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Beyond the shortest path: Identifying optimal walkable routes using a street walkability index derived from deep learning and micro-scale pedestrian environment features

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Research Article

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Abstract: Urban streets are fundamental public spaces that underpin residents' daily non-motorized travel, and their on-street pedestrian environment and walkability directly shape people's walking mode decisions and walking experiences. However, few existing studies have systematically examined street-level walkability from the perspective of micro-scale pedestrian environment features—particularly its critical role in identifying the truly optimal walkable routes. This study develops a Street Walkability Index (SWI) based on street view image data, deep learning and seven specific street micro-environmental indicators. Leveraging this index, we propose an innovative method for optimal walkable route identification, and conduct empirical validation and performance testing in a historic urban district of Guangzhou. The results show that the average SWI in this district is 35.0638, with 56.25% of the streets scoring below this mean value. Overall, arterial roads exhibit the poorest walkability, while branch roads and internal roads show relatively better walkability. The seven street micro-environmental indicators display distinct spatial distribution characteristics. Branch roads and internal roads perform outstandingly in terms of space vitality, enclosure, pedestrian conditions, and visual permeability. Secondary arterial roads generally have the best street greenery coverage, while arterial roads perform best in openness. For the vast majority of origin-destination pairs, the optimal walkable route is not equivalent to the path with the shortest walking distance. Although the total travel distance of the optimal walkable route increases only marginally, its overall walkability can be improved by a substantially larger margin. This study advances our in-depth understanding of street walkability and optimal walkable route planning, and facilitates their practical implementation in pedestrian navigation systems.

Keywords: Street walkability; Pedestrian; Micro-scale environment; Optimal walkable route; Deep learning

1 Introduction

Walking, as a health-beneficial and low-carbon mode of travel, has its accessibility and experiential quality predominantly shaped by the spatial layout, design features, and overall quality of the pedestrian environment (Adhikari et al., 2021; Barajas & Braun, 2021; Van Dyck et al., 2020). Walking-friendly urban environments, designed to prioritize pedestrians' needs, provide accessible, safe, convenient, inclusive, and environmentally friendly pedestrian spaces, thereby encouraging greater physical activity, social interaction, and community engagement (Gao et al., 2022; Lu & Chen, 2024; Santos et al., 2022; Tabatabaie et al., 2023). With the growing emphasis on sustainable development, walking has become a key focus in urban planning and transport policy research worldwide. Against the backdrop of rapid urbanization, motorization levels in China continue to rise. Specifically, the surge in private car ownership has led many Chinese cities to adopt vehicle-oriented road system planning, which has significantly impacted original pedestrian networks and human-scale streets (Yang et al., 2017; Yang & Cao, 2018; Zhao, 2010). Furthermore, compared to Western cities, Chinese cities exhibit distinctive features in built environment characteristics, residents' travel behaviors, and preferences. They are predominantly characterized by high-density, compact neighborhoods with frequent mixing of motorized and non-motorized traffic, and residents generally exhibit a higher reliance on walking (Fan et al., 2018; Jiang et al., 2025). These unique

characteristics render the optimization of micro-scale walking environments in Chinese cities vital for ensuring daily travel safety and convenience, promoting inclusive urban development, and enhancing public (Loo et al., 2024; Yang et al., 2020; Yang et al., 2024).

Although walkability research has expanded considerably in recent years, most studies focus on macro- or meso-scales, relying on block- or neighborhood-level indicators such as land use mix, road density, and transit accessibility to construct composite walkability indices (Frank et al., 2006; Frank et al., 2010; Hall & Ram, 2018; Kim & Woo, 2022; Qiu et al., 2022; Shashank & Schuurman, 2019; Wang et al., 2022). While these studies provide valuable insights for policymaking and city planning, they often overlook the relationship between the micro-level physical attributes of street spaces and pedestrians' perceptual experiences (Alosaimi et al., 2025; Koo et al., 2022; Koo et al., 2022; Tabatabaie et al., 2023). In recent years, some studies have begun to incorporate street view imagery, computer vision analysis, and deep learning models to evaluate the visual perception and attractiveness of walking environments based on features like street greenery, spatial enclosure, and facility allocation (Li et al., 2023; Shin & Woo, 2024). However, there remains a relative scarcity of research that constructs a street-level walkability indicator system from the perspective of micro-scale pedestrian environment features and further applies it to identify optimal walking routes. Walkability evaluations based on street micro-features can more closely align with pedestrians' actual experiences, help determine the walkability of individual streets, and provide a scientific basis for detailed urban road improvements. Meanwhile, identifying the most suitable walking routes based on street environmental quality can overcome the limitations of the "shortest route" approach regarding actual walking experiences, thereby offering more practical support for slow-traffic system optimization and route choice.

Building on the above theoretical background and identified research gaps, this study selects a historic urban district in Guangzhou, China, as the case study area. This district represents one of the oldest and most compact historic neighborhoods in Guangzhou. In contrast to the automobile-centered planning prevalent in newer urban expansions, its street network retains a traditional pedestrian-oriented pattern, characterized by small block scales, a dense street layout, high population density, and a significantly aging demographic profile. These distinct features render it both a representative and practically valuable context for street walkability research. In this study, we first construct an evaluation framework comprising seven targeted micro-environmental indicators for street-level pedestrian space assessment and conduct a quantitative assessment of all streets within the study area. Subsequently, we analyze the spatial characteristics and variations of street walkability and propose a method for identifying optimal walkable routes based on these measurements. This study aims to address the following research question: How can street walkability be systematically quantified using these multi-dimensional micro-scale pedestrian environment features? Is an optimal walkable route identification method developed based on this measurement approach applicable and effective in the study area? The findings of this study are expected to offer scientific evidence to advance the understanding of street walkability and its impact on pedestrian experiences and route choices.

The remainder of this paper is organized as follows: Section 2 reviews the literature on street walkability and its measurement approaches. Section 3 details the research data and methodologies employed. Section 4 presents the empirical findings, and Section 5 discusses their implications. Finally, Section 6 concludes the paper by summarizing the main contributions and limitations.

