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Exploring bikeability: conceptual development, approaches, and a critical review of cycling research in Central and Eastern Europe

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Abstract

Cycling in Central and Eastern Europe (CEE) remains underdeveloped, reflecting decades of automobile-oriented planning that have shaped how bikeable the region's urban streets and environments are today. This paper first aims to clarify the concept of bikeability and explore the methodological approaches used in its assessment, with particular emphasis on European research. Second, it uses a bibliometric keyword analysis to examine whether thematic elements common in broader European bikeability literature appear in CEE cycling studies, followed by a critical review of relevant regional research. The findings highlight the marginal position of CEE countries within the European bikeability discourse and reveal a limited conceptualization and a lack of multidimensional approaches. Finally, the paper proposes a future research agenda for advancing bikeability assessment in the CEE context, which aims to address existing gaps and support evidence-based sustainable mobility planning. It argues that existing European frameworks could serve as a valuable starting point for evaluating cycling conditions in CEE cities, provided that the local context, data availability, and the needs of different user groups are considered.

Key words: *bikeability, cycling, Central and Eastern Europe, sustainable urban mobility, review*

1 INTRODUCTION: RETHINKING URBAN TRANSPORT – CYCLING, BIKEABILITY AND THE CEE CONTEXT

Transport is widely considered one of the most challenging sectors to decarbonize (de Blas et al., 2020; Danielis et al., 2022). Despite the European Union's sustainability targets, transport-related CO_2 emissions have continued to rise between 1990 and 2019 (Danielis et al., 2022). Road transport remains a major source of greenhouse gas emissions, air pollution, noise, and accidents, with individual motorized transport playing a dominant role in these impacts (EEA, 2024; EC & Eurostat, 2024), making current mobility patterns unsustainable (Holden et al., 2020). Urban areas are uniquely positioned to drive the shift toward sustainable mobility in the EU, but they also face the externalities of car-centric transport systems that are strongly reliant on fossil fuels and have low occupancy rates below 1.5 passengers per trip (Armoogum et al., 2022). The growing popularity of SUVs, which accounted for 48% of new vehicle registrations in the EU in 2023 (ICCT, 2025), further intensifies spatial inefficiencies in urban public space. These statistics underscore the need for sustainable, space-efficient, and health-promoting transport alternatives, as reflected in policies adopted by many European cities (Loorbach et al., 2021).

The shift toward sustainable urban mobility requires a transformation of transport planning from car-focused, speed-driven systems to people-oriented approaches that accommodate all modes of transport (Banister, 2008; Foltýnová et al., 2020). Key transition pathways toward sustainable mobility involve shifting to more environmentally friendly transport modes (Banister, 2008), as illustrated by emerging urban models such as Superblocks, low-traffic neighbourhoods, and the 15-minute city (Nieuwenhuijsen, 2021). Cycling plays a central role in these strategies, delivering well-documented benefits, such as lifecycle CO^2 emissions that are over 10 times lower per passenger kilometre than those of private cars with internal combustion engines (ITF, 2024), an exceptional spatial efficiency (Nello-Deakin, 2019) and additional environmental, social, and economic benefits, with broader impacts on human well-being as outlined in the Sustainable Development Goals framework (Roy et al., 2021).

Cycling's greatest potential lies in short-range mobility, as most bicycle trips typically remain within 5 km, while e-bikes can extend this distance to around 10 km (Castro et al., 2019). This distance range accounts for 52% of urban car trips in the EU (Armoogum et al., 2022), highlighting a potential to substitute these journeys with active modes. However, cycling can serve not only as a direct alternative to private car use but also as part of multimodal travel, as evidence from Denmark shows that combining cycling with private cars is common, particularly among residents of smaller urban areas and low-density settings (Olafsson et al., 2016). For such synergies to be effective, both convenient routes and targeted infrastructure interventions, such as park-and-ride facilities, are essential (Panter et al., 2013).

To encourage cycling, areas may provide a high level of bikeability (Hagen & Rynning, 2021) as recent research has shown that bikeable environments are positively associated with cycling frequency (Codina et al., 2022), and an increased likelihood of being a cyclist (Krenn et al., 2015). Nevertheless, the term bikeability remains conceptually ambiguous, as it has been interpreted differently across studies, with no universally accepted definition established to date (Schmid-Querg et al., 2021). One interpretation is that it reflects the extent to which the built environment provides conditions that are convenient and safe for cycling (Reggiani et al., 2022).

In CEE, cycling remains underdeveloped and marginal within the transport mix (Kaplan et al., 2019; Iwińska et al., 2018). Although comparable statistics on cycling's modal share across European countries remain limited, evidence from the Special Eurobarometer 495 confirms this pattern: in most CEE countries, the share of daily trips made by privately owned bicycles or scooters remains below the EU average of 8%, with Hungary standing out as the only exception, with a modal share of around 14%. According to this source, these modes account for 2% of daily trips in Bulgaria, 4% in Estonia, Romania, and Slovenia, 5–6% in Lithuania, Slovakia, Czechia and Croatia, 7% in Poland, and 8% in Latvia (EC, 2020). O'Reilly et al. (2024) show that differences in bicycle use across 31 European countries are associated with demographic and subjective socio-cultural factors, alongside certain geospatial factors such as topography and temperature. Complementing this perspective, Haustein et al. (2020) argue that differences in cycling frequency may be shaped by cycling culture. The low level of cycling highlights the necessity to improve conditions. Specifically, safety-related concerns have been identified as the main barrier to cycling uptake in CEE cities (Iwińska et al., 2018; Šťastná et al., 2018). Barnfield and Plyushteva (2016) further described cycling in the post-socialist urban context as a purely individualistic mode of transport. These facts further indicate a weak and underdeveloped cycling culture, reinforced by the view of cycling primarily as a recreational activity (Iwińska et al., 2018; Šťastná et al., 2018; Kwiatkowski & Karbowiński, 2023), which is highly seasonal and weather-sensitive (Németh & Horňák, 2025).

The above-mentioned points underscore the importance of studying bikeability in this region. For this study, CEE countries are understood as the EU member states in this region: Bulgaria, Croatia, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovenia, Slovakia, and the Czech Republic. This paper addresses three main objectives:

- to explore the development and understanding of the concept of bikeability in international scientific literature, with an emphasis on Europe, including an analysis of the methods commonly used in European studies;
- to identify and assess the extent to which thematic and conceptual elements typical of European bikeability research appear in academic cycling studies from CEE, and to critically review the CEE literature;
- to outline a future research agenda addressing gaps in both CEE and the broader European bikeability literature.

