on the modal share of transport, which may increase the ridership of e-bikes. One of the critical points related to this substitution scale is that the comfort of e-bikes could be discussed in relation to the discomfort of using other transport modes.

The research related to e-bike riding comfort can be discussed in two ways. On one hand, it is possible to explore the research related to the comfort provided by using e-bikes, such as saving time and money, enjoying the experience of electrically assisted cycling and enabling the planning of long-distance trips (Plazier, Weitkamp, & van den Berg, 2017; Kazemzadeh & Ronchi, 2021). As an illustration, MacArthur, Dill and Person (2014) reported a wide range of variables related to e-bike riding comfort, such as more cycling, the possibility of long-distance trips and the ability to carry more cargo.

On the other hand, the variables associated with the inconvenience or discomfort of using other transport modes (e.g. public transport) can be analysed. Section 4.2, ‘E-bike comfort research’, of Paper 1 and Paper 2 discusses in detail the e-bike research comfort domain. This category contains variables such as the unreliable schedule of public transport, crowded public transport and the inconvenience of its use. For example, Liu and Suzuki (2019) presented the concept of e-bike applicability. Within their study, travel time and energy expenditure variables were used to compare the comfort of e-bikes in relation to bikes and public transport. They document that the e-bike is applicable in areas of public transport deficiency.

Riding characteristics related to e-bikes

The similarity of e-bikes’ and bikes’ shape and size may imply similar riding characteristics. However, even considering the case of comparable speed for bikes and e-bikes, the riding characteristics of the e-bike are different from those of bikes. As an illustration, speed is a critical variable that has application in different domains, such as safety and comfort. For instance, e-bikes could gain speed up to 25 km/h. Considering the average speed of bikes, there is a 2–9 km/h speed difference that has been documented between bikes and e-bikes. Also, the average weight of e-bikes is 10 kg heavier compared to bikes (Kazemzadeh & Ronchi, 2021; Vlakveld et al., 2015).

Beyond the speed regime differences of bikes and e-bikes, the additional riding characteristics of these modes of transport are diverse. For instance, the acceleration and deceleration characteristics of e-bikes (due to the presence of an electric motor) introduce different riding experiences for e-bike riders compared to bikes. As a result, e-bike riders can travel faster; however, they require a harder brake, and they experience a new level of conflicts and comfort (or lack thereof) compared to bikes (Huertas-Leyva, Dozza, & Baldanzini, 2018). Consequently, the higher probability of hard brakes and sharper acceleration in e-bikes compared to bikes introduces different riding characteristics. Simultaneously, the heavier frame of e-bikes compared to that of bikes highlights the riding differences of these two modes. These nested comfort variables related to the use of e-bikes call for a dedicated ELOS to understand users' concerns. Regardless of all the aforementioned riding characteristics of bikes and e-bikes, these modes of transport are the most similar in terms of mobility. For instance, they have a similar size and shape, share the same transport facilities and have identical traffic enforcement (e.g. helmet and driver's license). Therefore, the well-established research domain of BLOS could be insightful for the development of ELOS.

From vulnerable road users' interactions to BLOS

The concept of the LOS idea – originating with the HCM manual – has been further influenced by different studies across the world (HCM, 2016). Europe, with an extensive cycling culture, had a great influence on the development of the BLOS concept and, eventually, resulted in the introduction of the BLOS concept (i.e. the concept of hindrance) by the HCM. As an example, the development of BLOS for off-road facilities in the HCM is influenced by a Dutch study, Botma's 1995 framework (HCM, 2000). Botma (1995) introduced the concept of the hindrance as a new method by which to quantify the quality of manoeuvring in cycling facilities. This method is based on how a road user's manoeuvring is restricted by other road users. For instance, a pedestrian or a low-speed cyclist can impede faster cyclists on a bike track. This obstacle (e.g. pedestrians) imposes difficulty for fast cyclists, and therefore they need to perform certain manoeuvres to keep the intended speed and avoid collisions. Hence, the concept of hindrance, which depicts this situation, is associated with cyclists' QOS and, subsequently, BLOS.

The hindrance concept mainly deals with quantifying the case where a cyclist overtakes (passes) or meets a slower vulnerable road user. Different types of events, including passing (same-direction encounters) and meeting (opposite-direction encounter), have been considered in various studies in the literature. The concept of hindrance has been suggested as a method for BLOS analysis by the HCM from its version in 2000 up to now (the latest version of HCM, 6th edition, 2016). As an example, the HCM (2016) mentions that the presence of other road users (e.g. cyclists and pedestrians) increases the riding delay, decreases capacity and restricts the freedom of manoeuvres for a bike rider. Table 1 presents some research highlights that have used the hindrance concept for the quantification of the cycling

QOS. More details related to different methods and studies associated with BLOS are provided in Table A1 and Table A2 of the study by Kazemzadeh et al. (2020).

The concept of hindrance is one of the predominant methods for the analysis of BLOS in off-road facilities. The adaptation of this concept can be useful for the assessment of the e-bike rider's comfort in off-road facilities. Indeed, an in-depth understanding of e-bikes' interactions in off-road facilities requires a varied combination of road users. However, the quantification of e-bike-pedestrian interactions can serve as a first step towards an understanding of the e-bike rider's comfort in relation to the modes which have the greatest speed difference.

Table 1
Previous Studies Based on the Hindrance Concept

Author(s) (Year)	Region	Road users	Interactions
Botma and Papendrecht (1991)	The Netherlands	Bike & moped	Passing & paired riding
Botma (1995)	The Netherlands	Bike & pedestrian	Passing & meeting
Virkler and Balasubramanian (1998)	The US/ Australia	Hiking, biking, & jogging	Passing & delayed passing
Khan and Raksuntorn (2001)	The US	Bike	Passing & meeting
Li, et al., (2013)	China	Bike	Passing
Xu, Liu, Song, and Jin (2018)	China	Bike & e-bike	Passing
Chen, Yue, and Han (2018)	China	Bike & moped	Passing
Yuan, Daamen, Goñi-Ros, and Hoogendoorn (2018)	The Netherlands	Bike	Passing, meeting & crossing
Nikiforiadis, Basbas, and Garyfalou (2020)	Greece	Bike & pedestrian	Passing & meeting

Are other LOS indices applicable for developing ELOS?

The aforementioned travel behaviour and riding characteristics associated with e-bikes increase the complexity underlying the assessment of e-bike riding comfort. As mentioned in previous sections, e-bikes have the travel behaviour and riding characteristics of both motorised and non-motorised vehicles. This is due to the required pedalling efforts for e-bikes, similar to bikes, and the enabled planning of long-distance trips, similar to motorised vehicles (e.g. public transport). Nevertheless, the long history of LOS related to other modes of transport (e.g. bikes, pedestrians and public transport) could be insightful for the development of ELOS.

As an example, BLOS could provide insight into the development of ELOS. This is because e-bikes have a similar size and shape to bikes, and they often share similar facilities. However, as mentioned in the previous section, the different travel behaviours and riding characteristics associated with e-bikes (e.g. utilitarian trip purposes, acceleration and deceleration) compared to bikes prevent the direct applicability of BLOS for developing ELOS. This argument could also be extended for the LOS of other modes of transport, such as motorised vehicles. For instance, variables related to the quantification of public transport LOS, such as the crowding level, air conditioning and cleanliness of a bus (Eboli & Mazzulla, 2011), are not applicable for e-bikes. However, both e-bikes and public transport enable users to plan long-distance trips.

The overall differences between e-bikes and other modes of transport call for a dedicated evaluation process of e-bike riders' comfort. This is due to the specific travel behaviour and riding characteristics of e-bikes, which position this mode of transport as a unique approach to mobility. Thus, an *ad hoc* framework is required for the analysis of the e-bike riding experience and its requirements and comfort. This is important as an in-depth understanding of e-bike riders' requirements and, eventually, the improvement of their facilities contribute to sustaining the ridership of e-bikes in mobility. Section 4.3, 'Bike vs. e-bike', of Paper 1 discusses this subject in detail. The specific travel behaviour of e-bikes in different situations (e.g. pre- and peri-pandemic) and its relation to other modes of transport are further discussed in Paper 2. The following section advances the workflow for the development of a preliminary framework of ELOS. More details related to the workflow of the framework and the characteristics of the proposed framework are provided in section 6, 'The conceptual framework for ELOS development', in Paper 1.

The workflow of developing an ELOS framework

The development of ELOS could be facilitated by proposing a framework that can serve as a roadmap for conducting different types of research. The progression of different studies concerning the development framework can be followed by understanding the travel behaviour and riding characteristics related to e-bikes. From the strategic perspective (travel behaviour point of view), the different travel behaviours of e-bike users is discussed, and the role of e-bikes in various situations (e.g. pandemics) is explored. The information regarding travel behaviour is deemed to feed the discussion on different research domains related to the development of ELOS, such as riding characteristics.

As e-bikes could be operated in off-road facilities where all vulnerable road users are present, the interaction of e-bikes with other road users provides a realistic picture of the e-bike rider's comfort. Therefore, understanding the interactions of e-bike riders in shared mobility is considered as a step for the adjustment of the BLOS modelling procedure for the development of ELOS. This level of analysis provides fundamental knowledge for exploring the tactical behaviour of e-bike riders.

Indeed, both domains (travel behaviour and riding characteristics) are inherently connected and needed for the development of ELOS. For example, the travel behaviour domain guides the modelling procedure of the riding characteristics studies. Figure 1 represents the workflow of the framework.

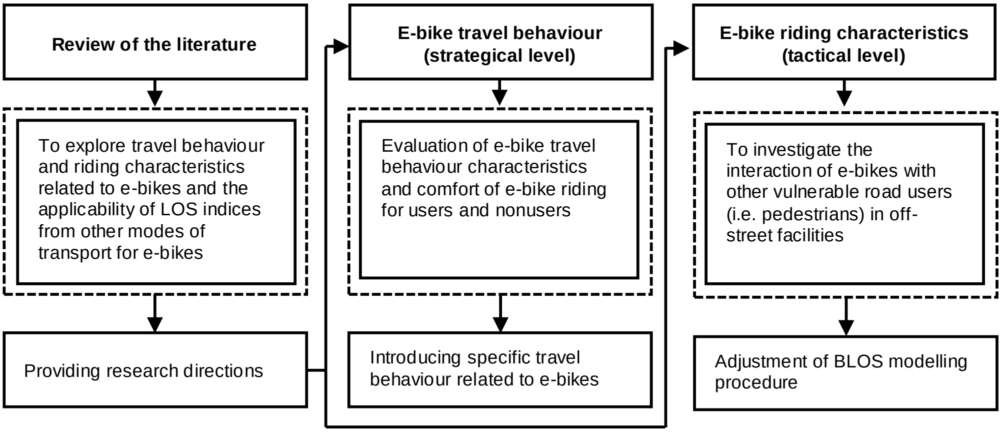

Figure 1 The workflow of the framework developed for the analysis of ELOS

Each paper of this thesis fulfils some of the objectives of this work and contributes to the development of ELOS. The thesis as a whole (all studies together) serves as a holistic image of the development of ELOS. It should be noted that the detailed applications of each study are presented in the respective papers.

To provide a framework for developing ELOS, both the strategical and tactical levels of analysis are considered. This is due to the fact that the e-bike research is in its nascent stage, and the aforementioned levels of analysis are deemed to pave the way for the further development of ELOS. From the strategical perspective, different research domains related to the road users' comfort were explored, which can be considered as the first step in the workflow of the framework (see Figure 1). In the second step, the travel behaviour related to e-bikes was further explored (and compared to other similar modes, such as cycling). These first two steps provide information related to the travel behaviour of e-bikes (i.e. strategical level of analysis), which are the needed steps towards the development of ELOS. Based on exploring the travel behaviour of e-bikes (step 1 and step 2), the specific riding characteristics associated with e-bikes in shared mobility (e.g. e-bike interactions with pedestrians) were further investigated (third step). This phase of analysis (third step) provides the tactical level of information for the development of ELOS. This part of the framework can also be helpful in exploring the applicability of similar modelling procedure (e.g. BLOS) for the development of ELOS.

Based on the overarching aim of the thesis, the individual studies (appended papers) are designed to pave the way for developing ELOS (see Table 2).

