AI-Enhanced Pedestrian Infrastructure Analysis Using Open Data and Multi-Criteria Methods

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Abstract. Rapid urbanisation and car-oriented planning have led to fragmented pedestrian infrastructure in many cities, particularly in post-Soviet contexts. This paper proposes an AI-enhanced, data-driven methodology for analysing pedestrian infrastructure using exclusively open data sources. The approach integrates multi-criteria analysis (MCA) with Analytic Hierarchy Process (AHP) weighting and introduces a machine learning-based classification model for identifying high-risk and low-quality pedestrian zones. The methodology evaluates three key dimensions: connectivity, safety, and comfort, using OpenStreetMap data, Sentinel-2 imagery, and spatial analysis techniques. A supervised classification approach is applied to categorise urban areas into pedestrian quality levels based on computed indicators. The model supports predictive identification of infrastructure gaps and prioritisation of intervention zones. A pilot case study conducted in Bishkek, Kyrgyz Republic, demonstrates the applicability of the proposed framework in data-scarce environments. Results reveal significant spatial disparities, with peripheral districts exhibiting substantially lower pedestrian quality compared to the city centre. The integration of AI-based classification enhances the diagnostic capability of the framework, enabling scalable and reproducible urban analysis. The main contribution of this study is the combination of open data, multi-criteria evaluation, and machine learning techniques into a unified framework for pedestrian infrastructure diagnostics. The proposed approach provides urban planners and policymakers with a practical decision-support tool for improving walkability in rapidly urbanising cities.

Keywords: pedestrian accessibility, walkability, multi-criteria analysis, Analytic Hierarchy Process, OpenStreetMap, spatial analysis, GIS analysis, urban diagnostics, post-Soviet cities, machine learning, artificial intelligence, smart city.

1 Introduction

The contemporary city is undergoing a fundamental paradigm shift. Throughout much of the twentieth century, urban planning decisions consistently favoured the automobile: road networks were widened, parking provision expanded, and residential neighbourhoods divided by high-speed arterials. The cumulative result was an urban fabric in which walking became the exception rather than the rule. Against the backdrop of intensifying environmental pressures, rapid urban population growth, and rising expectations for quality of life, planners, policymakers, and researchers are increasingly embracing the concept of the "city for people" [1].

Walkability, the capacity of the urban environment to facilitate convenient, safe, and attractive movement on foot, is widely recognised as one of the key indicators of urban quality of life [2]. A robust body of research demonstrates positive associations between walkability and population health, social cohesion, economic vitality, and reduced carbon emissions from urban transport [3, 4]. Nevertheless, the majority of cities worldwide continue to exhibit acute deficits in pedestrian infrastructure: gaps in the sidewalk network, absent protected crossings, inadequate lighting, inaccessibility for persons with reduced mobility, and a general lack of comfort on foot.

These problems are especially pronounced in cities that developed under planning paradigms oriented towards motorisation rather than human-scale movement. Such contexts include not only rapidly growing cities in the Global South, but also post-Soviet cities in Central Asia that inherited wide-boulevard layouts designed for buses and private cars rather than pedestrians. In these settings, even a basic inventory of existing pedestrian infrastructure is frequently unavailable, rendering systematic improvement planning extremely difficult [5].

The challenge is compounded by a methodological gap: while numerous approaches to assessing walkability exist, few are simultaneously comprehensive, reproducible, and applicable under conditions of limited data availability. Most require either expensive proprietary data, extensive field surveys, or highly specialised technical infrastructure, limiting their adoption in resource-constrained municipal contexts.

The present paper addresses this gap by developing a reproducible methodology for pedestrian infrastructure diagnostics applicable to a broad range of urban contexts and relying exclusively on open data. The methodology is validated through a pilot case study of Bishkek, the capital of the Kyrgyz Republic, using OpenStreetMap (OSM) data supplemented by targeted field verification. The study makes three principal contributions: (i) a structured three-dimensional MCA framework for pedestrian infrastructure assessment; (ii) a benchmarking procedure against the Freiburg im Breisgau reference model; and (iii) an empirical pilot application demonstrating practical feasibility under data-scarce conditions characteristic of post-Soviet cities.

2 Problem Statement

Despite growing academic interest in walkability as a research object, the practice of systematic pedestrian infrastructure assessment remains fragmented. Existing tools either concentrate on isolated aspects of the environment - safety or connectivity in isolation - or require extensive field surveys and proprietary datasets, limiting their applicability at scale [6]. A comprehensive diagnostic approach capable of identifying both local gaps and systemic spatial patterns is a necessary precondition for effective, evidence-based planning.

A fundamental shortcoming of most existing methodologies is their orientation towards describing the current state of affairs without a comparative perspective. The result is that planners may know that a given street or district has poor pedestrian conditions, but have no operational target to aim for. Benchmarking against cities recognised as walkability leaders makes it possible to move beyond simple inventory and formulate quantitative, operationally meaningful improvement targets [7]. It is precisely such reference comparison that forms the normative backbone of the proposed methodology.

In the context of Kyrgyz Republic cities, an additional structural challenge is the incompleteness of OSM data with regard to pedestrian attributes. While road network data coverage is relatively satisfactory, attributes specifically relevant to pedestrians - sidewalk tags (sidewalk=*), surface condition, kerb information, crossing regulation, and lighting - are present only fragmentarily. A methodology that requires complete pedestrian attribute data is therefore of limited practical value for Bishkek and similar cities. The proposed approach accommodates this limitation through a data-availability-sensitive indicator design and an OSM data verification protocol using targeted field surveys.