2 CAR-DEPENDENCE IN CEE CITIES: PERSPECTIVE ON UNDERDEVELOPED BIKEABILITY

Recent studies describe cities in CEE as experiencing a phase of „car-adolescence" characterized by rapid motorization, dispersed post-socialist urban growth, and transport planning that prioritizes private car use, which has led to persistent car dependence, even in densely populated areas (see Rudolph et al., 2021; Saeidizand et al., 2022). Political and economic changes after 1990 in post-socialist contexts accelerated car ownership and transformed urban form through suburbanisation, retail sprawl, and fragmented service provision, which in turn produce trip patterns and infrastructural constraints that are hard to reverse by conventional bicycle promotion measures without systemic change in planning priorities. Evidence from post-communist Europe demonstrates a marked increase in car ownership in both rural and urban environments, as well as increased motorised mobility linked to institutional change and rising incomes (Taczanowski et al., 2018; Antczak & Wiaderny, 2023; Kudłak et al., 2024). Preferences for passenger cars are specifically high in communities residing in suburban environments surrounding post-socialist cities, where public transport infrastructure has been underdeveloped or where gaps in public transport encourage individual passenger car use among those who can afford it (see, for example, Holota et al., 2024; Kraft & Tonev, 2025; Malý, 2025). According to Eurostat (2025) the motorisation rate in Estonia, Lithuania, Poland, Czechia, and Slovenia exceeds the EU average of 576 passenger cars per 1,000 inhabitants (2024), while Hungary and Slovakia are approaching this level.

Based on literature (Rišová, 2020; Fási, 2023; Górka, 2024; Hluško et al., 2024; Holota et al., 2024), effects of automobile-oriented planning in the CEE context consistently translate into several interrelated consequences that reduce bikeability: (1) environmental externalities (air pollution, noise, large public-space allocation to parked and moving cars); (2) spatial fragmentation and functional separation of key destinations that lengthen everyday trips beyond comfortable cycling ranges; and (3) safety deficiencies for cyclists due to mixed traffic, high speeds on urban arterials, and discontinuous cycling networks. Authors also argue that these effects are compounded by institutional legacies, including planning norms, regulatory frameworks, and investment logics that historically favoured motor traffic.

At the same time, several CEE states have signed political commitments, such as the European Bicycle Declaration (ECF, 2023), and have increased the use of EU Structural Funds for cycling and active travel projects. Between 2014 and 2020, Lithuania and Estonia recorded the highest per capita use of these funds within the EU, while Poland led in total spending (EC, 2023). However, financial resources alone do not guarantee effective outcomes, as the experience from Slovakia shows that investments often focused on building recreational rather than utilitarian routes with limited impact on everyday mobility (Kollár et al., 2022). This example highlights the need for planning and evaluation tools that can better guide cycling investments.

3 CONCEPTUAL BACKGROUND: WHAT IS BIKEABILITY?

Bikeability can be regarded as a relatively new and emerging concept. Its development is closely linked to walkability, which has a longer tradition in research and planning of active and non-motorized transport (Muhs & Clifton, 2016). This relationship is also reflected in the first studies on bikeability, which focused on neighbourhood characteristics influencing the propensity to increase walking and cycling (Greenberg & Renne, 2005) or provided environmental overviews along routes and within neighbourhoods to analyse the links between the built environment and physical activity (Hoedl et al., 2010).

Although the concept of bikeability is very recent, researchers have attempted to define it from various perspectives. As summarised in Figure 1, one of the most common approaches conceptualises bikeability in terms of friendliness, conduciveness, and the pleasure of the environment for cycling (e.g., Krenn et al., 2015; Hagen & Rynning, 2021; Moinse, 2025). Another line of research frames bikeability in terms of suitability of infrastructure and urban environments for cycling (e.g., Kellershohn et al., 2025; Werner et al., 2024). Bicycle suitability is also expressed through the level of service (Galanis et al., 2014) or the level of traffic stress that roads present to cyclists (Vierø & Szell, 2025). The concept of Bicycle Level of Service (BLOS), Level of Traffic Stress (LTS) and bicycle suitability operate primarily at the street-segment level. BLOS reflects the comfort and safety experienced by cyclists on roadway corridors (Ilie et al., 2016). The LTS framework introduced by Mekuria et al. (2012) shows how suitable different streets are for cyclists with varying skill and confidence levels. Similarly, the concept of bicycle suitability describes how well a particular street segment supports cycling, in terms of perceived comfort and safety (Lowry et al., 2012; Wysling & Purves, 2022). Cycling quality expands this perspective by incorporating perceived attractiveness (Grigore et al., 2019).

Others frame bikeability in terms of how accessible different points of interest are by bicycle (McNeil, 2011; Saghapour et al., 2017), which closely aligns with cycling accessibility. While accessibility generally denotes the ease of reaching desirable destinations (Saghapour et al., 2017), cycling accessibility can specifically refer to the ability to access relevant activities by bicycle (Vale et al., 2016). McNeil (2011) operationalises bikeability through the temporal accessibility of destinations, using an isochrone-based approach. Saghapour et al. (2017) frame bikeability as an accessibility measure that employs travel distance as an impedance factor along with cycling catchment areas. Both conceptions map onto two of the main categories of active accessibility measurement identified by Vale et al. (2016): (1) activity-based measures (isochrone-based and gravity-based measures) and (2) distance-based measures. For a comprehensive overview of accessibility metrics for non-motorised modes, see the review by Vale et al. (2016). Beyond these interpretations, a group of authors treat bikeability as a specialised form of bicycle accessibility that explicitly incorporates street-network suitability into the measurement of accessibility (Lowry et al., 2012; Grigore et al., 2019; Wysling & Purves, 2022).

Bikeability has also been applied in broader ways, for example, Nielsen and Skov-Petersen (2018) conceptualise it as both a person‘s ability to cycle and the urban landscape‘s ability to be cycled. Overall, these perspectives indicate that bikeability integrates and overlaps with many concepts, which likely contributes to the difficulty of establishing a single, universally accepted definition. The literature further introduces several alternative approaches to conceptualizing bikeability, including perceived bikeability (Moinse, 2025), e-bikeability (Santos et al. 2024), school bikeability (Paulusová & Sharmeen 2025), and connected bikeability (Beecham et al. ,2023). This complexity of bikeability is reinforced by its interdisciplinary nature, rooted primarily in transport studies but also enriched by contributions from many other fields.

