Journal of Cycling and Micromobility Research 6 (2025) 100089

Contents lists available at ScienceDirect

Journal of Cycling and Micromobility Research

journal homepage: www.sciencedirect.com/journal/journal-of-cycling-and-micromobility-research

Are we measuring what matters? A multilayered framework evaluating active mobility infrastructure through PLOS, BLOS and 15 minute city principles

Richa Maheshwari [a,*], Martin Loidl [b], Rupali Khare [c], Mario Cools [a,d]

[a] Local Environment Management & Analysis (LEMA), Urban and Environmental, Engineering (UEE), University of Liège, Quartier Polytech 1, Allée de la Découverte 9, Liège 4000, Belgium
[b] Department of Geoinformatics-Z GIS, Paris Lodron University of Salzburg (PLUS), Austria
[c] Department of Electrical and Computer Engineering, Aarhus University, Denmark
[d] Faculty of Business Economics, Hasselt University, Belgium

ARTICLE INFO

Keywords:
PLOS
BLOS
15 minute city (15MC)
Indicator-based
Active mobility
Multi-layered framework
Urban sustainability

ABSTRACT

Active mobility is increasingly recognised as the cornerstone of sustainable urban development. Providing suitable infrastructure for walking and cycling is essential for promoting active transport and achieving its associated environmental and health benefits. However, systematically evaluating the suitability of active mobility infrastructure remains a methodological challenge. This paper presents a multilayered conceptual framework designed to assist policymakers, practitioners, and researchers in assessing active mobility infrastructure by integrating Pedestrian and Bicycle Level of Service models with the principles of the 15 min city. The hierarchical framework organises six broad constructs, such as Facilities, Geometric Design, Built and Natural Environment, Amenities, Proximity and Accessibility, and Flow and Traffic Characteristics, under which 138 unique indicators are classified. A systematic review of 78 studies using the PRISMA protocol guided the development of this structure, revealing both commonly cited and underutilised indicators critical for infrastructure evaluation. The three-layered framework illustrates how pedestrian and cyclist experiences are shaped by the interplay between physical infrastructure, its surrounding environment, and functional performance. It enhances conceptual clarity, reduces redundancy and ambiguities caused by overlapping terminologies, and supports evaluation at both micro and macro scales. It introduces the "Golden Nuggets", i.e., the essential indicators for evaluating non-motorised infrastructure and highlights underused but important metrics. The framework also recommends scaling segment-based assessments to route- and network-based levels, advancing current PLOS and BLOS models. Future research should focus on empirical validation across spatial scales and the development of indicator weighting schemes to enhance the framework's application as a practical, scalable, and transferable evaluation tool.

1. Introduction

The 15 min city concept (15MC), popularised by Carlos Moreno, has become a leading framework in contemporary urban planning, placing proximity at the heart of strategies to redesign cities in response to urgent climate, mobility, and social equity issues (Moreno et al., 2021). Although increasingly embraced worldwide, the 15MC concept builds on a rich history of urban planning traditions, including the Garden City, Neighbourhood Unit, New Urbanism, and Chrono-urbanism. Despite their differing methodologies, these models aimed to overcome the spatial and social fragmentation caused by modernist planning. However, what distinctly characterises the 15MC is its emphasis on "repairing" existing urban environments rather than creating entirely new ones from scratch. It is defined as a proximity-based urban model where essential services such as living, working, commerce, healthcare, education, and entertainment are accessible within a maximum of a 15 min walk or bike ride.

One of the earliest large-scale implementations explicitly framed under the 15MC label took place in 2016 through the Porte de Paris project, initiated by Mayor Anne Hidalgo to transform Paris into a

* Corresponding author.
E-mail address: richa.maheshwari@uliege.be (R. Maheshwari).

https://doi.org/10.1016/j.jcmr.2025.100089
Received 13 May 2025; Received in revised form 4 August 2025; Accepted 17 September 2025
Available online 23 September 2025

proximity-based urban environment (Allam et al., 2022). This project aligned closely with Moreno's framework, emphasising reduced travel distances and the promotion of sustainable lifestyles. The initiative aimed at enhancing the city's resilience to climate change, improving equitable access to essential services regardless of residents' geographical location or socio-economic status, and stimulating local economic activity by fostering small businesses and community-oriented development.

Since its initial conceptualisation, cities worldwide have adopted, adapted, and refined the principles of the 15MC. Milan, for instance, embraced the concept through key principles such as proximity, polycentrism, multifunctionality, and citizen participation as catalysts for urban transformation (Abdelfattah, Deponte, and Fossa, 2022). This approach focuses on revitalising neighbourhoods, streets, and public spaces to foster social interaction, improve residents' safety, and encourage effective collaboration between residents and local government. Similarly, Portland introduced the 20 min neighbourhood principle, anchoring its urban transformation in a proximity-based policy, which assessed accessibility to urban functions, parks, schools, and public services within a 20-minute radius. This transformation has been facilitated by improvements in street connectivity, pedestrian infrastructure, and public transit systems (City of Portland, 2012). The city of Sousse in Tunisia adopted the 15MC framework in response to the COVID-19 pandemic, aiming to create an inclusive, creative, and attractive urban environment (Transitec, 2025). Likewise, Melbourne's 20 min neighbourhood initiative envisions a city where residents can access essential services such as schools, shops, parks, leisure centres, and employment opportunities within a 20-minute walk, bike ride, or public transit journey (The State of Victoria Department of Transport and Planning, 2023). For a broader overview of how the 15MC concept has been implemented across different global contexts, see, for instance, Teixeira et al. (2024).

Proximity-based urban planning models, such as the 10-, 15-, 20-, and 30 min neighbourhood, aim to enhance sustainability by promoting accessibility to essential services such as living, working, commerce, healthcare, education, and entertainment through active transport modes such as walking and cycling (Da Silva et al., 2020; Logan et al., 2022; McNeil, 2011; Moreno et al., 2021). However, the effective implementation of these concepts at the local level requires more than spatial proximity alone. After all, the decision to walk or cycle to essential amenities is not only influenced by distance but also by the quality of non-motorised infrastructure, including sidewalk and cycle track width, path continuity, safety, and user comfort, to name a few. To evaluate the quality of walking and cycling infrastructure, researchers and planners have increasingly relied on structured assessment tools.

This review focuses specifically on Pedestrian Level of Service (PLOS) and Bicycle Level of Service (BLOS) models, which are widely used in engineering-inspired transport planning to evaluate the suitability of non-motorised infrastructure. While we acknowledge the rich and overlapping bodies of research in related fields such as walkability, bikeability, accessibility studies, and broader mobility research across urbanism, planning, geography, and social sciences, this study focuses on the PLOS/BLOS literature. This choice allows for a systematic exploration of how these models might be integrated with the principles of the 15MC.

PLOS and BLOS models rooted in the principles of vehicular Level of Service (LOS) frameworks introduced in the Highway Capacity Manual (1965) have evolved significantly from engineering-focused assessments to more user-centred approaches that emphasise safety, security, comfort, and convenience. Early PLOS models, such as the model by Fruin (1971), primarily evaluated physical infrastructure elements, such as sidewalk capacity and pedestrian volume. Subsequent studies expanded these models by integrating pedestrian flow variables (speed, volume, density) and qualitative factors related to comfort and safety (Mozer, 1994; Polus, Schofer, and Ushpiz, 1983; Sarkar, 1993). In parallel, Dixon (1996) introduced infrastructural elements (pedestrian facilities and conflict points), while Jaskiewicz (2000); Gallin, (2001) incorporated built environment features (enclosure and path complexity), along with user characteristics. Further refinements extended PLOS and BLOS models to incorporate traffic-related variables (e.g. Landis et al. 2001). Subsequent modifications in the Highway Capacity Manual (Highway Capacity Manual, 2016, 2010) refined PLOS models further by integrating pedestrian delays and traffic signal timing, highlighting the importance of optimised coordination between vehicular and pedestrian flows.

Similarly, Davis (1987) introduced the first BLOS model with physical indicators such as traffic volume and pavement conditions. Sorton and Walsh (1994) introduced psychological constructs such as stress. Later, Davis (1995) refined his approach by adding constructs like route coherence and safety. On the other hand, Landis, Vattikuti, and Brannick (1997) and Harkey, Reinfurt, and Knuiman (1998) incorporated cyclist perceptions and built environment constructs (parking turnover and roadside development) in their models. Hallett, Luskin, and Machemehl (2006) developed a model to analyse cyclist-vehicle interactions, Petritsch et al. (2008) emphasised safety on high-traffic roads in their model, Lowry et al. (2012) integrated network connectivity and user comfort, Broach, Dill, and Gliebe (2012) utilised GPS data to capture cyclists' preferences and Furth, Peter, Mekuria. (2013) developed a low-stress network model to guide infrastructure improvements. Lastly, Ahmed et al. (2023) incorporated portable bicycle lights and real-time data that highlight the role of technology in the advancement of BLOS assessment models.

Despite significant advancements in PLOS and BLOS methodologies, these models lack conceptual coherence and fail to align with the structured principles of the 15MC framework (Nag et al., 2020; Werner et al., 2024). While PLOS and BLOS frameworks predate the 15MC concept, their independent evolution has resulted in methodological fragmentation, characterised by the absence of a unified set of constructs and relevant indicators for the comprehensive evaluation of non-motorised transport infrastructure (Asadi-Shekari, Moeinaddini, and Shah, 2013; Sisiopiku, Byrd, and Chittoor, 2007). This fragmented development, marked by inconsistent terminology and the absence of a systematic, synthesised indicator framework, has produced models that are difficult to compare and limited in capturing the full complexity of non-motorised infrastructure networks (Kazemzadeh et al., 2020). While some studies selectively incorporate subsets of indicators for specific purposes (e.g., the Bicycle Comfort Level Rating (BCLR) model developed by Sambit Kumar Beura et al. 2021 to assess comfort), the absence of a standardised, hierarchical framework continues to hinder cross-contextual evaluation and generalizability. Addressing this gap is crucial to ensure conceptual rigour and establish a structured methodology that aligns with the integrative principles of the 15MC.

A further limitation of existing PLOS and BLOS models is a lack of integration with the proximity and accessibility principles of the 15MC into their evaluation frameworks. Non-motorised infrastructure cannot be evaluated solely at the segment level but must be understood within a broader network context. Yet, current PLOS and BLOS models largely neglect these critical constructs. While several reviews have consolidated findings from PLOS and BLOS studies (Ahmed et al., 2024; Asadi-Shekari, Moeinaddini, and Shah, 2013; Kadali and Vedagiri, 2016; Kazemzadeh et al., 2020; Nag et al., 2020; Raad and Burke, 2017), neither theoretical discourse nor empirical research has successfully aligned PLOS and BLOS models with the overarching paradigm of the 15MC. This omission represents a significant gap, particularly given that the shared objective is to create more walkable and bike-friendly urban environments (Kim et al., 2014; Jin et al., 2024). Addressing this gap requires the development of an integrated framework that systematically interweaves insights from PLOS, BLOS, and the 15MC literature to enable a comprehensive evaluation of pedestrian and cycling infrastructure (Fig. 1).