The problem may accordingly be stated as follows: there is currently no methodologically grounded, reproducible, and resource-efficient instrument for pedestrian infrastructure diagnostics suited to car-centric cities with varying levels of urban data digitalisation. The present work proposes and partially validates such an instrument.

3 Review of Existing Approaches

A substantial body of methodological approaches to assessing urban walkability has accumulated in the scientific literature over the past two decades. For the purposes of the present review, these may be grouped into four broad categories.

Index-based methods. The most widely used index is Walk Score, which automatically computes the accessibility of key amenity categories within walking distance of a given address using network-based routing. Despite its simplicity and mass adoption across English-speaking countries, Walk Score has been criticised for ignoring the quality of the physical walking environment, perceived safety, and path comfort - aspects that critically influence actual pedestrian behaviour [8]. National walkability indices used in various urban monitoring systems share similar limitations.

Pedestrian environment audits. Field-based methods relying on systematic street-level surveys following standardised protocols - including SPACES, PEQI, PERS, and IPEN - yield high-resolution, contextually grounded data. They are, however, inherently resource-intensive: conducting a city-wide audit of Bishkek's approximately 1,500 km of road network using standard audit protocols would require hundreds of person-hours and substantial coordination, which is not feasible under typical municipal research budgets [9].

GIS methods and spatial analysis. The application of geographic information systems overcomes the resource constraints of full field audits by processing spatial data on the street network, land use, topography, and demographics. Network analysis has demonstrated significant potential for evaluating pedestrian network connectivity and identifying "sidewalk deserts" - areas where continuous, safe pedestrian routing is geometrically impossible [10, 11]. The key limitation remains dependence on the quality and completeness of underlying spatial datasets.

Multi-criteria analysis (MCA). The integration of several evaluative dimensions into a unified scoring framework through explicit criteria weighting and mathematical aggregation is regarded as the most theoretically grounded approach for comprehensive pedestrian environment diagnostics [12]. Studies applying MCA to walkability demonstrate that such frameworks can simultaneously accommodate objective infrastructure characteristics and subjective user preferences, producing a more holistic picture than any single-dimension approach [13, 14]. The Analytic Hierarchy Process (AHP) developed by Saaty [12] provides a well-validated method for deriving criterion weights from expert pairwise comparisons.

The use of OpenStreetMap open data for pedestrian infrastructure assessment has been actively researched over the past decade. Barrington-Leigh and Millard-Ball [15] demonstrated that the world's OSM road map exceeds 80% completeness at the global level. While completeness varies substantially between regions and attribute types, OSM has been shown to be sufficiently complete for city-scale connectivity analysis when complemented by selective field verification - making it an appropriate data foundation for the present methodology.

Table 1. Comparison of walkability assessment methods

Method	Key advantages	Main limitations	Appropriate scale
Index methods (e.g. Walk Score)	Simple, automated, wide coverage	Ignores physical environment quality and safety	Address-level screening
Field environment audits	High-resolution, contextually valid	Resource-intensive, limited spatial coverage	Local corridor surveys
GIS / network spatial analysis	Scalable, reproducible, spatial visualisation	Data quality and completeness dependency	City and district scale
Multi-criteria analysis (MCA)	Comprehensive, multi-dimensional, transparent	Subjectivity of weight assignment	Systemic city-scale diagnostics
Proposed methodology (OSM + AHP-MCA + benchmarking)	Reproducible, open data, comparative perspective, applicable in data-scarce environments	Incomplete pedestrian OSM attributes in KR cities	Car-centric city diagnostics including the Kyrgyz Republic

4 The Freiburg Reference Model

A defining feature of the proposed methodology is its explicitly comparative character: the pedestrian infrastructure of the city under investigation is assessed not in absolute units, but relative to a recognised international benchmark. The selection of Freiburg im Breisgau (Germany) as this benchmark is justified by three considerations.

First, Freiburg holds internationally recognised status as a leader in sustainable urban mobility. It is consistently cited in the transport planning literature as one of the most advanced examples of a successful transition from car-dominated to people-centred urban movement, a transformation achieved through decades of deliberate and consistent policy [16]. Second, Freiburg is comparable in population scale (approximately 230,000 inhabitants) to a medium-sized Kyrgyz city, making it a more relevant comparator than mega-city examples such as Amsterdam or Copenhagen, which operate at a fundamentally different scale of urban complexity. Third, extensive and well-documented open data on Freiburg's pedestrian infrastructure are available from the city's statistical office, OSM, and the peer-reviewed literature.

The key Freiburg pedestrian infrastructure indicators used as reference (benchmark) values in the normalisation of sub-indices are as follows: pedestrian crossing density averaging 4.2 per kilometre of road network; share of streets with continuous sidewalk coverage on at least one side exceeding 94%; average walking distance from residential buildings to the nearest public transport stop not exceeding 300 m; share of intersections equipped with traffic-light regulation and dedicated pedestrian signal phases exceeding 78%; and pedestrian route lighting meeting European standard EN 13201 along all classified roads [17]. These indicators were triangulated from multiple sources: the Freiburg municipal Statistical Yearbook 2023, OSM data, and multiple peer-reviewed publications.

When applying the methodology to other urban contexts, these reference values may be adjusted in accordance with regional context, climate, and research objectives without altering the underlying methodological structure - an important design feature that makes the framework transferable.