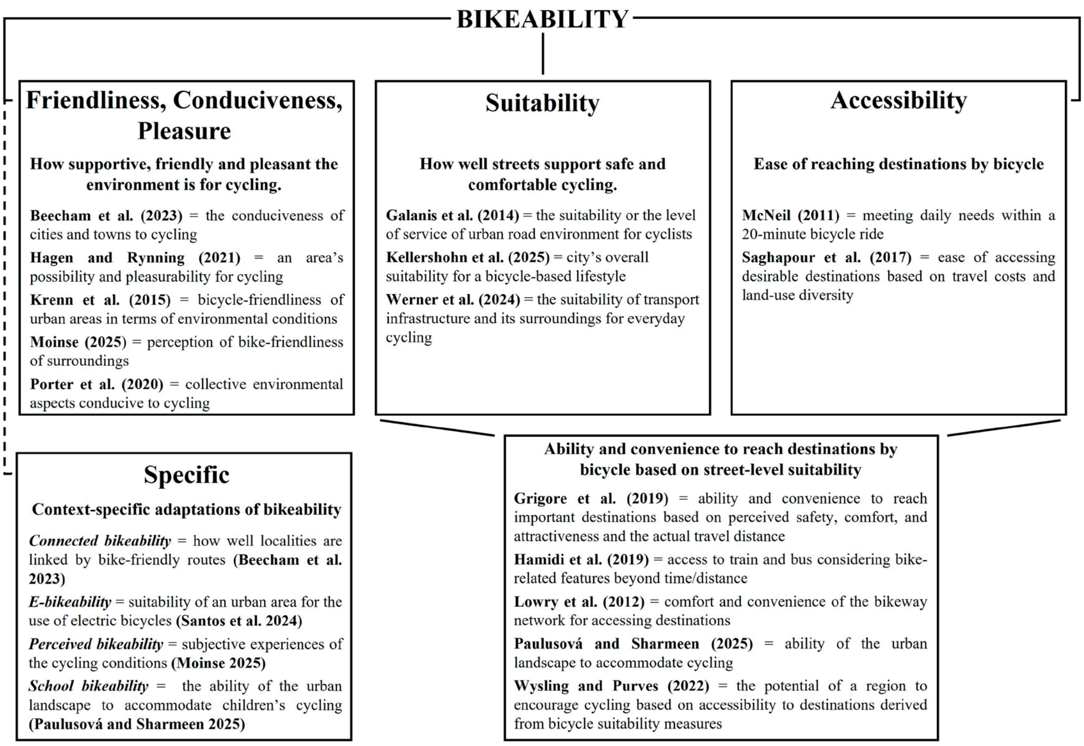

Fig. 1. Main approaches to defining bikeability in the literature
Source: authors' own processing

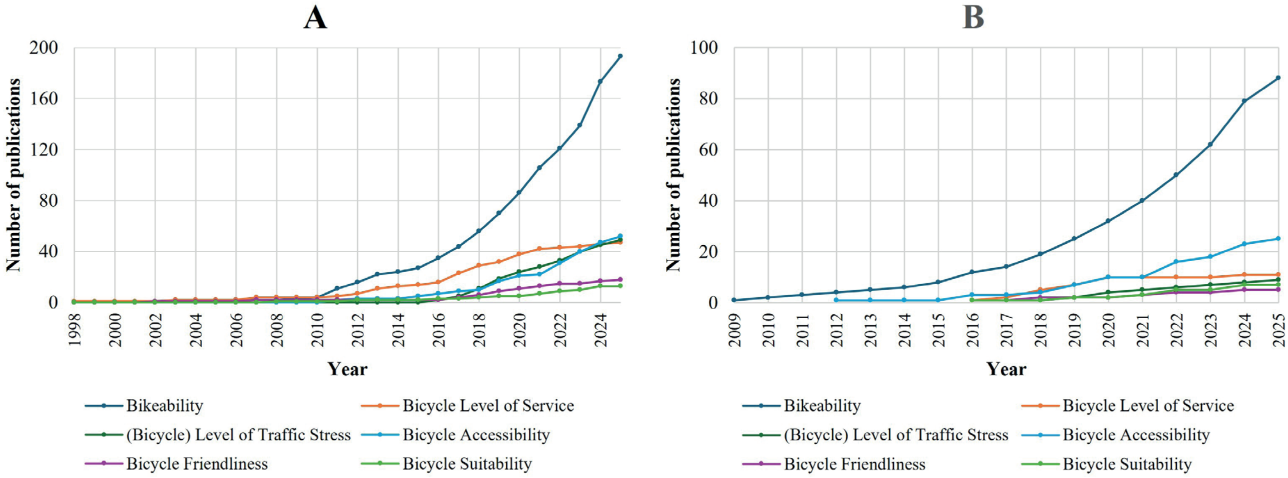

Fig. 2. Cumulative trends in scientific publications on bikeability and related concepts in the international (A) and European (B) literature
Source: Web of Science Core Collection (data retrieved on 1 August 2025), authors' own processing
Note: data for 2025 include publications indexed up to 1 August 2025

The development of scientific papers globally (Fig. 2A) shows that the first works on bikeability-related concepts appeared before 2000, but their number remained relatively low until 2010. A growing interest in the topic emerged around 2016, followed by the largest increase in 2024, when more than 50 papers were published. However, the trajectories of individual concepts differ, with bikeability steadily rising as the dominant concept. In European literature, this trend is even stronger, with bikeability clearly prevailing, followed by bicycle accessibility, while BLOS and LTS, which are more established in the U.S., play only a marginal role (Fig. 2B).

4 BIKEABILITY ASSESSMENT METHODS

In recent years, several methods have been developed to measure bikeability, with the core objective of evaluating the conditions that support or hinder cycling within urban environments. Consequently, they serve as evidence-based tools for municipalities, guiding intervention priorities and the effective allocation of financial resources (Grigore et al., 2019; Codina et al., 2022; Paulusová & Sharmeen, 2025). A characteristic trend in the research trajectory is the shift from an early focus on roadway characteristics to more holistic, human-centred approaches that integrate a broader spectrum of built environment attributes (Arellana et al., 2020; Paulusová & Sharmeen, 2025). The following section reviews methods for assessing bikeability in recent European studies, focusing on spatial scale, computational approaches, and key indicators. Finally, critiques of bikeability methods are noted.

Spatial Frameworks in European Bikeability Research: Segment/Route-Based and Area/Zone-Based Methods

In the European literature, most empirical approaches to assessing bikeability follow two dominant spatial logics: (1) segment- or route-based methods, and (2) area- or zone-based methods.

Segment/Route-Based Methods

Studies in this category assess bikeability at varying spatial levels, ranging from entire city street networks (Karolemeas et al., 2022; Castañon et al., 2024; Werner et al., 2024), to selected street segments or routes within a part of the city (Galanis et al., 2014; Berger & Dörrzapf, 2018; Werner et al., 2019; Schmid-Querg et al., 2021; Ahmed et al., 2025) and cyclists' actual routes (Wahlgren & Schantz, 2012, 2014). These methods can be grouped into the following methodological families:

1. *GIS-based multi-criteria (or weighted-additive) index approaches*: These methods are the most widely used and typically gather infrastructure- and context-related indicators from open geodata, combine them through weighted additive formulas or multi-criteria decision analysis, and produce bikeability scores per segment. Examples include reproducible, automated open-source workflows such as NetAScore (Werner et al., 2024), which applies knowledge-based weighting informed by scientific literature, expert input, and user feedback. Schmid-Querg et al. (2021) used commuter interviews to determine attribute weights, while Ahmed et al. (2025) combined cyclist survey responses with factor analysis to weight indicators. Among studies that combine GIS with different multi-criteria approaches are Castañon et al. (2024), Karolemeas et al. (2022), and Santos et al. (2024).