2 Literature review

2.1 Walkability and measurement methods

The concept of walkability emerged as a research focus in the 1990s, largely in response to growing concerns over public health and climate change (Dovey & Pafka, 2020; Frank et al., 2010; Shashank & Schuurman, 2019; Southworth, 1997; Tobin et al., 2022). Existing studies generally categorize the factors influencing walkability into two groups: macro-scale and micro-scale (Adkins et al., 2012; Bivina et al., 2020; Sallis et al., 2015; Tobin et al., 2022). Macro-scale measurement is predominantly grounded in the "3Ds" framework, which identifies density, diversity, and design as the key built environment factors shaping travel demand (Cervero & Kockelman, 1997). This framework was later expanded into the "5Ds" by incorporating destination accessibility and distance to transit (Cervero et al., 2009). Consequently, walkability at this scale is typically assessed through built environment attributes such as residential density, intersection density, block length, and street network density.

In contrast, micro-scale research focuses on street-level built environment features, emphasizing the physical details and functionality of pedestrian infrastructure. Commonly used indicators include street greenery, street furniture, traffic signage, and sidewalk presence, which collectively reflect design quality and pedestrian amenity (Bivina et al., 2020; Ki et al., 2023). Compared to macro-scale approaches, micro-scale measures place greater emphasis on the three-dimensional qualities of street environments, offering a more holistic perspective for evaluating walkability (Adkins et al., 2012; Foltête & Piombini, 2007; Gallimore et al., 2011). This is because the micro-scale provides more detailed, street-level information that more closely reflects pedestrians' on-the-ground perceptions and experiences, thereby complementing the limitations of macro-scale measures (Adkins et al., 2012; Ewing & Handy, 2009; Kim et al., 2014).

In recent years, rapid advancements in computer vision and the increasing availability of street view imagery have driven methodological innovations for measuring micro-scale walking environments (Ki et al., 2023; Lu, 2019; Lu & Chen, 2024; Nagata et al., 2020; Yin & Wang, 2016). Compared to traditional methods relying on GIS data or field audits, the integration of street view images and computer vision represents a significant methodological advance in walkability assessment. On one hand, this approach enables the identification and quantification of street details—such as greenery density, building frontage, and spatial permeability—that are difficult to capture using traditional methods (Cambra & Moura, 2020; Moura et al., 2017; Yin, 2017; Zhou et al., 2019). On the other hand, it offers advantages in efficiency and cost-effectiveness, facilitating automated, fine-grained assessments across extensive urban areas (Jeon & Woo, 2023; Kim & Woo, 2022; Li et al., 2023). Moreover, this pedestrian-oriented mode of data collection provides a closer approximation of actual walking experiences. By relying on data captured from the pedestrian's visual perspective, it further ensures that assessments more accurately reflect real-world walking conditions (Adkins et al., 2012; Foltête & Piombini, 2007; Gallimore et al., 2011; Kim et al., 2014).

Utilizing these technologies, existing studies have demonstrated that micro-scale built environment factors extracted via image recognition—such as street greenery, degree of enclosure, and shading level—show significant correlations with walking duration and frequency. For instance, residents in neighborhoods characterized by high levels of greenery or enclosure are more likely to walk more frequently and for longer durations (Guo & Loo, 2013; Jiang et al., 2014; Ma et al., 2021; Ma et al., 2021; Yin & Wang, 2016). The interaction between the street's built environment and

pedestrians similarly influences walking behavior (Bonaiuto et al., 2015; Mendes De Leon et al., 2009). Furthermore, street-level factors exert a more pronounced impact on walking patterns compared to neighborhood-level factors (Koo et al., 2022).

2.2 Street walkability from the perspective of micro-scale pedestrian environment features

Micro-scale street walkability focuses on the physical structure and layout features of streets. Compared to meso- or macro-scale studies, micro-scale approaches offer a more refined analytical perspective by capturing elements directly perceived by pedestrians during walking, such as street width, pedestrian facilities, pavement quality, and the presence of street trees (Alfonzo, 2005; Kim et al., 2014; Moura et al., 2017). These physical attributes are closely linked to pedestrians' comfort, enjoyment, and aesthetic experiences within the street environment. Moreover, compared to neighborhood-level indicators, micro-scale features are more amenable to adjustment through design and management interventions, enabling research findings to be translated into practice more rapidly and effectively (Steinmetz-Wood et al., 2020).

Over the years, theoretical frameworks such as the "street eye," "livable street," and "soft boundary" have provided foundational underpinnings for evaluating street walkability (Appleyard, 1981; Jacobs, 1961). Pikora (2003) proposed a framework of potential environmental correlates, systematically categorizing key street-level elements—including pavement conditions, width, lighting, surveillance, landscape quality, street trees, and public spaces—into four dimensions: functionality, safety, aesthetics, and destinations. This framework offers an important reference for quantitative research on micro-scale walking environments. Some scholars have further delineated design quality dimensions such as imageability, visual enclosure, human scale, transparency, and complexity, identifying key environmental elements like distinctive architecture, street furniture, public art, and the proportion of street-level windows (Ewing et al., 2016). More recently, three-dimensional indicators such as the green view index and sky view factor have been incorporated to provide a more comprehensive evaluation of how street environments shape walking experiences (Yin & Wang, 2016).

Concurrently, street walkability also emphasizes pedestrians' subjective perceptions and experiential responses to the street environment. The London Planning Advisory Committee proposed the "5Cs" framework—connected, convenient, comfortable, convivial, and conspicuous—which defines the characteristics of pedestrian-friendly places based on users' perceptions and needs. Moura et al. (Moura et al., 2017) expanded this to the "7Cs" by adding coexistence and commitment, further highlighting the importance of safety and environmental synergy in the walking experience. Building on socio-ecological models, (Alfonzo, 2005) proposed a hierarchical model of walking needs, ranging from basic feasibility and accessibility to higher-order safety, comfort, and pleasurability. Other scholars have categorized the micro-environmental features influencing pedestrian perception into three types: physical characteristics, land-use characteristics, and socio-environmental characteristics. These encompass elements such as sidewalk width, street trees, store types, community gathering spaces, and street vitality, which collectively shape pedestrians' sense of practicality, security, comfort, pleasure, and belonging (Mehta, 2008). Additionally, sensory dimensions including thermal, acoustic, and visual conditions also significantly influence psychological perceptions of walking (Ma et al., 2021; Tabatabaie et al., 2023).