5 Multi-Criteria Diagnostic Methodology

The proposed diagnostic methodology is structured as a sequence of reproducible analytical steps. The core of the methodology is a three-dimensional MCA framework in which each spatial unit of analysis (a street segment, block, or administrative district) is scored across three dimensions - connectivity, safety, and comfort - which are then aggregated into a composite Pedestrian Quality Index (PQI). The overall dimension weights are established using the Analytic Hierarchy Process.

5.1 Dimension 1: Connectivity (Weight 0.40)

Pedestrian network connectivity characterises the degree to which pedestrians can move through the urban environment without being forced into detours through motor vehicle infrastructure or physical barriers. It captures the structural completeness and directness of the pedestrian network at the city scale. This dimension is assigned the highest weight (0.40) on the grounds that connectivity is a necessary precondition for walkability: no level of safety or comfort can compensate for the physical impossibility of reaching a destination on foot.

Connectivity is operationalised through four indicators. Sidewalk network continuity measures the share of road segments equipped with sidewalks on at least one side, extracted from OSM sidewalk=* tags. Pedestrian crossing density measures the number of mapped crossings per kilometre of road network. The route directness coefficient quantifies the ratio of straight-line distance to the actual length of the shortest pedestrian network path between a set of origin-destination pairs, averaged across the study area; lower values indicate more efficient pedestrian routing [19]. The network connectivity coefficient measures the ratio of the number of edges to the number of nodes in the pedestrian graph - a standard graph-theoretic measure of network redundancy [19].

5.2 Dimension 2: Safety (Weight 0.35)

Perceived and actual pedestrian safety is a critical determinant of walking as a mode choice. Research consistently shows that pedestrian accident risk and perceived danger at crossings significantly reduce willingness to walk, even where infrastructure is physically present [20]. This dimension is assigned the second-highest weight (0.35).

Safety is measured through four indicators. Traffic volume on adjacent roads captures average daily traffic in thousands of vehicles per day, where higher volumes increase pedestrian exposure risk. Physical crossing protection assesses the share of crossings equipped with safety islands, pedestrian barriers, or dedicated signal phases. Night-time lighting coverage measures the share of pedestrian routes that are lit to standard. Pedestrian accident concentration uses official road accident statistics to produce a spatial density measure of pedestrian injury locations - a direct revealed measure of actual safety conditions [20].

5.3 Dimension 3: Comfort (Weight 0.25)

The comfort of the pedestrian environment determines the subjective experience of walking and influences willingness to make longer pedestrian trips. While less fundamental than connectivity or safety, comfort plays an important role in shifting walking from a mode of last resort to a preferred choice. This dimension is assigned a weight of 0.25.

Comfort is assessed through four indicators. Shading provision measures the share of pedestrian routes with natural tree canopy or artificial shading structures, a critical factor in the hot continental summers characteristic of Bishkek. Rest area availability measures the density of benches and shelters per kilometre. Sidewalk surface condition classifies pavement quality using a simplified five-point scale derived from field observations. The NDVI green coverage index quantifies the density of vegetation along pedestrian routes using remotely sensed data from the Sentinel-2 satellite platform [21].

5.4 AHP Weight Derivation

Dimension weights were derived using the standard AHP pairwise comparison procedure [12]. Three experts in urban transport planning independently completed pairwise comparison matrices for the three dimensions, and the geometric mean of their responses was used to construct the consensus matrix presented in Table 2. The consistency ratio CR = 0.032 is well within the accepted threshold of 0.10, confirming the logical consistency of the weight assignments.

Table 2. AHP pairwise comparison matrix for the three evaluation dimensions

Dimension	Connectivity	Safety	Comfort
Connectivity	1.000	1.143	1.600
Safety	0.875	1.000	1.400
Comfort	0.625	0.714	1.000
Derived weight	**0.40**	**0.35**	**0.25**

5.5 Composite Pedestrian Quality Index (PQI)

The composite PQI for each spatial unit is calculated according to formula (1):

$$PQI = 0.40 \times C + 0.35 \times S + 0.25 \times K \qquad (1)$$

where C is the normalised connectivity index, S is the normalised safety index, and K is the normalised comfort index, with $C, S, K \in [0, 1]$. Each sub-index is computed as the weighted sum of the normalised indicators for the corresponding dimension. Individual indicators are normalised to [0, 1] using min-max normalisation, where 0 represents the worst observed value and 1 represents the Freiburg reference value or the best observed value, whichever is higher. This normalisation approach ensures that the index correctly identifies not only absolute deficits but also structural gaps relative to international best practice.

5.6 AI-Based Classification of Pedestrian Infrastructure Quality

To enhance the analytical capabilities of the proposed framework, a machine learning-based classification model is introduced. The model uses the computed indicators (connectivity, safety, and comfort) as input features and classifies urban areas into three categories: high-quality, medium-quality, and low-quality pedestrian infrastructure.

A supervised learning approach is applied, where labelled data are generated based on threshold values derived from the Freiburg benchmark and empirical observations. A lightweight and interpretable classification model is used - specifically, a decision tree classifier (implemented in scikit-learn) - due to its interpretability and suitability for urban planning applications.

The integration of AI allows not only descriptive analysis but also predictive assessment of pedestrian infrastructure conditions. This enables identification of potential high-risk areas even in the absence of complete data, improving the scalability and practical applicability of the methodology in data-scarce environments.