Table 2
Towards an E-bike Level-of-service Analysis

Research objectives	Paper 1	Paper 2	Paper 3	Paper 4
To explore e-bike travel behaviour and its riding characteristics and the applicability of LOS indices from other modes of transport for e-bikes	✓			✓
To explore the e-bike user and nonuser travel behaviours and their comfort concerns (and the possibility of modal substitution) and usage	✓	✓		✓
To investigate the interaction of e-bikes with other vulnerable road users (i.e. pedestrians) in off-street facilities	✓		✓	✓
To evaluate the imposed discomfort of other vulnerable road users on e-bike riding	✓	✓	✓	✓

Each paper provides information for both the travel behaviour and riding characteristics perspectives of ELOS development. For example, Paper 1 investigates the different travel behaviours and riding characteristics related to e-bikes, which highlights the e-bike's position from both travel behaviour and riding characteristics perspectives towards the development of ELOS. Similarly, Paper 4 documents information related to the travel behaviour of e-bikes and the quantification of e-bike riding characteristics.

3. Methodology

A comprehensive analysis of ELOS requires extensive research to explore different aspects of this transport mode. As mentioned in previous chapters, the research on the different aspects of the e-bike mode of transport is in its nascent stage. Therefore, there is a dire need to investigate both the travel behaviour (strategical level) and the riding characteristics (tactical level) associated with e-bikes. In response to this need, different methods, including qualitative and quantitative approaches, could be applied. Both quantitative and qualitative methods have their own advantages and disadvantages. Consequently, the selection of a suitable method based on the context of a study increases the reliability and generalisability of the results. In this thesis, both methods have been used for data analysis. In brief, qualitative methods are applied for the data analysis of e-bike travel behaviour (see Paper 1 and Paper 2), and quantitative methods have been used to analyse e-bike riding characteristics (see Paper 3 and Paper 4) in this thesis. A visual summary of the methods employed in this thesis is presented in Figure 2.

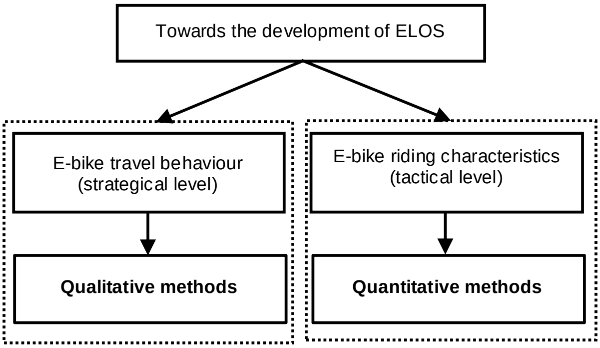

Figure 2 Overview of the methods applied in this thesis

The choice of methods could be varied based on different considerations, such as research questions, advancement of the literature, research context, time constraints and project budget. In this thesis, the strategical level of analysis is mainly based on qualitative set-ups, and quantitative methods are the primary approach to analysing the tactical level of analysis (see Figure 2). In sum, qualitative methods (e.g. systematic reviews – the review can also have a quantitative set-up) could provide a broad and strategical overview of the field. In contrast, a range of the tactical riding characteristics related to e-bikes (e.g. manoeuvring) could be analysed by quantitative analysis. Indeed, other set-ups (different from this thesis) could also be applied for the same research goal. In the following section, the motivations for using each method are provided.

Qualitative set-up: Knowledge related to e-bike users' perceptions, attitudes, modal choice/substitution and travel behaviour is crucial for the development of ELOS. A systematic review can help in assessing the knowledge and gaps related to different aspects of e-bike travel behaviour and riding characteristics. Furthermore, qualitative methods (e.g. in-depth interviews) are a powerful tool that enables interviewees to express their comfort concerns in their own words. Understanding interviewees' opinions/emotions, which addresses the limitation on expressing attitudes in predefined questions, is one of the main advantages of this method's set-up. Moreover, qualitative methods provide behavioural information on a relatively limited sample of the population.

Quantitative set-up: Working with numbers provides a quantifiable outcome for the researcher, which could possibly be directly used in engineering applications. Consequently, quantitative set-ups can possibly provide vital information related to the e-bike rider's interaction in shared mobility. In general, a quantitative set-up mainly relies on a larger sample size, which enables the inclusion of more variables in the data analysis. Simultaneous data collection for a wide range of participants in different regions is one of the crucial advantages of quantitative methods and results in a faster and easier method compared to qualitative set-up. The aforementioned advantages allow a relatively inexpensive data collection (based on the context of the study) in this type of set-up.

Data collection

To move towards the development of ELOS, different methodological set-ups have been selected. On one hand, approaching a new research area requires an evaluation of the state of the art in the field. A systematic review documents the travel behaviour and riding characteristics associated with e-bikes, which can be useful for developing different studies to address the knowledge gaps. The limited knowledge related to the comfort of e-bike users and nonusers (potential users) motivates researchers to study their comfort concerns. This research gap is addressed in qualitative set-ups via an in-depth interview approach. On the other hand, capturing the revealed riding characteristics related to e-bikes (during interactions with pedestrians) contributes to a realistic representation of users' interactions and discomfort in shared mobility. However, discussing possible interactions with other road users (e.g. pedestrians) would be difficult in qualitative set-ups (e.g. interviews). As a result, the quantitative research set-up (including data collection) is used for modelling e-bike riders' comfort based on their real-world interactions, which yields robust results. Table 3 represents an overview of the studies' datasets. The following sections briefly discuss the data collection and data processing of each study.

Table 3
Overview of the Datasets in the Different Studies Included in this Thesis (Data Collection)

Dataset	Paper	Type of study	Date for collection
Peer-reviewed scientific articles	I	Literature review (Web of Science, and Transport Research International Documentation)	November and December 2019, and February 2020
Responses on comfort concerns	II	Interviews	Pre-pandemic situation: January 2020 Peri-pandemic situation: April 2020
Trajectory and sociodemographic data	III and IV	Field experiment	May 2018

Literature review

There is limited knowledge related to e-bike riding comfort, and this knowledge deficiency directly affects the development of tools to analyse users' concerns and, eventually, to develop ELOS. To obtain a comprehensive overview of the literature, both the Web of Science and Transport Research International Documentation databases were searched. The review of the literature aimed to include both the e-bike comfort research and BLOS research domains, which are deemed relevant to the development of ELOS. The aforementioned databases were searched in November and December 2019, and the same process was repeated in February 2020 to include more up-to-date studies.

The motivation for the selected method

Different methods of reviewing the literature, such as expert reviews, meta-analyses, scoping reviews and systematic reviews, can be performed for the purpose of this study. The systematic review method is a rigorous approach to systematically identify scientific evidence and trends and alleviate potential biases in other set-ups, such as the expert review (O'Hagan, Matalon, & Riesenberg, 2018). This method is used to retrieve relevant literature on e-bike riding comfort and evaluate the trend of research in this field. Simultaneously, the BLOS literature was also reviewed as it was deemed relevant for the development of ELOS. The systematic review method was helpful to map e-bike comfort research against existing BLOS research, which may be difficult to perform using other approaches.

Literature review process

Searching the relevant papers for this study had two phases. In the first phase, the literature review study is designed to provide a comprehensive review of the literature related to BLOS, cycling comfort and cycling traffic flow (see Kazemzadeh et al, 2020). This is due to the fact that BLOS research has been highlighted as a promising benchmark for developing ELOS (see Chapter 2). This paper is used as a foundation to further study the travel behaviour and riding characteristics associated with e-bikes. In the next phase, the main focus of the systematic review was e-bike research. The process of reviewing the literature (see Paper 1) entails searching for relevant research related to e-bike travel behaviour (comfort), substitution scale and riding characteristics (e.g. the hindrance concept). In sum, the systematic review was designed to extract both levels of required information for developing ELOS, namely the strategical level (travel behaviour) and the tactical level (riding characteristics).

Interview study

The main aim of this data collection is to explore the comfort and health concerns of e-bike users and nonusers. The reasons for scrutinising health concerns are varied based on the pre- and peri-pandemic situations. In the pre-pandemic situation, the physical activity provided by e-bikes in comparison to motorised and non-motorised modes of transport highlighted the importance of considering e-bikes' health (dis)advantages. Also, the peri-pandemic situation introduces specific health concerns, such as social distancing because of virus transmission, which in turn affected the ridership of different modes of transport (e.g. public transport and cycling). An interpretive description qualitative method is adopted to conduct semi-structured in-depth interviews, and for qualitative content analysis, the inductive approach is employed.

The motivation for the employed method

Research into the understanding of different e-bike travel behaviours is limited. Qualitative methods are powerful tools to reveal the complexity of different aspects of travel behaviour. In the process of the interview, the interviewees can express their opinions related to the characteristics of e-bike riding, which is not constrained by predefined questions of the study. Nevertheless, different practical issues are connected to qualitative research, in particular for interviews. For example, the interviewee may have some problems related to lack of memory and advancing contradictory responses within one single interview (Johansson, 2020; Richards, 1996). Moreover, interviewees may use 'smarter' words in the interview process and present their argument as more than what they actually know regarding the underlying topic (Alvesson & Sveningsson, 2003).

To use the interview method efficiently, a semi-structured interview is selected as a method for this study. In this set-up, the interviewer does not strictly ask predefined questions and instead discusses more open-ended questions (Leavy, 2014). This format of the interview (semi-structured) is possibly the most widespread format of the interview in human and social sciences research (Leavy, 2014). This style of the interview (semi-structured) falls between structured and unstructured interview set-ups. On one hand, the semi-structured set-up (compared to the structured format) allows the interviewee better to engage in the knowledge-producing potentials of dialogue via following up the discussion from a more important angle from the interviewee perspective. Also, the interviewer can more actively participate in the process rather than only asking pre-set questions. On the other hand, compared to an unstructured interview set-up, the interviewer (in the semi-structured set-up) has an active role in adjusting the focus of the interview towards the main interest of the underlying research (Leavy, 2014).

The aforementioned discussion was considered in the selection of the proper method for the interview. Designing different follow-up questions and encouraging interviewees to express their ideas thorough the interview process contribute to improving the inherent shortcomings of interview set-ups. Figure 3 represents the workflow of the data collection (and data analysis).

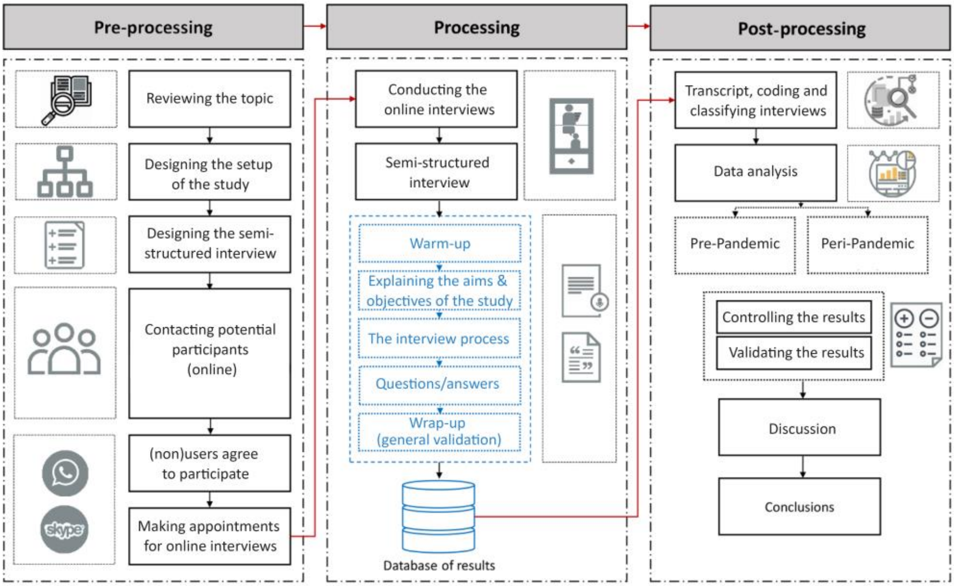

Figure 3 A schematic workflow of the qualitative study

Data collection procedure for the interview study

The data collection of this study was conducted in two phases (two periods of time). The first dataset is based on the period when COVID-19 was not widespread in Sweden (January 2020). This period, which is called the pre-pandemic situation in this thesis, is considered as a normal situation of travelling. On the other hand, the second phase of data collection was conducted in April 2020, in which COVID-19 was widespread worldwide. Participants were selected through different announcements, such as on social media platforms and an announcement at Lund University. The authors also contacted potential participants personally. Twenty-three users and nonusers were interviewed in the case of the pre-pandemic situation. Although all participants were invited to an interview again in the peri-pandemic situation, 12 of these participants agreed to participate again in the second phase of the interview (i.e. peri-pandemic). The sample of the interview considers only Swedish residents as the interview was mainly conducted in the Swedish context.

