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Planning nodes, places, and pedestrian experiences in mountainous cities: an empirical transit station assessment tool

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Introduction: In the context of ongoing discussions in Chongqing (China) about urban development strategies for the city's transit system, this paper introduces an empirical framework for assessing the development of urban transit stations in mountainous cities. Cities in mountainous areas possess unique natural topography, development patterns, cultures, and natural resources, leading to distinct urban development characteristics compared to cities built on plains.

Methods: Drawing on the node-place modelling literature, we develop a multidimensional station assessment methodology adapted for mountainous cities. By adding the dimension of pedestrian experience, we propose indicators that represent the unique challenges of accessing stations in such terrains that are not typically reflected in conventional node-place analysis.

Results: Our findings reveal station-specific development opportunities in greater detail and can guide more targeted planning for land use around stations.

Discussion: Our assessment method is particularly useful for cities facing terrain challenges that impact pedestrian experience.

KEYWORDS

mountainous city, pedestrian accessibility, sustainable city, node-place model, transportation planning, land use planning

1 Introduction

The municipal government of Chongqing has outlined their 14th Five-Year Plan (Chongqing Housing and Urban-Rural Development Commission, 2022), aiming to transform Chongqing into a metropolis by fully developing a "rail-based metropolitan area" with a "one-hour commute circle" (Chongqing Municipal Government, 2020). Existing transit lines will be extended and connected, with new lines being planned to stimulate the growth of specific urban areas. The plan is driven by the region's rapid development and strongly associated with Chongqing's mountainous spatial structure. Chongqing is characterized by a "multi-center, multi-cluster" city layout largely due to the scarcity of flat land (Gao et al., 2023). Dispersed urbanization requires and will be enhanced by strong connections between clusters, with public transport often seen as a key solution. However, effectively coordinating land use with transit development remains a challenge. This is particularly evident in newly constructed stations, where land use planning often fails to keep up with or meet the development needs at these stations.

Future transit development in Chongqing will focus on identifying stations with the potential for further land use development. This potential is determined by two main factors: (1) the accessibility of the location by transit, buses, urban traffic, and pedestrians, and (2) the employment opportunities, resident population, and development intensity within the station's coverage area. Existing "node-place" models (Bertolini and Spit, 1998; Zweedijk and Serlie, 1998; Bertolini, 1999) describe how well land use and transit development are coordinated within station areas. These models often classify stations into empirically informed typologies (Peek, 2006; Chorus and Bertolini, 2011), helping to identify stations that are ready for development or revitalization. This approach guides urban transportation planning to promote more balanced, integrated, and transit-oriented sites (Bertolini, 2008; Chorus and Bertolini, 2011).

In the context of mountainous cities, the conventional node-place model fails to adequately consider the importance of pedestrian experience to and from the node and the place. While subsequent studies have incorporated walkability dimensions into the original model (Schlossberg and Brown, 2004; Vale, 2015; Higgins and Kanaroglou, 2016; Lyu et al., 2016; Jeffrey et al., 2019), they still fall short of capturing pedestrian access conditions in cities built on mountainous terrains. In mountainous cities, like Chongqing, the topography features hilly landscapes with steep slopes, frequent elevation changes, fragmented sidewalks, and winding walking paths adapted to the terrain (Gao et al., 2023). These factors pose challenges to pedestrian movement, often resulting in longer walking times for equivalent distances compared to flat cities. This necessitates new indicators and contextualized empirical models to accurately reflect the dynamics.

This paper introduces new indicators and empirical typologies specifically adapted from node-place models for mountainous cities. Building on existing node-place models, some of which include additional assessment dimensions beyond the node and the place, we propose the dimension of pedestrian experience. This dimension reflects pedestrians' experiences in terms of comfort, effort, and aesthetic elements, and we have devised corresponding indicators to represent them. Based on our analyses, we refine the existing station categories in local transportation plans, which are broad at the strategic level, by introducing a more detailed classification that highlights the development priorities for each station.

The rest of this paper is organized as follows. Section 2 reviews the literature on node-place models and previous studies on pedestrian accessibility. Section 3 introduces our study area, research methods, and explains our indicators in detail. Section 4 presents our station typologies based on cluster analysis, summarizes station-specific accessibility profiles, and elaborates on model improvements using four exemplary cases. Sections 5 and 6 provide discussions and conclusions, illustrating the implications of our findings for other mountainous cities and their planning practices.