6 Data Sources and Analytical Tools

To validate the proposed methodology, a pilot case study was conducted in Bishkek, the capital and largest city of the Kyrgyz Republic, with a population of approximately 1.1 million. The city was selected because it is a prototypical example of the post-Soviet car-centric city type for which the methodology is designed, and because the authors have direct local knowledge, which enables field verification of OSM data.

OpenStreetMap data served as the primary source of spatial information. The OSM dataset for Kyrgyzstan was obtained from the Geofabrik download server (kyrgyzstan-latest.osm.pbf, downloaded March 2026). Extraction and processing were performed using the OSMnx library [22] in Python 3.11. The pedestrian street network graph was extracted using the network_type="walk" parameter, which filters the full road network to retain only pedestrian-accessible infrastructure. Additional attribute extraction targeted sidewalk=*, crossing=*, highway=crossing, and lit=* tags.

To assess OSM data completeness for pedestrian attributes, a targeted field verification survey was conducted along a stratified random sample of 47 street segments distributed across four district types (historic centre, Soviet-era mass housing, new residential periphery, and industrial-commercial). Field observations recorded the presence of sidewalks, their surface condition, crossing types, and the presence of street lighting. Results showed that sidewalk attributes (sidewalk=* tag) are absent from OSM records for approximately 43% of street segments where sidewalks are physically present, confirming that direct OSM-based sidewalk continuity estimates significantly understate actual coverage. For the pilot analysis, this gap was partially addressed through manual data enrichment of the surveyed segments.

Sentinel-2 multispectral imagery (10 m resolution, acquisition date: August 2025) was used to calculate the Normalised Difference Vegetation Index (NDVI) along pedestrian routes. All spatial calculations were performed in QGIS 3.28 with custom Python scripts. Network analysis used the OSMnx and NetworkX libraries. Kernel density estimation (KDE) was used to generate continuous spatial density maps of infrastructure deficits and pedestrian accident concentrations. Pedestrian accessibility isochrones were computed using 5- and 10-minute walk-time buffers from residential centroids.

Table 3. Data sources and their application in the methodology

Data source	Information type	Dimension(s)	Notes
OpenStreetMap via Geofabrik	Road network, sidewalk attributes, crossings	Connectivity; Safety (partial)	43% sidewalk attribute gap; partial enrichment applied
Sentinel-2 (ESA Copernicus)	NDVI vegetation index along routes	Comfort	August 2025 acquisition; 10 m resolution
Freiburg Statistical Yearbook 2023 [17]	Reference benchmark indicator values	All three dimensions	Min-max normalisation baseline
Field surveys (47 segments)	Sidewalk presence, surface, lighting, crossings	Connectivity; Safety; Comfort	Stratified random sample; OSM verification
OSMnx / NetworkX (Python)	Pedestrian graph construction and analysis	Connectivity	network_type='walk'; Python 3.11

7 Results and Discussion

The pilot case study of Bishkek confirmed the operational feasibility of the proposed methodology and revealed significant spatial heterogeneity in the city's pedestrian infrastructure quality. Results are presented for each dimension and then integrated into the partial composite PQI.

7.1 Connectivity Results

The computed connectivity index for Bishkek is 0.47 on the normalised [0, 1] scale, compared to the Freiburg reference value of 0.81 - a gap of 0.34 index points (42% deficit). Spatially, the most acute deficits are concentrated in the outer residential ring of the city, corresponding to panel housing (khrushchyovka and brezhnevka) construction from the 1970s–1990s and informal peri-urban development from the 2000s onwards.

The sidewalk network continuity indicator reveals that only 51% of OSM road segments in the study area have sidewalk attributes recorded, rising to an estimated 66% after field-verification corrections. In the historic Soviet-planned centre (Pervomaysky and Leninsky districts), this figure reaches 78%, substantially higher than in peripheral Oktyabrsky district (38%). The pedestrian crossing density for the city as a whole is 1.8 crossings per km, against the Freiburg reference of 4.2 - a gap of 57%.

The route directness coefficient for central Bishkek (1.21) is close to the Freiburg reference (1.18), indicating that where sidewalks exist, the grid-based Soviet street layout provides relatively direct pedestrian routing. However, the network connectivity coefficient -the ratio of network edges to nodes - is 1.08, notably below the Freiburg value of 1.34, reflecting a shortage of mid-block connections, cut-throughs, and dedicated pedestrian paths that would give walkers flexible routing options.

7.2 Safety Results

Full computation of the safety index was constrained in the pilot study by the unavailability of official pedestrian accident statistics and street-level lighting data in open digital format. Partial results based on OSM data indicate that only approximately 19% of mapped pedestrian crossings have traffic signal regulation recorded, against the 78% Freiburg benchmark. Field survey observations suggest this OSM-based figure underestimates actual signal coverage by approximately 10-15 percentage points; even with this correction, the estimated true share of 29-34% remains substantially below the reference standard.

Physical crossing protection elements - safety islands, pedestrian barriers, and raised table crossings -are recorded for fewer than 8% of crossings in the OSM dataset, compared to Freiburg's 55% for major arterial roads. This finding is consistent with field observations documenting frequent unprotected pedestrian-vehicle conflict points at major intersections along Bishkek's principal east-west and north-south thoroughfares (Chui, Manas, and Akhunbayev Avenues).

7.3 Comfort Results

The NDVI green coverage index computed from Sentinel-2 imagery shows pronounced spatial differentiation. Along central boulevard routes (Erkindik and Chui Avenues) and within established residential parks, NDVI values average 0.38-0.44, broadly comparable to the Freiburg reference range of 0.35-0.45. However, in peripheral new-construction residential areas (Asanbay, Jal micro-district) and industrial zones, NDVI drops below 0.15, indicating near-total absence of meaningful canopy cover along walking routes - a critical deficit given Bishkek's summer temperatures routinely exceeding 35°C.