The collected data and consequently their respective analysis in the pre-pandemic situation provide useful information related to the comfort concerns of e-bike users in their daily life. This procedure is deemed helpful for the development of ELOS as it provides rich behavioural data related to e-bike travel behaviour and specifically user comfort. The extracted travel behaviour aspects related to e-bikes introduced a new set of variables for adjusting the LOS of e-bikes. Furthermore, the peri-pandemic situation introduces different restrictions for travelling with different modes of transport, and consequently, users may have different concerns. These data could help to evaluate the comfort concerns of e-bike riders in pandemics and emergencies and adjust future ELOS indices. The health concerns of e-bike riders are also included in the analysis as the peri-pandemic situation introduced different health concerns related to travel behaviour which might directly affect the user's comfort. Due to the impacts of social distancing, health concerns are crucial for analysing users' concerns. The health concerns addressed in the pre-pandemic situation focus mainly on the provided physical activity of e-bikes for users and their opinions about the health benefits of using an e-bike.

Field experiment

The collected data in the field experiment were used for both interaction analysis (see Paper 3) and comfort modelling (see Paper 4). Although both studies have the same data collection process, the extraction of variables, data processing and modelling procedure are different in these studies. The main purpose of the experiment was to study the riding characteristics of an e-bike rider in pedestrian crowds. As mentioned in Chapter 2, this choice of the experimental set-up is due to the extreme speed difference between e-bike riders and pedestrians in off-road facilities and is in line with the BLOS literature. In order to consider only the impact of pedestrian crowds on e-bike riding characteristics, the experiment was designed in a way to ignore the presence of confounding variables, such as complex road geometry, weather conditions and pavement distress. This consideration was followed based on the early BLOS studies (e.g. Botma, 1995). An in-depth understanding of e-bike riding behaviour in pedestrian crowds provides useful information for developing ELOS specifically for off-road facilities.

The collected data led to three datasets. The first dataset contains the sociodemographic characteristics of participants and their riding experience, which was part of the registration process. This data collection phase was conducted prior to the field experiment. The trajectory of the participants (both pedestrians and e-bike riders) shapes the second dataset of the experiment. This dataset is based on the recordings from stationary cameras. More details related to the cameras, software for data processing (T-Analyst) and trajectories can be found in Paper 3. Finally, the data recorded by the action camera provided the third dataset, which is mainly designed to contribute in matching the trajectories and sociodemographic characteristics of users (dataset 1 and dataset 2). Table 4 provides a summary of each part of the data collection.

Table 4
Overview of the Datasets from the Field Experiment

Dataset	Method	Date for collection
Sociodemographic data	Registration information	March 2018
Trajectory data	Recording road users	May 2018
Face identification	Recording road users	May 2018

The linkage of the trajectory and sociodemographic databases was performed by identifying the participants' faces retrieved from the action camera. The workflow of merging the datasets is represented in Figure 4.

The motivation for the selected method

Experiment-based data collection has been proven to provide detailed traffic data on bike riders and pedestrians (Yuan et al., 2018). Performing this type of data collection also allows consideration of the sociodemographic characteristics of participants, which can be matched with their trajectories. Furthermore, the experimental set-up provides the opportunity to control the intended number of road users, the distribution of participants' characteristics, the flow set-up and the road geometry features. In contrast, distinguishing e-bikes from bikes could be challenging in observational study set-ups due to their similar size and shape as well as the ethical consideration of the high-resolution recording of users. The aforementioned characteristics of experiment-based data collection were the motivation for selecting this method. The following sections provide a summary of the important points related to data collection.

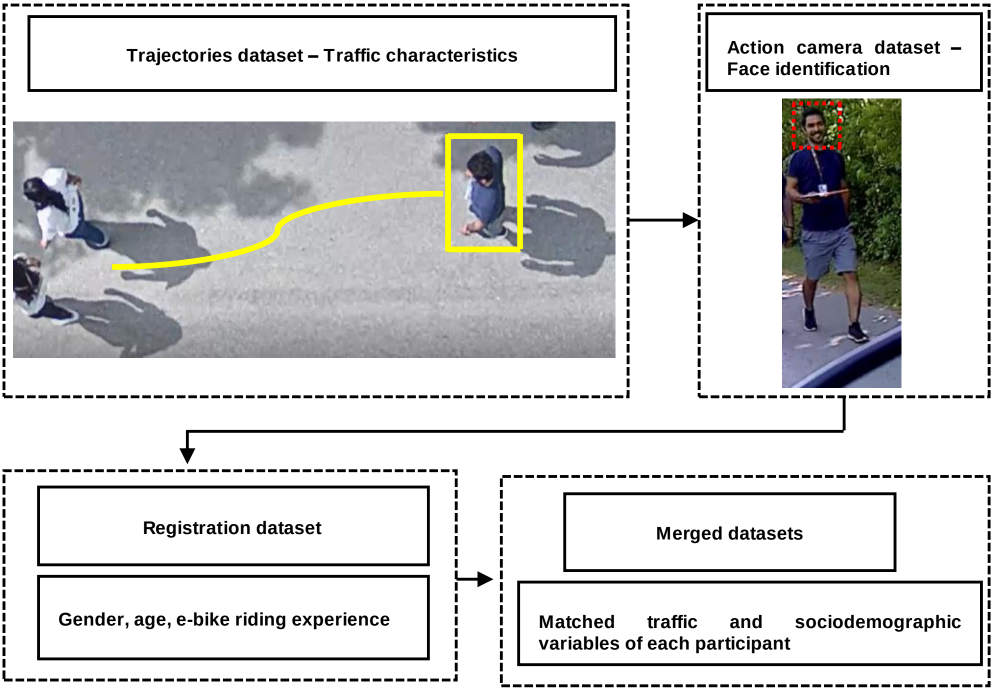

Figure 4 The workflow of merging the datasets from the field experiment (the person in the figure is the author of the thesis to avoid ethical issues)

The selection of study track

The research is designed based on the need to understand the riding characteristics of e-bike riders in off-road facilities. Therefore, the study track is selected as an area that accommodates only non-motorised vehicles. Different major and minor criteria were taken into account for the selection of the study track. The following section describe some important points regarding the selection of the study track.

The congestion of the track: Based on the need for experimental control in the field experiment, the track should be dedicated only to the participants of the experiment. This criterion affected the selection of the location used for the study. Moreover, the collected data would be more reliable if the study track was a regular bike facility, which helps to simulate real-world conditions for the participants. As a result, their riding behaviour would be comparable to their real-life behaviour. Three potential bike tracks in Lund, Sweden, were selected for the study. The volume of traffic (bikes and pedestrians) during different hours of the day was observed for the selected bike tracks. A bike track with a lower volume of traffic was selected as the case study.

The position of the study area: The position of the study space was selected to be close to a health centre (Norra Fäladen in Lund, Sweden). This issue was considered during the risk assessment performed prior to conducting the experiment. In selecting the stretch of the bike track, it was considered that the shoulder of the bike track should have enough space for placing camera equipment.

The infrastructure characteristics: Since only the interaction of e-bike riders and pedestrians was the aim of the study in the modelling procedure, the bike track was selected to have no geometric complexities, such as gradients, curves or bottlenecks. There was no curb on either side of the selected bike track, and the shoulder of the road was covered with lawn without any height differences compared to the bike track. Also, the selected stretch of path had no pavement distress (see Figure 5).

Figure 5 A schematic representation of the study area (meeting event is shown in the figure). The three persons in the green area (shown in grey colour) on the right side of the figure are the project assistants, who are equipped with medical kits for possible emergencies. The person on the left side of the figure in the green area (shown in grey colour) is the moderator of the experiment

Ethical assessment (participants, area and random road users)

All participants were informed about the research purposes. They were also informed that the experiment was recorded by action and stationary cameras. They were informed that the published results would not show their faces and that personal data would be handled only by the researcher (the author of the thesis) involved in the project. Informed consent was obtained in the first part of the registration process, before the experiment. Participants were also informed that they could leave the experiment anytime. The respective permits for filming the area was also issued before the experiment. The start and endpoint of the study area were marked before the experiment; however, the area was not totally blocked to random road users (test track). Thus, two signs were mounted on the start and end of the experiment area to inform random road users about the filming.

Classification of interactions

The classification of the interactions was based on the hindrance concept. Therefore, the data were extracted based on same-direction (passing) and opposite-direction (meeting) encounters. First, the e-bike rider passes the pedestrians in the same direction (passing) and then meets them in the opposite direction (meeting). The different speed regimes of the e-bike and pedestrians allow this interaction for each run of the experiment. Based on the literature, trajectories were classified based on passing and meeting events for each run of the experiment. The experiment procedure was repeated over 60 times; however, approximately 40 runs were selected for further analysis. The exclusion criteria were based on the fact that in some runs of the experiment, some random road users entered the experiment area. Also, some procedural faults, a tire puncture of the e-bike and difficulty in matching the datasets caused the removal of some runs of the experiment.

Data analysis

The following sections provide an overview of the data analysis approaches performed thorough the thesis. The information provided in this section includes a summary of the different data analysis process and does not include the entire data processing procedure. More details related to the data processing and modelling procedure are provided in each appended paper. Table 5 presents a summary of the data analysis tools for each study.

Table 5
The Relationship between the Papers, Datasets and Analysis Type

Paper	Dataset	Analysis type
I	Peer-reviewed scientific articles	Systematic review
II	Responses on comfort concerns	Qualitative analysis (In-vivo coding technique)
III	Trajectory data	Linear regression analysis
IV	Trajectory and sociodemographic data	Bayesian network analysis

Systematic review

The systematic review was selected as the main method for exploring the relevant literature for e-bike travel behaviour. This type of review allows the retrieval of different aspects of information from one paper. For example, one paper can discuss both e-bike riding comfort and its relation to the inconvenience of public transport. As a result, the systematic review method is performed to extract key findings from previous studies. This study has two key takeaways. First, different aspects of e-bike travel behaviour and riding characteristics are scrutinised. Second, a theoretical framework for the development of ELOS is proposed in this study (see Paper 1).

The findings were mainly used to shape Paper 1; however, the rest of the papers benefit from the findings of this study. For example, the study set-up and the selection of variables in previous studies related to bike/pedestrian interactions were used to design the experiments for Paper 3 and Paper 4. The explored knowledge gaps via systematic review related to e-bike riding comfort and usage were considered in the conceptualisation of Paper 2.

Qualitative data analysis

The interview was conducted based on the strategy of semi-structured interviews. The semi-structured interview is one of the most common structures of the interview in the human and social science field. In the process of the interview, participants were requested to share their ideas freely, and various follow-up questions (open-ended) were prepared and used based on the answers of participants. At the beginning of all the interviews, the interviewees were informed about the research objectives, confidentiality terms and estimated time of the interview. Also, the intended type of e-bike (pedelec) in the research was clarified for participants. The general opinion of participants was validated with them at the end of each interview. Their responses were validated again with the participants when the transcript of the interview was prepared. In all interviews, the process involved one interviewer and one interviewee.

The process of the interview was documented at the time of the interview. This document was used for the general validation of participants' opinions after the interview. After the interview, the audio-record documents were used to transcribe the interview. For the data analysis, the in vivo coding method was employed to code the data. The in vivo coding method is useful to retrieve codes directly from the transcript. For each theme of questions, respective codes were derived from the transcripts. This method of coding data contributes to retrieving the codes from the terminology and vocabulary of participants. The transcripts and assigned codes were reread several times in order to avoid any possible mistake in the system. The whole process was performed separately for the pre- and peri-pandemic situations.

Linear regression analysis

Understanding the relationship between the traffic characteristics of e-bike riding related to pedestrian crowds is the interest of this study. Correlation analysis can provide information related to the association of variables, while regression analysis explores the direction of the associations among variables. To assess the relationship between the pedestrian crowd and e-bike riding characteristics variables, regression analysis was used. Also, this method has been used in hindrance analysis in previous studies. The simple procedure of the methodology is an advantage of the employed method in which the method is understandable for a wide range of users and has applications for designing facilities and ELOS studies.