2 Literature review

The node-place model integrates land use and transportation planning by analyzing the relationship between a station's transport node function (connectivity and accessibility) and its place function (local land use and activities; Bertolini, 1999; Reusser et al., 2008; Chorus and Bertolini, 2011; Zemp et al., 2011; Cummings and Mahmassani, 2022). By comparing node and place values, it distinguishes typical situations for a station's area - balance, stress, dependence, unbalanced node, and unbalanced place, to guide urban development and transit-oriented planning. Previous applications of the node-place model are usually based on specific case studies and serve two primary functions: First, they generate station typologies for proposing tailored station development plans. For instance, Bertolini's (1999) study of nearly 1700 stations found most in the "unbalanced place" category, suggesting limited opportunities for new development due to high density and diversity (Reusser et al., 2008; Zemp et al., 2011). In Rio de Janeiro, the model classified new train line stations primarily as "balanced" or "dependent," which invites additional land use development to maintain pace (Gonçalves and Portugal, 2008). In Tokyo, most stations showed good equilibrium, with few "unbalanced" nodes or places that require investments in pedestrian space and easier transfer from trains to highway buses (Chorus and Bertolini, 2011). Second, they visualize the performance of stations to allow visual comparisons between stations. Such visualizations usually take the shape of scatter plots where node values are on one axis while place values on the other, or polar graphs where additional dimensions are included and plotted along scaled axes with a common origin. Caset et al. (2019) provide an overview of different types of polar graphs that include a 5-dimensional kite model (Stadsregio Arnhem Nijmegen, 2011), an eight-dimensional web diagram (Singh et al., 2017) and a rose diagram for directional representation of multi-dimensional data (Groenendijk et al., 2018; Caset et al., 2019).

Existing studies have enriched the set of indicators for the node and place components of the node-place model, as detailed in Table 1. Node values typically include the number of train connections, the number and type of feeder transportation connections, parking capacity, and street connectivity. Place values are often presented through Ewing and Cervero's "5Ds" framework, which includes Density, Diversity, Design, Destination accessibility, and Distance to transit (Ewing and Handy, 2009; Ewing and Cervero, 2010; Giles-Corti et al., 2016; Zhang et al., 2019). The shared objective of these models, regardless of their indicators and application context, is to empirically inform policy discussions. Considering that most node and place indicators focus on a limited set of physical dimensions related to transportation and land development, often missing nuanced details about people's experiences and behaviors, recent studies have added more dimensions to highlight demand-side constraints and needs (Caset et al., 2019). These new dimensions include walkability (Jeffrey et al., 2019), accessibility (Cummings and Mahmassani, 2022), ridership (Cao et al., 2020), orientation (Lyu et al., 2016), transport network centrality (Dou et al., 2021), social contact (Zhou et al., 2023), and so on. Emerging big and open data sources such as OpenStreetMap (OSM), the online map Points of Interest (POI) were increasingly employed to describe the dynamic activity in the physical environment (Dou et al., 2021; Zhou et al., 2023).

Walkability can be measured as a function of various indicators describing the structure of the road network, the land use characteristics of a neighbourhood, proximity to jobs, services, and public transport (Giles-Corti et al., 2016), visual attractiveness, comfort, infrastructure quality (Gori et al., 2014), and pedestrian safety (Macioszek and Wyderka, 2021; Macioszek et al., 2023). Researchers may use half-mile or quarter-mile buffers around public transportation stations to describe accessible service areas, based on an acceptable walking distance (El-Geneidy et al., 2014; Vale, 2015; Singh et al., 2017). Network travel time is also used to describe reachable areas, such as estimating the time it takes to walk from one point to another within a given urban network, accounting for factors

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TABLE 1 Indicators used in the reviewed node-place model literature.

Node index	Bertolini (1999), Reusser et al. (2008), Chorus and Bertolini (2011), Zemp et al. (2011), Ivan et al. (2012), Vale (2015), Higgins and Kanaroglou (2016), Singh et al. (2017), Vale et al. (2018), Cao et al. (2020), Dou et al. (2021), Cummings and Mahmassani (2022), Zhou et al. (2023)
(a) Transit service	
Number of directions served by transit	
Frequency of transit services	
Number of stations within 20–45 min of travel	
(b) Feeder transportation	
Number of directions served by bus	
Frequency of bus services	
Car parking capacity	
Intersection density	
Bicycle paths and parking facilities	
Place index	
(a) Density	
Number of residents/Population density	
Number of workers per economic cluster	
Number of POIs	Lyu et al. (2016); Vale et al. (2018)
(b) Diversity	
Land use mix	Vale et al. (2018), Dou et al. (2021), Su et al. (2022)
Variety of POIs	
(c) Design	
Intersection density	Vale et al. (2018); Higgins and Kanaroglou (2016); Zhang et al. (2019)
Accessible network length	
Extensions	
(a) Walkable environment	
Pedestrian shed ratio	Vale (2015)
Walkability	Jeffrey et al. (2019)
(b) Interaction	
The degree of orientation of transit and development components towards each other	Lyu et al. (2016), Liao and Scheuer (2022)
(c) Social contact	
Socio-demographic statistics	Cummings and Mahmassani (2022)
Social contact potential at and around station areas	Zhou et al. (2023)

