




Review

Expanding the Scope of the Bicycle Level-of-Service Concept: A Review of the Literature

Khashayar Kazemzadeh *, Aliaksei Laureshyn, Lena Winslott Hiselius and Enrico Ronchi

Transport and Roads, Department of Technology and Society, Faculty of Engineering, Lund University, Box118, 22100 Lund, Sweden; aliaksei.laureshyn@tft.lth.se (A.L.); lena.hiselius@tft.lth.se (L.W.H.); enrico.ronchi@brand.lth.se (E.R.)

* Correspondence: khashayar.kazemzadeh@tft.lth.se

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Abstract: Research into the bicycle level-of-service (BLOS) has been extensively conducted over the last three decades. This research has mostly focused on user perceptions of comfort to provide guidance for decision-makers and planners. Segments and nodes were studied first, followed by a network evaluation. Besides these investigations, several variables have also been utilized to depict the users' perspectives within the BLOS field, along with other cycling research domains that simultaneously scrutinized the users' preferences. This review investigates the variables and indices employed in the BLOS area in relation to the field of bicycle flow and comfort research. Despite general agreement among existing BLOS variables and the adopted indices, several important research gaps remain to be filled. First, BLOS indices are often categorized based on transport components, while scarce attention has been paid to BLOS studies in trip-end facilities such as bicycle parking facilities. The importance of these facilities has been highlighted instead within research related to comfort. Second, the advantages of separated bike facilities have been proven in many studies; however, scarce research has addressed the challenges associated with them (e.g., the heterogeneity within those facilities due to the presence of electric bikes and electric scooters). This issue is clearly noticeable within the research regarding flow studies. Furthermore, network evaluation (in comparison to segment and node indices) has been studied to a lesser extent, whereas issues such as connectivity can be evaluated mainly through a holistic approach to the system. This study takes one step toward demonstrating the importance of the integration of similar research domains in the BLOS field to eliminate the aforementioned shortcomings.

Keywords: bicycle; level-of-service; traffic flow; comfort; quality-of-service; cycling

1. Introduction

Cycling has been widely recognized as one of the best environmentally friendly modes of transport and is supported and thoroughly advocated by many governments all over the world [1]. Many governments aim to increase the quality of cycling experiences and thus increase the prevalence of cycling mode share [2–4]. Decision-makers need to know where the investments should be made and how the benefits would be expended after completing the project [5]. Therefore, it is crucial that they have a realistic image of the bicycle system. Over the last three decades, many studies have been conducted in the cycling field to evaluate different characteristics of this mode, mostly via producing indices such as the bicycle level-of-service (LOS or BLOS) [6,7]. To shed light on this topic, most of the relevant research concepts are defined in this section:

- Quality of service (QOS): the user's perspective of the operation of transportation facilities and services.

- Level of service (LOS): the quantitative stratification of performance measures of QOS.
- Service measures: performance measures that are used to define LOS (Highway Capacity Manual) [8].

The concept of comfort could be defined as harmony between humans and the environment due to the balance of physical, psychological and sociological aspects [9]. This makes the evaluation more complex because it is based on each person's characteristics. Another significant issue is that there is no consistent terminology in the field of BLOS, and many different terms have been coined and used to refer to comfort such as bikeability, suitability and bicycle friendliness [5]. The variety of terminology affects the accessibility of the literature and may lead to the neglect of some important research. Moreover, different research areas have been simultaneously working towards different aspects of cyclist comfort that could be aligned together in the BLOS area, such as bicycle flow [10,11] and bicycle comfort [12–20].

The literature has also been extensively reviewed within this field (see Table 1). Turner et al. [21] studied the BLOS indices that have been used in the US. They concluded that the majority of the criteria are based on urban contexts and that many indices require data that are beyond the data commonly available in the transportation sector. Allen et al. [22] performed a literature review aiming to develop a methodology for the operational study of uninterrupted bicycle flow. They concluded that there was an insufficient number of integrated analysis methods and data for the analysis of bicycles' facility operations. Taylor et al. [23] reviewed the traffic operation and facility design for bicycles. One of their findings indicated that future research on BLOS should be more focused on improving the methods for analyzing the characteristics of both on-road and off-road facilities, taking into account the interrupted and uninterrupted flow. Heinen et al. [24] reported the factors concerning the determinants of commuting by bicycle. They suggested that additional knowledge (knowledge that was specifically related to bicycles as opposed to other vehicles) is needed to predict the factors affecting the bicycle experience. Asadi-Shekari et al. [25] pointed out the major shortcomings in both pedestrian LOS and BLOS methods, such as the complicated and time-consuming methods and the difficulty in relating them to the design process. Figliozzi et al. [26] reviewed the existing literature of BLOS and cycling stress levels (as part of their study). They provided different categories for the variables affecting bicycle use and pointed out issues concerning the adopted terminology and clarity of the described concepts. Additionally, many reviews have individually evaluated significant aspects in cycling performance such as bikeways and networks [27], behavior modeling [28], infrastructure, policy and programs [29] and bicycle parking [30].

One of the main purposes of the existing reviews was to render a more realistic picture of a cyclist's perspective for the planners, a picture that was consistent with the BLOS definition. All of the aforementioned research in the BLOS field explores factors that mainly reflect user perspectives through the so-called BLOS indices. However, some of the related areas of research explore more of the variables that could potentially be used in BLOS assessments. Based on this concept, the research areas of bicycle flow and comfort were selected to assess the similarities and the suitability of the variables that have been investigated in the BLOS field. The tables presented in the Appendix A provide a summary of the research highlights in the aforementioned domains. The main aim of this paper is to explore the variables that have been used in different domains of cycling research and which are relevant to BLOS. The knowledge gap for each category and subcategory of the variables is discussed, and recommendations are then proposed.

Table 1. Previous review studies.

Author(s) (Year)	Reference No	General Theme	No. of References	Main Conclusion(s) or Recommendation(s)
Turner et al. (1997)	[21]	Reviews and summarizes bicycle suitability criteria	21	It is crucial to specify the definition of bicycle suitability since it has been used to represent many attributes of road facilities.
Allen et al. (1998)	[22]	Literature synthesis of bicycle facility analysis	27	There is a lack of integrated analysis methods and data that could be used for bicycle facility operational analysis. A methodology based on a Dutch approach is suggested.
Taylor and Davis (1999)	[23]	Review of traffic operations, and facility design	67	Future research should develop a method for analyzing mixed-use characteristics of off-road facilities
Heinen et al. (2010)	[24]	Review to identify the determinants for commuting by bicycle	110	Weather or cycling facilities are not often considered in mode choice studies. Little is known about the influence of some factors on bicycle use such as the presence of traffic lights and stop signs and pavement quality.
Pucher, Dill and Handy (2010)	[29]	Review of the infrastructure, programs and policies to increase cycling	222	Public policy has a critical influence in encourage cycling. For a considerable increase in cycling, there should be a coherence package of programs including infrastructure provision and pro-bicycle programs, supportive land use planning and restrictions on car use.
Asadi-Shekari et al. (2013)	[25]	Reviews of effective indicators for pedestrian and bicycle LOS (level-of-service)	151	Bicyclists assumed to use shared facilities and considered an equivalent to cars. Most of evaluating methods are time-consuming and it is complex to connect them to a design process.
Twaddle et al. (2014)	[28]	Review of the methods for modeling behavior	30	Different modeling approaches for bicycle summarized. There is a need to develop modeling of the tactical behavior of bicyclists.
Buehler and Dill (2016)	[27]	Review the effects of bikeway networks on cycling	89	Highlighting research gaps including the improvement of methods for better sampling, wider geographic diversity and consideration of more control variables such as policies.
Heinen and Buehler (2019)	[30]	Bicycle parking and its influence on cycling and travel behavior	98	The level of evidence on the significance of bicycle parking is limited. There are limited studies focused on bicycle parking in cities, and hardly any on parking at residential locations.