As mentioned in the experimental set-up section, pedestrian crowds are the only exogenous variable (independent) in the designed experiment. The purpose of this study was to explore the impact of pedestrian crowds on the traffic operation of the e-bike rider. Speed and lateral displacement were considered as a proxy for the e-bike riding characteristics. Different regression models were tested for the collected data, but the linear trend of the data (mean values) suggests linear regression as a suitable method for modelling the correlation of data. This simple procedure of the model allows a wide application of analysis as it can be used as a fundamental relationship of e-bike traffic characteristics compared to pedestrian crowds, the so-called density of different influence areas (IAs).

The first intended application of the analysis was to understand whether the regressor (i.e. pedestrian crowds) has any impact on the response variable (i.e. e-bike traffic characteristics). This analysis indeed provides information for the second envisioned purpose of the study, which is comparing passing and meeting events. Understanding the impact of the exogenous variable has an application for the development of ELOS analysis as pedestrian crowds are the main source of e-bike rider discomfort.

Bayesian network analysis

The e-bike user's perception of comfort requires a precise conceptualisation to develop LOS metrics. Since comfort itself is not directly measurable or observable, there is a need to develop a surrogate variable depending on the study set-up. For instance, in the stated preference surveys, participants can be asked to respond to various statements related to comfort on a Likert scale. Alternatively, in the revealed-preference set-up, comfort can be treated as a latent variable. In both methods, there is uncertainty associated with the measurement of the comfort variable. Such measurement noise motivates the application of probabilistic methods, which are powerful tools for the quantification and manipulation of uncertainty.

In this study, e-bike riding comfort is treated as a latent variable. The data generating process was modelled using a Bayesian network (or directed acyclic graphs), and fundamental principles from probability and statistics were employed to study the effect of pedestrian crowds on e-bike navigation comfort. This graphical method also specifies how the comfort of the e-bike rider affects their speed and lateral distance. Dependencies between e-bike rider comfort, the rider's driving characteristics and pedestrian crowds were also modelled using the Bayesian network.

4.Results

The goal of developing ELOS was addressed by designing the studies presented in this thesis. All the papers are connected to each other and partly fulfil the objectives of the overarching aim of the thesis (see Table 2). To facilitate the navigation of the results, this chapter provides a summary of the obtained results based on each study. Table 6 presents an overview of findings based on each paper.

Table 6
An Overview of Findings Based on Each Paper

Paper	Aim	Key findings
I	To explore the travel behaviour and riding characteristics related to e-bikes and the applicability of LOS indices from other modes of transport for e-bikes.	The knowledge gaps for developing ELOS are presented (e.g. lack of studies to quantify the interaction of e-bikes with other vulnerable road users in off-road facilities). E-bikes have different travel behaviours and riding characteristics compared to other modes of transport, and LOS indices from transport modes are not directly applicable for e-bikes. BLOS is a promising starting point for the development of ELOS. Finally, a preliminary conceptual framework for the development of ELOS is suggested.
II	To explore e-bike users' and nonusers' comfort and health concerns. The aforementioned concerns are evaluated in both pre- and peri-pandemic situations.	The comfort provided by e-bikes is different between users and nonusers. The attitude of both users and nonusers related to e-bike comfort changes in relation to pre- and peri-pandemic situations. The comfort of riding e-bikes in the pre-pandemic situation does not outweigh its initial investment for nonusers. However, peri-pandemic situations triggered nonusers to invest in purchasing e-bikes. Furthermore, the performance of e-bikes and infrastructure is more highlighted for users in the case of the peri-pandemic situation.
III	To investigate the interaction of e-bikes with pedestrians in off-street facilities.	The interactions of e-bikes are classified based on passing and meeting events (i.e. using the hindrance concept). Passing and meeting resulted in different interactions for e-bike riders. Passing events led to higher speed changes and lateral displacement compared to meeting. This result is mainly in line with previous studies (e.g. Botma,1995) based on the concept of hindrance for bike and pedestrian interactions.
IV	To evaluate the imposed discomfort of e-bike users due to the presence of pedestrians in off-street facilities.	The e-bike interaction with pedestrian crowds has a highly negative impact on e-bike riding comfort. The scale of discomfort is investigated based on the sociodemographic characteristics of riders. For example, pedestrian crowds impose a highly negative impact on young e-bike riders in passing events, while such a negative impact was not found for older adults in meeting events.

Paper 1 – A conceptual framework for developing ELOS

E-bikes have been recognised as a remedy to address different urban and societal issues, such as traffic congestion and air pollution. Regardless of the political desire across the world to push towards the use of e-bikes, little is known about the travel behaviour, the riding characteristics and, eventually, the experience of e-bike riders. ELOS is a promising tool through which to quantify the e-bike rider's experience. However, extensive information is needed to move towards the development of ELOS. This study aims to provide a comprehensive overview concerning the travel behaviour and riding characteristics related to e-bikes. This study also provides the state of the art of the information related to the substitutional scale of e-bikes (and modal choice) in the transport system. The presence of e-bikes in the transport system has been scarcely considered in the literature. This scarcity of knowledge is twofold. First, few BLOS studies consider e-bikes in their analysis process. The lack of consideration of e-bikes, specifically in off-road facilities, affects the comfort of all road users. In addition, there is no dedicated ELOS index in the literature, which could be used for the assessment of the e-bike rider's experience.

The BLOS research domain is deemed the most relevant research domain for developing ELOS. The similarity of the size and shape of e-bikes and bikes and their sharing of the same facilities (e.g. off-road) highlight the applications of BLOS for the development of ELOS. However, the speed regimes of bikes and e-bikes are largely different. Along with different speed regimes, riding characteristics such as acceleration and deceleration introduce different experiences for riders. This fact implies that BLOS is not able to realistically depict e-bike riders' comfort. Also, exploring the literature related to e-bike travel behaviour revealed that e-bikes have an extensive function in utilitarian trip purposes along with recreational trip purposes. This feature is due to the fact that e-bikes are equipped with an electric motor, which allows riders to plan long-distance trips. These features imply a potential substitution for motorised vehicles, such as from public transport to e-bikes.

The overview of the literature extended, and the scale of substitution from motorised and non-motorised vehicles to e-bikes are included. This consideration is important for understanding which characteristics of LOS from other modes of transport could be considered for the development of ELOS (e.g. the similarity of long-distance trips with public transport). The results suggest that the extent of substitution can vary from partial to complete replacement. The specification of other transport modes' substitution by e-bikes can contribute to adopting relevant variables to depict a realistic picture of e-bike riders.

Finally, the interaction between users, specifically in off-road facilities, requires more attention for developing ELOS. An in-depth understanding of e-bike interactions with road users with different speed regimes contributes to the quantification of e-bike riders' comfort. More specifically, e-bikes and pedestrians have the greatest speed differences in off-road facilities, which could substantially affect the e-bike riding experiences. This is due to the increasing chance of interactions (i.e. passing and meeting) and requires a collision-avoidance action by e-bike riders.

As mentioned earlier, the BLOS research domain could be insightful for the development of ELOS. Therefore, framing this study was inspired by an extensive stream of research in BLOS and its potential impact on the development of ELOS. The history of BLOS and related research domains such as comfort and traffic flow were included in a dedicated study that provides information complementary to Paper 1 (see Kazemzadeh et al., 2020). The findings suggest that trip-end amenities such as bike parking facilities are currently not considered in the user's perception of comfort. Off-road facilities can provide better riding conditions for vulnerable road users compared to on-road facilities. However, few studies have considered the challenges connected to off-road facilities. As an example, the presence of e-bikes and e-scooters can strongly affect the perceived comfort of road users. This issue could be explored further based on different road users. The review highlighted that evaluating the interaction among road users (i.e. using the hindrance concept) can be beneficial in addressing this research shortcoming. Finally, network-based BLOS evaluations are limited. Some specific characteristics of riding comfort could be mainly explored by a holistic view of the system. For instance, the comfort concerns of users related to the connectivity of the infrastructure and the transitions between transport components could be scrutinised at a road network level.

Paper 2 – E-bike riders' comfort concerns

The exploration of e-bike travel behaviour and its substitutional scale in mobility plays a crucial role in the development of ELOS. This knowledge is important to provide information related to the usage of e-bikes in different situations. Moreover, this study takes one step further to explore the comfort concerns of both e-bike users and nonusers to develop a comprehensive ELOS. In this context, the unprecedented COVID-19 pandemic affected the transport domain and subsequently provided a different situation for the ridership of e-bikes, such as social distancing recommendations and a drop in the ridership of public transport. Thus, this study explores the e-bike users' and nonusers' comfort concerns in pre- and peri-pandemic situations as follows:

Pre-pandemic situation: the comfort provided by e-bikes can be used as one of the main variables for sustaining the role of e-bikes in mobility. An understanding of nonusers' reasons for not purchasing e-bikes and possible willingness to pay (based on provided comfort) can also be insightful for ELOS analysis. In the pre-pandemic situation, nonusers were in agreement that the initial investment for purchasing an e-bike is a barrier to using it. Also, they coupled bike and public transport for short- and long-distance trips, respectively, which implied that using an e-bike is unnecessary for them. The perceived physical activity provided by bikes was also reported as an obstacle to using e-bikes. In contrast, users admire the comfort that e-bike provides for long-distance trips, which enables them to plan for more long commuting trip purposes. Cycling infrastructure (e.g. bike parking) was reported as one of the discomfort factors for users as they would be worried about the security of their e-bikes. This factor highlights the importance of end-trip facilities, especially when the two-wheeled vehicle is expensive, in this case, e-bikes.

Peri-pandemic situation: the social distancing recommendations and restriction of the use of public transport motivated nonusers to invest in purchasing e-bikes in the peri-pandemic situation. This means that the provided (imagined) comfort of e-bikes in the peri-pandemic situation outweighs its initial investment for nonusers. In some cases, nonusers were more interested in renting e-bikes rather than investing in purchasing e-bikes. This fact implies nonusers' financial concerns over investment in e-bikes. Alternatively, the performance of e-bikes was the key reason for the discomfort of users in the case of the peri-pandemic situation. More specifically, battery life span and the weight of the e-bike were mostly described as the variables of the user's discomfort.

Paper 3 – The interaction of e-bikes with pedestrian

The concept of hindrance has been widely used as a frequent method in the BLOS research domain to quantify the QOS of cyclists in off-road facilities. The quantification of road users' interactions provides robust information related to their experience in different situations. Based on the concept of hindrance, the interactions could be classified considering the directions of encounters, the so-called passing and meeting events. Regardless of the fast-growing ridership and the presence of e-bikes in off-road facilities, there is no research to evaluate the interaction of e-bikes with other vulnerable road users, such as pedestrians. Therefore, the main aim of this study is to provide information related to the riding characteristics of e-bikes based on the concept of hindrance. The main results of the comparison (passing vs. meeting events) are as follows:

Pedestrian crowds cause e-bike riders to decrease their speed in passing events. The results yield a linear relationship between increasing crowding level and decreasing e-bike speed. Alternatively, the same relationship was not found between speed and pedestrian crowds for the meeting event. The aforementioned process has been tested for different sizes of IA. The results suggest that passing events cause more discomfort for e-bike riders as the rider has to adjust the speed based on the crowding levels. In contrast, meeting events do not require the rider to adjust their traffic characteristics in relation to crowding levels.

The same process was repeated for pedestrian crowds and the lateral displacement of the e-bike. The relationship is tested for different sizes of IA. The data yield an inverse relationship for passing compared to the aforementioned speed-crowd relationship. This means that a higher number of pedestrians leads to a linear increase in lateral displacement for the e-bike rider. This finding implies that a higher number of pedestrians resulted in greater e-bike riding discomfort. Similar to the results of the speed and pedestrian crowd relationship, no correlation was recorded for the relationship between lateral displacement and pedestrian crowds in meeting events. More detailed results related to the impact of pedestrian crowds on e-bike riding characteristics can be found in Paper 3. More specifically, Table 1 and Table 2 of the aforementioned paper presens the goodness of fit for all IAs for the pedestrian crowd and e-bike speed and lateral displacement.