To address these gaps, this study aims to develop a unified, hierarchical conceptual framework that integrates the overlapping principles

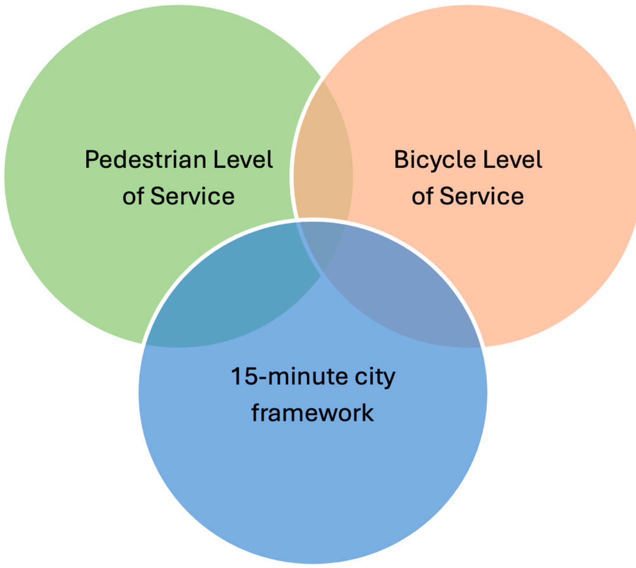

Fig. 1. Identifying overlaps between the three strands of literature.

of the 15MC, such as proximity and accessibility, with existing PLOS and BLOS models. This integration will enable a holistic, consistent, and comparable assessment of pedestrian and cycling infrastructure across diverse urban contexts. The conceptual framework will establish a hierarchical structure comprising broad, standardised constructs, a definitive set of relevant indicators, and an explanation of their interrelationships in evaluating infrastructure suitability. The central hypothesis of this study posits that the recurrence of specific indicators across PLOS and BLOS studies highlights their critical relevance, enabling the identification of 'Golden Nuggets', i.e. key indicators essential for assessing walkable and bike-friendly infrastructure within a standardised framework. This overarching aim is structured around the following research objectives:

1. To systematically review the existing PLOS and BLOS literature within the context of the 15MC, identifying key overlaps and synergies.
2. To identify, combine and categorise the key broad constructs necessary for evaluating pedestrian and cycling infrastructure across diverse urban contexts.
3. To classify and prioritise key indicators (most cited, least cited, and proxy) critical for assessing pedestrian and cycling infrastructure suitability.
4. To develop a hierarchical and unified conceptual framework that integrates BLOS and PLOS methodologies with the principles of the 15MC, enabling a comprehensive evaluation of pedestrian and cycling infrastructure.

This study makes three principal contributions to the domains of active mobility and proximity-based planning. First, it addresses a longstanding methodological gap by proposing an integrated, multi-scalar conceptual framework that synthesises PLOS and BLOS models with the principles of the 15MC. In doing so, it advances current infrastructure evaluation paradigms beyond segment-based metrics (micro level) toward a more holistic, network-sensitive, and proximity-aware (macro level) assessment logic. Second, through a systematic review of 78 peer-reviewed studies, this study distils a corpus of 1124 raw indicators into 138 unique and hierarchically categorised metrics across six standardised broad constructs. This resolves critical issues of conceptual redundancy, terminological inconsistency, and operational fragmentation that have limited cross-context comparability in past research. Third, the study introduces a three-layered evaluative model that distinguishes between infrastructural elements, their spatial-urban context, and functional performance, enabling researchers, planners, and policymakers to undertake more nuanced, transferable, and scalable assessments of walking and cycling infrastructure suitability and contribute to sustainable and inclusive urban transformation.

The remainder of the paper is structured as follows: Section 2 outlines the methodology used for the systematic review. Section 3 presents the key findings, while Section 4 introduces the hierarchical and unified conceptual framework. Finally, Section 5 offers a critical discussion of the key takeaways from this comprehensive review paper.

2. Methodology

To systematically identify relevant literature on Pedestrian Level of Service (PLOS) and Bicycle Level of Service (BLOS) within the context of the 15MC concept, this study employed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology (Moher et al., 2009). This methodology ensured a rigorous selection process, applying well-defined screening and eligibility criteria to enhance transparency across all stages of the systematic review. By adopting this structured methodology, the review remains reproducible and minimises potential biases.

2.1. Initial syntax

Before conducting the main literature search for PLOS and BLOS, a preliminary review of the 15MC literature was undertaken to identify relevant key terms, possible synonyms, and technical terminologies associated with active transport (walking and cycling). This initial analysis informed the development of the initial search syntax, presented in Table 1, which retrieved 190 scientific articles from the Web of Science and SCOPUS databases.

A Python script was developed to parse the RIS files (of the 190 articles) and to conduct keyword categorisation analysis, enabling the extraction of possible synonyms or technical terminology related to active transport in the 15MC literature. This analysis identified the most common keywords, including walk, walkability, pedestrian, cycling, bike-ability, mobility, and accessibility. These keywords were then incorporated into the final syntax (Syntax 2), alongside PLOS and BLOS keywords, to refine the search for relevant scientific literature.

It is important to note that the 15MC was deliberately excluded from the final search syntax. The primary objective of this study is to develop a conceptual framework that integrates the overlapping principles of the 15MC with PLOS and BLOS methodologies, establishing a standardised hierarchical structure of key constructs and indicators. This study does not seek to introduce a new conceptual framework for the 15MC but rather to align existing PLOS and BLOS models with the 15MC's core principles.

Table 1
Syntax development process.

Syntax		Theme	Total Hits
Syntax 1	(TITLE-ABS-KEY ("15 min city" OR "15 min city" OR "15 min cities" OR "15 min cities"))	15 min city	190
Syntax 2	(TITLE-ABS-KEY ("pedestrian level of service") AND TITLE-ABS-KEY (walk OR walkability OR pedestrian OR accessibility OR mobility)) OR (TITLE-ABS-KEY ("bicycle level of service") AND TITLE-ABS-KEY (cycling OR bicycle OR bikeability OR accessibility OR mobility))	PLOS and BLOS in relation to a 15 min city	336

2.2. Final syntax

The final search syntax incorporated the previously identified keywords to specifically target literature assessing PLOS and BLOS within the 15MC framework (see Syntax 2 in Table 1). The search was conducted across titles, abstracts, and keywords in scientific papers related to the concepts of "Pedestrian level of service in a 15 min city" and "Bicycle level of service in a 15 min city." To ensure comprehensive coverage, the "OR" operator was applied between the main concepts, while the "AND" operator was used within each concept to refine search precision. This approach maximised the inclusion of relevant studies while maintaining specificity. This final search strategy resulted in 336 scientific articles.

The literature search was restricted to studies assessing PLOS and BLOS within the 15MC concept. Only full-length papers published in English up to June 2024 were considered. The selection process included peer-reviewed journal articles and review papers, while conference papers, books, book chapters, and retracted articles (n = 97) were excluded. To further refine the selection of articles, multiple filtering criteria were applied using Rayyan, an open-source web tool designed to facilitate systematic reviews (Ouzzani et al., 2016). This filtering process identified 98 duplicate articles that were subsequently removed.

The remaining 136 articles were assessed based on full-text eligibility. The inclusion criteria were as follows:

- Studies explicitly employing the PLOS or BLOS frameworks.
- Studies assessing PLOS or BLOS within the 15MC concept.
- Studies exclusively focusing on sidewalks and cycle tracks as primary infrastructure types. These facilities play a central role in shaping active mobility, influencing a wide range of factors.

The exclusion criteria were as follows:

- Studies focused on PLOS and BLOS methodologies, LOS scoring thresholds or general walkability indices (n = 35). While walkability and PLOS are related concepts, they remain distinct in theoretical and methodological approaches (Lo, 2009).
- Studies examining intersection design and mid-block crossings facilities, including metrics such as signal timing, delay function, turning traffic, and crosswalk spacing, were removed because these indicators do not directly affect the suitability of sidewalks and cycle paths (n = 23) (Bellizzi, Forciniti, and Mazzulla, 2021; Landis et al., 2001; Raad and Burke, 2017; Zhao et al., 2014).

Fig. 2 presents the PRISMA diagram, illustrating the different stages of the article selection process.

As a result, 78 articles were retained for the analysis, comprising 73 journal articles and 5 review papers. The review papers were included to understand the emergence of important general constructs within PLOS and BLOS studies, whereas the journal articles contributed to the development of a robust conceptual framework for assessing the suitability of PLOS and BLOS infrastructure within the 15MC framework. Among the selected studies, 49 focused on PLOS, 22 on BLOS, and two addressed both pedestrian and cyclist LOS perspectives. Additionally, forward and backwards snowballing were conducted to identify further relevant papers; however, this process did not yield any additional articles.

To systematically analyse the selected studies, AI-assisted tools were initially employed to automate data extraction. This was followed by the application of quantitative methods, including statistical analysis using Python, Microsoft Excel, and Voyant (an open-source tool). These computation techniques were complemented by manual thematic analysis, resulting in the extraction of 216 potential constructs and 1124 indicators. Fig. 3 provides an overview of the step-by-step methodology used in the modelling process.

3. Results and discussion

Building on this initial extraction, a systematic review of the selected papers was conducted to identify the key constructs and relevant indicators that define various aspects of PLOS and BLOS infrastructure within the 15MC framework. To facilitate this process, Scholar-GPT, a GPT model with built-in scientific reading capabilities, was used for automated text analysis. The model was guided by a carefully structured prompt designed to extract measurable constructs and indicators while avoiding duplication. The prompt was iteratively refined to ensure clarity, precision, and alignment with the study objectives. This refinement process ensured the generation of a comprehensive, structured, and non-redundant list of measurable constructs and corresponding indicators, thereby enhancing the completeness and accuracy of the dataset.[1]

3.1. Key broad constructs

From 78 papers, a total of 216 potential constructs were extracted using automation. To validate the extracted constructs, 60 full-text papers were manually reviewed, achieving a 77 % validity rate. Consequently, the next set involved an in-depth analysis of terminologies and thematic focus, drawing from previous studies to ensure coherence in classification. Thematic analysis was used to identify fundamental overlaps and group related constructs based on their emphasis on physical infrastructure, the broader network or context, and the use of infrastructure. This process resulted in the categorisation of six overarching categories: (*i*) Facilities, (*ii*) Geometric Design, (*iii*) Built and Natural Environment, (*iv*) Amenities, (*v*) Proximity and Accessibility, and (*vi*) Flow and Traffic Characteristics.

This categorisation was essential, as previous studies frequently presented overlapping classifications that measured similar underlying concepts under varying terminologies. By systematically regrouping these constructs into coherent categories, this study ensured that each category represented a core dimension of pedestrian and cycling infrastructure evaluation. This process was informed by established review studies, strengthening the conceptual clarity of the categorisation.

The 'Facilities' construct encompasses both core infrastructure elements (such as sidewalks, cycle tracks, number of lanes, and on-street parking) and supplementary elements (such as pavement type, road markings, zebra crossings, and traffic signals), which are essential for enabling walking and cycling functionality. It also includes legal and regulatory indicators such as signals, speed limits, and road signs (such as one-way traffic). From the initial pool of 216 constructs, all constructs directly related to roadway facilities, such as Pedestrian Infrastructure, Bicycle Facilities, Carriageway Facilities, On-Street Parking, Disabled Pedestrian Infrastructure, Footpath Facilities, Main Facilities, Quality of physical facilities, and Mobility and Infrastructure (Dixon, 1996; Huang, Fournier, and Skabardonis, 2021; Noronha, Celani, and Duarte, 2022), were systematically consolidated under the 'Facilities' construct. This streamlined categorisation eliminates redundant terminologies and enhances conceptual clarity in representing roadway-related infrastructure elements. The 'Facilities' construct serves as the foundation of pedestrian and cycling infrastructure, directly influencing their functionality, safety, and accessibility.