2. Method

In order to have a comprehensive overview of the variables affecting the BLOS, the Web of Science—including both the social science and science records—and the International Transport Research Documentation (TRID) database (<http://trid.trb.org/>) were used in order to retrieve relevant literature. The TRID database includes both the Transportation Research Information Services database and the OECD's Joint Transport Research Center's International Transport Research Documentation database.

The process of searching databases was performed between January and February 2019; however, the process was refreshed in February 2020 to include more recent references. The search contained the following terms, coupled with cycling, bicycle, bicycling, e-bike, electric bike, and/or bike: level-of-service, quality-of-service, LOS, QOS, flow, comfort, convenience, easiness, directness and attractiveness. Citation searches were also performed to identify relevant studies. The search resulted in more than 3000 papers. Since some general words, such as “cycling”, can be related to various domains, the first hit on the databases yielded a large number of papers. The screening protocol was based on the research that developed the BLOS index. The bicycle flow and comfort studies were also limited to research that examined the variables that reflected the user perspectives on the cycling experience. Studies that examined safety-related variables and their implications for cyclists' comfort were excluded from this review. The current review considered only peer-reviewed English-language articles and scientific reports. Based on this protocol, the number of relevant papers was reduced to 190. A similar method of searching databases has been used in previous studies within the transportation domain [27,30].

3. Bicycle LOS (Results)

The results of this paper are organized into three sections. First, the variables of the BLOS, bicycle flow and comfort studies were classified into three main groups (see Appendix A). The first two groups included the variables whose effects planners could have more control over, namely bicycle flow and infrastructure. Exogenous variables are external variables that are not only related to cycling. The proposed category contributes to classifying the variables precisely; however, it can be rearranged in different ways since some variables could be placed in more than one subcategory.

The discussion section highlights the knowledge gaps that are present among these three fields and how the variables concerning bicycle flow and comfort relate to the BLOS. Some suggestions for future research are also provided in the discussion section, followed by the conclusion. Figure 1 clarifies the main and sub-variable definitions (some variables are presented with abbreviated names).

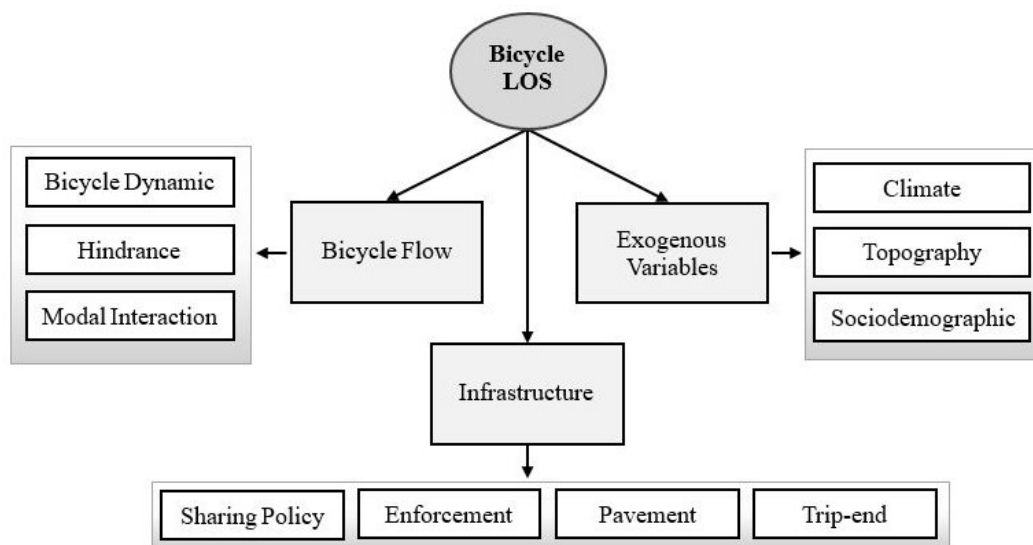


Figure 1. List of variables for the definition of the BLOS (bicycle level-of-service) concept adopted in the present work.

3.1. Bicycle Flow

Bicycle flow is particularly important in BLOS studies because it helps us to understand bicycle movement and how this affects the user perception. Research into the theory of bicycle flow and its effects on BLOS is quite limited and sometimes comes down to the adoption of tools and methods developed for motor traffic [10,31]. However, bicycle flow is very different from the flow of motor vehicles, as characteristics such as speed, acceleration and deceleration are dictated by physical human abilities [28]. Some of the basic flow studies have included LOS discussions [10,11], which have further circulated in this field as a basis for the study of the BLOS.

The relationship between vehicle speed and distance form the basis for traffic flow models, the so-called fundamental relationship that was first proposed by Greenshields. The fundamental relationship is a useful concept to relate key variables such as speed, density and flow, which can then be used as tools for LOS estimations and macroscopic traffic modeling [32]. On the other hand, there is a debate surrounding the fact that this is not really a “fundamental” relationship, as this link can change significantly based on the individual characteristics of the elements affecting it. Unlike motor vehicle flow and pedestrian flow, there are few studies on cycling behaviors and the flow properties of its associated traffic [33,34]. This section discusses some of the significant aspects of other flow studies that have been incorporated into BLOS studies.

3.1.1. Bicycle Dynamics

Bike dynamics (movement) are a crucial factor that affects both off-road and on-road facilities. However, scientific and engineering knowledge that relates to the understanding of bicycle movement is rather limited [31], mostly lagging behind research conducted for motor vehicle and pedestrian flows [33]. Botma et al. [11] state that the mean speed can only be used as a criterion for the quality of the flow when the mean speed changes with volume. In their study, they differentiated between bicycles and mopeds based on their speed (“speed > 30 km/h” is categorized as a moped). They concluded that there is only a tenuous correlation between the mean speed and the flow.

Navin [10] conducted an experiment on single-file bicycles in order to evaluate the so-called traditional traffic flow characteristics and compare them with data observed in the field. He compared his data with that of Botma et al. [11] and concluded that bicycle flow can be assumed to be similar to motor vehicle flow under certain conditions. He argued that the LOS should depict comfort and freedom of lateral movement for the rider, meaning that a LOS index should be the area occupied

by the bicycles or the “space” around a bicycle. This idea was borrowed from motor vehicle and pedestrian research (i.e., personal space) in order to be applied to bicycles. Navin [10] defined three oval zones from the smallest to the largest, namely, the collision, comfort and circulation zones. In the collision zone (0.9 m × 2.4 m), evasive actions take place. The comfort zone (1.7 m × 3.4 m) is where the bicycle is not interrupted by other bicycles, and the circulation zone (2.3 m × 4 m) is the area within which bicyclists can move freely. Two extreme conditions were defined: LOS A, when all bicycles have the freedom to circulate a random vehicle, and LOS F, which is defined as when bicycles are threatening to collide and become unable to circulate (collision zone) [10].

Many studies have since been conducted that deal with the different aspects of bicycle flow. As a pure form of bike flow rarely exists, the characteristics of mixed flow have been elaborated to some extent [35–37], some of which depict bicyclists’ behavior [38].