Paper 4 – Modelling e-bike riding comfort

The operation of e-bikes in cycling facilities and their interaction with vulnerable road users highlight the need to consider the evaluation of e-bike riders' level of comfort in transport systems. This is also important as the quantification of e-bike riders' comfort plays an indispensable role in developing ELOS. The main results of the study are as follows:

This study mainly aims to quantify the impact of the pedestrian crowd on the comfort of e-bike riders. The analysis allows distinguishing between the comfort of e-bike riders based on passing and meeting events by introducing the meeting event as an indicator or dummy variable. Information related to dependencies between different variables in the adopted Bayesian network is detailed in Paper 4. The results of the Bayesian network estimation suggest that the pedestrian crowd negatively affects the comfort of e-bike riders. This impact can be interpreted beyond association and can be linked to a causal effect because the pedestrian crowd is the only exogenous variable in the experiment. The low t-value suggests that this causal effect is statistically significant at a low significance level.

The impact of pedestrian crowds on speed and lateral distance was also investigated by parameterising their mean values as a function of the pedestrian crowding levels and comfort while accounting for autocorrelation. The results indicate the positive and negative effects of the pedestrian crowd on the e-bike rider's speed and lateral distance, respectively. We further explore heterogeneity in these relationships. Whereas pedestrian crowding has a highly negative impact on the comfort of young e-bike riders in overtaking conditions, there is almost no such negative impact for e-bike riders of age 30 years or above in meeting conditions. Perhaps, older e-bikers are more experienced, and meeting further ease down with communication between e-bikers and pedestrians, leading to a negligible effect on the comfort of e-bike riders.

The results show that the interaction between comfort and the meeting indicator does not have a statistically significant effect on speed and lateral distance. In other words, the impact of comfort on the travel characteristics of e-bike riders does not appear to vary between passing and meeting events. However, the lack of statistical significance might have resulted due to the low sample size, and further investigation is needed. To evaluate the model performance, the probability distribution of the observed lateral distance and speed was generated using model parameters. The matching between the reproduced and observed probability distribution shows that the developed model is empirically suitable for the intended application.

5. Discussion

The limited knowledge related to e-bike travel behaviour and riding characteristics and subsequently the lack of research related to e-bike riders' experience introduce difficulties for the development of ELOS. Therefore, the overarching aim of the thesis is how ELOS could be developed. Based on this aim, four specific research objectives were defined to achieve the aim of the thesis (see Figure 6). To comprehensively discuss the findings obtained in each paper in this thesis, the results of previous studies are mapped against the findings of the papers. Positioning research objectives in the stream of research and discussing related research outcomes provide comprehensive knowledge regarding e-bike travel behaviour and riding characteristics deemed to facilitate the development of ELOS. In each section, first, brief information related to current studies is provided to motivate the position of the studies. Then, the results of the different studies are discussed related to how they fulfil the research objectives.

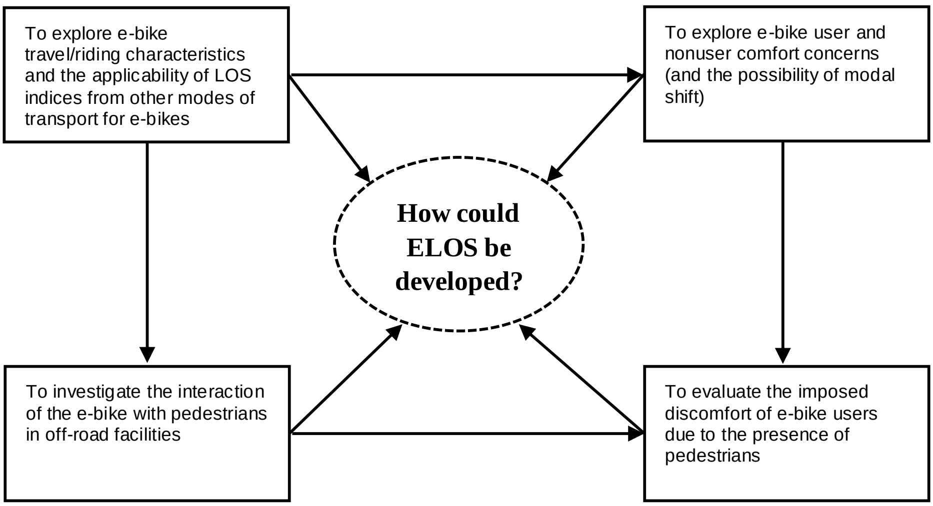

Figure 6 The linkages between the research objectives with respect to the overarching aim of the thesis

Exploration of e-bike travel behaviour and riding characteristics

E-bikes are considered one of the fast-growing markets in the transport system (Fishman & Cherry, 2016). In addition, the ridership of e-bikes has substantially increased over recent decades, which renders the importance of this mode. Understanding, evaluating and, eventually, improving facilities provided for e-bike riders are a needed step to sustain the ridership of this mode. ELOS is a promising approach to address the aforementioned objectives. Over the last three decades, a vast body of research has discussed the LOS for active mobility (i.e. BLOS and PLOS). This stream of review studies has been mainly focused on retrieving different characteristics of previous LOS studies. In the BLOS research domain, extensive review studies have discussed knowledge gaps and provided research directions. For example, Turner, Shafer and Stewart (1997) reviewed the literature concerning bike suitability. They discussed the variation in the definition of suitability criteria and the required databases for the implementation of studies. In line with the Turner et al. (1997) study, Allen, Rouphail, Hummer and Milazzo (1998) summarised the literature regarding bike facility analysis. They concluded that there is a need for an integrated analysis of bike facilities (e.g. operational analysis). The Dutch concept, the concept of hindrance, was suggested by this study to analyse cycling facilities. The literature then progressed from the early studies, and different characteristics of cycling have been further analysed. For instance, Pucher, Dill and Handy (2010) discussed infrastructure and policies related to cycling. Asadi-Shekari, Moeinaddini and Zaly Shah (2013) scrutinised BLOS and PLOS research shortcomings, and Twaddle, Schendzielorz and Fakler (2014) discussed the methods for modelling the behaviour of cycling.

The review set-up (in general) is a prospective approach that not only provides the state of the art regarding the current literature but also advances research directions and frameworks for future study set-ups (Taylor & Davis, 1999). In a similar vein, e-bike research is at its early stage; therefore, reviewing the literature and proposing a framework could be insightful for the development of ELOS (see Paper 1). Considering the similarity of bikes and e-bikes, the BLOS research domain could be considered insightful for the development of ELOS. To document the knowledge related to BLOS, different BLOS research set-ups (e.g. review, survey and interaction analysis set-ups) were reviewed. This research also includes research related to traffic flow and the comfort analysis of bikes. The findings of this study suggest that there is no review study related to ELOS and that e-bikes have not been comprehensively considered in the BLOS modelling procedure (see Kazemzadeh et al., 2020). This research is used as a foundation to further explore e-bike travel behaviour and riding characteristics. To obtain a picture of the current knowledge related to e-bikes, previous review studies related to e-bikes were also scrutinised.

The body of research related to e-bike review studies is far more limited compared to the BLOS research domain. For example, Fishman and Cherry (2016) reviewed over a decade of research on e-bikes and rendered the research needs for policy-makers and industry. Moreover, Salmeron-Manzano and Manzano-Agugliaro (2018) and Hung and Lim (2020) reviewed e-bikes’ historical research trends, and Bigazzi and Wong (2020) reviewed the substitution scales of e-bikes in the transport system. The results of reviewing the e-bike research domain with the consideration of the BLOS research area suggest a lack of comprehensive studies regarding ELOS and the e-bike comfort analysis. To fulfil this knowledge gap, the e-bike research review study (see Paper 1) was conducted in this thesis. In light of current knowledge, the position of this study is to provide insight into the development of ELOS.

This study suggests that there is limited research related to e-bike travel behaviour and riding characteristics as well as ELOS analysis. This shortcoming might stem from the fact that e-bikes are mainly regulated as bikes and that BLOS indices are assumed to be applicable to e-bikes as well. However, the different speed regimes of bikes and e-bikes, the various riding characteristics (e.g. acceleration and deceleration) and the diverse travel behaviour may violate the applicability of BLOS for ELOS (see Paper 1).

The electric-assisted motor of e-bikes introduces the ability to plan long-distance trips for e-bike riders. This aspect of e-bikes can be discussed from different perspectives. For example, the ability of long-distance trips by e-bikes introduces different travel demands compared to a similar mode such as bikes. In a similar vein, e-bikes have extensive applications for utilitarian trip purposes. This is also due to the power-assisted characteristics of e-bikes, which facilitates managing different trip purposes (see Paper 1 and Paper 2). The application of e-bikes for utilitarian trip purposes may introduce different travel demands compared to other active mobility (e.g. cycling and walking). This feature of e-bikes, along with their required physical activity, introduces a specific travel behaviour for e-bikes. The unique travel characteristics of e-bikes could be reflected in the development of ELOS to provide a realistic picture of the e-bike rider’s experience (see Paper 2).

Furthermore, the electric motor of e-bikes positions the e-bike as a transport mode that can substitute for motorised vehicles, specifically public transport. As a result, a body of research has discussed the issues related to the substitution aspects of e-bikes (see Paper 1 and Paper 2). The extent of substitution of motorised and non-motorised vehicles by e-bikes varies from partial to complete replacement. This result implies that there is a dire need for the specification of e-bikes’ substitution role in this field. This is indeed crucial for developing the ELOS concept as the characteristics of substitution can directly reflect the users’ preferences and concerns over modal choice. For example, if the e-bike is considered to be the main replacement for public transport, the capability of travelling for long-distance trip purposes should be reflected in the developed ELOS indices (see Paper 2).

Regarding e-bike riding characteristics, the concept of hindrance has a long history in supporting the development of BLOS for off-road facilities. This concept can potentially be adopted for developing ELOS. The findings of the review study reveal that there is a lack of research in evaluating and quantifying the interactions of e-bikes in off-road facilities. Concerning the high-speed differences and the vulnerability of road users in off-street facilities (e.g. e-bikes and pedestrians), analysing e-bikes' interaction is necessary to understand the e-bike rider's experience (this is one of the main motivations for developing the third study in this thesis). Also, the quantification of e-bike riding interaction with other users is a crucial step in assessing whether the historical assumptions of BLOS in off-road facilities are valid for e-bikes. Furthermore, the quantification of e-bike interaction can aid the development of ELOS. For example, if passing and meeting would result in different interactions scenarios, the adopted ELOS indices should consider these differences in the modelling procedure as users would experience a different level of comfort based on the type of the events (see Paper 1, Paper 3 and Paper 4).

In sum, e-bike travel behaviour and riding characteristics are complex and different from other modes of transport. This fact implies that the direct adaptation of LOS from either active mobility or motorised vehicles for developing ELOS would not be reliable. The explored different riding characteristics of e-bikes compared to bikes (e.g. speed, acceleration, deceleration) limit the direct adaptation of BLOS for e-bikes. This fact motivates the dedicated exploration of the BLOS concepts (e.g. the concept of hindrance) for e-bikes.

The central application of this research objective is to provide fundamental information related to e-bike travel behaviour and riding characteristics. Also, a preliminary theoretical framework is proposed by this study to aid the development of ELOS. This is in line with the early research on bike facilities, such as Botma (1955), which provided a framework for the development of BLOS. In a similar vein, Taylor and Davis (1999) also provided a framework categorising topics in bike research, which is useful for the development of BLOS. Reviewing the literature and proposing frameworks seem to be a promising approach for the development of LOS in the field of active mobility. In general, the proposed framework in this thesis has application for the development of ELOS for different research domains (e.g. off- and on-road facilities). From the thesis perspective, this research served as a roadmap for conducting the following studies (see the workflow of the framework in Paper 1). Moreover, this research objective, along with the others, plays its role as a piece of a puzzle for the development of ELOS.

Understanding the e-bike (non)user comfort concerns

The fast-growing ridership of e-bikes and the diversity in applications of e-bikes for different trip purposes call for more extensive research to evaluate different aspects of this mode of transport. An in-depth understanding of e-bike travel behaviour opens several avenues of research for the development of ELOS. First, an evaluation of the user's experience could introduce specific variables to consider unique characteristics of travelling by e-bike. This process can be extended to include nonusers' comfort concerns for the development of ELOS. Second, understanding the function of e-bikes for different trip purposes provides information related to e-bike travel behaviour. For example, utilitarian trip purposes could be the main trip function of e-bikes, which may imply different requirements for riders, such as trip-end facilities. Third, exploring the extent of modal substitution by e-bikes could contribute to considering a proper set of variables to depict a realistic picture of the user's experience.