The 'Geometric design' construct focuses on the spatial configuration and maintenance of individual features. It includes elements such as physical layout, width, length, and the overall condition and quality of the individual features, all of which directly influence user comfort and safety. To define this broad construct, various related constructs, such as Geometrical Layout, Infrastructure Design, Intersection Design, Path

[1] Exemplary prompt: *"Can you identify all measurable items, variables, or indicators that are used to calculate the Pedestrian and/or Bicycle Level of Service from the attached pdf file and ensure there is no repetition in the list?"*

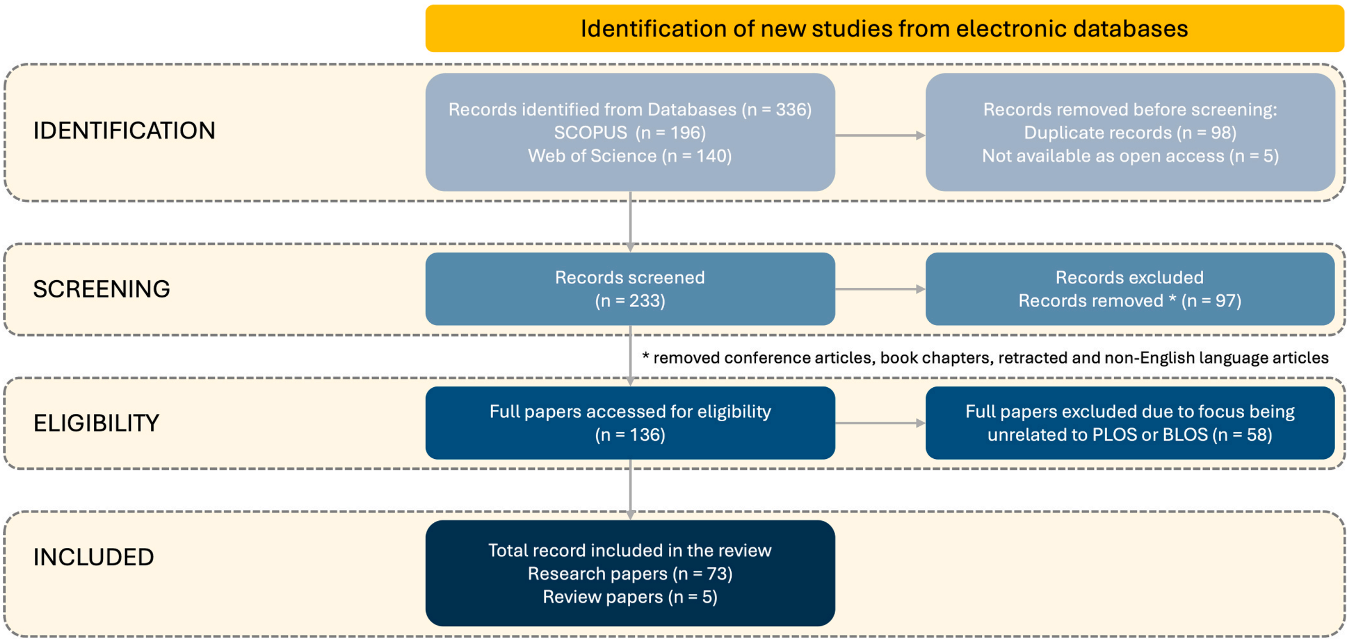

Fig. 2. Workflow according to PRISMA protocol.

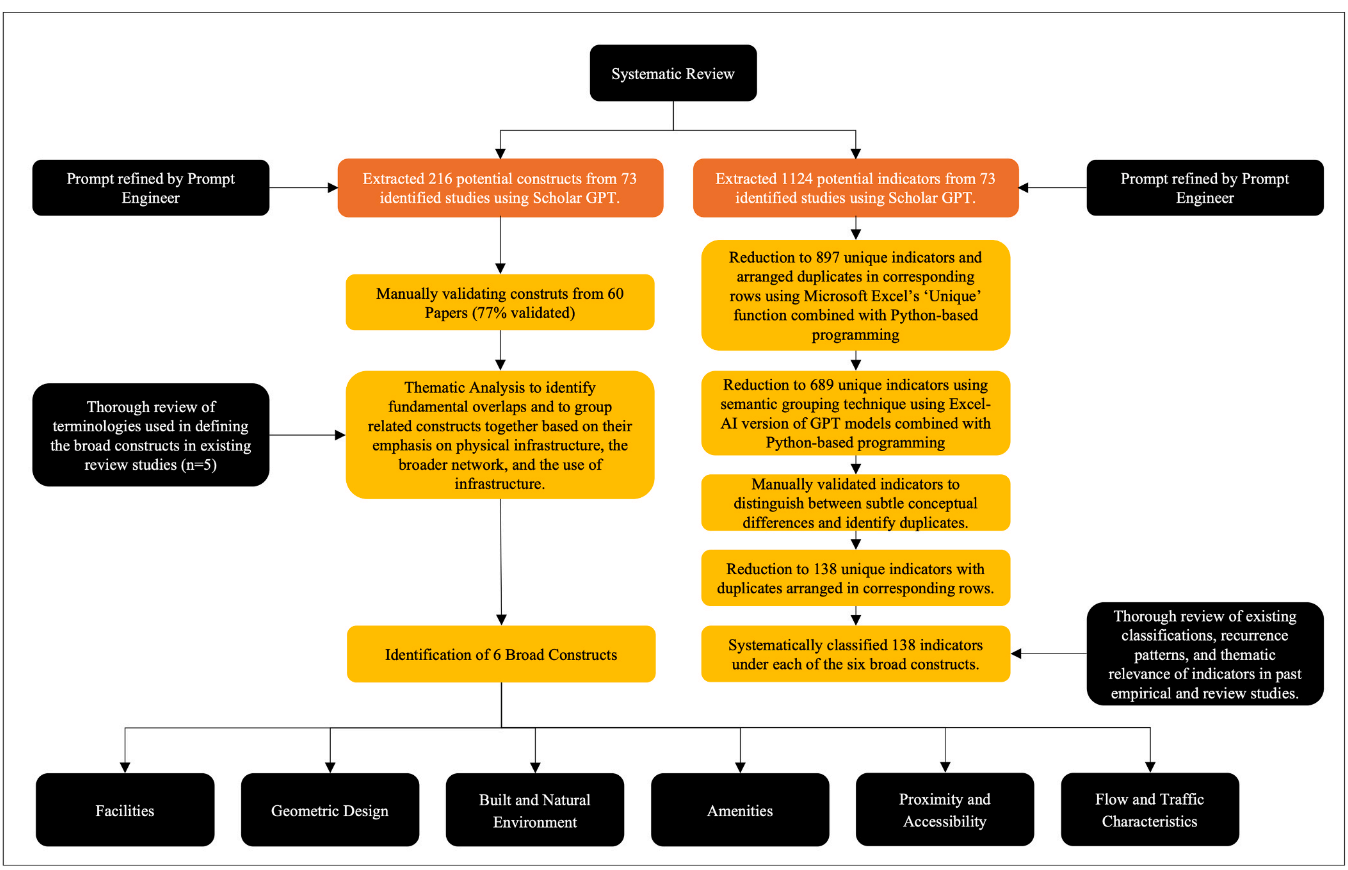

Fig. 3. A step-by-step methodology used in the modelling process.

Attributes, Path Characteristics, and Roadway Geometrics, were systematically regrouped based on their shared emphasis on spatial design (S. K. Beura, Chellapilla, and Bhuyan, 2017; Hasan et al., 2015; Jia et al., 2022; LaMondia and Moore, 2015; Okon and Moreno, 2019). This regrouping eliminated redundancy and combined overlapping elements into a coherent classification. The consistent inclusion of spatial design-related constructs in previous PLOS and BLOS assessment models highlights their foundational role in evaluating non-motorised infrastructure.

The 'Built environment' construct focuses on the surroundings of core physical infrastructure, influencing the systemic integration of elements within the urban morphology and mediating user interaction with adjacent spatial configurations. Various related constructs, such as Land-Use Characteristics, Land-Use Type, Environmental Conditions, Environmental Factors, Spatial Factors, Surrounding Characteristics, and Temporal Factors, were methodically categorised under the 'Built Environment' construct (Das et al., 2019; Karatas and Tuydes-Yaman, 2018; S. Marisamynathan and Lakshmi, 2018; Tuydes-Yaman and Karatas, 2018). This construct is labelled as 'Built and Natural environment' because previous studies consistently identified it as a key determinant in assessing the suitability of PLOS and BLOS infrastructure. For instance, some studies emphasise the role of land-use diversity in fostering active transport (Tuydes-Yaman and Karatas, 2018), while others underscore the impact of roadside commercial density on non-motorised transport (S. K. Beura and Bhuyan, 2022).

The 'Amenities' construct refers to elements that enhance user comfort, safety, security and convenience on the sidewalk and cycle track. These include indicators such as seating, shade, lighting, trash cans, toilets, bike racks, and drinking fountains, all of which contribute to the overall usability and accessibility of non-motorised transport infrastructure. The availability and quality of these amenities are often shaped by the design and integration of the surrounding built environment. For instance, a well-designed plaza or green space naturally enhances the functionality and user experience of adjacent pedestrian and cycling infrastructure (Bivina and Parida, 2019; Sisiopiku, Byrd, and Chittoor, 2007; Rodriguez-Valencia et al., 2022). By systematically consolidating and classifying related indicators, the methodology ensures a clear and comprehensive categorisation, reinforcing the importance of amenities as a core component in the evaluation of non-motorised transport infrastructure.

The 'Proximity and Accessibility' construct, rooted in the principles of the 15MC framework, plays a pivotal role in assessing non-motorised transport infrastructure by examining how individual features, such as sidewalks or cycle tracks, are integrated into broader urban networks. Rather than focusing on perceived accessibility, this construct emphasises access to essential services within a short walk or bike ride, aligning with the core principles of the 15MC model. Relevant constructs from past studies that can be classified under this construct include Accessibility Metrics, Network Connectivity, Network Design, and Network Characteristics (Dias and Wijeweera, 2021; Lowry et al., 2012; Vallejo-Borda, Cantillo, and Rodriguez-Valencia, 2020). It is important to note that although proximity and accessibility are not always explicitly labelled as constructs in PLOS and BLOS models, they are often implicitly addressed. For example, some studies include network connectivity or accessibility metrics in their assessments, recognising their importance in linking individual infrastructure features to broader networks (Karatas and Tuydes-Yaman, 2018; Tuydes-Yaman and Karatas, 2018; Nag and Goswami, 2019). However, despite their importance, this construct remains underutilised compared to others, reinforcing the need to integrate the principles of the 15MC into existing PLOS and BLOS assessment models.

The 'Flow and Traffic Characteristics' construct provides essential insights into the manifold patterns of use. This construct captures how infrastructure design influences both motorised and non-motorised flow dynamics, consolidating constructs from past studies, such as Pedestrian Trajectory, Pedestrian Interactive Behaviour, Collision Frequency, Bicycle Abreast Riding, Traffic characteristics, Traffic conditions, among others, providing a comprehensive framework for assessing flow dynamics (Benhadou, El Gonnouni, and Lyhyaoui, 2024; Petritsch et al., 2008; Sahani and Bhuyan, 2017; Talavera-Garcia and Soria-Lara, 2015; Tan et al., 2007). Previous research has highlighted the critical link between infrastructure design and pedestrian flow. Fruin (1971); Polus, Schofer, and Ushpiz, (1983) underscored the relationship between pedestrian flow, space requirements, and core infrastructure design, demonstrating how well-designed spaces can accommodate smooth pedestrian movement. Similarly, Landis, Vattikuti, and Brannick (1997) evaluated cyclist flows, focusing on route volume and directness, revealing that efficient flow enhances service quality while minimising delays. By including these critical aspects, the construct underscores the importance of optimising infrastructure to ensure seamless and balanced mobility for all modes of transport.

By identifying and classifying these six broad constructs, this study establishes a standardised and conceptually robust framework for evaluating non-motorised transport infrastructure. Each broad construct represents a distinct yet interconnected dimension of both motorised and non-motorised environments, offering a multidimensional approach that integrates both physical and contextual factors essential for fostering active mobility (Table 2). This structured approach not only eliminates redundancy and enhances conceptual clarity but also provides a practical and adaptable tool for researchers, urban planners, and policymakers seeking to assess, design, and improve pedestrian and cycling infrastructure across diverse urban contexts.