3.1.2. Hindrance Phenomena

Hindrance is the degree to which a user is denied the freedom to maneuver; it occurs while a cyclist passes or meets with another slower cyclist or pedestrian [39]. As far as heterogeneous bicycle flow is concerned, overtaking is a high-frequency behavior [40]. However, a scarce amount of research has addressed overtaking behavior in off-road bicycle flow (e.g., regular, e-bike, e-scooter and pedestrian flow, all demonstrating broadly different ranges of speed). This issue was investigated in the early research that was conducted on bicycle flow. Subsequently, the concept of hindrance was introduced by Botma as a new method of BLOS research [6,22]: when the frequency of events (passing and meeting) that were experienced by the users increased, the quality of the operations decreased. “Passing” was defined as a same-direction encounter and “meeting” was defined as an opposite-direction encounter. After his first study, in which he could not find a strong correlation between speed and volume, Botma proposed an interpretation of the BLOS based on the amount of hindrance that was experienced by the users. He concluded that meeting led to a level of hindrance to a lower extent than passing did, since both users (cyclists and pedestrians) are involved in the decision. The relative speed of meeting was found to be much higher than passing, which may increase the potential fear of having an accident. After this study, most studies explored the different characteristics of passing and meeting through different methods and in different countries. This method was used and proved afterwards on a shared-use path in Brisbane, Australia [41]. It was also adapted into the Highway Capacity Manual (HCM) (2000) as a recommendation for how to approach the BLOS when it came to bicycle paths [42]. Additionally, Khan [43] elaborated on the characteristics of passing and meeting on bicycle-exclusive paths in the US. They reported significantly higher speeds than in the Botma et al. [11] study, and the average lateral spacing during meetings was larger than in passings.

Hummer et al. [39] proposed a new model to estimate overtaking behavior within different speed scenarios through the travelling process. They adopted Botma’s [6] method as the basic structure for their study. Four types of hindrance were defined in this model, namely active passing, passive passing, meeting and delayed passing. Active passing refers to the condition in which the average bicycle (traveling at the average bicycle speed) passes a slower moving vehicle on the path. Passive passing refers to a situation in which the average bicycle is overtaken by either a faster bicycle or by modes. Meeting refers to the number of opposing vehicles encountered when the bicycle is moving on the path. These three events are defined based on the assumption that path geometry is not a constraining factor for these events. However, delayed passing depicts the fact that the path geometry applies the restriction to perform passing. HCM [44] has recommended the “hindrance” concept to be used for BLOS estimation.

Li et al. [45] proposed a new model for passing that is classified into free, adjacent and delayed passing based on the lateral distance between bicyclists during the passing. The model estimates the number of passings (inclusive of all three types of passing) on unidirectional two-, three- and four-lane bicycle paths based on the observational data of bicycle traffic in China. This study concludes that the frequency of all passing types increases with the increase of bicycle flow and also that, on a wider

path, the probability of active passing increases while the probability of adjacent and delayed passing decreases significantly [45]. Zhao et al. [46] used the cellular automata method to model the passing events in mixed bicycle traffic on separated paths. Garcia et al. [47] conducted a study to evaluate the effect of bike lane width and boundary conditions on meetings. They concluded that meeting clearance increases with the increasing of cycle track width and decreases if there are lateral obstacles, mainly obstacles with a height higher than the bicycle's handlebars. Li et al. [48] conducted a study in China and suggested that the probability of overtaking was at its highest when bicycle traffic was slightly congested. Xu et al. [40] proposed a model of passing in relation to one-way bicycle flow. They concluded that passing frequency increases with an increase in flow and density. Additionally, in heterogeneous traffic, passing increases with the increase in the proportion of e-bikes; at first the frequency of passing events increases and later it decreases. Chen et al. [49] suggested that both widening the bicycle lane and applying a speed limit could make for a lessened frequency of overtaking disturbances on mixed moped and bicycle shared paths. Mohammed et al. [50] assessed the cyclists' maneuvers during their following and overtaking interactions. They clustered cyclists' interactions into constrained and unconstrained states (with a threshold longitudinal distance of 25m). Overtaking was also clustered into initiation, merging and post-overtaking states. Kazemzadeh et al. [51] investigated the influence of pedestrian crowdedness on e-bike navigation behavior in a controlled field experiment. They concluded that passing causes more speed changes and lateral displacement for e-bike riders compared to meeting. This stream of existing hindrance research has been adapted to BLOS studies. This literature contributes to a better understanding of users' characteristics in bicycle flow.

3.1.3. Modal Interaction

Modal interaction is defined as how different transport modes interact on road facilities. Since each mode has its own characteristics, these interactions affect cyclists' comfort. These aspects were already discussed partly as being the potential causes of hindrances that lead to overtaking in the "hindrance phenomenon"; they were also discussed partly as a sharing policy within an infrastructure section. The e-bike as a case in point can be considered one of the common modes of transport across all cycling facilities. The e-bike is also considered to be the fastest-growing means of transportation [52]. Although the e-bike has an average speed of 16.9 km/h, the maximum e-bike operating speed can actually exceed 30 km/h [53,54]. Recent studies have documented average speed differences of 2–9 km/h between e-bikes and regular bicycle [55,56]. This difference in speeds calls for specific considerations in terms of the combination of e-bikes and bike-pedestrian facilities. In relation to this, the impact of bikes on pedestrians in shared contexts has been addressed through examinations of the pedestrian LOS [7,57]; however, there are few studies that address the challenges of the presence of pedestrians for cyclists, especially e-bikers [6,58]. Joo et al. [59] used global positioning systems (GPS) on public bicycles to collect speed data. They developed a methodology for categorizing cycling environments defined by the cyclist's perceived levels of comfort and safety.

Moreover, in the BLOS field, mainly when considering on-road facilities, motor vehicle characteristics have been extensively considered in terms of cyclists' safety and comfort. From the earliest attempts by the researchers of BLOS studies (Davis's model, 1987), motor vehicle characteristics have been used for the estimation of the cyclists' comfort within this field. As an example, the motor vehicles' volumes and speeds [42,60–65], heavy vehicles [65–67] and the motor vehicles' LOSs [68] have also been used in most BLOS studies.

Path capacity and crowdedness could also affect cyclists' comfort levels due to the resulting increased interaction rate. The design of bike paths in terms of accommodating different types of transport modes necessitates a comprehensive consideration since this can affect both comfort and safety [69]. Bike path capacity is also an important factor in the planning, design and management of facilities. Knowledge regarding the microscopic characteristics of bicycle flow is meager and this knowledge gap makes the design and analysis of bike-related facilities difficult [31]. Consequently, cycle track design guidelines rarely depend on scientific studies [47]. Many urban systems provide

on-street bike lanes to increase the right of way for cyclists; however, a large amount of bike flow could lead to bicycles having to occupy vehicle lanes and therefore interfere with vehicle traffic [70], decreasing both cyclists' comfort and safety. Botma [6] developed a capacity evaluation that related the BLOS to hindrance [6,23]. Zhou et al. [71] conducted a study in China to estimate the capacity of a cycle path. They found that the capacity of the bike path increases with the increase in the percentage of e-bikes or with the decrease in the percentage of carriages. Another study in China proposed that bicycle equivalent units were appropriate for e-bikes and confirmed that the capacity of a cycle path increases with the proportion of e-bikes depending on the cyclists' ages and genders [69]. Greibe et al. [72] conducted a study in Denmark in order to analyze the capacity and behavior of one-way bike paths with different widths. Among other conclusions is the idea that width does not affect the capacity significantly, except when there is an increasing or decreasing number of lanes. Additionally, the presence of cargo bikes decreases the capacity of a bike lane. Pu et al. [70] evaluated the interference of bike flow with motor vehicles. They concluded that when the bike density of bike lanes continuously increased, faster bikes ran into motor vehicle lanes and caused motor vehicles to reduce their speeds. Bai et al. [58] conducted a study in China to estimate the capacity of mid-block bike paths with mixed traffic flow. They also concluded that pure e-bike or e-scooter lanes had a higher capacity than that of pure bike lanes. Ye et al. [73] used the lane width, the time influence of parking maneuvers and the proportion of e-bikes as indicators for the actual capacity of a bicycle lane with curb parking. Liang [74] demonstrated that bike path width directly impacts the capacity of the path; that is, with an increase in width, the capacity decreases.