Micro-scale street environmental elements directly influence pedestrians' comfort and

perceptual experiences. Research indicates that streets with greater tree canopy coverage are more appealing for walking, as the shade provided by street trees effectively blocks solar radiation, lowers ambient temperatures, and enhances thermal comfort (Dai et al., 2021; Jiang et al., 2014). Openness, which pertains to the degree of sky visibility and is typically measured by the sky view factor, is strongly correlated with the street height-to-width ratio (Dai et al., 2021; Tang & Long, 2019). Moreover, openness can improve urban ventilation, mitigate the heat island effect, and disperse low-altitude pollutants, thereby enhancing overall environmental quality (Gong et al., 2018; Hien & Jusuf, 2010; Xia et al., 2021). An open street environment not only enhances residents' sense of safety but also alleviates feelings of dullness and monotony, creating a more pleasant and comfortable walking experience (Ewing & Handy, 2009; Van Cauwenberg et al., 2012). Wider pedestrian spaces increase street capacity for walking, enabling safer and more comfortable movement for more people. In contrast, narrow pedestrian spaces impede movement and reduce both walking speed and comfort (Bereitschaft, 2018; Frackelton et al., 2013; Kim et al., 2019). Such strong sensitivity to micro-environmental quality also shapes pedestrians' path selection logic. Recent studies have explicitly linked streetscape features extracted from street view imagery and computer vision to observed walking behavior, demonstrating that pedestrians' actual route choices are systematically associated with street attributes and that pedestrians are willing to accept a certain degree of detour for a more attractive walking environment (Basu & Sevtsuk, 2022; Lieu & Guhathakurta, 2025; Loo et al., 2024). In summary, the measurement and evaluation of street walkability should be grounded in systematic quantification of micro-scale pedestrian environment features, accounting for the effects of street physical structures and micro-scale environmental characteristics on pedestrians' comfort, pleasure, and subjective perceptual experiences, in order to accurately assess and effectively improve the quality of the street walking environment.

3 Methodology

3.1 Study Area

This study selected a historic district in the southwestern part of Yuexiu District, Guangzhou, China, as the case study area (Fig. 1). The district is bordered by Dongfeng Road to the north, Yanjiang West Road and Yanjiang Middle Road to the south, Dongchuan Road to the east, and Renmin Viaduct to the west. It covers an area of approximately 6.5 km² and comprises 368 street segments. As one of Guangzhou's most quintessential historic areas, the district retains traditional street patterns, historic buildings, and arcade structures. These features preserve the unique urban fabric of the old city and reflect its enduring historical heritage. According to the Seventh National Census, the population density is 40,350 people/km², and the aging population ratio is 25.6%—both figures significantly exceed Guangzhou's averages. Consequently, the pedestrian environment and walkability of this historic district are of immense significance to both residents and tourists.

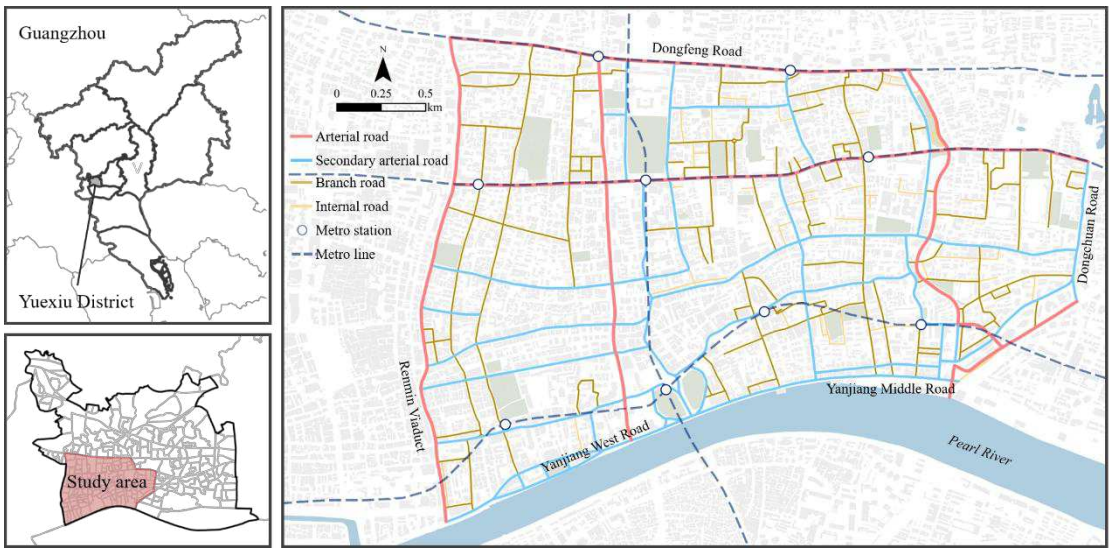


Fig.1. Geographical location of the study area and its street network.

3.2 Street walkability index (SWI)

Based on multi-dimensional micro-scale pedestrian environment features, we developed a Street Walkability Index (SWI). This index is constructed based on four dimensions—environmental safety, walking comfort, streetscape attractiveness, and street interactivity—comprising seven corresponding micro-scale walking environment indicators (Table 1). Specifically, environmental safety is assessed by Space Vitality (SV) and Enclosure (E); walking comfort is indicated by Pedestrian Conditions (PC) and Street Shade Rate (SS); streetscape attractiveness is represented by Street Greenery (SG) and Openness (O); and street interactivity is reflected by Visual Permeability (VP). The total weight of these seven indicators sums to 1. Detailed calculation methods for each indicator are provided in Table 2.

Table 1

Dimensions and corresponding indicators of the Street Walkability Index.

Dimension	Definition	Indicators
Environmental Safety	The level of safety perceived by an individual regarding factors such as traffic conditions and crime risks in their surrounding walking environment.	Space Vitality（SV）
		Enclosure（E）
Walking Comfort	The level of enjoyment and convenience perceived by an individual during the walking process in the walking environment.	Pedestrian Conditions（PC）
		Street Shade Rate（SS）
Streetscape Attractiveness	The degree of visual attraction to pedestrians generated by the street's unique landscape, spatial design, and other features.	Street Greenery（SG）
		Openness（O）
Street Interactivity	The positive role of street walking facilities in promoting social interaction and communication among people.	Visual Permeability（VP）

Given that the indicators differ considerably in both calculation methods and value ranges, the z-score method was applied to standardize them (Ki et al., 2023). Subsequently, the calculated SWI results were adjusted to a scale of 0–100. The specific calculation process for the SWI is as follows:

$$SWI = 0.2*z_SV + 0.1*z_E + 0.2*z_PC + 0.15*z_SS + 0.15*z_SG + 0.1*z_O + 0.1*z_VP \quad (1)$$

$$z = \frac{x - \mu}{\delta} \tag{2}$$

where x represents the observed values; μ is the mean of all observations; δ is the standard deviation of all observations.