3.2. Key indicators

Within each construct, indicators were identified and prioritised based on their frequency and relevance in the literature. Using the PRISMA methodology, 78 articles were analysed, resulting in the identification of 1124 indicators. To refine this list, Microsoft Excel's 'unique' function, combined with Python-based processing, was applied to remove duplicates, resulting in 897 unique indicators listed in a single column, with their exact duplicates organised in corresponding rows (see Supplementary Material to access the corresponding code). Further refinement was carried out using semantic grouping techniques using the Excel-AI version of GPT models. This process consolidated indicators with minor variations in terminology, such as synonyms, phrasing differences, and regional spelling variations (such as "footpath width" vs "sidewalk width", "roadway width" vs "road width", and "motorised speed" vs "motorized speed"), ultimately reducing the list to 689 unique indicators.

While automation facilitated the initial identification process, an intensive manual review remained essential to distinguish between indicators with subtle conceptual differences that could not be

Table 2
Constructs and their definition.

Construct	Definition
Facilities	The 'Facilities' construct encompasses core infrastructure elements (such as sidewalks, cycle tracks, number of lanes, and on-street parking) and supplementary elements (such as pavement type, road markings, zebra crossings, and traffic signals) essential for enabling walking and cycling functionality.
Geometric design	The 'Geometric design' construct focuses on the spatial configuration and upkeep of the individual features. It constitutes elements such as physical layout, width, length, and the current condition/ quality of the individual features, which directly influence users' comfort and safety while navigating these features.
Built and Natural environment	The 'Built and Natural environment' construct focuses on the surroundings of the core physical infrastructure and the environmental conditions. It influences how the individual features are embedded in a broader system and how users interact with these surrounding spaces.
Amenities	The 'Amenities' construct refers to elements that enhance user comfort, safety, security and convenience on the sidewalk and cycle track.
Proximity and Accessibility	The 'Proximity and Accessibility' construct, inspired by the principles of the 15MC framework, focuses on the physical integration of individual features into broader urban networks rather than on perceived accessibility.
Flow and Traffic Characteristics	The 'Flow and Traffic Characteristics' construct is integral to understanding the movements and dynamics of pedestrians, cyclists, and vehicles within the built environment. It captures how infrastructure design can shape motorised and non-motorised flow dynamics.

distinguished programmatically. For instance, indicators such as "On-street parking" and "Proportion of on-street parking", though related, measure different aspects. The former is a binary variable, indicating the presence or absence of on-street parking, whereas the latter is a mathematical calculation expressing the percentage of total cars parked on the street. These distinctions required careful evaluation to ensure indicators were not incorrectly treated as duplicates. In contrast, indicators like "lateral separation from traffic" vs "buffer between pedestrians and vehicles" and "accessibility to important destinations" vs "access to important destinations" were determined to measure the same underlying construct. These could be considered as duplicates based on their shared intent to measure a specific element of interest (Elias, 2011; Lowry et al., 2012).

This final optimisation step ensured that all unique indicators were listed in a single column, with duplicates and semantically similar terms systematically organised in corresponding rows. Through this iterative and rigorous manual categorisation process, the dataset was further refined to 138 unique indicators, each classified under one of the six broad constructs.

The systematic classification of indicators under each of the six broad constructs involved a methodologically rigorous process, as many indicators in the existing literature were found to be associated with multiple constructs, leading to potential conceptual ambiguity and redundancy. For instance, "separation from traffic" is a critical indicator in both PLOS and BLOS literature. While some studies have classified it under "Safety and Security" due to its role in protecting users from vehicle-related risks (Tuydes-Yaman and Karatas, 2018; Ujjwal and Bandyopadhyaya, 2021), others have categorised it under "Geometric Design" for its relationship to spatial layout (Hasan et al., 2015). However, the majority of studies align this indicator with the "Facility" construct, as it represents a core infrastructural element (Dias and Wijeweera, 2021; Dowling et al., 2002; Griswold et al., 2018; Sisiopiku, Byrd, and Chittoor, 2007).

To ensure conceptual clarity and minimise redundancy, each indicator was assigned to a primary construct based on a thorough review of existing classifications, recurrence patterns, thematic relevance, and dominant conceptual alignment. While some indicators spanned multiple constructs, they were systematically classified into the most relevant category.

Acknowledging this inherent overlap, Fig. 4 presents selected examples of indicators categorised under their primary construct while also illustrating their additional connections. This approach highlights the multiple connections between constructs and indicators while providing the primary connection for indicator assignment.

3.3. Relationship between indicators and broad constructs

A total of 138 indicators were categorised into constructs based on their thematic alignment and functional relevance (see Supplementary Material to access the full Table). The 'Facilities' construct, comprising 32 indicators, encompasses core infrastructure elements such as the presence of sidewalks, cycle tracks, buffer zones, and legal and regulatory indicators such as speed limit and signals (Abbood and Fadel, 2023; Miller, Bigelow, and Garber, 2000; Petritsch et al., 2007).

The 'Geometric Design' construct, with 26 indicators, focuses on spatial and dimensional attributes such as sidewalk width, cycle track width, buffer area width, lane width, and carriageway width, and the current condition of the infrastructure such as pavement condition and the presence of cracks (S. K. Beura, Chellapilla, and Bhuyan, 2017; Callister and Lowry, 2013; Kim, Choi, and Kim, 2011; Rahmati and Kashi, 2019).

The 'Built and Natural Environment' construct consists of 19 indicators related to the surrounding urban context, including land use, land use diversity, the presence of commercial activities, and environmental conditions such as trees, weather, and noise. (S. K. Beura, Chellapilla, and Bhuyan, 2017; Bivina et al., 2018; Das et al., 2019; Karatas and Tuydes-Yaman, 2018; Nag and Goswami, 2019).

The 'Amenities construct', comprising 17 indicators, focuses on elements that enhance user comfort, such as street lighting, benches, and public toilets (Asadi-Shekari et al., 2019; Ghani, Hussein, and Mokhtar, 2013; Meneses and Buluran, 2022; Vallejo-Borda, Cantillo, and Rodriguez-Valencia, 2020; Zannat, Raja, and Adnan, 2019).

The 'Proximity and Accessibility' construct includes 10 indicators related to connectivity, capturing aspects such as path continuity, destination proximity, and network complexity (Kretz, 2011; Lowry et al., 2012; Rahul and Manoj, 2020).

Finally, the 'Flow and Traffic Characteristics' construct, containing 34 indicators, assesses movement and performance with indicators such

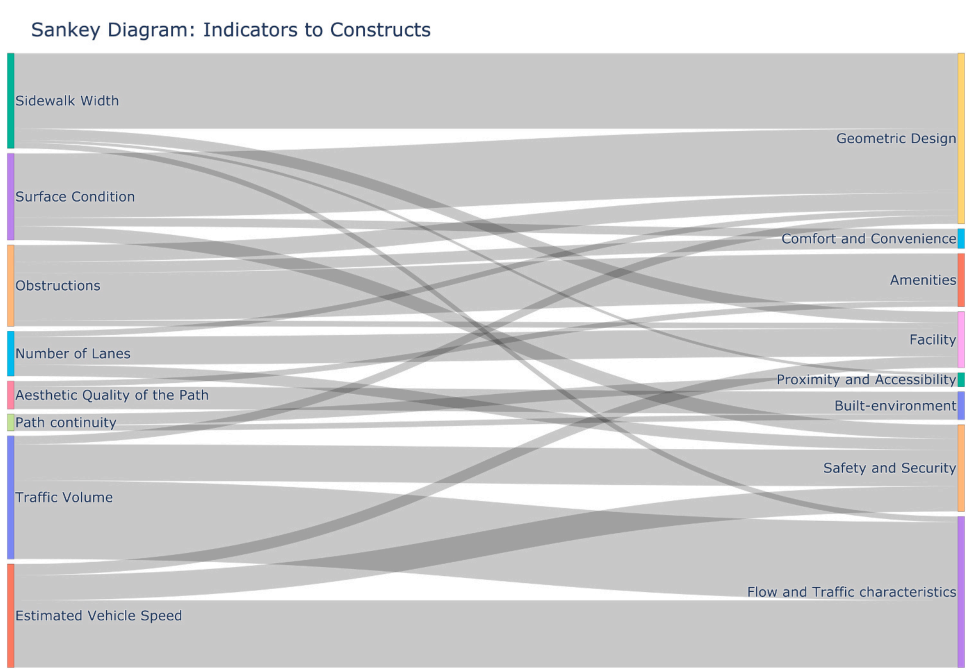

Fig. 4. An example of classification of indicators under the primary construct while acknowledging inherent multiple connecting constructs.

as pedestrian flow, traffic volume, heavy vehicle flow, and conflicts (Bunevska Talevska, Todorova, 2012; Cepolina, Menichini, and Gonzalez Rojas, 2017; Liang et al., 2021; Paul, Moridpour, and Nguyen, 2023; Xu et al., 2018; Zhao et al., 2016). This structured categorisation ensures a holistic and methodologically robust approach to evaluating non-motorised transport infrastructure.

It is important to note that several indicators, especially of the Proximity and Accessibility construct, such as destination proximity, network connectivity, and path directness, often require route-based or area-based assessment rather than traditional segment-level assessment, as seen in past PLOS and BLOS studies. This spatial mismatch reflects a deeper methodological challenge, as different constructs inherently rely on different spatial reference units such as segment, route, areal, or location-based units - each of which facilitates distinct types of analysis and interpretation. Thus, segment-based indicators must be extended to make PLOS/BLOS compatible with the 15MC. Future research needs to advance methodological innovation to reconcile and align these different spatial units within a unified analytical framework while accounting for zoning and scaling effects (Wong, 2009).

3.4. Most cited indicators

Using Python, the list of indicators was analysed to identify the most frequently cited ones. Indicators with a frequency greater than 10 were classified as the most cited. Among these, 28 indicators emerged as the most frequently referenced, including pedestrian volume, speed, density, flow, space, and flow rate; bicycle flow, volume, and speed; traffic volume and speed; buffer zones between sidewalks and carriageways; number of lanes; crossing facilities; and curbside parking. Other commonly used indicators included pavement quality, pavement condition, width and quality of pedestrian paths, width of outside lanes, functional width, crossing opportunities, lighting, obstructions on sidewalks or cycle tracks, presence of trees and street furniture, and encroachment.

Flow characteristics, amenities, and geometric design were prominently represented among the most cited indicators, highlighting their significance in assessing the suitability of the PLOS and BLOS models. These findings suggest that researchers prioritise the constructs when evaluating non-motorised transport infrastructure. Conversely, the built and natural environment and proximity and accessibility constructs were notably under-represented in the list of most common indicators. This underscores the need to integrate PLOS and BLOS tools with the 15MC concept, thereby reinforcing the critical gap in existing literature. Addressing this gap would enable a more holistic evaluation of pedestrian and cyclist infrastructure, bridging the disconnect between conventional models and emerging urban planning paradigms.

A detailed list of most cited indicators under each construct, along with their frequency and the types of studies documenting them, is provided in Table 3. This table serves as a valuable resource for researchers and practitioners embarking on the assessment of pedestrian and bicycle infrastructure. In this regard, we strongly recommend that those evaluating the suitability of PLOS and BLOS ensure the availability of data on these “golden nuggets”, as they represent the most critical indicators for a holistic assessment of non-motorised infrastructure. Without the inclusion of these key indicators and reliable data, a thorough and accurate evaluation of non-motorised transport infrastructure within the framework of the 15MC cannot be effectively achieved.

Table 3
The Golden Nuggets.