3.2. Infrastructure

The presence of a cycling infrastructure with sufficient quality plays a crucial role in increasing the ratio of cycling mode share [29,75,76]. Cost-benefit analyses demonstrate that the benefits of increased cycling are worth approximately four to five times the costs of investing in new cycling infrastructures [77,78]. The presence of a cycling infrastructure is crucial all over the transport network. However, the cycling infrastructures that are close to the origin and the destination of the trip can either contribute or be an obstacle to one making the decision of whether or not to cycle [76]. Nodes (specifically roundabouts) are an important component of infrastructure, and the challenges of adaptation with new vehicles (such as e-scooters, e-bikes and autonomous vehicle) are important considerations of infrastructure in respect to cyclists' comfort [79,80]. Due to the heterogeneity in both off-road and on-road facilities, an infrastructure's characteristics should be able to fulfill a wide range of needs for its users. Some significant aspects of this subject are discussed in the following section.

3.2.1. Sharing Policy

The sharing policy determines where cyclists can ride within transport network facilities. Two terms that are widely used regarding street infrastructures are "on-street" and "off-street" facilities. On-street facilities, where bicyclists share lanes with motorized vehicles, include shared lanes, paved shoulders, on-street bicycle lanes and buffered bicycle lanes, where a painted island separates the bicycle and the motorized vehicle lanes. On the other hand, off-street facilities are dedicated to the exclusive use of cyclists, and the pathway is shared with pedestrians and other types of users [8]. Sidewalks (as an example of an off-road facility) accommodate both modes and always have some potential risk of conflict among modes. In the US for instance, regulations of the use of bikes on urban sidewalks vary widely across the country, from being illegal to being permitted. However, in China, riding a bike on the sidewalk is more unanimously accepted [57]. Several studies within the literature have confirmed that cyclists prefer to use off-road facilities [12,14,81–84] and that cyclists generally consider off-road facilities to be safer than on-road ones [85–87]. Where cycling lanes on key routes are separated, the cyclists' cumulative intake of pollutants on heavily-trafficked roads are appreciably reduced [88]. This separation is claimed to be a strategic way to make bicycle transport more appealing to adults [89]. This separation can also make drivers more comfortable in the presence of cyclists [90];

however, on-road lanes are often a more practical and less costly alternative for cities and planning authorities [75]. Many indices have been developed for both on-street and off-street facilities, yet many of them do not consider physically protected bike lanes [91,92]. Li et al. [93] investigated cyclists' perceptions of comfort in physically separated facilities in China. They concluded that the width of the bicycle pathway and shoulder, the presence of steeper gradients and a bus stop and the adjacent land use and the flow rate of electric and conventional bicycles all significantly affect cyclists' perceptions of comfort. Bai et al. [94] identified the factors that affect the cyclists' perception of comfort in mixed traffic on mid-block bicycle lanes on urban streets. These factors included the type and volume of agents, the proportions of e-bikes and e-scooters, the peak periods, the physical separations between the motorized and bicycle and pedestrian lanes, bicycle lane slopes, roadside access points and land usage. Foster et al. [91] conducted a BLOS study for protected bicycle lanes in the US. They concluded that the type of buffer, the direction of travel, the adjacent motor vehicle speed limit and the average daily motor vehicle volumes significantly affected cyclists' comfort when using these facilities. Bai et al. [95] conducted a BLOS study on mid-block bicycle lanes. They reported on similar factors [94], such as the cyclists' age and the width of mid-block bicycle lanes, excluding the peak periods. Both studies reported that bicycle riders (compared to e-bike and e-scooter riders) were more likely to have a higher level of comfort.

3.2.2. Traffic Enforcement

Traffic enforcement can help guide, regulate and warn cyclists; however, experiencing frequent stops for red traffic lights is one of the sources of inconvenience for cyclists at intersections [96]. Traffic signs, signals and road markings are a vital part of a given road's infrastructure, because they act to control and regulate the traffic system [97]. Traffic signs may be used separately for bicycle traffic to indicate shared facilities, entrance restrictions, route guidance, certain hazards, steep hills and railroad crossings [98]. Because of the effectiveness of pictorial symbols on traffic signs in conveying complex information, these types of signs have been widely used within transportation systems. These types of signs can provide safety through providing information regarding possible risks with graphic cues instead of verbal cues, and, if well designed, can convey the information rapidly. The most critical aspect of these signs is whether or not they can convey the intended message [99]. This issue can be discussed in relation to off-road facilities such as sidewalks where traffic signs divide the facility into bicycle and pedestrian sections, which can be confusing if users do not know the correct direction and section that applies to them. This affects cyclist comfort and their respective BLOS. Hunter [100] found more wrong-way cycling and sidewalk riding at wide curb lane sites, which happened to exist in contrast with bicycle lanes; by contrast, more cyclists complied with stop signs on bicycle lanes.

A marking lane is used to enhance cycling conditions and to clarify where cyclists are expected to ride, demonstrating for motorists that they need to move around the cyclists with care [101]. Pavement markings and bike lanes are useful tools to increase cyclists' comfort. Additionally, cyclists are more visible for motorists [102,103]. The presence of a bicycle lane or shoulder strip decreases the frequency of motor vehicle encroachment into bike lanes [104,105]. However, few BLOS indices include the lane markings as a main variable for their BLOS indices [68,106,107]. The use of marked bike lanes has been introduced as a facility option on streets, which can make cyclists feel more comfortable and be more noticeable to motorcycles [103]. McHenry [108] also found that when passing cyclists in the presence of marked bicycle lanes, motorists would swing over less than when they were absent. Hunter et al. [109] evaluated the effect of blue bike lane treatment in the US. It was shown that in blue pavement areas, a higher number of motorists would slow down or stop for cyclists and that more cyclists would follow the colored bike lane. Yet, as if they were feeling a little too much within their comfort zone, it was highlighted that fewer cyclists would turn their heads to watch out for traffic or imminent hazards. Schimek [110] reviewed the effects of cycling facilities that were adjacent to on-street parking through crash data, design standards and cyclist positions. They reported that lane markings contribute to keeping cyclists away from the car doors; however, cultural norms are powerful enough to keep cyclists

close to car doors regardless of the signs and markings that are available. Another study found that striped lanes provide direction to both cyclists and drivers. This results in the reduction of deviations and queuing that potentially lead to smooth traffic flows and higher safety levels [111]. Pavement markings could also prioritize intersections for cyclists through the implementation of a bike box. Bike boxes are advanced stop boxes that increase the visibility of cyclists and potentially reduce conflicts between vehicles and cyclists in right-hook situations [112–114]. The effects of the bike box have also been inadequately considered in the literature and they might be significant in terms of network-based BLOS studies.

3.2.3. Pavement Conditions

This section discusses two distinctive elements—traditional pavement distress that is caused by asphalt fatigue or a quality disorder, and on-purpose devices that are applied for safety such as speed humps. Poor surface pavement quality leads to bicycles using the pavement to vibrate, which strongly influences the users' perceptions of a given cycle track, general cycling comfort and the choice of route [115]. However, there has been little attention paid to cycling infrastructures and pavement quality [29]. Hölzel et al. [116] compared the cyclists' comfort levels on different road surfaces based on the rolling resistances and the resulting accelerations due to the external agitations that were initiated by the different surfaces; they expanded upon certain suggestions for systematic bike lane design.

Calvey et al. [117] assessed the role of cycling infrastructures on cyclists' perceptions of satisfaction and comfort. They concluded that maintenance issues have the highest importance, particularly ones that relate to surface issues. Wu et al. [118] conducted a study in China to evaluate the impacts of pavement damage to a sewer well on the operation of bikes. They concluded that more than half of the bikes changed their trajectories, and the bike speeds significantly changed near the sewer well if the height of the sewer well was equal to, or greater than, 15 mm. They added that even if the height of the sewer well was around zero, a 51.38% rate of lane changes occurred, which led to negative impacts on the comfort levels of cyclists and the capacity of the bike path. Thigpen et al. [119] conducted a study in the US and found that the surface macrotexture and roughness of a given bike path can strongly affect cyclists' comfort. Bíl et al. [115] proposed a dynamic comfort index in order to evaluate the vibration that occurred due to issues with the surface of the pavement's properties. They applied this method to an entire road network within the center of Olomouc in the Czech Republic.