Table 2

Definitions and calculation formulas (methods) for each walking environment indicator.

Dimension	Indicators	Definition	Formula (Method)
Environmental Safety	Space Vitality (SV)	The average proportion of pedestrian pixels at all sampling points.	$SV_i = \frac{1}{n}\sum_{i=1}^{n} P_n$
	Enclosure (E)	The average ratio of vertical street view elements (e.g., buildings, trees) to horizontal elements (e.g., roads, sidewalks) across all sampling points.	$E_i = \frac{\frac{1}{n}\sum_{i=1}^{n} B_n + \frac{1}{n}\sum_{i=1}^{n} T_n}{\frac{1}{n}\sum_{i=1}^{n} PR_n + \frac{1}{n}\sum_{i=1}^{n} R_n}$
Walking Comfort	Pedestrian Conditions (PC)	The average proportion of sidewalk pixels at all sampling points.	$PC_i = \frac{1}{n}\sum_{i=1}^{n} PR_n$
	Street Shade Rate (SS)	The degree of shading formed by vegetation covering the street surface.	The average green space per unit length (m) within a 60-meter buffer zone, extending 30 meters on each side of the street centerline.
Streetscape Attractiveness	Street Greenery (SG)	The average proportion of green vegetation pixels across all sampling points.	$SG_i = \frac{1}{n}\sum_{i=1}^{n} T_n$
	Openness (O)	The average proportion of sky pixels at all sampling points.	$O_i = \frac{1}{n}\sum_{i=1}^{n} S_n$
Street Interactivity	Visual Permeability (VP)	The average proportion of non-wall and non-fence pixels at all sampling points.	$VP_i = 1 - \frac{1}{n}\sum_{i=1}^{n}(W_n + F_n)$

3.3 Street view image data processing based on deep learning

The road network vector data used in this study was obtained from OpenStreetMap in 2024 and validated through on-site investigations. Among the seven indicators for measuring the SWI, the Street Shade Rate was calculated using 1-meter resolution urban green space raster data obtained from the Science Data Bank Platform(Qian et al., 2023). The remaining six indicators were derived from street view imagery via deep learning methods.

The street view image dataset was sourced from Baidu Maps, and the data collection process is detailed as follows. First, sampling points for street view images were placed at 35-meter intervals along the road network within the study area. Subsequently, the street view image Application Programming Interface (API) provided by Baidu Maps was called, using the geographic coordinates of the sampling points as parameters, to collect street view images in four horizontal directions: 0°, 90°, 180°, and 270°. After acquiring the valid images, we employed the deep learning semantic segmentation model DeepLabv3+ to perform pixel-level classification on the collected street view

images (Lu & Chen, 2024; Nagata et al., 2020; Shin & Woo, 2024). This model can identify 18 categories of street view elements, including roads, sidewalks, buildings, transportation facilities, greenery, sky, pedestrians, and vehicles, and output the corresponding pixel classification results. The DeepLabv3+ model adopted in this study was trained on the Cityscapes dataset, achieving an overall accuracy of approximately 81.7%. Fig. 2 illustrates the complete workflow from street view image collection to semantic segmentation in this study.

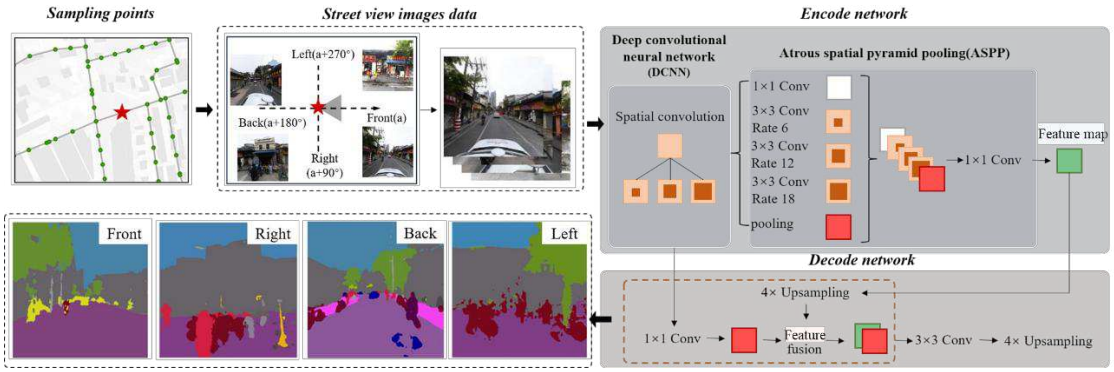


Fig. 2. Workflow for street view image data acquisition and semantic segmentation.

3.4 Method for identifying the optimal walkable route based on SWI

Based on the self-developed Street Walkability Index (SWI), this study proposes a novel approach to identify the optimal walkable route. Currently, walking routes recommended by mainstream mobile map services are typically generated based on the shortest distance, which only considers the path length between the origin and destination while ignoring the walkability of the entire route. The proposed optimal walkable route identification method integrates not only basic elements such as walking distance and travel time, but also the street-level walkability of the route. For the same pair of origin and destination, the shortest walking route and the optimal walkable route are not necessarily identical, as illustrated in Fig. 3. A higher cumulative SWI score of a route indicates a better-quality street environment along the path, which can deliver a more pleasant walking experience for pedestrians and contribute to promoting active walking behavior.

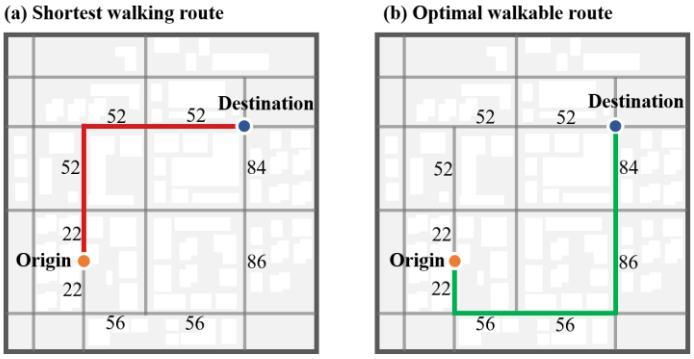


Fig. 3. Conceptual diagram of the shortest walking route and the optimal walkable route (Numbers beside each road segment represent its corresponding SWI value).