Previous studies have scrutinised different aspects of e-bike travel behaviour. This stream of research could be considered to shed light on e-bike travel behaviour and highlight the variables that play a role in the comfort of e-bike riders. For example, Plazier et al. (2017) documented that their research participants are motivated by specific characteristics of e-bikes, such as ease of use, speed and independence from public transport schedules. The latter variable implies the relationship between e-bike riding comfort and the inconvenience of using other modes of transport (e.g. unreliable schedule of public transport). Simsekoglu and Klöckner (2019) advanced three main variables related to the use of e-bikes, including ease of use, health impact and self-image. Understanding the different comfort variables of e-bike riding could also be extended in relation to the sociodemographic characteristics of the users. For instance, Van Cauwenberg et al. (2019) explored the travel behaviour of e-bikes among older e-bike users with consideration of different genders. They claimed that requiring less physical effort compared to bikes was the most common reason for using e-bikes.

One of the crucial facts related to the understanding of e-bike riding comfort is the association of comfort variables based on users and nonusers (potential users). An in-depth understanding of nonusers (potential users) could be important in the procedure of ELOS development as this group may have different comfort concerns compared to users.

Considering e-bike nonusers' travel behaviour could have different advantages for developing ELOS. For example, the reflection of nonusers' comfort concerns could contribute to the development of a more comprehensive ELOS for a wide range of users. Furthermore, estimating ELOS for both users and nonusers provides a more realistic picture of (non)users' experience for planners and facilitates the improvement of facilities, which in turn sustains the ridership of e-bikes. The aforementioned argument motivated the consideration of both e-bike users' and nonusers' comfort concerns in this thesis. Therefore, this study simultaneously fills the knowledge gap related to the consideration of e-bike users' and nonusers' comfort concerns in the literature. The findings of the thesis (see Paper 2) suggest that users and nonusers have different sets of comfort concerns when it comes to the usage of e-bikes. For instance, the findings suggest that the comfort provided by e-bikes does not outweigh its initial investment (willingness to pay) for nonusers. This argument is different for users as the easiness of using an e-bike triggered them to purchase an e-bike. The results suggest that the financial support of governments can be helpful in addressing the initial investment for nonusers and help their modal choice (e-bikes). For example, the Swedish Government supported 25% of the e-bike cost for each purchaser in 2018 to sustain the role of active mobility ('Swedish law for e-bike', 2018). This type of policy seems to be helpful and is in line with the findings of the study.

The findings of the thesis suggest that nonusers in the peri-pandemic situation are triggered to use e-bikes. This finding can be interpreted in two ways. First, the comfort of transport facilities and their LOS indices are related to each other (e.g. e-bike and public transport). This is due to the restrictions on the use of public transport, which decreased the perceived comfort and the LOS of public transport, and, subsequently, nonusers are becoming interested in using e-bikes. Second, the (envisioned) experience of using e-bikes can trigger nonusers to consider e-bikes as their regular mode of transport. This means that that the experienced advantages of e-bikes contribute to sustaining the ridership of e-bikes. This finding is in line with the literature and can be connected to previous studies, such as that by Fyhri, Heinen, Fearnley and Sundfør (2017), which demonstrated that having experience with e-bikes could increase consumers' willingness to pay for them. For example, providing e-bikes for e-bike nonusers over a short period could facilitate the adaptation of e-bikes in mobility (see Paper 2). At the same time, some nonusers prefer to rent an e-bike in some cases (e.g. peri-pandemic) and use a bike or public transport on a regular basis. This result calls for more extensive e-bike sharing facilities to address the temporary needs of users. For example, Campbell et al. (2016) investigated variables such as trip distance, high temperatures, poor air quality and precipitation in association with the choice of e-bike sharing. This finding also highlights the governmental contributions to provide the requirements for e-bike-sharing facilities.

To facilitate the e-bike riding experience, a wide range of variables related to the modal choice of e-bikes for both users and nonusers could be considered. For example, trip-end facilities such as bike parking were rendered as the main discomfort variable for users in the pre-pandemic situation. Cycling infrastructure is a place that accommodates e-bikes and therefore needs to be well-equipped to satisfy e-bike riders' concerns. This variable is in line with previous studies in the literature. For instance, Fitch and Handy (2019) reported that fear of theft and the cost of e-bikes are the main barriers to the adoption of e-bikes. This argument is crucial as the initial investment of e-bikes is quite high compared to other forms of active mobility, such as bikes. Providing secure e-bike parking as an illustration of trip-end facilities could be beneficial in the development of ELOS. Historically, this variable has not been prominently considered in the BLOS literature (see Kazemzadeh et al., 2020). However, considering the expensive initial investment of e-bikes and their function in utilitarian trip purposes highlights the importance of trip-end facilities in the ELOS modelling procedure.

The main aim of the related research in the thesis was to understand the travel behaviour of e-bikes in normal situations (i.e. pre-pandemic). However, the unprecedented COVID-19 pandemic affects different domains of transport, especially public transport, and motivated the study of e-bike travel behaviour in the peri-pandemic situation. As a result, the travel demands of public transport can be substituted by other modes, including e-bikes. E-bikes have been acknowledged as a promising mode of transport to substitute for public transport in the peri-pandemic situation. This is due to the fact that e-bikes provide relative ease in travelling for different users (especially users with physical limitations) and enable them to plan for long-distance trips. However, the practical performance of the e-bike, such as the battery life span and heavy frame of e-bikes, was reported as the main source of discomfort for users in the peri-pandemic situation. Different domains should be collaborating to address this shortcoming. For instance, different commercial designs could contribute to improving battery performance and lightening the frame of e-bikes. From the transport sector view, cycling infrastructure can be equipped with different facilities such as charging stations, where users can easily plug their batteries into chargers. The travel behaviour and mobility patterns that have changed in the peri-pandemic situation may affect the trend of mobility in the post-pandemic situation. This hypothesis calls for more research in the field of e-bikes and e-scooters for future mobility.

In sum, e-bike travel behaviour could be varied based on different factors, such as the comfort provided by e-bikes and the inconvenience of other modes of transport (e.g. public transport). For instance, e-bikes could facilitate riding exertion and improve travel time compared to other forms of active mobility and, at the same time, enable riders' planning of long-distance trips, similar to motorised vehicles. This fact could be reflected in the development of ELOS. The developed methodology of HCM considers both recreational and utilitarian trip purposes for cyclists (HCM, 2016); however, the electrically assisted system of e-bikes could make e-bikes more appealing for utilitarian trip purposes, and thus this can be reflected in the developed ELOS.

Furthermore, bikes require a level of physical activity based on different factors such as type of bike, gradient level and weather condition, which may limit their use in cases of people with physical limitations. However, e-bikes enable a wide range of riders, including the elderly and users with limited physical limitations. These types of users could rely on the electric power of e-bikes and enjoy riding active mobility. For instance, a vast body of research has scrutinised different comfort concerns of e-bike riding related to older adults (Leger, Dean, Edge, & Casello, 2019; Van Cauwenberg et al., 2019). This fact highlights the importance of reflecting the different riding characteristics, perception and reaction time and manoeuvring abilities of these users in future ELOS indices. A specific ELOS index for users with physical limitations (with consideration of the aforementioned variables) could depict a realistic picture of their e-bike riding experience.

The main application of this research objective is to render two important facts related to specific characteristics of e-bikes. First, the role of the e-bike in utilitarian trip purposes should be highlighted in the ELOS. This can be discussed as the user who uses e-bikes for this type of purposes may expect a different level of comfort compared to a road user who considers it for recreational trip purposes. Second, e-bikes could enable the vast majority of road users to be part of the active mobility system. This feature is indeed beneficial for both users and society as it can sustain the ridership of active mobility. Consequently, this requires the specific consideration of different road users' riding experience in the development of ELOS. For instance, the young rider would experience a different level of comfort compared to older adults, which could be reflected in the developed ELOS (see Paper 1, Paper 2 and Paper 4). All in all, the specific characteristics of e-bikes, such as travel behaviour, trip purposes and the sociodemographic characteristics of riders in the ELOS methodology, could depict a more realistic picture of the e-bike riding experience.

Evaluating the e-bike interaction with pedestrians

An in-depth understanding of the road user's experience in off-road facilities has had a crucial impact on the development of BLOS. In order to assess BLOS, different methods such as surveys, observations and experiments have been adopted in this field. The classification of road user's experience based on passing and meeting events provides a clear picture of the perceived comfort and direction of encounters, which is helpful to the development of LOS. In this context, the present work (Paper 3) highlights that meeting events impose less hindrance compared to passing events. This finding is in line with the research on bike-pedestrian interaction (see Botma, 1995).

After the early study by Botma (1995) in this field, the hindrance concept has been implemented in different regions of the world to quantify the user's experience in different facilities (see Table 1). As can be seen from Table 1, this concept has been used for off-road facilities where different types of vulnerable road users, such as cyclists, pedestrians, hikers and joggers, are present. Among all these, e-bikes have not been comprehensively studied. The evaluation of different research methods (e.g. survey studies) also reveals that few studies have scrutinised the discomfort of road users in the presence of e-bikes (Bai et al., 2017). The lack of e-bike consideration in the development of LOS could affect the comfort of both e-bikes and other vulnerable road users. First, the high-speed regimes of road users increase the chance of overtaking and subsequently the interaction of road users. Moreover, in the case of any interaction, the high speed of the e-bike may introduce more difficulty for e-bike riders to navigate in pedestrian crowds (see Paper 1, Paper 3 and Paper 4).

An in-depth understanding of the different characteristics of events provides a clear picture of the experienced interactions for e-bike riders. This study (Paper 3) provides fundamental information regarding the differences in passing and meeting events. It appears evident that passing imposes more hindrance for e-bike riders compared to meeting. The impact of this result can be discussed in different ways, such as the possible causal mechanisms and consequent applications for planners and policy-makers. One of the key takeaways is its alignment with early BLOS research findings. In fact, both pedestrian-bike and pedestrian-e-bike interactions in passing impose more discomfort for riders compared to meeting events. This finding suggests the general applicability of BLOS in the development of ELOS. However, the different riding characteristics of e-bikes compared to bikes require detailed analysis for the adaptation for BLOS for ELOS. For instance, the higher speed of e-bikes compared to bikes needs to be further studied in the case of meetings as the very different speed regimes of e-bikes and pedestrians could possibly impose a different level of discomfort for the e-bike rider (see Paper 1 and Paper 4).

Different scenarios can be discussed for a different level of hindrance in passing and meeting events. First, in passing events, e-bike riders can only adjust their riding characteristics to avoid possible conflicts. This requires more navigation actions (e.g. speed adjustment) from riders in passing compared to meeting events. In contrast, the non-verbal communication of road users in meeting events may contribute to the adjustment of both users' positions and impose less hindrance in interactions. Consequently, e-bike riders would experience less discomfort in meeting events compared to passing events. This communication mechanism may lead to different riding characteristics as well. As an illustration, when an e-bike rider is assumed to handle the interactions, s/he may be more confident/comfortable in maintaining a higher speed in meeting events compared to passing. In contrast, in passing events, as pedestrians walk freely in different directions on the sidewalk and may not check behind when changing positions, there is a possible conflict for both parties considering the high speed of e-bikes. This fact might be intuitively considered for e-bike riders to have more control over possible conflicts. As a result, they should keep lower speed regimes in passing compared to meeting events.

The aforementioned results have different practical relevance. At the tactical level of analysis and under the same crowding level, the imposed hindrance for the e-bike rider is different for passing and for meeting events. In simpler words, the same number of pedestrians resulted in a different level of hindrance for e-bike riders based on the encounters' directions. These results provide a sort of threshold for the management of facilities, which implies that at the same crowding level, the QOS for e-bike riders could be drastically different based on passing and meeting events. This can also be helpful to evaluate the impact of the segregation of cycling facilities. Indeed, the quantification of the rider's comfort at different crowding levels could provide a better picture of facilities for planners and policy-makers.