Construct	Indicator	Frequency	Relevant Studies
Flow and Traffic Characteristics	Traffic Volume (vehicles/unit time)	45	PLOS and BLOS
Flow and Traffic Characteristics	Estimated Vehicle Speed (distance / unit time)	38	PLOS and BLOS
Geometric Design	Sidewalk Width	35	PLOS
Geometric Design	Surface Condition (e.g., cracks, potholes, debris)	31	PLOS and BLOS
Amenities	Presence of Obstructions (Utility Poles, Signs)	29	PLOS and BLOS
Flow and Traffic Characteristics	Average Speed of Pedestrians (distance / time)	28	PLOS
Flow and Traffic Characteristics	Pedestrian Density (pedestrians/m^2)	28	PLOS
Flow and Traffic Characteristics	Average Speed of Bicycles (distance/time)	28	BLOS
Facility	Buffer Zone Between Sidewalk and Carriageway (Yes, No)	27	PLOS
Flow and Traffic Characteristics	Average Pedestrian Volume (Pedestrians/unit time)	25	PLOS
Amenities	Presence of Streetlights (Yes, No)	20	PLOS and BLOS
Built and Natural Environment	Presence of Trees (Yes, No)	17	PLOS and BLOS
Facility	Number of Lanes	17	PLOS and BLOS
Flow and Traffic Characteristics	Pedestrian Flow (uni, bi, multi-directional)	17	PLOS
Amenities	Encroachments by Shops and Vendors	16	PLOS and BLOS
Amenities	Presence of Benches (Yes, No)	16	PLOS and BLOS
Facility	Crossing Facility	15	PLOS and BLOS
Facility	Curbside Parking	14	PLOS and BLOS
Flow and Traffic Characteristics	Potential for Conflicts with Vehicles	14	PLOS and BLOS
Flow and Traffic Characteristics	Flow Rate of Pedestrians (Pedestrians/unit time)	14	PLOS
Geometric Design	Surface Quality (e.g., comfort, smoothness, aesthetic experience)	13	PLOS and BLOS
Built and Natural Environment	Aesthetic Quality of the Path (e.g., imageability)	12	PLOS and BLOS
Built and Natural Environment	Landscape (Overall composition and quality of streetscape)	12	PLOS and BLOS
Geometric Design	Effective Sidewalk Width	12	PLOS
Geometric Design	Width of Outside Lane	12	PLOS and BLOS
Flow and Traffic Characteristics	Pedestrian Space (m^2/p)	11	PLOS
Geometric Design	Bicycle Facility Width	11	BLOS
Amenities	Path Cleanliness	10	PLOS and BLOS

3.4.1. Least cited indicators

Most existing review studies provide comprehensive lists of essential indicators for evaluating the suitability of PLOS and BLOS models. However, they often overlook the equally critical task of identifying underutilised or less frequently cited indicators that may be excluded not due to irrelevance, but because of data limitations or methodological constraints. To address this gap, Table 4 presents 36 of the least cited indicators, each appearing only once across the reviewed literature. These span a diverse range of constructs and highlight significant omissions in current evaluation practices.

For instance, the quality of streetlights, a critical determinant of perceived safety during nighttime travel, is included in only one study, despite its relevance for both pedestrians and cyclists. Pavement colour visibility, which is a strong psychological measure to improve user navigation, is another overlooked metric. Presence of ramps to support accessibility for the disabled groups also remains underrepresented (some exceptions include (Georgiou, Skoufas, and Basbas, 2021; Zannat, Raja, and Adnan, 2019).

Additionally, ’Proximity and Accessibility’ constructs, central to the 15MC paradigm, remain severely underrepresented. This underrepresentation is inherent because, in part, PLOS and BLOS assessments are typically conducted at the segment level, whereas

Table 4
Least cited indicators.

Construct	Indicator	Frequency	Relevant Studies
Amenities	Presence of Wi-Fi and Charging Stations (Yes, No)	1	PLOS
Amenities	Drainage (Yes, No)	1	PLOS
Amenities	Pedestrian Visibility (e.g., sightlines between pedestrian paths and surroundings)	1	PLOS
Amenities	Regular Cleaning of Public Toilets	1	PLOS
Amenities	Street Sweeping (Yes, No)	1	PLOS
Amenities	Quality of Streetlights	1	PLOS
Built and Natural Environment	Construction Sites	1	PLOS
Built and Natural Environment	Proportion of Roadside Planting (per cent of roadside edge with planted vegetation)	1	PLOS
Built and Natural Environment	Green Looking Ratio	1	PLOS
Built and Natural Environment	Tree Density (trees/km^2)	1	PLOS
Facility	Pavement Colour Visibility	1	PLOS
Facility	Elevators (Yes, No)	1	PLOS
Facility	Bicycle Parking Availability (Yes, No)	1	BLOS
Facility	Pedestrian Overbridges with Ramps (Yes, No)	1	PLOS
Facility	Pedestrian Overbridges with Stairs (Yes, No)	1	PLOS
Facility	Presence of Intersection (Yes, No)	1	PLOS
Facility	Presence of Left/ Right-Turn Islands (Yes, No)	1	PLOS
Facility	Presence of Shared-Use Paths (Yes, No)	1	PLOS
Facility	Presence of Shoulder Lane (Yes, No)	1	PLOS
Facility	Roadway Crossing Difficulty Factor (i.e., index based on crossing width, traffic speed, number of lanes, presence of signals)	1	PLOS
Facility	Speed Breakers	1	PLOS
Facility	Total Number of Lanes at Intersection	1	PLOS
Flow and Traffic Characteristics	Frequency of Cross-Traffic Events	1	PLOS
Flow and Traffic Characteristics	Overtaking Distance	1	PLOS
Flow and Traffic Characteristics	Probability of Overtaking	1	PLOS
Flow and Traffic Characteristics	Severity of Collisions	1	PLOS
Geometric Design	Width of Pedestrian Crossing	1	PLOS
Geometric Design	Carriageway Width	1	PLOS
Geometric Design	Distance to Curb or Roadway	1	PLOS
Geometric Design	Effective Width of Outside Lane	1	PLOS
Geometric Design	Median Height	1	PLOS
Geometric Design	On-Street Parking Turnover	1	PLOS
Geometric Design	Taper Length (i.e., gradual narrowing or widening of lanes approaching an intersection)	1	PLOS
Geometric Design	Total Road Length	1	PLOS
Proximity and Accessibility	Connectivity to Important Destinations	1	PLOS
Proximity and Accessibility	Network Continuity	1	PLOS

accessibility measures require network-, route-, or area-based spatial references. As a result, indicators such as the most direct path and network continuity are often overlooked. The omission of these indicators can lead to oversimplified or incomplete assessments of infrastructure suitability, potentially resulting in suboptimal policy and planning decisions. To ensure the integration of these critical indicators in assessment models, future research should explore methodological solutions that reconcile these spatial units, such as aggregating segment-level data to broader spatial reference frames or adapting accessibility metrics for use in micro-scale assessments.

It is also worth noting that some indicators not included in this table, such as slope of the facility, evasive movements, and speed breakers appear slightly more frequently, offer valuable insights into perceived safety and comfort, but largely remain neglected due to the difficulty in collecting reliable observational data (Asadi-Shekari, Moeinaddini, and Zaly Shah, 2013; Y.-X. Chen et al., 2014; Kim et al., 2014; Shan, Ye, and Chen, 2016). Due to scope constraints, this table includes only those indicators cited once, but we acknowledge that a more comprehensive audit of all underrepresented metrics is warranted in future research.

3.5. Proxy indicators

Proxy indicators facilitate the substitution of similar indicators when specific data points are unavailable. For example, Werner et al. (2024) suggest that road category can serve as a proxy for traffic volume, while designated cycle routes can serve as a proxy to capture elements such as signage for wayfinding, overall quality and continuity of infrastructure. Additionally, the number of evasive movements by pedestrians and cyclists per minute can serve as a proxy for the level of crowdedness (Kim et al., 2014). The inclusion of such proxy indicators enables assessments to be conducted in data-scarce environments, providing flexibility in evaluation while maintaining a reasonable degree of accuracy.

3.6. Other/targeted constructs

While many PLOS and BLOS assessment models are structured around the six broad constructs discussed earlier, others diverge to focus on more targeted constructs such as safety, security, convenience, and comfort. This variation suggests that certain studies examine only a subset of PLOS and BLOS dimensions rather than evaluating overall suitability, likely due to the specific focus of their research (Adinarayana and Kasinayana, 2022; Campisi et al., 2020; Cepolina, Menichini, and Gonzalez Rojas, 2018; Y.-X. Chen et al., 2014; Jia et al., 2022; Mahmudah et al., 2018; Sankaran Marisamynathan and Vedagiri, 2020; Mofolasayo, 2020).

For instance, some studies focus exclusively on the safety aspect of PLOS and BLOS infrastructure (Mofolasayo, 2020), whereas others focus solely on the level of comfort, providing insights into the experiential quality of walking and cycling infrastructure (Benhadou, El Gonnouni, and Lyhyaoui, 2024; Cepolina, Menichini, and Gonzalez Rojas, 2017, 2018; Jia et al., 2022). In contrast, a few studies focus on the security aspect of PLOS, exploring how safe users feel in these environments (Bivina and Parida, 2024). Some researchers have also combined these targeted constructs to provide a more integrated assessment. For example, Kang and Lee (2012); Lowry et al., (2012) combined safety and comfort to evaluate BLOS and PLOS indices. Similarly, other studies integrated safety, security, and comfort into a single assessment model (C. Chen et al., 2017; Jegan Bharath Kumar and Ramakrishnan, 2020).

These alternative approaches highlight a deliberate prioritisation of specific constructs to evaluate the suitability of pedestrian and cycling infrastructure from the user's perspective. Such focused assessments often reveal aspects that broad constructs may either overlook or inadequately address, offering valuable insights into critical user experiences. However, the differentiation between broad and targeted constructs in PLOS and BLOS assessment models has not been comprehensively examined. The fragmented nature of these assessments, relying either on broad constructs or more targeted (narrowly defined) constructs, raises questions about the comparability and consistency of existing models.

Therefore, we argue that safety, security, comfort, and convenience should be treated as distinct constructs rather than being subsumed within broad constructs, as has been done in previous studies. These dimensions can serve as sub-assessment models tailored to the specific scope and objectives of a study. Establishing these four targeted constructs as distinct categories not only enhances conceptual clarity but also strengthens the overall evaluation of PLOS and BLOS models across diverse research contexts.

4. Conceptual framework

The broad constructs and indicators were integrated into a three-layered conceptual framework designed to capture the complexity of non-motorised transport systems, as presented in Fig. 5. This framework represents a hierarchical and interrelated model that explains how an individual feature, such as a sidewalk or a cycle track (Layer 1), is embedded within a broader system (Layer 2) and how these two layers collectively influence the overall functioning of the system (Layer 3). In essence, this three-layered structure visually demonstrates how pedestrian and cyclist experiences are shaped by multiple interdependent factors, particularly the relationship between physical infrastructure, its surrounding environment, and its functional performance. These three layers ultimately determine the overall (sub)assessment of PLOS and BLOS.

4.1. Layer 1: a single feature

The first layer represents the most basic and tangible elements of infrastructure, such as bike lanes, sidewalks, the number of vehicular lanes or crossings. These segment-based individual features form the foundation layer upon which pedestrian and cycling networks are built, providing the core infrastructural components necessary for pedestrian and cycling facilities to function. Constructs like Facilities and Geometric Design are central to this layer, as they directly influence how people move in the built environment. This “base layer” forms the foundation for the upper layers.

4.2. Layer 2: feature in a system

The second layer focuses on how these individual features (Layer 1) function within a larger system or network. It considers the broader context, such as how sidewalks and bike lanes interact with elements such as the built environment, amenities, and surrounding infrastructure. This “contextual layer” captures how individual features are embedded in and interact with the wider context. Constructs like the Built Environment, Amenities, and Proximity and Accessibility are particularly relevant to this layer, emphasising how users experience the space as part of a larger network.