The calculation formula for the optimal walkable route proposed in this study is specified as follows:

$$C_r = \sum_{i=1}^{n} \frac{t_i}{SWI_i} \tag{3}$$

where C_r represents the comprehensive cost of route r; t_i denotes the walking time for street

segment *i*; SWI_i refers to the Street Walkability Index value of street segment *i*, where a higher value indicates a higher level of walkability for that segment.

To validate the proposed optimal walkable route identification method, this study selected six walking routes within the study area and conducted a comparative analysis between their corresponding shortest walking routes and optimal walkable routes. The origins and destinations of these six routes were randomly predefined, covering multiple highly attractive locations in the study area, including People's Park, Tianzi Wharf, Guangzhou Uprising Memorial Hall, Haizhu Square, and several residential communities. The overall research framework and analytical workflow of this study are visualized in Fig. 4.

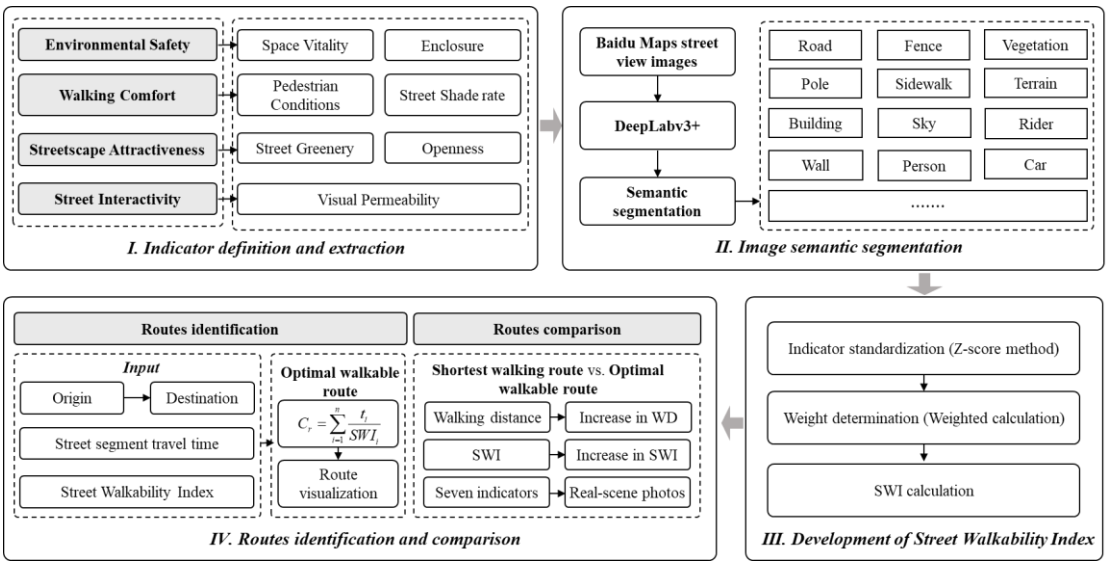


Fig.4. Research framework and analysis process.

4 Results

4.1 Spatial characteristics of street walkability

The calculated Street Walkability Index (SWI) values for all street segments in the study district are visualized in Fig. 5a. From a spatial distribution perspective, streets with high SWI scores are predominantly concentrated in the vicinity of parks, green spaces, public squares, the Beijing Road commercial area, and the waterfront streets along the Pearl River. As summarized in the descriptive statistics (Table 3), the average SWI across the district is **35.06**, with approximately 56.25% of street segments scoring below this mean value, indicating substantial room for improvement in the walking environment for a large proportion of streets.

Moreover, significant disparities in SWI are observed across different road hierarchy categories. Arterial roads record the lowest average SWI at 6.15, accompanied by a high coefficient of variation (CV) of 45.35%, which suggests that arterial roads generally exhibit subpar walkability with considerable heterogeneity across individual segments. The average SWI of secondary arterial roads reaches 33.57, markedly higher than that of arterial roads, with a CV of 37.26% — indicating a generally better and more evenly distributed walkability performance. Compared with arterial and secondary arterial roads, branch roads and internal roads demonstrate notably higher street walkability, with average SWI values of 38.28 and 38.25 respectively. Certain internal variations still exist within this category, as the CV of internal roads (44.19%) is significantly higher than that

of branch roads (35.44%).