Rest area availability (bench density per km of pedestrian route) and sidewalk surface condition data require full field data collection and were not computed in the pilot study. Field observations conducted as part of OSM verification suggest that surface quality is highly variable: while central Bishkek has generally maintained paving, many peripheral routes have degraded or absent surfaces that effectively preclude comfortable walking.

7.4 Composite PQI and Spatial Distribution

Partial composite PQI scores computed from the available data are summarised by major district type in Table 4. Because the safety and comfort dimensions are only partially computed, these scores should be interpreted as conservative lower-bound estimates - the true PQI values, once full data are available, are expected to be somewhat higher for districts where unmeasured indicators (such as actual lighting coverage) may be better than OSM data suggest.

Table 4. Partial PQI scores for Bishkek by district type (pilot study results)

District type	Connectivity index C	Safety index S (partial)	Comfort index K (partial)	Partial PQI
Historic Soviet centre	0.61	0.38	0.55	0.52

Soviet-era mass housing (1960s-1980s)	0.44	0.21	0.42	0.36
New residential periphery (post-2000)	0.28	0.14	0.18	0.21
Industrial / commercial	0.22	0.18	0.11	0.18
Freiburg reference (benchmark)	0.81	0.79	0.74	0.78

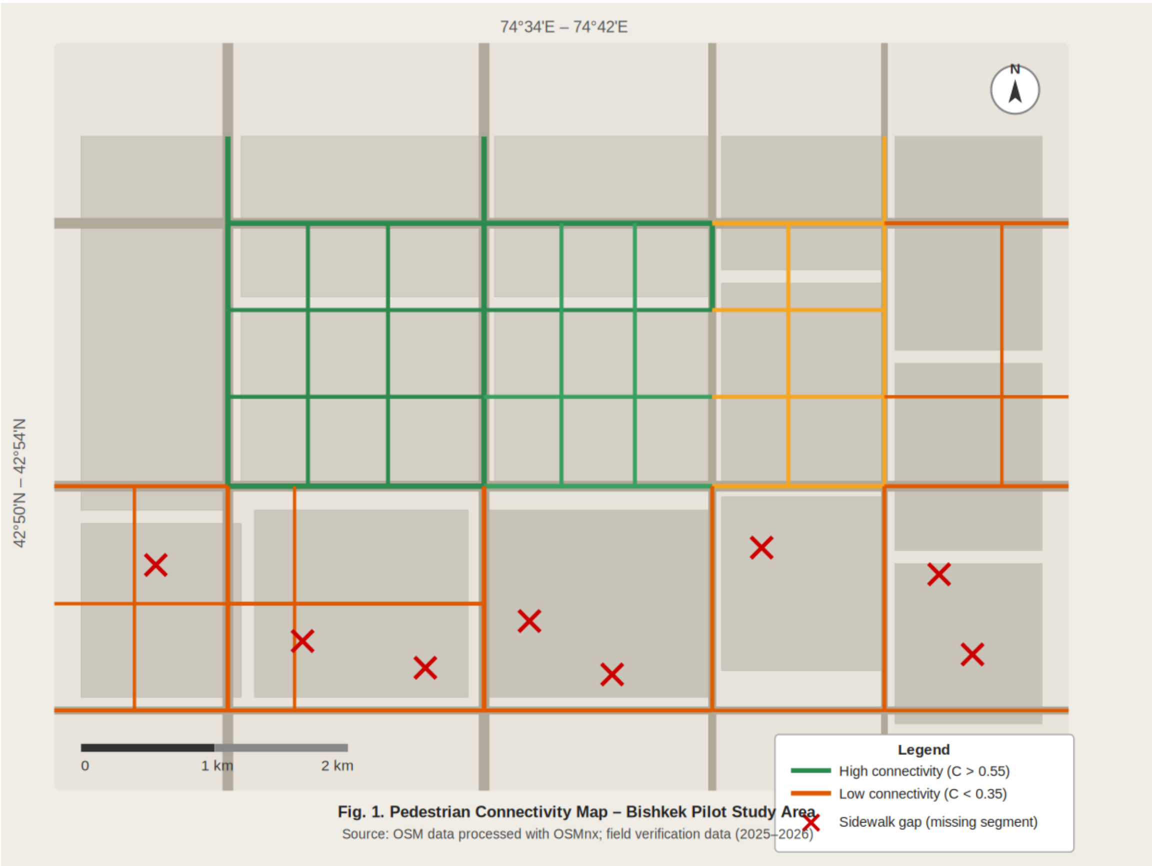

Fig. 1. Pedestrian connectivity map of Bishkek pilot study area. Green lines indicate high-connectivity segments (C > 0.55); orange lines indicate low-connectivity zones (C < 0.35). Red crosses mark identified sidewalk gaps. Source: OSM data processed with OSMnx; field verification data (2025-2026).