4.3. Layer 3: function of the feature

The third layer evaluates the overall functionality and performance that emerge from the interaction of the first two layers. It assesses how well the infrastructure supports real-world usage, such as the flow of pedestrians, cyclists, and vehicles. For example, diverse land use might lead to higher pedestrian volumes and increased activity, reflecting how well the infrastructure meets user needs. This “performance layer” serves as a key measure of how the physical features (Layer 1) and their broader context (Layer 2) contribute to the infrastructure’s effectiveness. The Flow and Traffic Characteristics construct primarily contributes to this layer.

The final step of this layered diagram involves expert consultation to assess the suitability of the infrastructure. This is essential for effective policy implementation, ensuring that pedestrian and cycling infrastructure is designed to foster walking and cycling in 15 min cities. Expert input helps cities develop high-quality pedestrian and cycling infrastructure that enhances mobility, encourages active transport, and creates safer and more accessible environments for all types of users. Experts can also aid in determining the weights of the broad constructs for the overall assessment. In doing so, this three-layered conceptual framework can offer significant versatility, making it applicable at both micro and macro scales. It can be used to assess individual streets as well as entire networks of pedestrian and cycling paths. This flexibility allows urban planners, transport engineers, and policymakers to adapt the model to different contexts and scales.

Overall, this three-layered framework provides a comprehensive and holistic perspective on how pedestrian and cycling experiences are shaped by multiple interconnected factors within the 15MC paradigm. Unlike previous models that often focus on isolated constructs, this framework integrates the Foundational, Contextual, and Performance layers into a cohesive system while remaining flexible to incorporate additional input variables without disrupting its core logic. The true

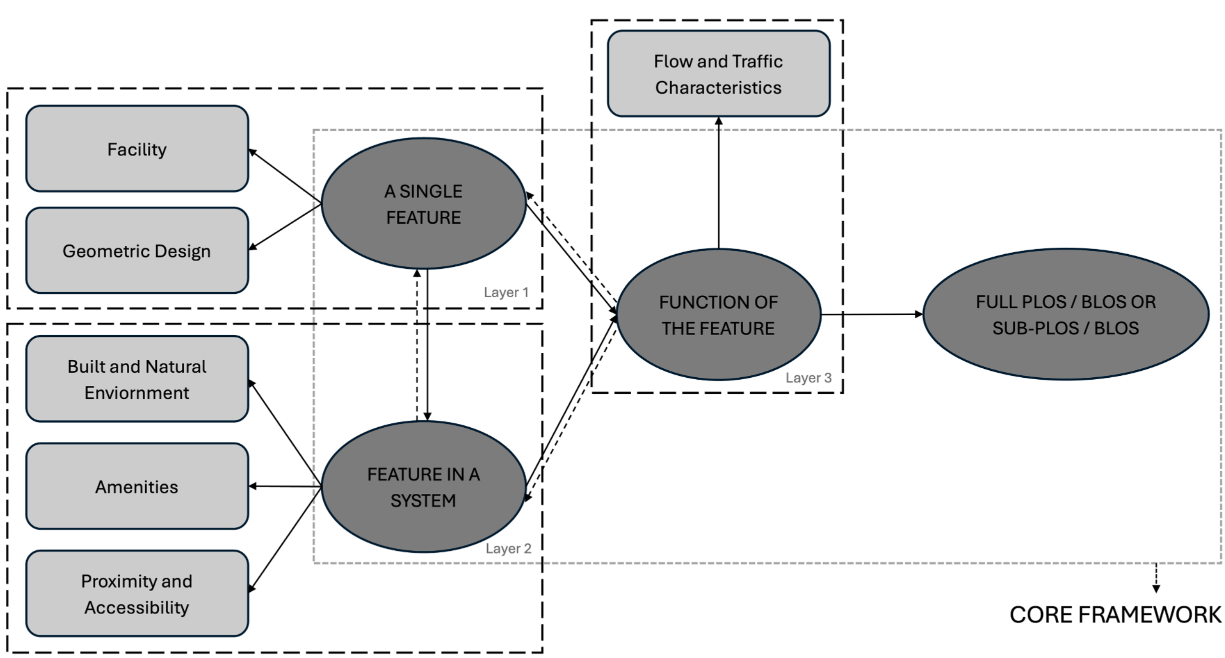

Fig. 5. Conceptual Framework.

novelty of this model lies in its ability to systematically illustrate the dynamic interactions between these layers, an aspect that has not been fully established in prior research. By unifying assessments of PLOS and BLOS and within the broader principles of the 15MC, the framework offers an innovative and versatile tool for urban planning and design. In doing so, this framework bridges the gap between traditional infrastructure models and contemporary urban planning paradigms, offering a more integrated, forward-thinking, and adaptable approach to the assessment of non-motorised transport infrastructure.

Furthermore, the integration of targeted constructs such as safety, security, comfort, and convenience, alongside a user-centred approach that accounts for socio-demographic characteristics (age and gender), external factors (weather conditions), and user characteristics (cyclist experience, trip purpose) ensures a comprehensive and balanced assessment model (Paul et al., 2024). Additionally, the model can include feedback effects. For instance, congestion or delays from Layer 3 might feed into Layer 2, affecting how future infrastructure is designed. However, this dynamic interaction requires further empirical testing. Therefore, future studies should employ methodologies capable of capturing these cause-and-effect relationships.

5. Conclusion

This paper addresses a critical gap in the active mobility literature by developing a unified and hierarchical conceptual framework that integrates the principles of the 15MC with existing PLOS and BLOS models. The framework systematically identifies and categorises six broad constructs while providing a comprehensive corpus of 138 unique and relevant indicators, thereby resolving conceptual inconsistencies caused by overlapping terminologies, enhancing clarity, and facilitating cross-context comparability in infrastructure evaluation.

The novelty of this work lies in its multi-layered approach, which systematically embeds individual infrastructure elements (e.g., sidewalks or cycle tracks) within a broader system (e.g., the built environment and proximity) and examines how these layers collectively influence the functioning of the broader system (e.g., flow and traffic characteristics). This layered structure ensures versatility, making the framework applicable at both micro (e.g., individual streets) and macro (e.g., city-wide networks) scales and supports integration across spatial units often treated in isolation.

The conceptual framework developed in this study has direct utility for planners, policymakers, and professionals aiming to implement sustainable, proximity-based mobility strategies. First, it offers a diagnostic tool to audit and benchmark existing walking and cycling infrastructure using a standardised, indicator-based evaluation matrix that captures both physical features and contextual quality. Second, the classification of indicators into the Golden Nuggets (most cited), underutilised (least cited), and proxy metrics helps practitioners prioritise feasible data collection strategies in resource-constrained settings. More specifically, the Golden Nuggets offer a methodologically grounded yet operationally pragmatic subset that can serve as an entry point for applying the framework in real-world contexts. Excluding this core set of indicators from assessment models might risk undermining the representativeness and validity of infrastructure evaluations, as these variables consistently emerge as foundational across diverse empirical and conceptual studies.

Third, by embedding proximity and accessibility dimensions of the 15MC literature into traditional PLOS and BLOS evaluation, the framework supports multi-scalar assessments that align street-level design interventions with city-wide accessibility goals. Planners can use the framework to identify gaps between infrastructure provision and accessibility outcomes, while policymakers can adopt it to inform investment decisions, zoning policies, or the formulation of mobility performance standards. Finally, the framework's adaptability makes it suitable for use in both Global North and Global South contexts, where data limitations and infrastructure diversity often hinder comparative assessments. In low- and middle-income settings in particular, the prioritisation of empirically recurrent indicators (the Golden Nuggets) could enable meaningful evaluation even in the absence of comprehensive data.

Building on this conceptual contribution, future research should focus on empirical validation of the framework across spatial contexts, including the development of indicator weighting schemes. Such indicator weighing schemes can be drawn on expert elicitation or multi-criteria methods such as the Analytic Hierarchy Process (AHP), as applied in similar walkability and bikeability studies (e.g. Werner et al. 2024). Advancing such methodological refinements will enhance the model's utility as an actionable, data-driven decision-making tool and support its broader adoption in policy, planning, and infrastructure design aimed at achieving sustainable and proximity-based urban development.

It is also important to acknowledge that different constructs within the framework rely on varying spatial reference units. While many PLOS and BLOS indicators are assessed at the segment level, proximity and accessibility indicators often require route-based, network-wide, or areal spatial units. This spatial mismatch presents a methodological challenge that must be addressed in future work to enable integration across scales by developing multi-scalar or hybrid assessment models.

Lastly, while we acknowledge that the suitability of pedestrian and cycling infrastructure is a concern shared across disciplines and research traditions, including those studying walkability, bikeability, and accessibility, this study seeks to contribute to the broader interdisciplinary discourse on active and sustainable mobility by advancing a unified conceptual framework that integrates PLOS and BLOS models with the principles of the 15MC.

CRediT authorship contribution statement

Richa Maheshwari: Writing – original draft, Visualization, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Martin Loidl:** Writing – review & editing, Supervision, Conceptualization. **Rupali Khare:** Writing – review & editing. **Mario Cools:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Funding

This work was supported by the Fonds de la Recherche Scientifique (FNRS) under Grant n° R.8005.23, by the Austrian Research Promotion Agency (FFG) under Grant n° FO999905451, and by Innovation Fund Denmark under Grant 3114-00005B under the Driving Urban Transitions Partnership, co-funded by the European Union.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement(s)

The authors thank Damien Enrst and Lize Pirenne of the University of Liège for their suggestions on the Large Language Module script.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jcmr.2025.100089.

Data availability

Data will be made available on request.

References

Abbood, A.N., Fadel, L.S., 2023. Study of basic traffic elements for pedestrians movement and their impacted on level of service efficiency in urban area. J. Ecol. Eng. 24 (8), 322–328. https://doi.org/10.12911/22998993/166453.

Abdelfattah, L., Deponte, D., Fossa, G., 2022. The 15 min city: interpreting the model to bring out urban resiliencies. Transp. Res. Procedia 60, 330–337. https://doi.org/10.1016/j.trpro.2021.12.043.

Adinarayana, B., Kasinayana, B., 2022. Bicycle safety index for bicycle level of service on urban streets with extreme mixed weather conditions. Innov. Infrastruct. Solut. 7 (4). https://doi.org/10.1007/s41062-022-00853-5.

Ahmed, Tufail, Pirdavani, Ali, Janssens, Davy, Wets, Geert, 2023. Utilizing intelligent portable bicycle lights to assess urban bicycle infrastructure surfaces. Sustainability 15 (5). https://doi.org/10.3390/su15054495.

Ahmed, Tufail, Pirdavani, Ali, Wets, Geert, Janssens, Davy, 2024. Bicycle infrastructure design principles in urban bikeability indices: a systematic review. Multidiscip. Digit. Publ. Inst. https://doi.org/10.3390/su16062545.

Allam, Z., Bibri, S.E., Chabaud, D., Moreno, C., 2022. The theoretical, practical, and technological foundations of the 15 min city model: proximity and its environmental, social and economic benefits for sustainability. Energies 15 (16). https://doi.org/10.3390/en15166042.

Asadi-Shekari, Z., Moeinaddini, M., Shah, M.Z., 2013. Disabled pedestrian level of service method for evaluating and promoting inclusive walking facilities on urban streets. J. Transp. Eng. 139 (2), 181–192. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000492.

Asadi-Shekari, Z., Moeinaddini, M., Zaly Shah, M., 2013. Non-motorised level of service: addressing challenges in pedestrian and bicycle level of service. Transp. Rev. 33 (2), 166–194. https://doi.org/10.1080/01441647.2013.775613.

Asadi-Shekari, Z., Moeinaddini, M., Aghaabbasi, M., Cools, M., Zaly Shah, M., 2019. Exploring effective micro-level items for evaluating inclusive walking facilities on urban streets (applied in Johor Bahru, Malaysia). Sustain. Cities Soc. 49. https://doi.org/10.1016/j.scs.2019.101563.