Speed humps and bumps are the most commonly used traffic-calming devices around the world due to their low-cost implementation and maintenance; however, their impact on cyclist comfort has not been studied thoroughly enough yet [120]. Mertens et al. [89] indicated in their study that the speed bump is the least preferred environmental factor for cyclists, and they suggested this in order to evaluate the effect of speed bumps on interactions with other factors such as density. Mertens et al. [121] stipulated in their study that participants could not find any relation between the speed bumps and the cyclists' comfort. Vasudevan et al. [120] analyzed the discomfort levels of cyclists while passing over speed humps. They concluded that cyclists experienced a higher discomfort level compared to motor vehicles.

In some BLOS indices, pavement conditions have been used as one of the main comfort indicators [60,62,63,67,68,107]. However, the evaluation of pavement conditions with the interactions of other variables such as weather conditions, speed bumps and speed humps could be incorporated into a better understanding of BLOS.

3.2.4. Trip-End Facility

Trip-end facilities can encourage cyclists and improve their comfort levels; however, few studies have included the effects of this facility on BLOS studies. For example, if the questionnaire is the means of data collection in the research, the user's perspective of trip-end facilities can be evaluated through questions (e.g., how would you rate bicycle parking comfort on your campus?) with the help of a Likert scale. Additionally, few studies have evaluated the relationship between bike commuting and

trip-end facilities at work [24], and the results are mixed despite the fact that the majority of findings confirm positive relations between trip-end facilities and bike commuting [122]. Bicycle parking (as one of the main trip-end facilities) could affect cyclists' comfort levels as well [30]. Abraham et al. [123] suggested that secure bike parking was the most significant facility. Safe bike parking was proven to be an important factor for cyclists in previous studies [124–128]. In China, bicycle parking was reported to be a serious problem in urban contexts in 1994 and more recently reported to be inadequate in some areas [129,130]. Titze et al. [131] suggested that with improvements in bike parking, the psychological experience and convenience of cycling may increase in quality among university students. Yuan et al. [132] conducted a study in China on cycle track and parking evaluation. They concluded that with parking improvements, three quarters of individuals would bike more. They also identified the biggest bike parking problems as being a lack of shade, a lack of security (guard, camera) and a lack of orderly parking. Furthermore, the cyclists indicated that the chances of cycling to work when they were provided with both bike parking spaces and showers is higher than when they were just provided with bike parking spaces. Marqués et al. [133] suggested that the promotion of closed and/or indoor parking facilities is significant in places where people are reluctant to park their bikes outside, mainly due to the fear of theft. Furthermore, the presence of shower facilities has been found to be an important trip-end element for cyclists [123,134]. However, some studies could not find a significant relation between the presence of shower facilities and the frequency of cycling to work [127,135]. Therefore, there is no clear picture of the effect of the presence of shower facilities. The research methods and dependent variables that differ from country to country also render these statistics unclear [136]. Thus, there is a remaining crucial need to evaluate trip-end facilities and determine their role in BLOS studies and cycling mode share.

3.3. Exogenous Factors

This section presents some general points that are relevant to the BLOS. Obtaining a comprehensive picture of the cycling experience and the levels of comfort, and consequently the BLOS index, requires an evaluation of not only the factors that can be controlled by the cycling itself, but also of the other factors that are not dependent upon the cycling process. Weather is one example that could be considered as a variable that planners have no control over; however, knowing the effects of this variable can contribute to further considerations of specific weather conditions such as snow in winter. To offer an illustration of this point, pavement potholes or rutting may have more impact on cyclists in different (or more hazardous) weather conditions. The sociodemographic characteristics of cyclists (for example, age and gender) whose patterns and other aspects are discussed within the literature can help planners to achieve a better understanding of users' perspectives.

3.3.1. Climate

Both weather and climate coupled with landscape and hilliness have been considered as the factors which most strongly affect the decision of a person to cycle, which is in contrast with the choices made by the users of motor vehicles [24]. The effects of weather on people who tend to cycle was also evaluated by season [137]. As an example, it was reported that numerous US cyclists travel in summer as opposed to during other seasons [127]; the same result was proven in Australia [138]. In Sweden, a clear difference in mode choice was reported, in which the number of bicycle trips decreased by 47% in winter [139]. It is worth noting that the season is also related to daylight hours as well as the weather conditions themselves—darkness has been found to have a negative effect on those who are commuting by bike [127,140]. Rain has also been considered to be one of the most negative aspects of weather conditions [138]. Temperature also influences increases or decreases in the amount of people who elect to cycle, leading to a higher amount of cycling the higher the temperature [138,141]. Thomas et al. [142] indicated that the weather has a higher impact on recreational cycling demand than on utilitarian demand. Wang et al. [143] concluded that the probability of violation for e-bike riders cycling under bad weather conditions is higher than when they cycle during good weather;

bad weather conditions are associated with the increase of risk. The effects of weather can also be evaluated based on the day of the week. Nosal et al. [144] indicated that urban bike flow is more sensitive to weather conditions on weekends than it is on weekdays and that recreational facilities are more sensitive than utilitarian facilities. Ayachi et al. [13] identified weather conditions as one of the main factors that affect cyclists' comfort levels. Swiers et al. [145] named weather and safety as the two main barriers to cycling. There has also been inadequate attention paid to travel time in relation to weather conditions, which may inherently be related [146]. Thus, the results show that the impact of weather on cyclists is crucial and weather plays a role as a variable within the research, data collection and planning that are associated with cycling [147]. This issue is also significant for policy design and infrastructure management, the interaction of which could be significant. BLOS studies have mainly either excluded weather conditions in their process or have included good weather conditions only, with an emphasis usually being placed on sunny weather [6,7,80,95].

3.3.2. Topography

Topography conditions have an impact on cyclists' comfort. However, few studies consider this factor in cycling comfort and BLOS studies. Due to the physical activity that is increased in the presence of slopes, this factor is expected to be significant for cyclists [24,148]. The negative impact of slopes on cyclists has been shown in the literature [141,149–151]. On the other hand, Moudon et al. [152] argued that slope severity has no important effects on bike-sharing for all trips. In addition, Fyhri et al. [153] investigated the role of e-bikes in overcoming cycling barriers. They concluded that the barriers of hilliness and physical stress were found to be of medium importance to the respondents. In terms of considering slopes in BLOS studies, only a few studies reflect this effect in their final indexes [62,67,107,154]. An attractive environment can have a crucial role in leading one towards walking and cycling [155]. The factors that create favorable conditions or better environments for cycling and the urban design of spaces can also affect bicycle use [14]. In the BLOS studies, the aesthetic aspects of routes have rarely been evaluated. As an example, the San Francisco Department of Public Health [67] developed the Bicycle Environmental Quality Index, which considers the "presence of trees" as a variable in the process of examining the BLOS.

3.3.3. Sociodemographic Aspects

Sociodemographic variables usually include age, gender and educational level [156,157]. There is a consistent pattern that can be considered in regards to gender differences, as, statistically, women cycle less than men do [158]. This initially refers to the risk of cycling, particularly in countries with relatively poor infrastructures, networks, policies and regulations and a low cycling prevalence [75,159,160]. A consideration of gender differences seems to be significant for planners and decision-makers. Most bikeway network studies consider the demographic or socio-economic characteristics of respondents such as age, gender, income and educational constants [27]. BLOS studies are also mostly directed in this way. Bai et al. [95] estimated the BLOS for a mid-block bike lane in China. They reported that gender had no statistical significance and was hence excluded from the model. Abadi et al. [106] evaluated cyclists' perceived comfort levels in dense urban contexts. They found that women are affected more than men by the presence of a truck in the adjacent lane but also that they are more likely to increase their perceived comfort level by the implementation of engineering treatment.