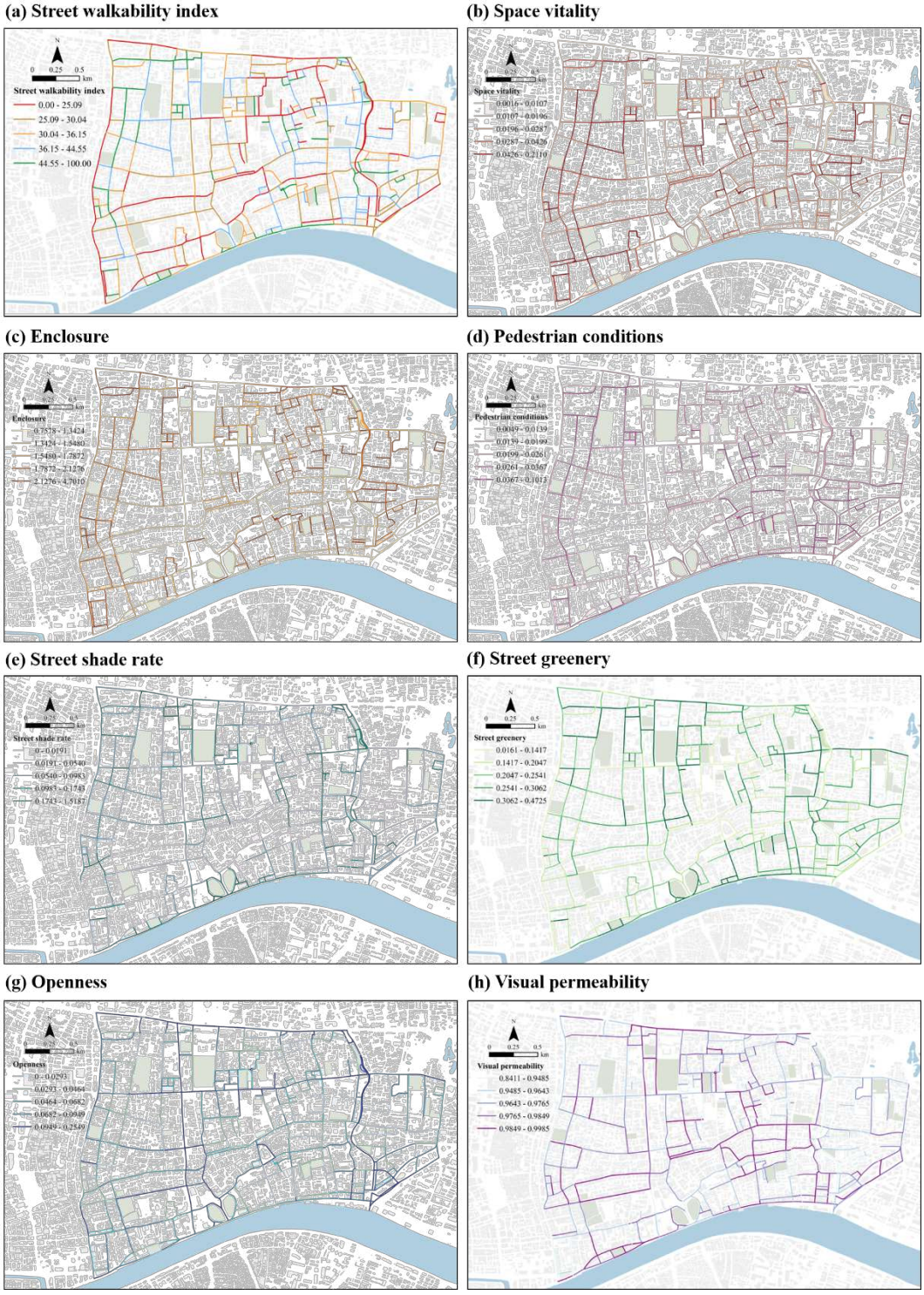


Fig. 5. Spatial pattern of the Street Walkability Index and its underlying walking environment indicator.

Table 3

Descriptive statistics of the Street Walkability Index and its corresponding dimensions.

Dimension	Indicator	Min.	Max.	Mean	SD	CV (%)
Environmental Safety	SV	0.0016	0.2111	0.0309	0.0284	91.89

	E	0.7579	4.7010	1.7898	0.5810	32.47
Walking Comfort	PC	0.0049	0.1014	0.0256	0.0142	55.47
	SS	0	1.5187	0.1278	0.1801	140.86
Streetscape Attractiveness	SG	0.0161	0.4725	0.2276	0.0966	42.47
	O	0	0.2550	0.0662	0.0459	69.44
Street Interactivity	VP	0.8411	0.9985	0.9644	0.0264	2.74
SWI		0	100	35.0638	14.3059	40.80

Fig. 5b–h illustrate the distinct spatial patterns of the seven individual walking environment indicators. For the space vitality indicator, streets with high SV values are predominantly distributed in the central area of the district, exhibiting clear characteristics of spatial agglomeration (Fig. 5b). Significant disparities in space vitality are also observed across different road hierarchy categories: branch roads (mean = 0.0416) and internal roads (mean = 0.0360) show notably higher space vitality than arterial roads (mean = 0.0130) and secondary arterial roads (mean = 0.0223). This finding indicates that branch roads and internal roads, characterized by larger pedestrian flows, demonstrate stronger space vitality. In contrast, arterial roads and secondary arterial roads are primarily designated for motorized traffic passage, with limited public space reserved for pedestrians. This further confirms that roads with higher hierarchy and greater widths do not necessarily correspond to stronger space vitality.

For street enclosure, shorter branch roads and internal roads generally present higher enclosure degrees, with several local clusters of high-enclosure streets identified across the district. In comparison, long, continuous arterial roads and secondary arterial roads show relatively lower enclosure levels, particularly the riverside streets in the southern part of the district and Guangzhou Uprising Road in the mid-northern area (Fig. 5c).

In terms of walking comfort, pedestrian conditions deteriorate progressively as road hierarchy increases. The mean values of pedestrian conditions for arterial roads, secondary arterial roads, branch roads, and internal roads are 0.0169, 0.0232, 0.0284 and 0.0316, respectively. Spatially, streets with high PC scores are mainly concentrated in the southern riverside zone and the southeastern region. Among them, Yanjiang Middle Road, Zhihang Road and Shishu Road (two north-south streets in the western part), and Wenming Road in the eastern part form relatively long, continuous segments with high-quality pedestrian conditions (Fig. 5d). For the street shade rate indicator, the relatively continuous high-value segments are primarily located along Dezheng Road in the eastern part and Yanjing Middle Road in the southern part. Streets with moderate shade rates are usually spatially connected to high-shade segments, and no statistically significant difference in street shade rate is detected across different road hierarchy categories (Fig. 5e).

In terms of streetscape attractiveness, secondary arterial roads present the highest level of street greenery with strong internal uniformity (mean = 0.256; CV = 36%), while substantial internal variations in street greenery are observed among arterial roads and internal roads. Streets with high SG values are mostly located in the vicinity of urban green spaces and the riverside area (Fig. 5f). For the openness indicator, arterial roads show relatively favorable openness, with the highest mean value (0.118) and the smallest internal variation (CV = 42%). Overall, branch roads and internal roads have relatively poor openness, which is mainly attributed to their narrower cross-sections and the high-density urban context of Guangzhou as a typical megacity (Fig. 5g).

In terms of street interactivity, the overall visual permeability of streets in the study district is

generally high, especially for internal roads and branch roads. Streets with high VP values are mainly distributed in the central and southern parts of the district and along the riverside, including Danan Road, Wenming Road, and Yanjiang Middle Road (Fig. 5h).