In sum, the concept of hindrance seems to be a promising approach to study the interactions of e-bike riders where other vulnerable road users are present. This concept has already been adopted to understand bike-moped (Botma & Papendrecht, 1991), bike-bike (Khan & Raksuntorn, 2001) and bike-pedestrian (Botma, 1995) interactions. The presented study in the thesis fills the knowledge gap as it evaluates the e-bike-pedestrian interaction in off-road facilities. Obtaining a similar trend of interactions in different studies (bike-pedestrians and e-bike-pedestrians) reinforces the applicability of the hindrance concept for the evaluation of vulnerable road users in off-road facilities.

Modelling the e-bike riding comfort in pedestrian crowds

The quantification of the road user's experience and subsequently user comfort, particularly for active mobility, has had a long history over the last three decades (see Kazemzadeh et al., 2020). More specifically, different studies in the bike literature have been dealing with this concept. The elaboration on modelling approaches for the quantification of cyclists' experience is also beneficial to the development of methods for the e-bike rider's comfort. Therefore, it is crucial to understand the different perspectives of the cycling comfort modelling research domain. Several methodological approaches have been used in the cycling literature to evaluate riding experience/comfort. As an illustration, two contemporary types of datasets are used to quantify cyclists' comfort and stress – galvanic skin response (GSR) data and field data.

On one hand, GSR-based methods work well because stressful situations, such as overtaking (passing), cause anomalous changes in heart rate, blood pressure and GSR (Sharma & Gedeon, 2012). For example, Fitch, Sharpnack and Handy (2020) performed a naturalistic crossover field experiment to examine cyclists' stress via heart-rate variability. They elaborated on the relation between heart-rate variability and the road environment through multilevel Bayesian models. Stress levels are also assessed using field data, such as the number of motorised travel lanes, motorised vehicle speeds and type of bike infrastructure.

On the other hand, the evaluation of riding comfort in relation to directly measurable variables such as speed and infrastructure characteristics provides a more straightforward assessment. As discussed in Chapter 2, for instance, Sorton and Walsh (1994) introduced the concept of stress level to evaluate the comfortability of cyclists in on-road facilities. They defined the stress concept based on three variables, including motor vehicle traffic volume, motor vehicle speed and curb lane width. Mekuria et al. (2012) elaborated on the concept of cycling stress and introduced the index of Level of Traffic Stress, which relies on a different set of variables, such as the number of vehicle lanes, speed limit and bike lane width.

Abadi and Hurwitz (2018) introduced the concept of the perceived level of comfort for cyclists adjacent to urban loading zones. They used variables such as traffic volume, pavement markings of bike lanes and traffic signs for the evaluation of the perceived comfort of cyclists.

However, both GSR- and field-experiment-based methods have methodological limitations. For instance, the causal relationship between psychological stress and road environments is estimated under various strict assumptions, such as no carryover effect from prior sections of the road (Fitch et al., 2020). Potential violations of these assumptions raise concerns regarding the generalisability of these studies. Moreover, evaluating e-bike riders' comfort remains an understudied area. Considering the different speed regimes and riding characteristics of e-bikes compared to other forms of active mobility reinforces the specific modelling procedure for the comfort analysis of e-bikes. Tracing back to BLOS studies and their modelling procedures, the interaction of road users was the main set of variables for modelling cyclists' comfort (Botma, 1995; Botma & Papendrecht, 1991; Khan & Raksuntorn, 2001). This strategy is followed in this thesis to develop the modelling procedure of e-bike's riding comfort and fills the knowledge gap in the literature related to the quantification of e-bike riding comfort in pedestrian crowds (see Paper 1, Paper 3 and Paper 4).

In this thesis, the main theme for modelling e-bike comfort (in pedestrian crowds) is based on the hindrance concept, which follows the BLOS modelling procedure (see Paper 1, Paper 3 and Paper 4). The configuration of the e-bike rider and the pedestrian is due to the extreme speed difference of these road users in off-road facilities. Considering the experimental set-up of the study, the pedestrian crowd is the only exogenous variable and the main source of discomfort for the e-bike rider. The aforementioned discomfort can be interpreted due to the conflict-avoidance mechanism that the e-bike rider may subjectively employ, which consequently affects the rider's speed and lateral distance. The imposed discomfort is different based on event characteristics, and the meeting is documented to cause lower discomfort for the riders (based on sociodemographic characteristics of riders). This might be due to the fact that both parties are involved in the decision process to adjust their traffic characteristics (see Paper 1, Paper 3 and Paper 4).

The results of this study open new avenues for the ex-ante evaluation of the cycling infrastructure by providing a precise set of values for e-bike riders under different crowding levels. Indeed, the retrieved comfort values under different crowding levels can be useful for developing the letter-based ELOS index when the focus is on the impact of pedestrian crowds. The modelling procedure in this study is based on the quantification of interactions, which is in line with the suggested methodology by HCM for evaluating BLOS in off-road facilities (see Paper 1, Paper 3 and Paper 4). The modelling procedure takes advantage of differentiating ELOS based on passing and meeting events, which can be useful for the evaluation and management of facilities based on different scenarios.

One of the specifications of the proposed model incorporates a consideration of the sociodemographic characteristics of users as e-bikes are acknowledged to support a wide range of users, specifically older adults and users with (certain) physical limitations. Understanding users' sociodemographic characteristics along with traffic variables and consequently their relationship to comfort provides a practical framework for planners and policy-makers to keep track of the comfort provided by facilities based on the proportion of user characteristics. Furthermore, the evaluation of the provided comfort based on different sociodemographic characteristics empowers policy-makers to adopt their policies to increase the comfort for a wider range of users. This indeed also helps sustain the role of e-bikes in mobility (see Paper 1, Paper 2 and Paper 4).

The studies included in the thesis have different practical applications beyond ELOS development (see Paper 4). For example, microsimulation models were employed along with the hindrance concept for capturing and consequently for quantifying different bike interactions. The review of the literature suggested that there are limited modelling studies that have considered e-bikes' interactions. The lack of such research leads to a knowledge gap for developing e-bike microsimulation models in shared mobility where vulnerable road users are present. The different specifications of the models retrieved from this study help to provide an in-depth understanding of e-bike rider behaviour in shared mobility. Consequently, the empirically learned parameters of the dynamic behaviour of e-bike riders can aid the calibration of simulation models to improve the realism of future models (Kazemzadeh & Bansal, 2021).

In sum, the proposed modelling procedure of e-bike riding comfort fills the knowledge gap related to modelling e-bike-pedestrian interaction in the literature of off-road facilities. This modelling procedure could be used as a foundation for the evaluation of other vulnerable road users in off-road facilities as the underlying assessment is based on the most extreme speed regime differences in active mobility. Indeed, in future studies, the modelling procedure could be updated and include the interaction of different road users.

How could ELOS be developed?

An in-depth understanding of the different aspects of e-bike travel behaviour and riding characteristics is a needed step towards developing ELOS. The requirement of pedalling exertion and simultaneously facilitating the pedalling effort positions e-bikes as a form of mobility which has features of both motorised and non-motorised modes. This feature increases the complexity underlying the travel behaviour and riding characteristics related to e-bikes. In this thesis, different studies were conducted to aid the development of ELOS. In the first step (strategical level), a general literature review of BLOS, traffic flow and comfort was implemented to understand the modelling procedure of a similar research domain (see Kazemzadeh et al., 2020). This research domain was selected as bikes and e-bikes have a similar physical shape and often share similar infrastructures. The findings suggested that the consideration of e-bikes was often ignored in the modelling procedure of BLOS. This study motivates a dedicated study to review the state of the art related to e-bikes as a mode of transport. This study could be considered as the main stage (roadmap) towards the development of ELOS. The findings of this study revealed the fundamental differences between e-bikes and other motorised and non-motorised vehicles and reinforced the need for an *ad hoc* ELOS (see Paper 1). Simultaneously, the revealed potential of modal substitution by e-bikes (e.g. shifting the travel demand for public transport to e-bikes) renders the importance of understanding the scale of this substitution compared to other modes of transport. This information was deemed necessary to feed the discussion related to understanding the different travel behaviours and comfort concerns of e-bike users and nonusers in relation to other modes of transport (see Paper 2). As a result, the comfort concerns and user preferences concerning the use of e-bikes could provide a set of variables for the development of ELOS.

Furthermore, the strategical level of analysis (see Paper 1 and Paper 2) confirmed significant advantages of e-bike travel behaviour and riding characteristics compared to other modes of transport. For example, e-bikes could enable a wider range of users to use active mobility and have a great impact on the response the utilitarian trip purposes demand. At the same time, the speed regime and riding characterises of e-bikes, such acceleration and deceleration, are different compared to other modes of transport. The aforementioned discussion led to a more in-depth evaluation of e-bike riding characteristics.

From the tactical level of analysis, based on the literature of the BLOS research domain, an evaluation of e-bike riding characteristics and behaviour was conceptualised (see Paper 3 and Paper 4). The primary findings suggested that the BLOS framework (i.e. the concept of hindrance) could be applicable to the development of ELOS (see Paper 3). The logic of hindrance was followed, and the role of the sociodemographic characteristics of e-bike riders along with their riding characteristics for comfort modelling were investigated in a dedicated study. This assessment was mainly motived as the literature and background study of this thesis (see Paper 1 and Paper 2) revealed that the sociodemographic characteristics of riders play an important role in their perceived comfort. However, mapping the finding of this stage against previous BLOS may seem to be difficult as few of the previous BLOS studies have considered this factor specifically in their modelling procedure (Kazemzadeh et al., 2020).

Furthermore, different approaches could be followed for developing a dedicated ELOS. As presented by this thesis, developing a dedicated ELOS requires considering the specific e-bike travel behaviour and riding characteristics to represent a realistic picture of the e-bike rider's experience. As a first step in the development of ELOS, the BLOS framework based on the concept of hindrance could be used to depict e-bike riding characteristics in off-road facilities. Then, the specific travel behaviours related to e-bikes, such as their ability to be used for long-distance trips and utilitarian trip purposes and the presence of users with different physical limitations and the elderly could be considered in the modelling procedure. This can be performed via different forms of ELOS, each considering specific aspects of e-bike travel behaviour.

In sum, BLOS could be a promising starting point for developing a dedicated ELOS. Along with the BLOS framework, three important variables, including the sociodemographic characteristics of riders, trip purpose and modal choice, could be considered in the development of ELOS. The consideration of the aforementioned variables contributes to representing a realistic picture of the e-bike riding experience. These variables could be discussed in various ways. For example, the modal choice is a broad research area, and this thesis was discussed in the frame of modal substitution. This was due to first understand the potential possibility of modal substitution for e-bikes and other modes of transport and therefore to evaluate its potential impact on the development of ELOS. This argument could be extended for understanding the sociodemographic characteristics of e-bike riders as they could have an impact on the development of ELOS. The proposed theoretical framework in Paper 1 could serve as a preliminary effort towards the development of ELOS.

Contributions

The objective of this thesis is to address the gap in the e-bike comfort research stream by providing knowledge for developing ELOS. Each study in the thesis has different research objectives and, consequently, covers contributions from both the strategical and tactical levels. From the strategical perspective, a comprehensive review study was conducted in order to scrutinise e-bike travel behaviour and riding characteristics. This study contributes to providing fundamental knowledge to understand the riding characteristics of e-bikes as a mode of transport. The findings of the aforementioned studies led to the proposition of a preliminary theoretical framework for the development of ELOS. The framework is proposed in a general format that can be used for developing ELOS in both on- and off-road facilities. Furthermore, focusing only on e-bike users' comfort characteristics may neglect the understanding of nonusers, who may potentially otherwise be users. This thesis contributes to providing knowledge related to both e-bike users and nonusers. The basic analysis in a normal situation (i.e. pre-pandemic) is extended to depict (non)users' comfort concerns in the peri-pandemic situation. This analysis contributes to an understanding of and reasoning for (non)users' concerns in the post-pandemic situation.

From a tactical point of view, the thesis takes one step further to understand the riding characteristics associated with e-bikes. In this stage, the concept of hindrance, which is a well-established method in the BLOS research domain for off-road facility analysis, is tested for e-bikes. This analysis provides fundamental knowledge for the further development of ELOS in off-road facilities. Furthermore, a dedicated study was performed, and the sociodemographic and traffic characteristics of e-bike riders were considered to model e-bike riding comfort in pedestrian crowds. This study contributes to developing ELOS in off-road facilities, in which the modelling procedure can also be adopted for on-road facilities. The final contribution of the thesis is the consideration of all studies as one package, providing a holistic view of e-bike riding comfort, which helps in the development of ELOS. Each article appended to the thesis is positioned based on the proposed theoretical framework (see Paper 1), and the process can be adopted for developing ELOS in different contexts.