Infrastructure characteristics can have different priorities based on gender. Darkness was found to be more significant for women cyclists than for men [139]. Krizek et al. [82] reported that a lack of cycle paths leads women to feel more unsafe. Women also prefer to choose a safer form of infrastructure despite the longer travel time, whereas men are less inclined to make this decision. Tilahun et al. [161] argue that women have a higher tendency to choose safer and better quality options than men do. Emond et al. [162] indicated that comfort levels were one of the crucial factors for women and that they were more comfortable in off-street facilities [163]. Additionally, women seem to have a lower risk tolerance and more fear than men do in mixed traffic [161,164]. Zhao et al. [165] concluded that

in air pollution conditions, men are more persistent in their cycling. Furthermore, women showed a higher tendency to shift to public transport than men in air pollution conditions.

4. Discussion

The research on the different aspects of cycling that are related to BLOS studies is quite broad. In this literature review, variables related to bicycle flow and comfort in relation to the BLOS field have been discussed. This review provides a better understanding of BLOS studies and highlights knowledge gaps in this field. Although some of the core BLOS indices have been developed in Europe [6,7,80], most BLOS indices have been developed in the US (see Appendix A Table A1), which actually has a smaller cycling mode share in comparison to Europe. China also shares a great deal of research in this field. It seems that European planners are required to carry out research based on their own European contexts, which call for more research into BLOS studies in a European setting (see Appendix A Table A1).

Most research into e-bikes (either their flow characteristics or BLOS studies) has been conducted in China, which makes sense since China leads the world in e-bike sales, followed by the Netherlands and Germany [52]. In European countries, the support of the government for using e-bikes has increased. For example, Sweden paid back 25% of the cost of purchasing an e-bike to each purchaser in 2018 [166]. This trend should be considered to develop more studies regarding e-bike LOS studies: planners and practitioners could practically use them in their design, evaluation and management of heterogenous facilities.

In terms of bicycle facilities, off-road facilities were proven to be preferred by their users [85–87]; however, there is a limited body of research addressing the heterogeneity of these facilities [58,94]. Subjects such as the presence of e-bikes and e-scooters and the effect of speed differentials on users and passing and meeting all need to be better understood in terms of heterogeneous facilities. The results of this review show that there are few studies that either specifically elaborate on e-bike LOS or include e-bikes in mixed traffic flow. Regardless of the type of data collection, the hindrance concept for e-bikes and pedestrians or regular bicycles has not been investigated comprehensively within this field. E-bike speed is higher than a regular bicycle or pedestrian speed. This issue is associated with the need for research assessing which assumptions can be adopted for e-bikes from those related to bicycle–pedestrians interactions. Research in respect to BLOS studies is mostly based on transport components, including segments [91,167–172], nodes [63,173–175] and networks [5,176–179]. However, network-based BLOS studies compared to link and node studies require more extensive research [180–184]. Some factors, such as connectivity, the effects of the node on a link and vice versa and the full perception of cycling, can mainly be reflected through network-based evaluations.

Regarding the node studies, they are discussed in the literature via roundabout and intersection studies. Roundabouts are potentially risky spots in an infrastructure [185], and they need to be carefully evaluated for the sake of cyclists' safety. However, in BLOS and comfort studies and particularly in node studies, the evaluation of roundabouts has been studied to a lesser extent [80,186,187]. In some cases, such as in mixed traffic, roundabouts can impose delays on cyclists [188]. Additionally, in node studies, evaluating and considering the effect of queuing and its impact on the BLOS might be helpful [189,190].

Cycling as a transport mode that does not have regulations as strict as motor vehicles transport does, needs to be evaluated carefully. Some considerations such as red-light-running [191], the elderly and e-bikes [192] might be helpful in terms of conducting and evaluating BLOS studies. Gender characteristics especially provide us with the ability to facilitate better conditions for women cyclists; this can be addressed through BLOS indices. Furthermore, the traffic enforcement and control aspects of cycling (such as traffic signs and lane markings) have been covered neither in comfort-related nor BLOS studies. This tool could contribute to the regulation of cyclists in terms of both on-street and off-street facilities and could potentially reduce the conflict between agents [193]. Traffic signs and signals (as traffic enforcement) can directly affect cyclists' comfort through imposing unnecessary stops

and the process of stop-and-go. Since cycling is associated with physical activity, this factor could play a crucial role in BLOS.

Few studies have considered the impact of pavement distress, either by material disorder or applied safety tools (for example, speed bumps and humps), in comfort-related and BLOS studies [120]. This might be due to the lack of systematic tools that are purely developed for cyclists' pavement evaluations [115].

Trip-end facilities (such as bike parking and the presence of shower facilities) have been explored and examined through comfort studies, while they have not been considered in BLOS studies. This is particularly due to the way that BLOS studies have been conducted based on road components. A consideration of these facilities in BLOS studies may help planners improve cyclists' comfort levels throughout all the networks.

The negative effects of hilliness have been proven mostly by comfort level studies, while this variable has been addressed less comprehensively through BLOS indices. With an awareness of this negative effect, planners can provide some facilities on hilly roads for cyclists in order to increase comfort levels and QOS. Planners could consider the negative effect of hilliness to improve (with a higher priority compared to flat areas) other measures to enhance cycling comfort in the presence of a hilly track. For example, it can be suggested to provide cyclists with off-road facilities in the presence of hilliness. Additionally, the negative effects of weather conditions were mostly filtered out during good or sunny weather conditions in previous research; however, these factors can be critical in examining how cyclists evaluate transport facilities in harsh weather conditions.

Most surveys tend to focus on imagined biking experiences or on the evaluation of opinions right after biking on a transport network [95]; however, there is insufficient knowledge regarding the connection between imagined and real cycling experiences [194,195]. The policies related to data collection administrations in BLOS could be further evaluated in future research to have a clear picture of user perception.

Juxtaposing research between urban and rural networks shows us that inadequate research has been conducted in rural areas [7,65,124]. In order to facilitate cycling in rural areas, there is a dire need to evaluate that network.

5. Conclusions

BLOS studies play a crucial role in system improvements and cycling mode share. Investigations within BLOS studies are sometimes difficult since there are different terminologies that are interchangeably used in this field, such as the level-of-service, level of comfort, bikeability, cyclability and bike friendliness. This study takes a step towards the integration of similar research variables into BLOS studies. To this end, both the bicycle flow and comfort domains were considered for further investigation. Some findings, such as the pros of separated bike facilities, have been proven quite thoroughly, and flow studies can be helpful to render a more in-depth view from within these facilities. The results show that there are few studies that either specifically elaborate on e-bikes' LOS or include e-bikes in the mixed traffic flow. There is a crucial need to have more studies on e-bikes' LOS specifically and the effect of e-bikes (and e-scooters) within cycling facilities. The studies regarding network BLOS indices are few in number when compared to those that examine segments and nodes; this might be a result of the costly analysis of network scales. This conclusion should draw the attention of planners to the need for further consideration of bicycle facilities, which entails that not all of the BLOS indices can provide us with a comprehensive picture of user experiences and that other similar research projects are needed to complete the evaluation process.

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Appendix A

Table A1. Studies based on BLOS indices. BLOS: bicycle level-of-service; LOS: level-of-service.