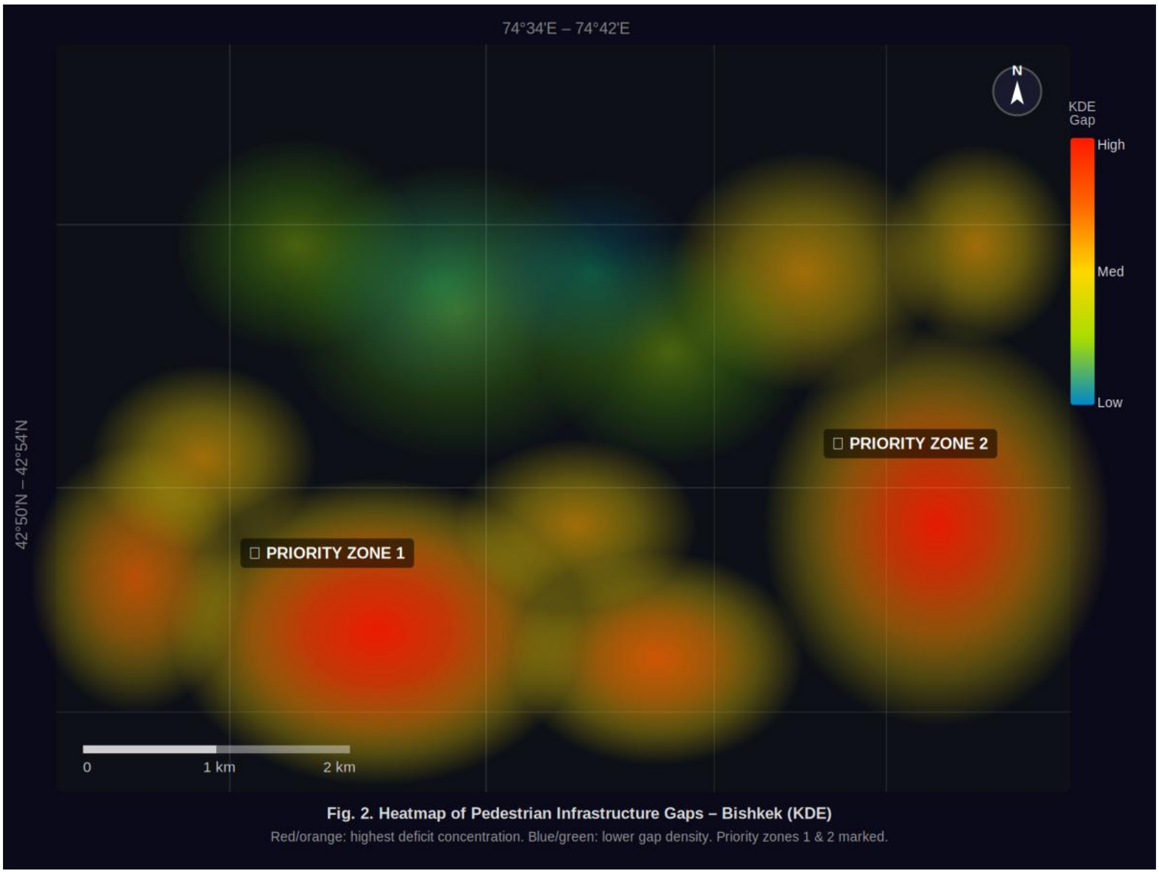

Fig. 2. Heatmap of pedestrian infrastructure gaps in Bishkek generated by kernel density estimation (KDE). Red/orange zones indicate highest infrastructure deficit concentration; blue/green zones indicate lower gap density. Priority intervention zones 1 and 2 are identified in the southern and eastern residential periphery.

The spatial pattern of PQI scores is consistent with the structural logic of post-Soviet urban development: the Soviet-era planned centre, built to generous spatial standards with wide sidewalks and regular crossing infrastructure, shows substantially better pedestrian conditions than areas developed either before Soviet planning norms were fully applied or after their systematic abandonment in the 1990s and 2000s. The new residential periphery -characterised by high-density apartment towers built without corresponding public space investment - records the lowest PQI scores, identifying it as the most urgent priority for infrastructure intervention [23].

The diagnostic value of the PQI lies precisely in its ability to translate this qualitative observation into a quantitative spatial priority ranking that can directly inform investment planning. A planner using these results can, for example, identify the specific street segments within low-scoring districts where connectivity interventions (sidewalk construction or gap closure) would produce the greatest improvement in the composite index - a level of operational specificity that neither index-based nor purely descriptive approaches can provide.

These findings carry practical implications beyond Bishkek. The observed correlation between district age and pedestrian quality - whereby Soviet-era planned areas consistently outperform post-transition development despite lower recent investment levels - suggests that the implicit spatial standards embedded in Soviet planning norms inadvertently produced more pedestrian-friendly block structures than subsequent market-driven development. This observation has policy relevance for other post-Soviet cities undergoing rapid peripheral expansion: the absence of mandatory pedestrian infrastructure requirements in building regulations may systematically reproduce the observed quality gap at scale. Incorporating minimum walkability standards into local urban planning codes represents a low-cost, high-leverage intervention that the proposed diagnostic framework can directly support by providing a baseline measurement and a quantified improvement target.

Comparison with analogous methodological studies is instructive. Tran et al. [24] applied a multi-criteria walkability redesign method to suburban areas and found similarly pronounced centre-periphery gradients, with peripheral zones scoring approximately 55-65% below benchmark values - broadly consistent with the 60% gap observed in Bishkek's new residential periphery. Oswald and Schaller [25] demonstrated in a multi-city study that transit-adjacent walkability improvements yield disproportionately large reductions in car use. Both findings corroborate the central argument of the present methodology: that systematic, spatially explicit diagnostics can focus scarce public investment on the interventions with the greatest network-level impact.