2. *On-site audit instruments:* These approaches rely on systematic, on-site observations of the built environment using standardized audit instruments. Hoedl et al. (2010) developed the Bikeability and Walkability Evaluation Table (BiWET), a standardized audit tool that scores 15 attributes on 10-m segments. Galanis et al. (2014) proposed a practical audit methodology based on two checklists (road-segment and intersection features) applied by trained auditors to produce route-level bikeability scores.

3. *Perceptual, route-based self-report methods*: Here, bikeability is assessed through cyclists' own evaluations of their actual commuting routes. Using the Active Commuting Route Environment Scale (ACRES) with a 15-point response scale, Wahlgren and Schantz (2012, 2014) collected self-reported perceptions of 18 attributes along respondents' chosen commuting routes in Greater Stockholm.

4. *Human-centered mixed-methods approaches:* This family of approaches combines wearable sensors, GPS tracking, video, and subjective reports to assess stress and comfort along specific routes (Berger & Dörrzapf, 2018; Werner et al., 2019; Resch et al., 2020).

Area/Zone-Based Methods

Spatial scales for assessing bikeability range from small grids (e.g., 100 x 100 m or 200 x 200 m) within cities to larger grids covering entire countries (Krenn et al., 2015; Grigore et al., 2019; Codina et al., 2022;

Wysling & Purves, 2022; Đordevic et al., 2023; Vierø & Szell, 2025; Xu et al., 2025). A few approaches focus on building, neighborhoods or municipality-level (Kellershohn et al., 2025; Moinse, 2025; Qi et al., 2025), and on built-up areas of varying size (Hagen & Rynning, 2021). Aggregation to larger units is also common (Hardinghaus et al., 2021; Beecham et al., 2023). In this paper, we classify the methods into the following categories:

1. GIS-based multi-criteria (or weighted-additive) index approaches: These approaches can be characterized in the same way as the corresponding category in segment-based methods, with the key difference that multiple spatial indicators are computed for grid cells or areas to generate a bikeability surface. Codina et al. (2022) employ 10 indicators grouped into 5 components, weighted by both a local bike-user survey and the literature. Krenn et al. (2015) derive five components from a route-choice analysis and combine them additively. Hardinghaus et al. (2021) use literature and expert surveys to weight five bikeability indicators, while Đordevic et al. (2023) rely on three survey-weighted indicators.

2. Perception-driven approaches: Bikeability is here treated as a subjective experience captured through surveys, typically Likert-scale items (Sottile et al., 2019; Qi et al., 2025). A similar approach is used by Moinse (2025), who aggregated opinions on cycling conditions to municipal scores.

3. Qualitative, holistic site analysis: This family is represented by Hagen and Rynning (2021), who employ an iterative site analysis that integrates map, aerial photos and local document review with field observations (bike-alongs, guided walks) to evaluate bikeability.

4. Network-based bikeability and accessibility methods: This line of research generally operationalizes cyclists' ease of reaching destinations by integrating link-level route quality with network-scale accessibility and connectivity metrics. Grigore et al. (2019), Wysling and Purves (2022), and Kellershohn et al. (2025) convert physical travel distances into perceived distances by applying segment-level suitability multipliers and then compute gravity-style accessibility scores from origins to destinations. Similarly, Hamidi et al. (2019) developed a composite grid-level bikeability indicator combining gravity-based cycling accessibility to public transport with infrastructure and amenity features. Vierø and Szell (2025) apply an LTS-based network analysis to Denmark and evaluate the network structure using three core network indicators (density, fragmentation, and reach), aggregated to grid cells to derive bikeability typologies via clustering. Beecham et al. (2023) calculated bikeability for routed origin–destination (OD) trips between grouped bikeshare "villages" in London, assigning routes a score for comfort, safety, attractiveness, and coherence. Finally, Nielsen and Skov-Petersen (2018) applied regression models to examine how population density, job and service accessibility, cycling infrastructure provision, terrain, and the city's regional position influence the likelihood of cycling.

5. Image-driven (street-view computer-vision) methods: This emerging group is illustrated by Xu et al. (2025), who apply deep-learning models on panoramic Street View imagery to extract built-environment attributes, aggregate these to grid cells, and combine them via factor analysis into a bikeability index.

Bikeability domains and indicators

The literature on bikeability consistently identifies several core domains that underpin most indices and assessment frameworks. The most frequently reported domains across recent studies include cycling infrastructure, accessibility or connectivity, safety, comfort, and the surrounding environment (Castañon & Ribeiro, 2021; Paulusová & Sharmeen, 2025; Zhang et al., 2025). We classify bikeability domains and key indicators according to the approaches used to apply them, organizing them into GIS-based, perception-based, and site-audit methods.

Approaches *using GIS tools* tend to rely primarily on globally or widely available sources, mostly OpenStreetMap for network geometry, cycle facility tags, and POIs (Hardinghaus et al., 2021; Schmid-Querg et al., 2021; Werner et al., 2024), DEM/LiDAR for gradients (Karolemeas et al., 2022; Santos et al., 2024), and other municipal or national datasets (Codina et al., 2022; Wysling & Purves, 2022). These base layers are frequently enriched with street-level imagery to capture visual attributes (Dai et al., 2023; Castañon et al., 2024; Xu et al., 2025), operator data such as bike-share or traffic counts (Grigore et al., 2019; Dai et al., 2023; Xu et al., 2025), and field visits where necessary to fill data gaps (Ahmed et al., 2025). Frequently applied domains across studies include safety and comfort, which relate to cyclists' risk-related concerns and overall suitability of conditions. Attractiveness complements this core by reflecting aesthetic and environmental qualities. In addition, many studies distinguish accessibility, connectivity, services, and usage or vitality (Tab. 1), which shape how easily destinations can be reached, how feasible locations are for cycling, and how extensively they are used by cyclists.

Perception-based methods centre on people's subjective judgments of safety, comfort, attractiveness, and overall perception of cycling conditions. Wahlgren and Schantz (2012, 2014) use the ACRES instrument, structured into three domains: physical environment, traffic environment and social environment. Moinse (2025) collects 26 questionnaire items aggregated into five thematic domains: general perception of cycling, safety, comfort, city efforts/policies, and services & parking. Sottile et al. (2018) focus on perceived safety and usefulness of existing infrastructure using multiple perception statements, while Qi et al. (2025) rely on a single question asking whether the respondent's neighborhood has good cycling infrastructure.

In site analysis and audit approaches, bikeability is commonly assessed across domains such as natural and place-specific preconditions, road infrastructure, traffic safety, land use, and the attractiveness of the surroundings (Hoedl et al., 2010; Galanis et al., 2014; Hagen & Rynning, 2021). Direct observation enables detailed recording of cycling environment attributes, such as personal safety factors (e.g., stray animals or threatening people), graffiti, attractive buildings, pavement condition, and other street features, which are often missing in open geodata and are not captured by surveys.