Author(s) (Year)	Reference No.	Index	Scope	Territory	Main Variables
Davis (1987)	[60]	Bicycle Safety Index Rating	Link	USA	Average motor vehicle traffic, number of lanes, speed limit, width of lane and pavement condition.
Sorton and Walsh (1994)	[61]	Bicycle Stress Level	Link	USA	Traffic variables of volume, speed and curb lane width.
Epperson (1994)	[62]	Road Condition Index	Link	USA	Parking presence, median presence, bike lane presence, topographical grade and the presence of conflicts with drainage grates or rough railroad crossings. These variables were added to Davis's original set.
Landis (1994)	[63]	Interaction Hazard Score	Node	USA	Motor vehicle traffic, number of lanes, width of modified outside lanes, land use intensity, access point frequency, pavement condition, speed limit, proportion of heavy vehicles
Botma (1995)	[6]	BLOS	Link	The Netherlands	Path width, the user volume, the user composition (proportions of bicycles or pedestrians) and the user speeds.
Dixon (1996)	[68]	BLOS	Link	USA	Facility type, presence of parallel facility, lane width, on-street parking, access point density, physical median presence, sight distance restriction, motor vehicle speed, motor vehicle LOS, facility maintenance condition, barrier presence, multi-modal presence
Harkey et al. (1998)	[64]	Bicycle Compatibility Index	Link	USA	Presence of bike lane or paved shoulder, bike lane width, curb lane width, curb lane volume, other lane volume, motor vehicle speed, presence of parking lane, residential area, truck volume factor, parking turnover factor, right turn volume factor
Emery and Crump (2003)	[107]	Bicycle Suitability Assessment	Link	USA	Annual Average Daily Traffic (AADT), number of lanes, speed limit, lane width, bike lane or paved shoulder width, pavement condition, presence of a curb, railroad crossing, drain grate, angled parking, parallel parking, right-turn only lane, center turn lane, physical median, paved shoulder, bike lane marking, topographic grade, frequent curves, sight distance restriction, numerous driveways, difficult intersections, industrial land use, commercial land use, sidewalk
Jones and Carlson (2003)	[65]	Rural Bicycle Compatibility Index	Link	USA	Traffic volume, traffic speed, volume of heavy vehicles, shoulder presence, intersection density and available space for cyclists

Table A1. Cont.

Author(s) (Year)	Reference No.	Index	Scope	Territory	Main Variables
Jensen (2007)	[7]	BLOS	Link	Denmark	Land use, motor vehicle traffic volume, buffer width, motor vehicle speed, on-street parking, width of bicycle facility, lane width, sidewalk, bus stop, number of lanes
Petritsch et al. (2007b)	[66]	BLOS	Link	USA	Motor vehicle traffic volume, number of lanes, speed limit, pavement condition, proportion of heavy vehicles, lane width, number of unsignalized intersections per mile
San Francisco Department of Public health (2009)	[67]	Bicycle Environmental Quality Index	Link Node	USA	Bike lane markings, lane slope, bike parking, lighting, connectivity of bike lanes, density of driveways, left turn bike lane, sight distance, no turn on red sign(s), number of vehicle lanes, on-street parking, pavement condition, percentage of heavy vehicles, bike signage, presence of trees, land use, traffic calming features, motor vehicle traffic volume, motor vehicle speed, width of bike facility
HCM (2010) (as a representative of versions)	[44]	BLOS	Link Node	USA	Lane width, bike lane width, shoulder width, on-street parking, vehicle traffic volume, vehicle speeds, percentage of heavy vehicles, pavement condition, presence of curb and number of lanes.
Mekuria et al. (2012)	[184]	Level of Traffic Stress	Network	USA	Facility type, number of motor vehicle lanes, bike lane width, speed limit, bike lane blockage, on-Street parking
Kang and Lee (2012)	[180]	BLOS	Link node	Korea	Bike road width, bike road type, total number of lanes on the approach to the intersection and number of encounters.
Lowry et al., (2012)	[5]	Communitywide Bikeability with Bicycle Level of Service	Network	USA	Highway Capacity Manual (HCM) (2010) variables are used; however, any other bike suitability method could be used in this assessment.
Jensen (2013)	[80]	BLOS at Intersections	Node	Denmark	Signalized Intersection: bike facility type before stop line, bike facility type within intersection, waiting time, urban or rural zone, crossing distance, motor vehicle volume. Roundabout: bike facility before and at roundabout, motor vehicle volume, crossing distance, circulating lane(s). Non-signalized crossing: sidewalk across minor approach presence, right-of-way condition, motor vehicle speed, motor vehicle volume
Foster et al., (2015)	[91]	LOS Model for Protected Bike Lanes	Link	USA	Type of buffer, direction of travel (one-way versus two-way), motor vehicle speed limit and average daily motor vehicle volumes

Table A1. Cont.

Author(s) (Year)	Reference No.	Index	Scope	Territory	Main Variables
Liang et al., (2017)	[92]	LOS of dedicated bike lanes	Link	China	A reactive zone represents cyclists' perceived comfort in passing maneuvers. The LOS index is developed based on the relationship between entropy of speed state and the density of bike flows.
Beura, Chellapilla, et al., (2017)	[171]	LOS	Link	India	Lane width, pavement condition, traffic volume, traffic speed, roadside commercial activities, interruptions by unauthorized stoppages of intermittent public transits, vehicular ingress-egress to on-street parking, and frequency of driveways carrying a high volume of traffic.
Beura and Bhuyan (2017)	[170]	LOS	Link	India	Average effective width of outermost through lane, peak hour traffic volume per lane, average traffic speed, pavement condition, commercial activities on roadside area, interruptions by unauthorized stoppages of intermittent public transits, vehicular ingress-egress volume to on-street parking area, frequency of driveways carrying a high volume of traffic
Bai et al., (2017)	[95]	LOS	Link	China	Cyclists' age, the type of two-wheeled vehicles, the volume of two-wheeled vehicles, the width of mid-block bike lanes, the proportions of e-bikes and e-scooters in two-wheeled vehicles, the physical separation between motorized, bike and pedestrian lanes, the slope of bike lanes, the roadside access points and the roadside land use
Griswold et al., (2018)	[169]	Behavioral bicycle LOS	Link	USA	Three classes of cyclists were defined as neighborhood, urban and fitness cyclists, and their cycling behavior and preferences were explained.
Ledezma-Navarro et al., (2018)	[174]	LOS and safety for cyclists and vehicle	Node	Canada	Three strategies (a partially protected design, a completely protected design and a completely protected with protected turn phase) were evaluated with a focus on LOS and safety for different traffic signal designs at intersections with bike facilities.
Beura et al., (2018)	[167]	Bicycle LOS	Link	India	Effective width of lane, peak hour volume per lane, average traffic speed, pavement condition, roadside commercial activities, interruptions by roadside stoppages of public transits, vehicular ingress-egress to the on-street parking, frequency of driveways carrying high traffic volume

Table A1. Cont.

Author(s) (Year)	Reference No.	Index	Scope	Territory	Main Variables
Majumdar and Mitra (2018)	[168]	Bicyclist perceived LOS	Link	India	Results indicated that among the variables measured in continuous scale, the on-street parking (ONP) proportion has the strongest influence on bicyclist-perceived LOS followed by motorized volume and the 85th percentile speed of motor vehicles.
Liu and Suzuki (2019)	[179]	E-bike applicability	Network	Japan	Travel time and energy expenditure
Okon and Moreno (2019)	[172]	BLOS	Link	Colombia	Side path separation, vehicle speed, motorized traffic volume and conflicts with pedestrians
Beura et al. (2020)	[175]	BLOS	Node	India	Effective width of the approach, peak hour volume on the approach, crossing pedestrian volume, volume of turning vehicular traffic across the path of through bicyclists, average stopped time delay incurred by through cyclists, on-street parking turnover and surrounding developmental pattern

Table A2. Previous flow studies (with application to BLOS studies). QOS: quality of service.