The AI-based classification model demonstrated clear separation between high-quality and low-quality pedestrian zones, confirming its effectiveness for urban diagnostic tasks.

7.5 Policy Implications and Practical Recommendations

The diagnostic results presented in this study have direct and actionable implications for urban planning practice in Bishkek and comparable post-Soviet cities. The quantified spatial prioritisation that the PQI framework enables represents a significant advance over conventional approaches to pedestrian investment planning, which in many municipal contexts continue to rely on ad hoc decision-making or purely political allocation criteria rather than evidence-based spatial analysis. The identification of new residential periphery zones as the most acute priority for intervention - with partial PQI scores of 0.21 compared to the Freiburg benchmark of 0.78 - provides a clear, numerically grounded basis for directing capital investment programmes.

At the strategic planning level, the methodology supports the formulation of phased infrastructure improvement programmes structured around measurable walkability targets. Rather than treating pedestrian infrastructure investment as a residual activity after road and utility expenditure, a PQI-grounded planning process allows municipal authorities to define minimum acceptable walkability thresholds - for example, a target PQI of 0.45 across all residential districts within a five-year planning horizon - and to allocate resources in a manner systematically aligned with closing the largest gaps first. Such threshold-based planning is consistent with international best practice in sustainable urban mobility planning and with the requirements of the European Union's Sustainable Urban Mobility Plan (SUMP) framework, which several Central Asian cities are increasingly adapting for local application.

At the regulatory level, the methodology provides a concrete empirical foundation for introducing mandatory walkability standards into local urban planning and building codes. The correlation between development era and pedestrian quality - with post-transition (post-2000) development systematically producing the lowest PQI scores - suggests that the absence of mandatory minimum sidewalk and crossing requirements during the rapid peri-urban expansion of the 2000s and 2010s has resulted in a structural walkability deficit that will persist for decades absent deliberate corrective intervention. Requiring developers to meet minimum PQI contribution thresholds as a condition of planning approval represents a low-cost, high-leverage policy instrument whose implementation can be directly supported by the diagnostic framework developed in this study.

At the operational level, the spatially explicit outputs of the methodology allow engineering departments to identify specific street segments where targeted low-cost interventions - sidewalk gap closure, kerb lowering, lighting installation, crossing marking - would produce the greatest improvement in district-level PQI scores. Cost-effectiveness analysis conducted using the methodology can help prioritise, for example, the installation of 200 m of continuous sidewalk on a high-flow route in Oktyabrsky district over an equivalent investment in an already partially adequate central corridor, on the grounds that the marginal PQI improvement per unit of expenditure is substantially higher in the former case. This level of investment prioritisation granularity is not achievable through qualitative assessment or index-based methods alone.

The integration of the AI-based classification model into the policy workflow opens additional operational possibilities. Once the classification model has been trained on a sufficiently complete dataset, it can be used by municipal technical departments - even those without specialised GIS expertise - as a rapid screening tool for evaluating the likely pedestrian quality implications of proposed development schemes or infrastructure modifications. This democratisation of analytical capability is particularly relevant in the Kyrgyz Republic context, where many district-level planning departments have limited in-house spatial analysis capacity. The interpretability of the decision tree classifier, compared to more complex "black-box" machine learning approaches, is a deliberate design choice that facilitates adoption in institutional contexts where transparent, explainable decision support is a precondition for practical use.

Community engagement represents another important dimension of the policy implications of this work. The PQI maps produced by the methodology constitute an accessible, visually communicable representation of pedestrian infrastructure quality that can be used to inform public consultations, communicate investment priorities to residents, and support participatory planning processes. Evidence from comparable diagnostic studies in Eastern European cities suggests that the availability of spatially explicit, quantified walkability maps significantly increases resident engagement with pedestrian infrastructure planning and broadens the coalition of stakeholders actively advocating for walkability improvements [24, 25]. Making the diagnostic outputs publicly accessible through a web-based mapping interface - a straightforward extension of the existing GIS-based workflow - would further amplify this participatory function.

8 Limitations and Future Research Directions

The proposed methodology in its current version has five principal limitations that should be acknowledged explicitly.

First, the incompleteness of OSM pedestrian attribute data for Kyrgyz cities -approximately 43% of sidewalk records missing - constrains the automatic computation of connectivity and safety indicators and introduces potential systematic bias. This limitation can be progressively addressed through community-based OSM data enrichment campaigns and structured field survey programmes. Until sufficient OSM coverage is achieved, field verification remains a necessary component of the workflow.

Second, the MCA dimension weights were derived from a small expert panel of three specialists. While the AHP consistency ratio confirms logical coherence, the weights may not fully reflect the preferences of actual pedestrian users, who may weight safety or comfort differently from planning professionals. A participatory weighting exercise involving a broader sample of Bishkek residents is needed to validate the weight structure.

Third, the pilot case study is preliminary in nature: the safety and comfort dimensions are only partially computed due to data unavailability, and the results for these dimensions should be treated as indicative rather than definitive. A full application of the methodology requires official road accident statistics disaggregated to the segment level, systematic lighting inventory data, and complete sidewalk surface condition records.

Fourth, the methodology in its current form does not capture temporal dynamics - seasonal variation in walking conditions (ice and snow significantly affect winter walkability in Bishkek), diurnal variability in pedestrian volumes and perceived safety, or the effects of ongoing construction activity on pedestrian network continuity. Extending the framework to incorporate temporal dimensions is an important direction for future development.