Bellizzi, M.G., Forciniti, C., Mazzulla, G., 2021. A stated preference survey for evaluating young Pedestrians' preferences on walkways. Sustainability 13 (22). https://doi.org/10.3390/su132212434.

Benhadou, M., El Gonnouni, A., Lyhyaoui, A., 2024. Pedestrian level of service for sidewalks in tangier city. Int. J. Electr. Comput. Eng. 14 (1), 1048–1057. https://doi.org/10.11591/ijece.v14i1.pp1048-1057.

Beura, S.K., Bhuyan, P.K., 2022. Development of artificial Intelligence-based bicycle level of service models for urban street segments. Int. J. Intell. Transp. Syst. Res. 20 (1), 142–156. https://doi.org/10.1007/s13177-021-00280-3.

Beura, S.K., Chellapilla, H., Bhuyan, P.K., 2017. Urban road segment level of service based on bicycle users' perception under mixed traffic conditions. J. Mod. Transp. 25 (2), 90–105. https://doi.org/10.1007/s40534-017-0127-9.

Beura, Sambit Kumar, Chellapilla, Haritha, Panda, Mahabir, Bhuyan, Prasanta Kumar, 2021. Bicycle comfort level rating (BCLR) model for urban street segments in Mid-Sized cities of India. J. Transp. Health 20, 100971. https://doi.org/10.1016/j.jth.2020.100971.

Bivina, G.R., Parida, P., Advani, M., Parida, M., 2018. Pedestrian level of service model for evaluating and improving sidewalks from various land uses. Eur. Transp. Trasp. Eur. 67 (67).

Bivina, G.R., Parida, M., 2019. Modelling perceived pedestrian level of service of sidewalks: a structural equation approach. Transport 34 (3), 339–350. https://doi.org/10.3846/transport.2019.9819.

Bivina, G.R., Parida, M., 2024. Gender disparities in defining factors of pedestrian level of service of sidewalks. Environ. Dev. Sustain. https://doi.org/10.1007/s10668-024-04796-y.

Broach, Joseph, Dill, Jennifer, Gliebe, John, 2012. Where do cyclists ride? A route choice model developed with revealed preference GPS data. Transp. Res. Part A Policy Pract. 46 (10), 1730–1740. https://doi.org/10.1016/j.tra.2012.07.005.

Bunevska Talevska, J., Todorova, M.Malenkovska, 2012. Contribution to sidewalk pedestrian level of service analysis. Transp. Probl. 7 (3), 5–13.

Callister, D., Lowry, M., 2013. Tools and strategies for wide-scale bicycle level-of-service analysis. J. Urban Plan. Dev. 139 (4), 250–257. https://doi.org/10.1061/(ASCE)UP.1943-5444.0000159.

Campisi, T., Acampa, G., Marino, G., Tesoriere, G., 2020. Cycling master plans in Italy: the I-BIM feasibility tool for cost and safety assessments. Sustainability 12 (11). https://doi.org/10.3390/su12114723.

Cepolina, E., Menichini, F., Gonzalez Rojas, P., 2017. Pedestrian level of service: the impact of social groups on pedestrian flow characteristics. Int. J. Sustain. Dev. Plan. 12 (4), 839–848. https://doi.org/10.2495/SDP-V12-N4-839-848.

Cepolina, E., Menichini, F., Gonzalez Rojas, P., 2018. Level of service of pedestrian facilities: modelling human comfort perception in the evaluation of pedestrian behaviour patterns. Transp. Res. Part F Traffic Psychol. Behav. 58, 365–381. https://doi.org/10.1016/j.trf.2018.06.028.

Chen, C., Anderson, J.C., Wang, H., Wang, Y., Vogt, R., Hernandez, S., 2017. How bicycle level of traffic stress correlate with reported cyclist accidents injury severities: a geospatial and mixed logit analysis. Accid. Anal. Prev. 108, 234–244. https://doi.org/10.1016/j.aap.2017.09.001.

Chen, Y.-X., He, Y.-L., Sun, X.-D., Ma, X.-L., 2014. A multi-index evaluation for the level of service of sidewalks based on the clustering Method. *Beijing Gongye*. Daxue Xuebao J. Beijing Univ. Technol. 40 (4), 549–554.

City of Portland. 2012. Portland Plan-20 minute neighborhoods analysis: Background report and analysis area summaries. Portland: City of Portland. https://www.portlandonline.com/ portlandplan/index.cfm?c=51427&a=395048.

Da Silva, Denise, Capasso, David A., King, Lemar, Shea, 2020. Accessibility in practice: 20-minute city as a sustainability planning goal. Sustainability 12 (1). https://doi.org/10.3390/SU12010129.

Das, P., Advani, M., Parida, P., Parida, M., Singh, S.P., 2019. Development of landuse based pedestrian level of service in Indian context. Eur. Transp. Trasp. Eur. 74, 1.

Davis, J.W., 1987. Bicycle Safety Evaluation." Auburn University, City of Chattanooga. Chattanooga-Hamilton County Regional Planning Commission, Chattanooga.

Davis, J.W., 1995. Bicycle test route evaluation for urban road conditions. Transp. Congr. San. Diego Calif.

Dias, I., Wijeweera, K.P., 2021. Assessing the Walk-Score of walking paths in kandy city area for better walking experience for the tourists. Eng. J. Inst. Eng. Sri Lanka 54, 27–37. https://doi.org/10.4038/engineer.v54i0.7450.

Dixon, L.B., 1996. Bicycle and pedestrian level-of-service performance measures and standards for congestion management systems. Transp. Res. Rec. 1538 (1), 1–9. https://doi.org/10.3141/1538-01.

Dowling, R.G., McLeod, D., Guttenplan, M., Zegeer, J.D., 2002. Multimodal corridor level-of-service analysis. Transp. Res. Rec. 1 (1802), 1–6. https://doi.org/10.3141/1802-01.

Elias, A., 2011. Automobile-oriented or complete street? Pedestrian and bicycle level of service in the new multimodal paradigm. Transp. Res. Rec. 2257 (1), 80–86. https://doi.org/10.3141/2257-09.

Fruin, J., 1971. Pedestrian Planning and Design. Metropolitan Association of Urban Designers; Environmental Planners, NewYork.

Furth, Peter, G., Mekuria, Maaza C., 2013. Network connectivity for Low-Stress Bicycling. TRB Annu. Meet. Compend. Pap.

Gallin, N., 2001. Quantifying pedestrian friendliness - guidelines for assessing pedestrian level of service. Road. Transp. Res. 10 (1), 47–55.

Georgiou, A., Skoufas, A., Basbas, S., 2021. Perceived pedestrian level of service in an urban central network: the case of a medium size Greek city. Case Stud. Transp. Policy 9 (2), 889–905. https://doi.org/10.1016/j.cstp.2021.04.009.

Ghani, N.A., Hussein, M.Z.S.M., Mokhtar, S., 2013. Incorporating pedestrian index into googlemaps. Plan. Malays. 11, 119–136.

Griswold, Julia B., Yu, Mengqiao, Filingeri, Victoria, Grembek, Offer, Walker, Joan L., 2018. A behavioral modeling approach to bicycle level of service. Transp. Res. Part A Policy Pract. 116, 166–177. https://doi.org/10.1016/j.tra.2018.06.006.

Hallett, Ian, Luskin, David, Machemehl, Randy, 2006. Evaluation of On-Street bicycle facilities added to existing Roadways. Austin: Center for Transportation Research. The University of Texas at Austin. ⟨www.ntis.gov⟩.

Harkey, David L., Reinfurt, Donald W., Knuiman, Matthew, 1998. Development of the bicycle compatibility index. Transp. Res. Rec. 1636 (1), 13–20. https://doi.org/10.3141/1636-03.

Hasan, T., Siddique, A., Hadiuzzaman, M., Musabbir, S.R., 2015. Determining the most suitable pedestrian level of service method for Dhaka city, Bangladesh, through a synthesis of measurements. Transp. Res. Rec. 2519, 104–115. https://doi.org/10.3141/2519-12.

Highway Capacity Manual. 2010. Highway Capacity Manual. Highway Research Board; Knovel.

Highway Capacity Manual. 2016. Highway Capacity Manual. Highway Research Board.

Huang, J., Fournier, N., Skabardonis, A., 2021. Bicycle level of service: proposed updated pavement quality index. Transp. Res. Rec. 2675 (11), 1346–1356. https://doi.org/10.1177/03611981211026661.

Jaskiewicz, Frank, 2000. Pedestrian level of service based on trip quality. Transp. Res. Board.

Jegan Bharath Kumar, A., Ramakrishnan, T., 2020. Assessment of walkability and pedestrian level of service in two cities of kerala. In: Mathew, T., Joshi, G., Velaga, N., Arkatkar, S. (Eds.), Lecture Notes in Civil Engineering, 45. Springer, Singapore, pp. 533–544. https://doi.org/10.1007/978-981-32-9042-6_42.

Jia, X., Feliciani, C., Murakami, H., Nagahama, A., Yanagisawa, D., Nishinari, K., 2022. Revisiting the level-of-service framework for pedestrian comfortability: velocity depicts more accurate perceived congestion than local density. Transp. Res. Part F Traffic Psychol. Behav. 87, 403–425. https://doi.org/10.1016/j.trf.2022.04.007.

Jin, T., Wang, K., Xin, Y., Shi, J., Hong, Y., Witlox, F., 2024. Is a 15 Minute city within reach? Measuring multimodal accessibility and carbon footprint in 12 major American cities. Land Use Policy 142. https://doi.org/10.1016/j.landusepol.2024.107180.

Kadali, B.R., Vedagiri, P., 2016. Review of pedestrian level of service: perspective in developing countries. Transp. Res. Rec. 2581, 37–47. https://doi.org/10.3141/2581-05.

Kang, K., Lee, K., 2012. Development of a bicycle level of service model from the user's perspective. KSCE J. Civ. Eng. 16 (6), 1032–1039. https://doi.org/10.1007/s12205-012-1146-z.

Karatas, P., Tuydes-Yaman, H., 2018. Variability in sidewalk pedestrian level of service measures and rating. J. Urban Plan. Dev. 144 (4). https://doi.org/10.1061/(ASCE)UP.1943-5444.0000483.

Kazemzadeh, K., Laureshyn, A., Hiselius, L.W., Ronchi, E., 2020. Expanding the scope of the bicycle level-of-service concept: a review of the literature. Sustain. (Switz.) 12 (7). https://doi.org/10.3390/su12072944.

Kim, S., Choi, J., Kim, Y., 2011. Determining the sidewalk pavement width by using pedestrian discomfort levels and movement characteristics. KSCE J. Civ. Eng. 15 (5), 883–889. https://doi.org/10.1007/s12205-011-1173-1.