Author(s) (Year)	Reference No	Agents	Scope	Data Collection	Territory	Main Conclusion(s) or Recommendation(s)
Botma and Papendrecht (1991)	[11]	Bicycle, pedestrian, moped	Link	Observation	The Netherland	The mean speed can only be used as the QOS indicator for LOS criteria when the mean speed changes with volume.
Navin (1994)	[10]	Bicycle	Link	Experiment	Canada	The BLOS of the pathway should be measured in bicycles per 2 m as is done for pedestrians.
Khan and Raksuntorn (2001)	[43]	Bicycle	Link	Observation	USA	In passing phase, the average difference of passing and passed bicycle speed was reported as 9.37 km/h
Zhao et al. (2013)	[46]	e-bike/bicycle	Link	Observation	China	Increase in the ratio of e-bikes would not significantly increase the number of passing events, but e-bikes contribute substantially to passing events in mixed bicycle traffic.
Li et al. (2013)	[45]	Bicycle	Link	Observation	China	Passing maneuvers linearly increase as the standard deviation of bicycle speeds increases.
Jin et al. (2015)	[69]	e-bike/bicycle	Link	Observation	China	The mean bicycle equivalent unit for the e-bike is 0.66, and the converted capacities of pure bicycles and pure e-bikes are 1800 and 2727 bicycle/h/m, respectively.
Hoogendoorn and Daamen (2016)	[31]	Bicycle	Node	Observation	The Netherland	The share of constrained cyclists could be used an indicator of the LOS that the facility provide.
Jiang et al. (2016)	[33]	Bicycle	Link	Experiment	China	The fundamental diagram and the spatiotemporal evolution of bicycle flow on the circular road were presented. They reported a critical density of about 0.37 bicycles/m.
Yuan et al. (2018)	[34]	Bicycle	Link Node	Experiment	The Netherland	Cyclists initiate to deviate from their current path when they are around 30 m from each other, and they prefer passing on the right-hand side.
Xu et al., (2018)	[40]	e-bike/bicycle	Link	Observation	China	An analytical approach to study the relationship between the characteristics of heterogeneous bicycle traffic flows and the number of passing events.
Mohammed et al. (2019)	[50]	Bicycle/pedestrian	Link	Observation	USA	The threshold of longitudinal distance between constrained and unconstrained states in following interactions is 25 m, which equates to a 5 s time headway at 5 m/s average speed.
Kazemzadeh et al. (2020)	[51]	E-bike pedestrian	Link	Experiment	Sweden	Passing causes more speed changes and lateral displacement for e-bikes compared to meeting.

Table A3. Previous comfort studies (with application to BLOS studies).

Author(s) (Year)	Reference No	General Theme	Territory	Main Variables or Main Conclusion(s)
Bergström and Magnusson (2003)	[139]	Climate impact	Sweden	Temperature, precipitation and road condition are the most important factors to those who cycled to work in summer but not in winter.
Parkin and Rotheram (2010)	[148]	Designing facilities	England	Recommendations: designers adopt 25 km/h as a design speed for gradients less than 3%, and design speeds of up to 35 km/h for steeper gradients.
Kirner Providelo and da Penha Sanches (2011)	[15]	Cycling comfort factors	Brazil	Lane width, motor vehicle speed, visibility at intersections, presence of intersections and street trees (shading)
Heinen et al., (2011)	[4]	Cycling comfort factors	The Netherlands	The attitudes and other psychological factors have a relatively solid impact on the choice to commute by bicycle.
Petritsch et al. (2010)	[16]	Cycling comfort factors (shared facilities)	USA	A model that represent cyclists' perceptions of how a shared-use path adjacent to a roadway meets their needs.
Li et al. (2012)	[93]	Cycling comfort factors(off-road facilities)	China	Physical environmental factors, including the width of the bicycle track, the width of the shoulder, the presence of grade, the presence of a bus stop, the surrounding land use and the flow rate of electric and conventional bicycles influence comfort.
Saneinejad et al. (2012)	[147]	Climate impact	Canada	Wind speed negatively influences cyclists about twice as much as pedestrians. Precipitation in the form of showers affects cyclists more than pedestrians.
Li et al. (2012)	[17]	Cycling comfort factors	China	Cyclists' comfort for off-road facilities: the road geometry and surrounding conditions. Cyclists' comfort for on-road facilities: the effective riding space and traffic situations.
Buehler (2012)	[122]	Cycling comfort factors	USA	Bicycle parking and cyclist showers are related to higher levels of bicycle commuting.
Thomas et al. (2013)	[142]	Climate impact	The Netherlands	Recreational demand is much more sensitive to weather than utilitarian demand.
Nosal and Miranda-Moreno (2014)	[144]	Climate impact	Canada USA	Precipitation has a substantial negative impact on cycling flows and its effect was detected to increase with rain intensity.
Fernández-Heredia et al. (2014)	[14]	Cycling comfort factors	Spain	The convenience (flexible, efficient) and exogenous restrictions (danger, vandalism, facilities) are the most important elements to understand the attitudes towards the bicycles.
Ayachi et al. (2015)	[13]	Cycling comfort factors	Various countries	Bicycle components (specifically the frame, saddle and handlebar), environmental factors (type or road, weather conditions) and factors related to the cyclist (position, adjustments, body parts) influence comfort.
Bil et al. (2015)	[115]	Cycling comfort factors	Czech	Dynamic comfort index (DCI) developed for describing the vibration properties of surface pavement on a track.

Table A3. Cont.

Author(s) (Year)	Reference No	General Theme	Territory	Main Variables or Main Conclusion(s)
Calvey et al. (2015)	[117]	Cycling comfort factors	England	People perceive maintenance issues to be of high importance, especially surface issues. From exploratory factor analysis of results, satisfaction is related to comfort and safety.
Liu et al., (2015)	[137]	Climate impact	Sweden	The impacts of weather are diverse in different seasons and different regions. The northern Sweden cyclists are more aware of temperature variation than cyclists in central and southern Sweden in spring and autumn when the temperature changes considerably.
Muñoz, Monzon and López (2016)	[18]	Cycling comfort factors	Spain	To have a cyclable city, safety and comfort factors are not the key barriers for all commuters, although more progress needs to be made to normalize cycling.
Fernández-Heredia et al., (2016)	[20]	Cycling comfort factors	Spain	Convenience, pro-bike, physical determinants and external restrictions contribute to explain the intention of using bikes.
Vasudevan and Patel (2017)	[120]	Traffic enforcement	India	Bicyclists experienced higher discomfort than that by riders of motorized two-wheelers while passing over humps (at the same speed).
Yuan et al. (2017)	[132]	Bicycle Parking	China	Almost half of participants thought campus bike parking lacked order. If parking were improved, three quarters indicated they would bicycle more.
Swiers et al. (2017)	[145]	Cycling comfort factors	England	Cycling motivators are enjoyment and improving fitness especially amongst regular cyclists. Weather and safety concerns are the main obstacles.
Fu and Farber (2017)	[19]	Cycling comfort factors	USA	Four factors concerning bicycling: safety, direct benefits, comfort and timesaving.
Abadi and Hurwitz (2018)	[106]	Especial environment(urban loading zones)	USA	Traffic factors (low traffic volume, high traffic volume and truck traffic), bicycle lane pavement markings (white lane markings, solid green and dashed green) and traffic signs (no sign or warning sign).
Caviedes and Figliozzi (2018)	[176]	Cyclists stress assessment	USA	On-road measurements of physiological stress of cyclists at different types of bicycle facilities at peak and off-peak traffic times.
Zhao et al. (2018)	[165]	Climate impact	China	In polluted weather, those who persist in cycling are more male, over 30 years old, lower income or those who travel short distances.
Lu et al. (2018)	[96]	Traffic enforcement	The Netherlands	Frequent stops for red traffic lights at intersections are a major source of inconvenience for cyclists. A green wave concept for cyclists is presented, with a focus on the traffic management and control aspects under cooperative intelligent transport systems applications.
Blau et al. (2018)	[79]	Adjustment with other users	USA	The increases in motorized traffic volumes, presence of driverless vehicles and speeds correlate with a greater preference for separated facilities.
De Angelis et al., (2019)	[97]	Traffic enforcement	Italy/the Netherlands	Assessment of users' evaluation and acceptance of different interfaces for cyclists' green waves.

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