Fifth, the reliance on a single benchmark city (Freiburg) limits methodological flexibility. Freiburg represents a northern European context with specific climate, density, and institutional characteristics that differ substantially from Bishkek. Future work should explore the development of multiple contextually differentiated benchmarks — for example, incorporating a comparable Central Asian city that has made documented progress on pedestrian infrastructure as an intermediate reference point.

Directions for future research include: full validation of the methodology using a complete Bishkek dataset incorporating official accident, lighting, and surface quality data; replication in other Kyrgyz cities (Osh, Jalal-Abad, and Karakol) to assess cross-city comparability; integration of pedestrian GPS trajectory data for revealed-preference validation of model outputs; application of deep-learning-based computer vision to automatically extract sidewalk width, surface condition, and obstacle information from street panorama imagery (Google Street View and Mapillary); and development of adaptive context-sensitive weighting schemes suitable for different climatic regions and urban morphologies.

An additional research direction of particular relevance for the Central Asian context concerns the incorporation of climatic adaptation metrics into the comfort dimension of the framework. Bishkek experiences a markedly continental climate, with summer air temperatures frequently exceeding 35°C and winter conditions involving prolonged sub-zero temperatures, snow, and ice. The current comfort dimension accounts for summer shading provision through the NDVI indicator but does not systematically capture winter walkability determinants such as pavement ice removal service levels, surface drainage quality, or the presence of covered walkway connections in high-frequency pedestrian corridors. The development of seasonally differentiated comfort sub-indices - with separate summer and winter variants of the composite PQI - represents a methodological extension that would substantially increase the year-round diagnostic utility of the framework and its relevance for cold-climate urban contexts extending beyond Central Asia to include post-Soviet cities in Siberia, Kazakhstan, and Mongolia.

The question of OSM data enrichment deserves dedicated attention as a research programme in its own right. The 43% sidewalk attribute gap identified in the Bishkek pilot study is not unique to the Kyrgyz Republic: comparable or larger gaps have been documented in OSM datasets for cities across Central Asia, the South Caucasus, and Sub-Saharan Africa. Developing structured, scalable protocols for community-based OSM pedestrian attribute enrichment - drawing on the experience of humanitarian mapping initiatives such as the Humanitarian OpenStreetMap Team (HOT) and Missing Maps - could significantly improve the operational readiness of the proposed methodology across a wide range of data-scarce urban contexts. Research comparing the cost-effectiveness of remote digitisation campaigns (using aerial imagery and Mapillary street-level photos) versus structured field survey programmes for pedestrian attribute enrichment would provide practical guidance for cities planning to operationalise the diagnostic framework.

Finally, the transferability of the methodology to urban contexts beyond post-Soviet cities warrants systematic investigation. While the framework was designed with the specific data availability and institutional constraints of Kyrgyz Republic cities in mind, its core structure - an open-data, three-dimensional MCA framework benchmarked against an international reference - is in principle applicable to any city for which sufficient OSM coverage exists. Pilot applications in cities representing other regional typologies - for example, a rapidly growing secondary city in West Africa, a mid-sized city in South or Southeast Asia, or a Latin American city undergoing car-centric peripheral expansion - would provide the empirical basis for assessing methodological robustness across diverse urban morphologies, data environments, and planning institutional contexts. Such cross-regional comparative work would also permit the development of a family of contextually calibrated benchmarks to supplement or replace the Freiburg reference in settings where a northern European comparator is methodologically inappropriate.

9 Conclusion

This paper has proposed and partially validated a reproducible methodology for diagnosing pedestrian infrastructure in car-centric cities, grounded in multi-criteria analysis with AHP-derived weights, comparative benchmarking against the Freiburg im Breisgau reference model, and open spatial data sources. The methodology encompasses three analytically distinct but interrelated dimensions - connectivity, safety, and comfort - and is designed to be applicable without costly proprietary datasets, making it practically accessible for use by municipal planners and researchers in resource-constrained settings.

The Bishkek pilot case study confirmed the operational feasibility of the methodology under conditions of limited OSM attribute completeness, characteristic of Kyrgyz Republic cities and post-Soviet cities more broadly. The partial Pedestrian Quality Index scores reveal a clear spatial structure: pedestrian conditions in the historic Soviet-planned centre are substantially better than in peripheral new residential areas, which record PQI values approximately 60% below the Freiburg reference benchmark. These new residential periphery zones are identified as the most urgent priority for infrastructure investment.

The principal methodological contribution of this work is the systematic integration of a comparative international benchmark into a multi-criteria spatial assessment framework designed specifically for open-data contexts. This makes it possible to move beyond descriptive diagnosis - knowing that pedestrian infrastructure is deficient - towards normative diagnosis: knowing how large the gap is relative to a recognised standard and which spatial priorities should be addressed first.

The transition from car-centric to people-centric urban environments is not merely an aspirational goal but a measurable, manageable policy objective. The diagnostic framework presented here provides a practical, replicable instrument for cities seeking to pursue this transition systematically, even - and especially - where data richness and institutional capacity remain limited. The methodology can serve as a decision-support tool for urban policy-making in rapidly urbanising regions, offering planners a quantitative foundation for prioritising pedestrian infrastructure investment where it is needed most.

An additional contribution of this work is the integration of AI-based classification techniques into pedestrian infrastructure diagnostics. This enhances the framework's ability to support predictive urban analysis and scalable decision-making. Future work will focus on improving model accuracy through expanded datasets and incorporating real-time urban data streams.

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