4.2 Identification of the optimal walkable route and its comparison with the shortest walking route

By comparing the identification results of the SWI-based optimal walkable route with the conventional shortest walking route, we find that none of the six paired routes fully overlap. Although the optimal walkable route presents a marginally longer travel distance than the shortest path, the magnitude of improvement in overall street walkability far outweighs the minor increase in route length, as systematically summarized in Table 4.

Table 4

Comparison between the shortest walking route and optimal walkable route.

Origin and destination	Route type	Walking distance (m)	SWI	SV	E	PC	SS	SG	O	VP	Increase in walking distance (%)	Increase in SWI (%)
People's Park—Tianzi Wharf	SWR	1898.59	28.41	0.03	1.60	0.02	0.05	0.21	0.06	0.97	0.20	26.15
	OWR	1902.48	35.84	0.02	1.30	0.02	0.13	0.31	0.10	0.97		
Guangzhou Uprising Memorial Hall—Tuanyida Former Site	SWR	2029.08	27.32	0.03	1.50	0.02	0.06	0.17	0.06	0.98	11.12	29.72
	OWR	2254.78	35.44	0.03	1.74	0.03	0.06	0.21	0.05	0.98		
Zhuguang Yaju—Haizhu Square	SWR	1184.27	30.42	0.03	1.45	0.02	0.04	0.25	0.05	0.97	14.75	44.04
	OWR	1359.00	43.82	0.03	1.59	0.03	0.15	0.29	0.03	0.98		
Yuehua Courtyard—Haizhu Square	SWR	2055.35	27.35	0.03	1.51	0.02	0.06	0.18	0.08	0.97	8.42	22.74
	OWR	2228.49	33.57	0.02	1.44	0.02	0.11	0.32	0.06	0.97		
Yuhua Lane Community—Chengyihui	SWR	1038.65	29.36	0.04	1.32	0.02	0.03	0.12	0.09	0.97	2.87	12.43
	OWR	1068.48	33.01	0.03	1.31	0.03	0.06	0.20	0.09	0.97		
Xiaoxin Street Community—Chengyihui	SWR	1443.89	33.74	0.03	1.38	0.03	0.04	0.16	0.07	0.98	3.63	4.92
	OWR	1496.32	35.40	0.03	1.40	0.03	0.07	0.20	0.07	0.98		

Note: SWR refers to shortest walking route, OWR refers to optimal walkable route.

Taking the route from People's Park to Tianzi Wharf as a representative example (Fig. 6), the shortest walking route has a total length of 1898.59 m, while the optimal walkable route extends to 1902.48 m. The average SWI values of the two routes are 28.41 and 35.84 respectively. Compared with the shortest walking route, the optimal walkable route only increases the travel distance by 0.2%, while the average SWI along the route is improved by 26.15% (Table 4).

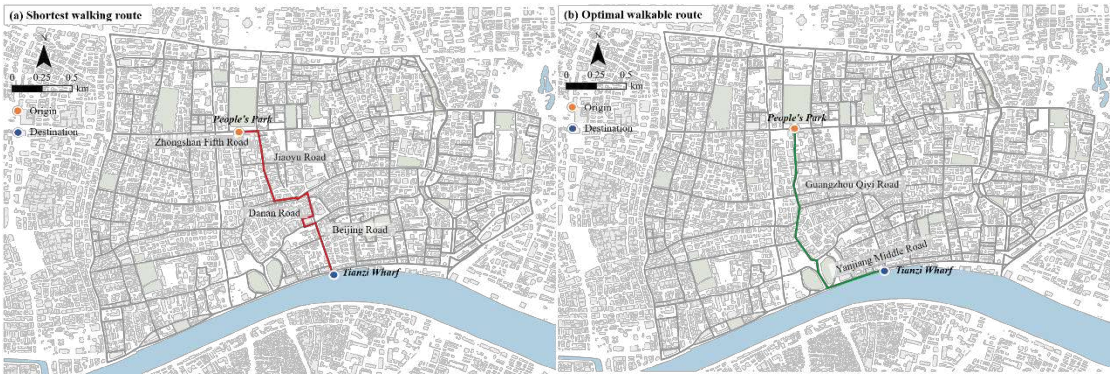


Fig. 6. Route layout of the paths connecting People's Park and Tianzi Wharf.

As documented in the on-site real-scene photographs (Fig. 7), the optimal walkable route presents distinct advantages over the shortest walking route in terms of street shade rate (SS), openness (O) and street greenery (SG). This superiority is particularly prominent along Guangzhou Uprising Road and Yanjiang Middle Road, where the greenery coverage and sky visibility are significantly better than those on Danan Road and the middle section of Beijing Road. Due to the limited number of street trees, Danan Road scores relatively low in the street shade rate dimension, though its arcade-side sidewalk design provides relatively effective shading for pedestrians. Overall, the optimal walkable route delivers substantially improved openness and street greenery. Although the optimal route extends the travel distance by merely 3.89 m, this negligible increment is far outweighed by the significant enhancements in overall walkability and pedestrian perceptual experience. Most pedestrians would perceive this slight extra distance as nearly negligible, while the comprehensive environmental upgrades make the route far more pleasant and walking-friendly.



Fig. 7. On-site real-scene photographs of the shortest walking route (a) and the optimal walkable route (b) from People's Park to Tianzi Wharf.

5 Discussion

Using the measurement logic of micro-scale pedestrian environment features, this study

developed a Street Walkability Index (SWI) consisting of seven micro-scale walking environment indicators, based on which a novel optimal walkable route identification method was further proposed. Subsequently, an empirical validation was conducted in a typical historic district of Guangzhou to verify the reliability of the aforementioned evaluation framework and analytical methods.