6. Applications

Research into the e-bike as a unique mode of transport is in its nascent stage, and therefore, there is a dire need to investigate different aspects of this mobility. The applications of this thesis are envisioned to fill several research gaps in the e-bike research domain and could be classified into the three following groups:

- Understanding e-bike travel behaviour
- Understanding e-bike riding characteristics
- Towards the development of ELOS

Within each category, the applications of the thesis could be discussed from different perspectives (e.g. theory and practice). This chapter summarises the aforementioned applications of this thesis.

Understanding e-bike travel behaviour

An in-depth understanding of e-bike travel behaviour is a key step towards the assessment of e-bike riders' experience. In this thesis, e-bike travel behaviour is extensively discussed. The provided knowledge regarding e-bike travel behaviour could be discussed based on theoretical and practical applications. From the theoretical perspective, a conceptual framework is proposed by this thesis which could serve as a roadmap for future ELOS studies based on different contexts. The framework also provides an overview related to BLOS variables, which could be potentially performed in future ELOS research. Moreover, the thesis puts forward information related to the comfort concerns of both e-bike users and nonusers in normal (pre-pandemic) and COVID-19 pandemic situations. Specifically, the information related to the health and comfort concerns of nonusers provides information for the set-up of future studies related to e-bike travel behaviour which considers the needs of potential users.

From the practical perspective, the provided information in the thesis highlights the importance of considering the e-bike as a unique mode of transport. This means that planners could not understand e-bike travel behaviour by adopting the tools in BLOS. This information is crucial for planners to know that only a dedicated ELOS framework could provide a realistic picture of the e-bike riding experience. Moreover, planners and policy-makers could navigate the proposed framework and understand the contributing variables for user comfort. Also, the provided information related to user and nonuser concerns (i.e. comfort and health) in peri-pandemic situations contributes to the preparation for future pandemics. In sum, planners and practitioners could get a picture of e-bike travel comfort and its relation to other modes of transport (e.g. public transport), which could be helpful for their holistic policy-making and management.

Understanding e-bike riding characteristics

A detailed level of analysis is required to understand e-bike riders' experience and, consequently, their perceived comfort. At the tactical level of analysis, different riding characteristics of e-bikes, such as obstacle avoidance, overtaking (passing), meeting, gap acceptance and turning, could be analysed. In line with previous BLOS research, understanding the passing and meeting characteristics of riders provides fundamental knowledge related to e-bike riding characteristics. From the theoretical perspective, the thesis introduces a series of analyses related to the passing and meeting events of e-bikes in pedestrian crowds. Considering the lack of information regarding e-bike and pedestrian interactions, the information provided in this thesis has applications for the validation of microsimulation models and fundamental traffic diagrams. Also, the proposed methodology for the assessment of the e-bike rider's comfort could be adopted in future studies with different types and combinations of road users (e.g. bike-e-bike, e-bike-moped).

From a practical perspective, the thesis provides a practice-ready framework (e.g. equations) for the analysis of passing and meeting events. The provided equations could be used by planners and practitioners to assess the experienced level of hindrance based on the direction of encounters. Indeed, specific consideration should be taken for the generalisability and transferability of the findings of this thesis (see the 'Delimitations of the thesis' section in Chapter 1). Furthermore, the procedure of comfort modelling in this thesis could be used by planners to evaluate the road users' experiences based on their traffic and sociodemographic characteristics. The series of information related to e-bike riding characteristics could also be used for the management of facilities based on different crowd levels.

Towards the development of ELOS

The LOS index has different types in which each type has its own range of applications. As mentioned in Chapter 2, there is no one right way to quantify QOS, and the performance of facilities and various approaches can be adopted. This argument can be extended and affects the interpretation of LOS applications. Thus, LOS applications can be classified in various ways. In this section, the findings of the thesis are discussed through three types of LOS applications, as follows.

Planning and Preliminary Engineering Analysis

Planning analysis contains broad subjects, including the identification of problem and performance monitoring. As mentioned earlier in this chapter, one of the central applications of the thesis (see Paper 1) is to highlight the research needs for developing ELOS. The thesis renders the differences between bikes and e-bikes and the reasoning for the adaptation of a dedicated ELOS concept in mobility. The thesis highlights the fast-growing market of e-bikes and links this advancement in the usage of e-bikes to the current world peri-pandemic situation. The particular condition of mobility in the case of the peri-pandemic situation and restriction on the use of public transport reinforces the use of e-bikes for different trip purposes. The travel habit that has changed in the case of the peri-pandemic situation may last over the long run. The possible impact of travel habit changes in the peri-pandemic situation can be used for reasoning for the post-pandemic situation.

This level of analysis also deals with potential operational deficiencies in different facilities. The findings of the thesis highlight the lack of consideration of trip-end facilities, such as e-bike parking facilities, in performance analysis. This is an important issue in planning and preliminary analysis which can affect both bike and e-bike riders. The findings of the thesis document that the lack of parking for e-bike users is a major concern considering the high initial investment for purchasing e-bikes. The lack of trip-end facilities for e-bike riders can potentially introduce an extensive source of discomfort. This issue can be considered in the planning process to remove a barrier to users' comfort. Thus, the potential variables that are identified by the thesis can be useful for developing ELOS with applications in planning and preliminary engineering analysis.

Design analysis

An in-depth understanding of e-bike riders' comfort can provide useful information for designing facilities. The findings of the thesis suggest that passing and meeting events impose different levels of navigation actions for e-bike riders. This aspect of e-bike riding behaviour can be considered in the designing process of cycling facilities. For example, designing a facility at the same crowding level introduces a different level of discomfort for riders. Planners can consider different policies, such as different segregation approaches and dedicated facilities for modes with similar speed regimes, to address user discomfort in different facilities. The derived relationships between e-bike riding characteristics and pedestrian crowds provide a threshold to understand the impact of the different levels of crowding on e-bike riding characteristics. The aforementioned threshold can be employed for designing facilities for e-bikes.

The documented concerns of e-bike riders in the peri-pandemic situation can be used for design analysis on a higher scale and consider the users' concerns in case of future pandemics. As shown in Paper 2, users were in agreement that the e-bike is a promising tool for long-distance trips (especially in the peri-pandemic situation). However, e-bike performance (e.g. battery life span and heavy frame) was considered the main source of discomfort for riders, which consequently decreases the intended QOS. In the bigger picture, different charging facilities can be designed in different spots of frequent cycling infrastructure to support long-distance travel by e-bikes. Equipping the e-bike infrastructure with charging facilities can contribute to an increase in the level of comfort for users.

Operational analysis

This level of analysis is mainly focused on the near-term condition of facilities and requires detailed analysis. The process of comfort quantification based on different numbers of pedestrian provides detailed information regarding the experienced (dis)comfort of riders in facilities. During analysis, a different combination of sociodemographic characteristics of riders along with their traffic characteristics yields different thresholds for the quantified comfort levels. The proposed model also provides an operational analysis of facilities based on passing and meeting events. The comprehensive analysis of the e-bike rider's comfort along with different model specifications provides a variety of tools for planners to monitor the operational characteristics of facilities.

7. Future Research Directions

The fast-growing trend of the e-bike market is leading to a paradigm shift in mobility, and research in this field should explore the specific characteristics of e-bike riding. The comparison of knowledge gaps in the literature and the addressed knowledge gaps by the thesis can provide robust suggestions for future research. Indeed, suggestions for future research directions can be based on different aspects of research such as theoretical and practical perspectives. In this section, some suggestions from different angles are provided. First, an in-depth understanding of e-bike travel behaviour is a needed step towards the development of ELOS. Future studies should reflect the impact of trip purposes, elderly users and rural trips in the developed ELOS indices. It is crucial to treat e-bikes as an independent transport mode that requires a dedicated LOS. Also, it is suggested that the presence of e-bikes (and possibly e-scooters) be considered in the modelling procedure of BLOS. Second, future research can evaluate the riding characteristics of e-bikes in on-road facilities. The higher speed of cars compared to e-bikes increases the risk of more severe collisions. The motorised vehicle variables and their impact on e-bike riders' comfort can be reflected in future ELOS studies for on-road facilities. Third, in the case of off-road facilities, the findings of the thesis are only based on the presence of e-bikes and pedestrians. Future research may consider different combinations of road users, such as e-scooters, bikes and pedestrians. Considering each type of road, users document a partial image of the comfort provided by infrastructure, and the consideration of a wide range of road users contributes to creating a holistic image. Fourth, safety is not often explicitly considered in LOS-based studies (e.g. BLOS). However, the high-speed regime differences among different modes of transport makes it worth trying to consider safety in the ELOS modelling procedure. Fifth, based on the findings of the thesis, the comfort of e-bike riders in the normal situation (i.e. pre-pandemic) is different from the case of the peri-pandemic situation. These results suggest the necessity of research in relation to understanding e-bike riders at different periods of time, especially in the cases of pandemics and emergencies. Future research could elaborate on the understanding of the user's comfort in the case of the peri-pandemic situation and study the trend of changes in travel behaviour due to the COVID-19 pandemic. This can also be helpful to understand users' comfort concerns in post-pandemic situations.

8. Conclusion

The e-bike is an environmentally friendly mode of transport that provides active mobility for a wide range of users. In order to sustain the role of e-bikes in mobility, there is a need to assess the e-bike user's experience and, eventually, evaluate their perception of comfort. This can be done via the LOS index for e-bikes. However, to date, there has been no comprehensive method by which to analyse ELOS. This thesis provides fundamental knowledge related to e-bike travel behaviour and riding characteristics and paves the way for developing dedicated ELOS indices. The findings of this thesis suggest that the LOS from other modes of transport are not directly applicable to ELOS analysis. This is due to the unique travel behaviour and riding characteristics of e-bikes. E-bikes require physical exertion, and they have a similar size and shape to bikes, which positions them as active mobility. However, the electrically assisted motor of e-bikes enables riders to plan long-distance trips compared to bikes. This feature place e-bikes as a mode of transport that could compete with public transport. Based on the aforementioned arguments, the e-bike is a promising substitute for both non-motorised vehicles (e.g. bikes) and motorised vehicles (e.g. bus). This hybrid function of e-bikes increases the complexity underlying e-bike travel behaviour and renders the importance of considering the specific travel behaviour of e-bikes in the ELOS modelling procedure.

To provide fundamental knowledge for the development of ELOS, both the travel behaviour (strategical level) and riding characteristics (tactical level) of e-bikes were scrutinised in this thesis. The analysis provides an overview of the state-of-the-art research, comfort and health concerns of e-bike users and nonusers and a detailed analysis of the interactions of e-bikes and pedestrians in an off-road facility. This series of studies is envisioned to pave the way for the development of ELOS.

The overall findings of the thesis related to e-bike travel behaviour and riding characteristics led to the proposition of a theoretical framework for the development of e-bikes. The framework uses BLOS as a foundation to understand e-bike riding characteristics. Furthermore, the unique travel behaviour of e-bike riding is discussed within the proposed framework to be considered in developing ELOS. The proposed framework and respective studies in this thesis first highlight the dire need to assess e-bike riders' comfort in shared mobility where vulnerable road users are present. Second, each study of the thesis could partly fill the knowledge gap related to e-bike travel behaviour and riding characteristics, which feed the discussion on the development of ELOS. In sum, the findings of this thesis take one step towards the development of ELOS, and yet there is a need for further studies exploring the travel behaviour and riding characteristics of e-bikes.

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Towards an electric bike level of service

Although gaining ground rapidly, scientific knowledge related to electric bikes (e-bikes) is at a nascent stage. Therefore, it is important to understand the e-bike users' experience in order to integrate this transport mode into mobility. The travel behaviour and riding characteristics (navigation) of e-bikes are substantially different from other modes of transport. Thus, an ad hoc tool (e.g. an e-bike level-of-service index) is needed to realistically depict the experience of e-bike riders and, eventually, their perceived comfort. In this thesis, I explore the necessity of analysing e-bike riding comfort and provide fundamental knowledge for the development of an e-bike level-of-service index to assess the quality of e-bike riding.

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