Critique of Bikeability Methods

Criticism applies to both objective and subjective methods, including their area- and segment-based applications. In *primarily objective GIS-supported methods*, one criticism is the lack of consensus on indicator selection, number, and weighting, which can lead to results that are difficult to interpret or replicate for the public (Codina et al., 2022; Ahmed et

Tab. 1. Domains and common indicators used in GIS-based bikeability studies

Domain	Indicators	References
Safety & Comfort	Road category; presence/type/length of bicycle infrastructure; speed limit; traffic volume;, prevalence of neighborhood/local streets; biking facilities on main streets; slope; pavement surface/quality/type; presence of sidewalk; traffic control devices; street lighting; car parking along cycle path, presence of heavy vehicles; weather (wind speed, precipitation, temperature); sky view index; air pollution (PM2.5)	Krenn et al. (2015); Grigore et al. (2019); Hardinghaus et al. (2021); Schmid-Querg et al. (2021); Karolemeas et al. (2022); Wysling and Purves (2022); Dai et al. (2023); Werner et al. (2024); Ahmed et al. (2025)
Accessibility & Level of Service	Accessibility to public transport stations; accessibility/ density of bike-sharing stations; bicycle parking (count, density, typology); repair/rental services (count, density); count/density of docking stations; count/diversity of destinations (POI)	Hamidi et al. (2019); Hardinghaus et al. (2021); Schmid-Querg et al. (2021); Codina et al. (2022); Karolemeas et al. (2022); Wysling and Purves (2022); Castañon et al. (2024); Kellershohn et al. (2025); Xu et al. (2025)
Connectivity & Directness	Count of bike-negotiable intersections; density/ connectivity of cycling facilities; presence of cycle facilities at traffic signals; road signage; interruptions; designated cycle network features on the route	Hardinghaus et al. (2021); Codina et al. (2022); Karolemeas et al. (2022); Beecham et al. (2023); Ahmed et al. (2025)
Attractiveness (Surrounding)	Presence of greenery (trees, parks) and waterfronts; greenness/building ratio; proximity to water bodies; visual quality proxies from street view imagery (e.g., cleanliness/maintenance); continuity of attractive elements along a route	Krenn et al. (2015); Grigore et al. (2019); Hardinghaus et al. (2021); Karolemeas et al. (2022); Castañon et al. (2024); Xu et al. (2025)
Vitality & Usage	Cyclist volume; number of bike-sharing trajectories; crowdedness (mobile phone signal density)	Codina et al. (2022), Dai et al. (2023)

Source: authors' own processing

al., 2024). Even when users or experts are involved in weighting, biases may be introduced, and indicators relevant in one city may fail to reflect local cultural or infrastructural conditions elsewhere, creating challenges for comparability and transferability (Hardinghaus et al., 2021; Codina et al., 2022; Ahmed et al., 2025). Uneven data coverage and availability further limit transferability (Hardinghaus et al., 2021). These methods commonly use proxies (e.g., road category for traffic volume), which only imperfectly capture cyclists‘ lived experience (Reggiani et al., 2022). Another consideration is the user groups targeted by these assessments. While some studies apply evaluations to specific population segments, such as commuters (Grigore et al., 2019) or families with children (Kellershohn et al., 2025), most bikeability indices assume an undefined average cyclist, underscoring the need to account for vulnerable or less-represented groups (Werner et al., 2024). Moreover, many indices omit dynamic factors, such as weather or time of day (Codina et al., 2022), and neglect micro-scale features (Werner et al., 2024; Ahmed et al., 2025). These approaches are often not empirically validated (Castañon & Ribeiro, 2021), which can cause mismatches between modeled outcomes, actual use, and user perceptions.

Subjective methods are often criticized for biases arising from participants, such as inaccurate questionnaire responses or overrepresentation of certain user groups (e.g., male, younger, or highly confident cyclists), and from researchers' interpretation of qualitative statements (Berger & Dörrzapf, 2018; Werner et al., 2024). Another frequently mentioned drawback is the substantial time required for data collection, as field audits and surveys are notably labor-intensive (Krenn et al., 2015; Xu et al., 2025). Non-representative samples are also noted as a limitation in *human-centered mixed-method studies*, such as Berger and Dörrzapf (2018), Resch et al. (2020), compounded by sensor noise and synchronization issues, privacy concerns, and scalability for city-wide planning.

Segment-based approaches typically aggregate 100–500 m stretches, which can fail to capture localized hazards (Ahmed et al., 2024). While these approaches can provide detailed information, they can be highly labor-intensive, dependent on accurate field observations, and ultimately limited by input data quality, raising the classic concern of "garbage in, garbage out" (Krykewycz et al., 2011). Another major limitation lies in the lack of reliable data on intersections (Werner et al., 2024). *Area-based approaches* share many of the critiques already discussed for both objective and subjective methods but add specific challenges of their own. While they capture destination potential, they can underrepresent route suitability (Hamidi et al., 2019), and outcomes are highly sensitive to methodological choices such as cell size, impedance functions, and destinations (Vale et al., 2016).

5 BIBLIOMETRIC INSIGHTS INTO BIKEABILITY: COMPARING EUROPEAN AND CEE LITERATURE AND CRITICAL REVIEW OF RESEARCH IN CEE COUNTRIES

Methodology

Scientific papers were retrieved from the Web of Science Core Collection database on 1 August 2025, with no date restrictions applied. This database was selected as the primary data source because of its data quality, its internationally recognised role in scientometric research, and its relevance for high-impact academic publications (Yan & Zhiping, 2023). The choice of database was aligned with one of the aims of this study, which focus on assessing the presence of thematic and conceptual elements characteristic of European bikeability research in academic cycling literature from the CEE region. The search focused on the keyword "bikeability" and its related concepts, limited to studies including at least one co-author from a European country. Out of 130 papers identified, fewer than 10 included authors from CEE, which is unsurprising given the recent emergence of bikeability research (Fig. 3).

To address the above-mentioned limitation, the search strategy was broadened to include additional terms directly linked to bikeability as well as more general expressions related to cycling, potentially relevant to the topic, resulting in 296 records from CEE-based researchers. Bibliographic information was exported from Web of Science, and a multi-stage screening process was then applied according to predefined inclusion criteria. Abstract screening reduced the dataset to 90 articles, and subsequent full-text screening to 59 publications (see Fig. 4).