Kim, S., Choi, J., Kim, S., Tay, R., 2014. Personal space, evasive movement and pedestrian level of service. J. Adv. Transp. 48 (6), 673–684. https://doi.org/10.1002/atr.1223.
Kretz, T., 2011. A level of service scheme for microscopic simulation of pedestrians that integrates queuing, Uni-and Multi-Directional flow situations. Eur. Transp. Res. Rev. 3 (4), 211–220. https://doi.org/10.1007/s12544-011-0060-7.
LaMondia, J.J., Moore, N., 2015. Using bicycle level of service for decision making comparison of common bicycle level-of-service measures, roadway characteristics, and perceived bike route suitability. Transp. Res. Rec. 2520, 123–131. https://doi.org/10.3141/2520-14.
Landis, B.W., Vattikuti, V.R., Brannick, M.T., 1997. Real-time human perceptions: toward a bicycle level of service. Transp. Res. Rec. 1578 (1), 119–131. https://doi.org/10.3141/1578-15.
Landis, B.W., Vattikuti, V.R., Ottenberg, R.M., McLeod, D.S., Guttenplan, M., 2001. Modeling the roadside walking environment: pedestrian level of service. Transp. Res. Rec. 1773 (1), 82–88. https://doi.org/10.3141/1773-10.
Liang, X., Zhang, T., Xie, M., Jia, X., 2021. Analyzing bicycle level of service using virtual reality and deep learning technologies. Transp. Res. Part A Policy Pract. 153, 115–129. https://doi.org/10.1016/j.tra.2021.09.003.
Lo, R.H., 2009. Walkability: what is it? J. Urban. 2 (2), 145–166. https://doi.org/10.1080/17549170903092867.
Logan, T.M., Hobbs, M.H., Conrow, L.C., Reid, N.L., Young, R.A., Anderson, M.J., 2022. The x-minute city: measuring the 10, 15, 20-minute city and an evaluation of its use for sustainable urban design. Cities 131. https://doi.org/10.1016/j.cities.2022.103924.
Lowry, M., Callister, D., Gresham, M., Moore, B., 2012. Assessment of communitywide bikeability with bicycle level of service. Transp. Res. Rec. 2314 (1), 41–48. https://doi.org/10.3141/2314-06.
Mahmudah, A., Legowo, S., Sumarsono, A., Linta, S., Irawan, B., 2018. Is the Indonesian regulation of standard level of service of a pedestrian path fulfill pedestrians' convenience. MATEC Web Conf. 147. https://doi.org/10.1051/matecconf/201814702003.
Marisamynathan, S., Lakshmi, S., 2018. Method to determine pedestrian level of service for sidewalks in Indian context. Transp. Lett. 10 (5), 294–301. https://doi.org/10.1080/19427867.2016.1264668.
Marisamynathan, Sankaran, Vedagiri, Perumal, 2020. Pedestrian safety evaluation of signalized intersections using surrogate safety measures. Transport 35 (1), 48–56. https://doi.org/10.3846/transport.2020.12157.
McNeil, Nathan, 2011. Bikeability and the 20-min neighborhood: how infrastructure and destinations influence bicycle accessibility. Transp. Res. Rec. 2247 (1), 53–63. https://doi.org/10.3141/2247-07.
Meneses, N.A.I., Buluran, J.S., 2022. Analysis of pedestrian performance by integrating both quantitative and qualitative factors. Civ. Eng. J. 8 (6), 1100–1114. https://doi.org/10.28991/CEJ-2022-08-06-02.
Miller, J.S., Bigelow, J.A., Garber, N.J., 2000. Calibrating pedestrian level-of-service metrics with 3-D visualization. Transp. Res. Rec. 1705 (1), 9–15. https://doi.org/10.3141/1705-02.
Mofolasayo, A., 2020. Complete street concept, and ensuring safety of vulnerable road users. Transp. Res. Procedia 48, 1142–1146. https://doi.org/10.1016/j.trpro.2020.08.139.
Moher, David, Liberati, Alessandro, Tetzlaff, Jennifer, Altman, Douglas G., Altman, Doug, Antes, Gerd, Atkins, David, et al., 2009. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. PLOS Med. 6 (7). https://doi.org/10.1371/journal.pmed.1000097.
Moreno, C., Allam, Z., Chabaud, D., Gall, C., Pratlong, F., 2021. Introducing the '15-minute city': sustainability, resilience and place identity in future post-pandemic cities. Smart Cities 4 (1), 93–111. https://doi.org/10.3390/smartcities4010006.
Mozer, David, 1994. Calculating Multi-Mode Levels-Of-Service. International Bicycle Fund, Seattle, WA.
Nag, D., Goswami, A.K., 2019. Identification of measures of effectiveness (MOEs) for developing pedestrian level of service (PLOS): a theoretical approach using expert opinion on a fuzzy Likert (FL) scale. Int. Rev. Spat. Plan. Sustain. Dev. 7 (4), 56–82. https://doi.org/10.14246/irspsd.7.4_56.
Nag, D., Goswami, A.K., Gupta, A., Sen, J., 2020. Assessing urban sidewalk networks based on three constructs: a synthesis of pedestrian level of service literature. Transp. Rev. 40 (2), 204–240. https://doi.org/10.1080/01441647.2019.1703841.
Noronha, M., Celani, G., Duarte, J.P., 2022. Computationally evaluating street retrofitting interventions. Nexus Netw. J. 24 (2), 481–502. https://doi.org/10.1007/s00004-022-00596-x.
Okon, I.E., Moreno, C.A., 2019. Bicycle level of service model for the cicloruta, Bogota, Colombia. Romanian J. Transp. Infrastruct. 8 (1), 1–33. https://doi.org/10.2478/rjti-2019-0001.
Ouzzani, Mourad, Hammady, Hossam, Fedorowicz, Zbys, Elmagarmid, Ahmed, 2016. Rayyan-a web and mobile app for systematic reviews. Syst. Rev. 5 (1). https://doi.org/10.1186/s13643-016-0384-4.
Paul, D., Moridpour, S., Nguyen, L.A., 2023. Evaluating the impact of COVID-19 on the behaviour of pedestrians. Sustainability 15 (3). https://doi.org/10.3390/su15031874.
Paul, D., Moridpour, S., Venkatesan, S., Withanagamage, N., 2024. Evaluating the pedestrian level of service for varying trip purposes using machine learning algorithms. Sci. Rep. 14 (1). https://doi.org/10.1038/s41598-024-53403-7.
Petritsch, T.A., Landis, B.W., Huang, H.F., McLeod, P.S., Lamb, D., Farah, W., Guttenplan, M., 2007. Bicycle level of service for arterials. Transp. Res. Rec. 2031 (1), 34–42. https://doi.org/10.3141/2031-05.
Petritsch, T.A., Landis, B.W., Huang, H.F., Dowling, R., 2008. Pedestrian level-of-service model for arterials. Transp. Res. Rec. 2073 (1), 58–68. https://doi.org/10.3141/2073-07.
Polus, A., Schofer, J., Ushpiz, A., 1983. Pedestrian flow and level of service. J. Transp. Eng. 109 (1), 46–56.
Raad, N., Burke, M., 2017. Pedestrian levels-of-service tools: problems of conception, factor identification, measurement and usefulness. ATRF 2017 Australas. Transp. Res. Forum 2017 Proc.
Rahmati, M., Kashi, E., 2019. Urban footpath analysis and simulation - a case study in sari - Iran. Proc. Inst. Civ. Eng. Munic. Eng. 172 (3), 164–174. https://doi.org/10.1680/jmuen.17.00023.
Rahul, T.M., Manoj, M., 2020. Categorization of pedestrian level of service perceptions and accounting its response heterogeneity and latent correlation on travel decisions. Transp. Res. Part A Policy Pract. 142, 40–55. https://doi.org/10.1016/j.tra.2020.10.011.
Rodriguez-Valencia, A., Ortiz-Ramirez, H.A., Simancas, W., Vallejo-Borda, J.A., 2022. Level of pedestrian stress in urban streetscapes. Transp. Res. Rec. 2676 (6), 87–98. https://doi.org/10.1177/03611981211072804.
Sahani, R., Bhuyan, P.K., 2017. Pedestrian level of service criteria for urban off-street facilities in mid-sized cities. Transport 32 (2), 221–232. https://doi.org/10.3846/16484142.2014.944210.
Sarkar, Sheila, 1993. Determination of service levels for pedestrians, with european examples. Transp. Res. Rec.
Shan, X., Ye, J., Chen, X., 2016. Proposing a revised pedestrian walkway level of service based on characteristics of pedestrian interactive behaviours in China. Promet Traffic Transp. 28 (6), 583–591. https://doi.org/10.7307/ptt.v28i6.1947.
Sisiopiku, V.P., Byrd, J., Chittoor, A., 2007. Application of level-of-service methods for evaluation of operations at pedestrian facilities. Transp. Res. Rec. Sisiopiku (1), 117–124. https://doi.org/10.3141/2002-15.
Sorton, Alex, Walsh, Thomas, 1994. Bicycle Stress Level as A Tool to Evaluate Urban and Suburban Bicycle Compatibility. In: In Transportation Research Record 1438, 1438. TRB, National Research Council, Washington, D.C, pp. 17–24.
Talavera-Garcia, R., Soria-Lara, J.A., 2015. Q-PLOS, developing an alternative walking index. A method based on urban design quality. Cities 45, 7–17. https://doi.org/10.1016/j.cities.2015.03.003.
Tan, D., Wang, W., Lu, J., Bian, Y., 2007. Research on methods of assessing pedestrian level of service for sidewalk. J. Transp. Syst. Eng. Inf. Technol. 7 (5), 74–79. https://doi.org/10.1016/S1570-6672(07)60041-5.
Teixeira, João Filipe, Silva, Cecília, Seisenberger, Sebastian, Büttner, Benjamin, McCormick, Bartosz, Papa, Enrica, Cao, Mengqiu, 2024. Classifying 15-Minute cities: a review of worldwide practices. Transp. Res. Part A Policy Pract. 189 (ember). https://doi.org/10.1016/j.tra.2024.104234.
The State of Victoria Department of Transport and Planning. 2023. "20-Minute Neighbourhoods Checklist Tool." Melbourne: City of Melbourne.
Transitec. 2025. Greater Sousse Is Moving Towards the "15-Minutes City" 〈https://transitec.net/en/news/item/11067-greater-sousse-is-moving-towards-the-15-minutes-city.html〉.
Tuydes-Yaman, H., Karatas, P., 2018. Evaluation of walkability and pedestrian level of service. IGI Glob. https://doi.org/10.4018/978-1-5225-5210-9.ch012.
Ujjwal, J., Bandyopadhyaya, R., 2021. Development of pedestrian level of service assessment guidelines for mixed land use areas considering quality of service parameters. Trans. Develo. Econo. 7 (1). https://doi.org/10.1007/s40890-021-00113-8.
Vallejo-Borda, J.A., Cantillo, V., Rodriguez-Valencia, A., 2020. A perception-based cognitive map of the pedestrian perceived quality of service on urban sidewalks. Transp. Res. Part F Traffic Psychol. Behav. 73, 107–118. https://doi.org/10.1016/j.trf.2020.06.013.
Werner, Christian, van der Meer, Lucas, Kaziyeva, Dana, Stutz, Petra, Wendel, Robin, Loidl, Martin, 2024. Bikeability of road segments: an open, adjustable and extendible model. J. Cycl. Micro Res. 2, 100040. https://doi.org/10.1016/j.jcmr.2024.100040.
Wong, D.W., 2009. Modifiable areal unit problem. Int. Encycl. Hum. Geogr. 169–174.
Xu, L., Liu, M., Song, X., Jin, S., 2018. Analytical model of passing events for One-Way heterogeneous bicycle traffic flows. Transp. Res. Rec. 2672 (36), 125–135. https://doi.org/10.1177/0361198118788425.
Zannat, K.E., Raja, D.R., Adnan, M.S.G., 2019. Pedestrian facilities and perceived pedestrian level of service (PLOS): a case study of chittagong metropolitan area, Bangladesh. Trans. Devel. Econo. 5 (2). https://doi.org/10.1007/s40890-019-0078-4.
Zhao, L., Bian, Y., Rong, J., Liu, X.-M., 2014. Evaluation on pedestrian level of service of sidewalks in Beijing transportation junction area." *Beijing Gongye*. Daxue Xuebao J. Beijing Univ. Technol. 40 (5), 725–732.
Zhao, L., Bian, Y., Rong, J., Liu, X., Shu, S., 2016. Evaluation method for pedestrian level of service on sidewalks based on fuzzy neural network model. J. Intell. Fuzzy Syst. 30 (5), 2905–2913. https://doi.org/10.3233/IFS-151753.