Previous walkability studies have predominantly focused on macro-scale environmental attributes, including urban density, land use mix, and road network connectivity (Coffee et al., 2013; Ewing & Handy, 2009; Frank et al., 2005; Leslie et al., 2007; Sundquist et al., 2011). These GIS-based analytical frameworks have greatly facilitated urban planners' understanding of walking environment performance across large geographic areas. However, widely adopted macro-scale assessment tools such as the classic walkability index developed by Frank et al. (2005) fail to incorporate street-level micro indicators, and thus cannot capture the fine-grained walking environment characteristics that are closely tied to pedestrians' real-time perceptual experiences. In recent years, scholarly attention has increasingly shifted toward the micro-level street walking environment, with consistent evidence confirming that factors such as street greenery, shading provision, and sidewalk width exert significant impacts on walking comfort and perceived safety (Ewing & Handy, 2009; Tabatabaie et al., 2023). For instance, Kim et al. (2014) explicitly pointed out that the quality of street greenery, shading, and pedestrian space directly determines pedestrians' walking duration and travel frequency. The SWI developed in this study is explicitly designed at the street scale, incorporating micro-level walking environment indicators including street shade rate, street greenery, enclosure, openness, and visual permeability. These metrics can more directly reflect pedestrians' perceived walking comfort, sense of security, as well as the attractiveness and social interactivity of streets. The empirical analysis conducted in the historic district of Guangzhou demonstrates that the SWI can not only effectively capture the overall walkability and its spatial disparities across different streets in the district, but also clearly reveal the heterogeneous performance of each street across distinct micro-environmental dimensions. This provides a solid scientific foundation for the targeted, street-by-street optimization and upgrading of the walking environment in future urban planning practices.

In high-density megacities, the pedestrian transportation system and high-quality walkable environment are of critical importance, particularly in historic districts that are typically characterized by narrow street layouts and complex mixed traffic conditions (Zhou et al., 2019). Existing walking route identification methods generally rely on shortest-distance or minimum-travel-time algorithms, largely overlooking the quality of the walking environment and pedestrians' perceptual experiences during the route planning process (Lu & Chen, 2024; Nagata et al., 2020; Shin & Woo, 2024). Nevertheless, a growing body of recent evidence suggests that walking path selection should not be solely determined by the shortest travel time or distance, but should also prioritize walking environment attributes such as greenery coverage, street width, and traffic safety (Lu & Chen, 2024). Based on the self-developed SWI, this study proposes an innovative optimal walkable route identification method, which fundamentally differs from conventional shortest-distance-oriented route planning frameworks. In current mainstream mobile mapping services such as Google Maps and Baidu Maps, the walking route recommendations generated for users between any given origin and destination are almost exclusively based on the shortest path algorithm. While the recommended shortest walking route may minimize travel time, it is not necessarily the most pedestrian-friendly or perceptually comfortable option. Walking is a travel behavior that is highly

sensitive to the surrounding built environment. Even though the shortest route may save marginal travel time, choosing a path with superior environmental quality—such as better greenery coverage, sufficient shading, and well-maintained pedestrian space—can substantially enhance walking comfort and perceived safety (Koo et al., 2022). This value is particularly prominent for older adults with limited walking capacity and pedestrians who are more sensitive to walking environment attributes. Therefore, the optimal walkable route identification method proposed in this study carries considerable practical application value. For example, it can be integrated into mainstream map services to provide users with more diversified, pedestrian-centered walking route options. Meanwhile, our empirical findings confirm that although the optimal walkable route may be slightly longer than the shortest path, its overall walking environment quality is substantially improved. This finding echoes the recent research on pedestrian detour preference, confirming that prioritizing walkability over strict shortest distance can deliver more satisfying travel experiences for pedestrians(Loo et al., 2024). This can significantly enhance pedestrians' walking experience and further encourage the public to choose walking as a preferred travel mode, especially for non-commuting trips such as leisure, recreation, and shopping activities.

Although the Street Walkability Index (SWI) and the optimal walkable route identification method proposed in this study demonstrate practicality and effectiveness, this study still has certain limitations that warrant further refinement and optimization in future research. First, the SWI was constructed from street view images sampled at 35-meter intervals along each street, meaning that the walkability of a street is represented by the environmental conditions at discrete sampling points rather than a continuous, complete record of its entire walking environment. Second, owing to the limitations of the available street view image data and deep learning methods, this study considered only visual comfort and micro-scale environmental attributes related to walking rather than other sensory dimensions or environmental exposure indicators, such as air quality and noise levels along walking routes (Frackelton et al., 2013; Van Dyck et al., 2020). Moreover, future research could incorporate dynamic factors such as real-time weather conditions and pedestrian traffic volume into route recommendation algorithms by integrating big data analytics and real-time monitoring technologies, thereby enhancing the responsiveness and adaptability of these algorithms (Tabatabaie et al., 2023).

6 Conclusion

Focusing on multi-dimensional micro-scale pedestrian environment features, this study developed a Street Walkability Index (SWI) incorporating seven micro-scale environmental indicators and applied it to evaluate the walking environment of a representative historic district in Yuexiu District, Guangzhou, China. Furthermore, an optimal walkable route identification method was proposed based on this SWI and empirically validated within the study area. The principal findings are summarized as follows:

Firstly, the mean SWI value across the historic district is 35.06, with 56.25% of the street segments scoring below this average. Streets with high SWI scores exhibit clear spatial clustering characteristics, and significant disparities in SWI are observed across different road hierarchy categories. Overall, arterial roads present the lowest walkability, whereas branch roads and internal roads demonstrate superior walkability performance compared to arterial and secondary arterial roads. These findings indicate that there remains substantial room for improvement in the walking environment for a considerable proportion of streets within this historic district.

Secondly, the seven micro-environmental indicators that constitute the SWI display diverse spatial distribution patterns, with notable clustering of high-value areas. Significant differences in indicator performance are evident across different road hierarchies. Branch roads and internal roads excel in terms of space vitality, enclosure, pedestrian conditions, and visual permeability, reflecting high levels of walking safety, comfort, and interactivity. However, they exhibit relatively poor performance in openness. Secondary arterial roads generally present the highest level of street greenery, while arterial roads perform best in terms of openness. This indicates that the performance of different walking environment indicators is influenced by a complex interplay of factors, including road hierarchy and spatial location. For future street walking environment renovation and improvement initiatives, targeted strategies can be formulated for individual streets based on the assessment results of these seven micro-environmental indicators.

Finally, the optimal walkable route identification method proposed in this study has been effectively validated. The results demonstrate that for all examined walking trip scenarios, the optimal walkable route does not coincide with the shortest walking route. Although the optimal walkable route entails a slight increase in walking distance (ranging from 0.2% to 14.75% across cases), it yields a more substantial improvement in overall walkability. This enhancement translates into greater walking safety and comfort for pedestrians, making walking a more attractive travel mode and fostering higher levels of social interaction. In the long term, such improvements can contribute to advancing the sustainable development of cities and communities across economic, social, and environmental dimensions.

Declaration of interests

The author declares that there are no conflict of interests concerning this article.

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