To identify the extent to which thematic and conceptual elements typical of European bikeability research appear in CEE cycling studies, a keyword co-occurrence analysis was conducted using VOSviewer. In this method, item relatedness is determined by how frequently they co-occur in the titles, abstracts, or keyword lists of documents. For the European dataset, a minimum threshold of 7 occurrences was applied, resulting in 35 items, while for the CEE dataset, the threshold was set at 3 occurrences, producing 38 items. In the visualization, keywords were clustered and connected based on their co-occurrence, where the thickness of each link indicates the strength of association, while the size of the circles and labels is proportional to the frequency (weight) of a keyword. Finally, the critical review builds upon the bibliometric mapping by analysing relevant CEE studies across thematic categories according to their proximity to bikeability, with the aim of identifying methodological limitations and research gaps.

Bibliometric keyword analysis

Based on keyword co-occurrence analysis of both the European bikeability literature and CEE cycling studies, clear thematic overlaps and conceptual gaps can be identified (Fig. 5). In the European dataset, bikeability emerges as a core concept (red cluster), strongly linked with walkability (green cluster). Additional clusters focus on accessibility (yellow) and on the built environment and travel behaviour (blue). By contrast, the CEE literature presents a more fragmented thematic landscape, with five clusters, and lacks a dominant concept such as bikeability or accessibility. The red cluster positions cycling mainly within broader urban transport systems, but also links to safety, infrastructure, and GIS. The purple and green clusters both address micromobility (bikesharing) systems, particularly user behaviour and usage patterns. The yellow cluster frames cycling primarily as a healthy mode of transport, while the blue cluster highlights behavioural and safety dimensions, focusing on route choice, perceptions, risks, and accidents. In summary, the comparison indicates that CEE literature is more oriented toward understanding "what prevents cycling" (safety issues, barriers, perceptions, behaviour), whereas European bikeability-related work focuses on "how to assess and measure conditions for cycling and active travel."

Main Research Directions and Methodological Approaches in CEE Cycling Studies

Building on the bibliometric mapping, this section examines the main research directions within the body of CEE cycling studies according to their conceptual proximity to bikeability and the methodological approaches they employ.

Studies on cycling / micromobility usage, barriers and travel behaviour

A large group of authors addresses cycling and micromobility through broad, policy-oriented research on urban mobility behaviour, seeking to identify the factors that encourage or discourage its use, and analyse users' and non-users' perceptions of cycling conditions. Although their focus is more general, they also engage with themes that are fundamental to bikeability, such as perceived safety, the quality of cycling infrastructure, end-trip facilities and terrain. Methodologically, these studies predominantly employ stated-preference survey methods, using multiple-choice and ranking questions to capture perceptions, barriers, and motivations related to cycling. Data collection formats are mostly based on computer-assisted personal interviews (CAPI) (e.g., Biernat et al., 2018; Bieliński et al., 2021) and

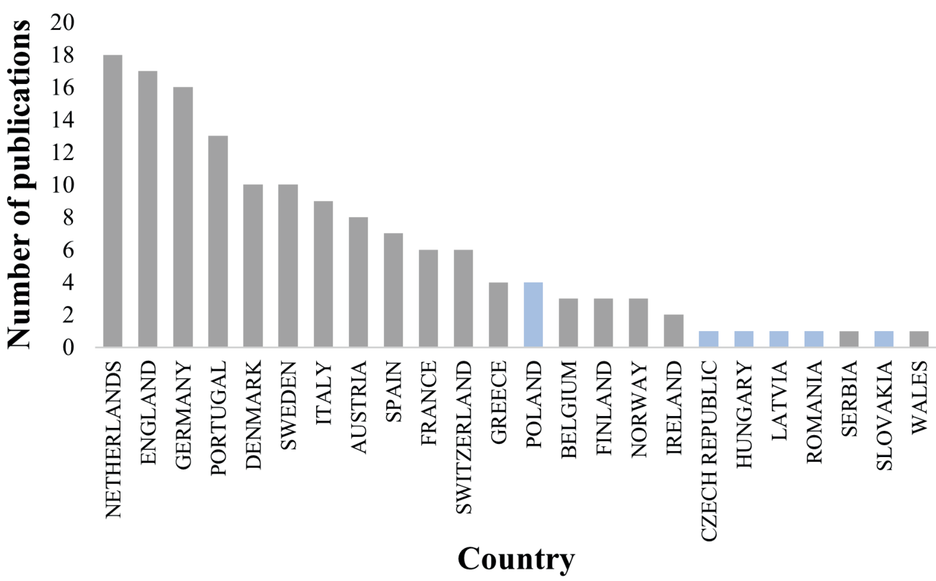

Fig. 3. Number of scientific papers on bikeability-related concepts in European literature (2009–2025)
Source: Web of Science Core Collection (data retrieved on 1 August 2025), authors' own processing

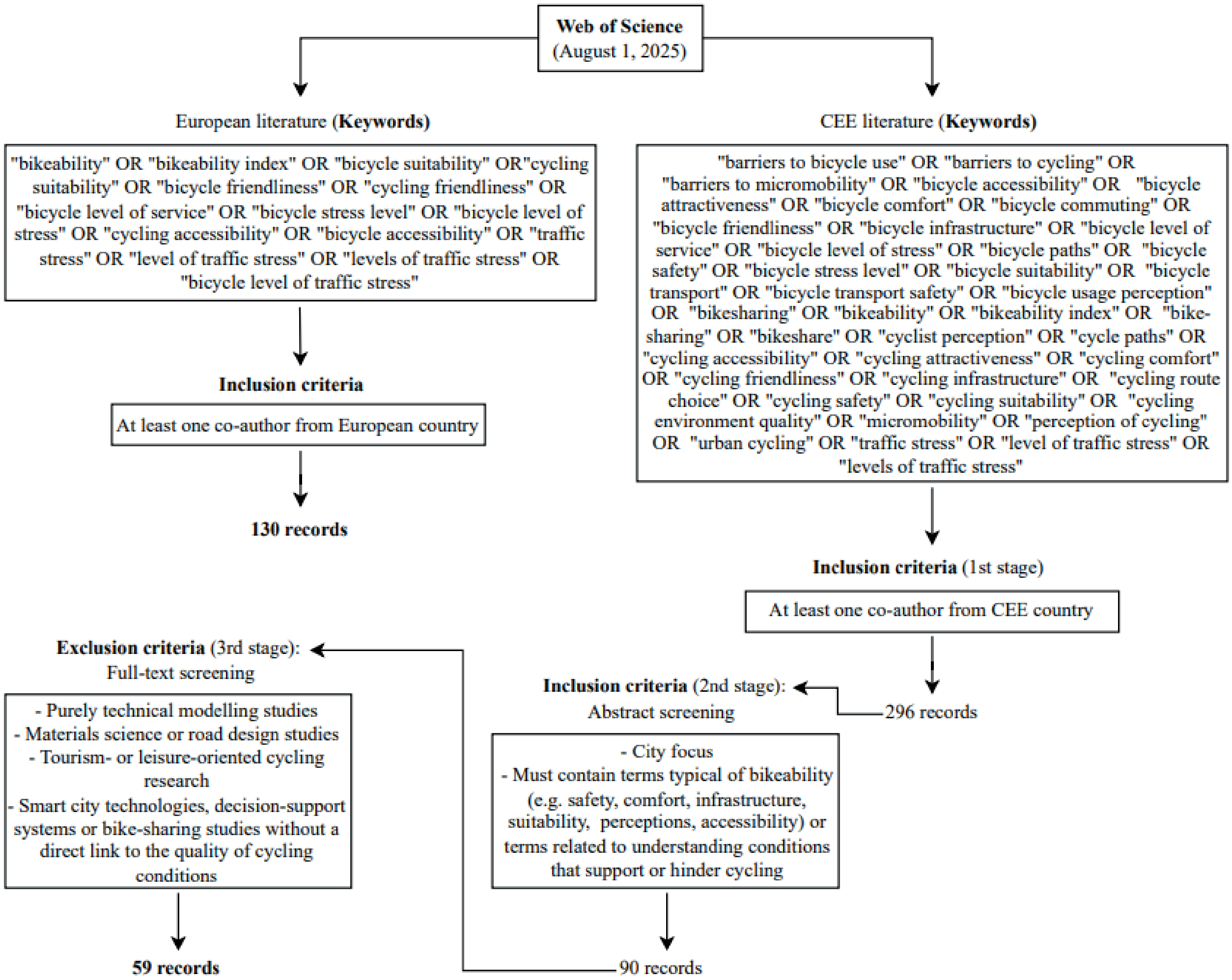

Fig. 4. Methodological flowchart of the literature search

online surveys (e.g., Kaplan et al., 2019; Esztergár-Kiss & Lopez Lizarraga, 2021; Teixeira et al., 2023). A limitation across this body of work is the reliance on predefined, closed-ended survey items, which can restrict respondents' ability to express more nuanced perceptions and contextual factors. The importance of integrating richer qualitative approaches is well illustrated by Iwińska et al. (2018), who combined in-depth interviews and focus groups with survey data. Other common methodological issues include representativeness challenges, response biases, and digital-access biases in web-based data collection. Despite these limitations, several studies demonstrate methodological strengths. Segmenting respondents (e.g., distinguishing cyclists from non-cyclists) helps reveal differences in the perception of cycling conditions. Mátrai et al. (2020) present an innovative approach that uses photographs depicting different infrastructure types and terrain conditions to assess perceived comfort and safety among active cyclists.

Studies that assess or quantify conditions for cycling

Numerous reviewed papers explicitly aim to quantify or evaluate the quality of cycling environments in terms of safety, comfort, or attractiveness. For example, Benoit et al. (2022) developed the Bike Barometer in Flanders, a location-based web platform that collected geo-referenced safety ratings from 1,916 adolescents along 959 km of home-to-school routes and linked them with objective environmental data using multilevel regression. The study provided spatial and perceptual insights, but faced data loss and incomplete coverage of objective datasets. Pánek and Benediktsson (2017) tested emotional mapping in Reykjavík using a web-based tool where cyclists marked points and lines associated with positive or negative emotions and could add comments. While this participatory method identifies pleasant or problematic locations, its small, non-random sample and limited spatial precision reduce accuracy. Expanding to larger-scale analyses, Timperio et al. (2025) analysed data from 6,302 adolescents and their parents across 16 international sites to examine how parental perceptions of neighbourhood walkability and safety influence active school travel. The study used the Neighbourhood Environment Walkability Scale for Youth (NEWS-Y), which included scores on several bikeability-related aspects such as traffic safety or aesthetics. Despite this, it lacked cycling-specific items (e.g., protected lanes) and relied only on parent-reported home-area perceptions.

Other approaches focus on attractiveness or comfort. Bíl et al. (2015) introduced the Dynamic Comfort Index (DCI) to quantify cycling comfort in the historical center of Olomouc using accelerometer and GPS data from real rides, showing a strong correlation with subjective comfort ratings. The method captures only the vibration-based physical dimension of comfort, with key limitations including speed dependence and restricted testing scope. Kwiatkowski and Karbowiński (2023) examined the attractiveness of a riverside cycling route in Rybnik using an online CAWI survey. However, the study may be limited by possible recall bias in reporting past-year use, underrepresentation of women, and its focus on a single route.

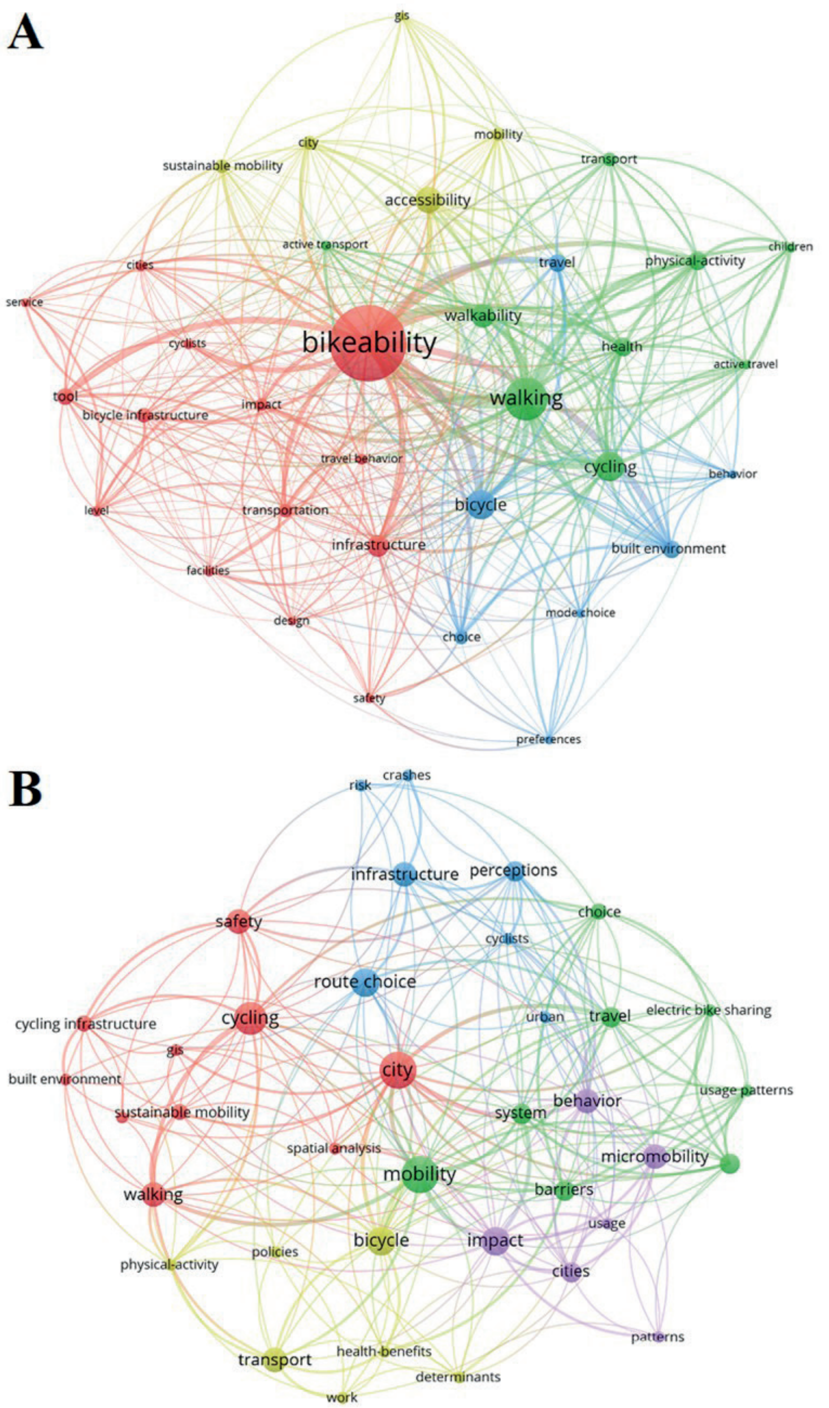

Fig. 5. Network analysis of keyword co-occurrence in (A) European bikeability-related literature and (B) CEE cycling studies with extended scope
Source: Web of Science Core Collection (data retrieved on 1 August 2025), authors' own processing

Several studies explicitly assess the quality, safety, comfort, and usability of cycling infrastructure. Gracin and Ištoka Otković (2017) combined an expert evaluation of Osijek's cycling network with a user perception survey. Their approach, however, was limited by a self-selected, event-linked sample of cyclists. Dyczkowska and Olkiewicz (2023) conducted a large-scale survey in Poland's West Pomeranian Voivodeship to evaluate the condition and safety of bicycle paths. This study did not spatially categorize or map infrastructure quality, and the outcomes are primarily self-reported perceptions of regular users. Ilie et al. (2016) applied the Bicycle Compatibility Index (BCI) and BLOS models to 10 proposed cycling corridors in Dej, Romania, to assess cyclist comfort. However, indices were originally calibrated on U.S. data, so their transferability to CEE remains uncertain without local recalibration.

Safety-, Risk- and other Planning-Oriented Studies

A smaller and more methodologically diverse group of studies addresses cycling safety, risk, and infrastructure planning. As these works are conceptually more distant from the core idea of bikeability, they are discussed more briefly. Most of them analyse crash risk or accident patterns at the national, regional or city level (Okraszewska et al., 2017; Głowiński et al., 2025; Blažek & Kraft, 2025; Macioszek et al., 2025). These studies rely on police-reported data, which tends to undercount minor or unreported crashes and usually has limited spatial detail. At a broader behavioural level, Useche et al. (2024) analysed how city size relates to cyclists' risky and protective behaviours across an international sample, but the study does not provide a spatial assessment of cycling safety or infrastructure hazards. At the micro-observational level, Włodarek and Olszewski (2020) analysed cyclist–vehicle conflicts at three intersections in Warsaw using continuous video data. Some practical-oriented studies directly support infrastructure planning decisions, aligning closely with the aims of bikeability indices. For example, Ruda (2019) combined geostatistical interpolation and multicriteria evaluation to prioritize cycle-path segments by safety and construction suitability. Zagorskas and Turskis (2020) developed a GIS-based multi-criteria model for bicycle path development in Kaunas, Lithuania, using 11 weighted GIS attributes across four domains (usefulness, safety, convenience, and comfort), but reliance on locally estimated values limits transferability.

6 CONCLUSIONS AND FUTURE RESEARCH AGENDA IN CEE

Over the past decade, bikeability has received increasing scholarly attention and been defined in multiple ways. Closely related to concepts such as bicycle accessibility, bicycle suitability, or level of traffic stress, it has become a dominant and integrative framework in both global and European research. In the European context, bikeability assessment methods primarily function as evidence-based planning tools, typically operationalized at either the segment/route or area/zone level. Across both categories, studies employ objective, subjective, or mixed-method frameworks. Studies using GIS tools have become increasingly widespread, focusing on key domains such as safety, comfort, attractiveness, accessibility, connectivity, and service availability.

In relation to the second objective, the bibliometric and critical review indicates that research on bikeability in CEE remains sporadic and conceptually underdeveloped. While studies investigating various aspects of cycling conditions are present throughout the region, these typically focus on isolated themes, such as safety or comfort, and rarely employ an explicit bikeability framework or a multidimensional assessment approach. Moreover, research at the city level is lacking, and existing outputs are often geographically scattered and rarely representative. Despite the dominance of survey-based subjective approaches, several promising directions have emerged, including emotional mapping (Pánek & Benediktsson, 2017) and geo-referenced safety analyses linked to objective spatial data (Benoit et al., 2022). However, these studies were not carried out in CEE cities. Drawing on the limitations identified in both CEE cycling studies and the broader European bikeability literature, we propose the following directions for future research:

First, given that cycling rates in CEE are generally low and that safety and poor infrastructure remain among the main barriers to cycling uptake, we believe that initial efforts should focus on adapting and experimenting with existing methods ("everything fits" approach). At this early stage, every suitable concept or methodological inspiration is valuable in creating evidence-based instruments in the region. Nevertheless, these approaches must be adjusted to the local context to ensure that the resulting tools are both meaningful and transferable between cities.

Second, both CEE and European bikeability research should become more inclusive. Most existing indices overlook the needs of vulnerable groups (e.g., children, women, the elderly) and potential users who may have very different requirements to use a bicycle regularly. In regions with low cycling levels, these groups are generally less likely to cycle (Goel et al., 2022), and the prevailing conditions are age-unfriendly (den Hoed, 2024). Moreover, demographic changes driven by rapid population ageing in many CEE countries (Chand, 2024) are likely to intensify these challenges, underscoring the need for more age-inclusive cycling environments. Considering the needs of these groups by developing separate user profiles or weighting schemes represents a valuable direction for future research.

Third, method selection should always reflect the study‘s spatial scale and purpose. More time-intensive, human-centred, or mixed-method approaches are well-suited for smaller areas. In contrast, GIS-based multi-criteria, or accessibility approaches, are more appropriate for network-level and city-wide analyses. Such approaches could help answer practical questions, such as whether key destinations are reachable through highly bikeable routes or how targeted infrastructure improvements could reshape accessibility to selected destinations.

Finally, validation must become an integral part of evaluation. Studies should establish validation frameworks that combine trip data (e.g., GPS traces, bike-share records) with human-centred techniques such as ride-along interviews, and web-based or in-person mapping exercises to better bridge the gap between assessment results and the lived cycling experience.

By addressing these gaps, future research can help create safer, more attractive urban cycling environments, ultimately supporting a transition toward sustainable mobility in post-socialist cities. For municipalities, advancing data collection and ensuring political support will be crucial to translate these insights into planning practice.

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