such as street layout, the presence of natural barriers, and walking speed (Monajem and Nosratian, 2015; Cong et al., 2022). Vale (2015) and Lyu et al. (2016) have emphasized the need to incorporate pedestrian walking environment of a neighbourhood into the node-place model. Jeffrey et al. (2019) isolated walkability from the node and place dimensions and derived a typology for evaluating access to metropolitan Melbourne's train stations based upon a cluster analysis methodology using 14 walkability measures. Their analyses distinguished stations located in high walkable neighbourhoods and those in areas with only some walkable features.

Mountainous cities differ significantly from flat cities in terms of walkability due to their unique topography. Gao et al. (2023) identified several factors that discourage pedestrian activity in mountainous cities. The steep inclines and slopes of the local terrain make walking difficult by shortening comfortable walking distances. The mountainous features, like changes in altitude and small-scale slopes, limit the number of pedestrian pathways. Limited available land for construction leads to higher building density, narrower walking paths and more intersections (Gao et al., 2023). Sun et al. (2015) highlighted that people's perception of hilly environments can discourage walking. Sun et al. (2020) found that significant detours can make some locations nearly inaccessible, reducing the actual walkable area around transit stations. Xiong et al. (2024) uncovered nonlinear effects of road network density and land use mix on walking, contrasting common assumptions based on flat cities.

As demonstrated in the literature above, pedestrian accessibility at transit stations is crucial for informing empirical policy discussions that coordinate transportation and land use for sustainable cities. However, current indicators may not adequately reflect the accessibility needs in cities with challenging terrains. Identifying this gap, we focus on evaluating pedestrian experience in mountainous cities, thereby broadening the scope of node-place analysis beyond existing metrics.

3 Methodology

3.1 Study area

Chongqing is a large sprawling city in western China of approximately 80,000 km^2 and is home to over 30 million people (Chongqing Municipal Government, 2023). By 2050, its population is projected to exceed 40 million. This rapid growth will require an additional 1.6 million residential dwellings to be built in the next 25 years (Li, 2007). Urban sprawl into suburbs has led to high rates of car dependency. Recent state government planning emphasizes the importance of preparing for future population growth in established areas, including through transit development (Chongqing Housing and Urban-Rural Development Commission, 2022). In 2005, Chongqing became the 9th city in mainland China and the first in western China to launch its metro system. By the end of 2023, the city had 11 metro lines in operation, spanning a total of 494,6 km and 253 stations (China Ministry of Transport, 2024). These lines cover major functional nodes, such as airports, high-speed rail stations, comprehensive hubs, and business districts, with a maximum daily ridership of more than 5 million passengers. New lines under construction, along with branches and extensions, total approximately 186 km^2, shaping the city's future development directions and connecting peripherals in the metropolitan area (Chongqing Housing and Urban-Rural Development Commission, 2022).

Walking accounts for over 40% of journeys made by commuters and is vital for last-mile mobility (Chongqing Municipal Government, 2019). Establishing a comprehensive regional urban transit system requires investment in pedestrian-friendly pathways and innovative solutions to ensure transit hubs are easily accessible despite the challenging terrain constraints. In December 2020, the Chongqing Municipal Government issued an implementation plan for Transit Oriented Development (TOD), announcing that 98 metro stations would undergo TOD integration (Chongqing Municipal Government, 2021). The goal is to enhance the surrounding infrastructure of these stations, strengthen the structure and functionality of pedestrian systems, and improve accessibility to rail transit. Considering the rapid development of its rail transit system, which often precedes and influences land development, Chongqing serves as an exemplary case study for exploring the relationship between transit and land use development. Moreover, it provides an opportunity to identify stations at various stages of development, making it suitable for implementing differentiated development strategies. The study area of this paper is shown in Figure 1.

3.2 A modified station assessment model for mountainous cities

We conducted an analysis encompassing 22 metro station areas in Chongqing, delineated based on the metro map (see Figure 1). Our model construction involved the utilization of two types of datasets: (Bertolini, 1999) spatial data, including sidewalk information sourced from the OpenStreetMap website, POI data and building footprint data acquired from Gaode Maps Place API, and (Bertolini, 2008) quantitative attribute data for each station area, including neighborhood-scale census data including population and employment. Refer to Table 2 for a list of data sources used in this study.

Building on the conventional node-place model, we incorporated pedestrian accessibility metrics to evaluate in detail the walking environment in mountainous cities. Our assessment model takes the shape of a rose diagram (Caset et al., 2019) with 3 dimensions and 11 indicators. The pedestrian experience dimension reflects the ease,

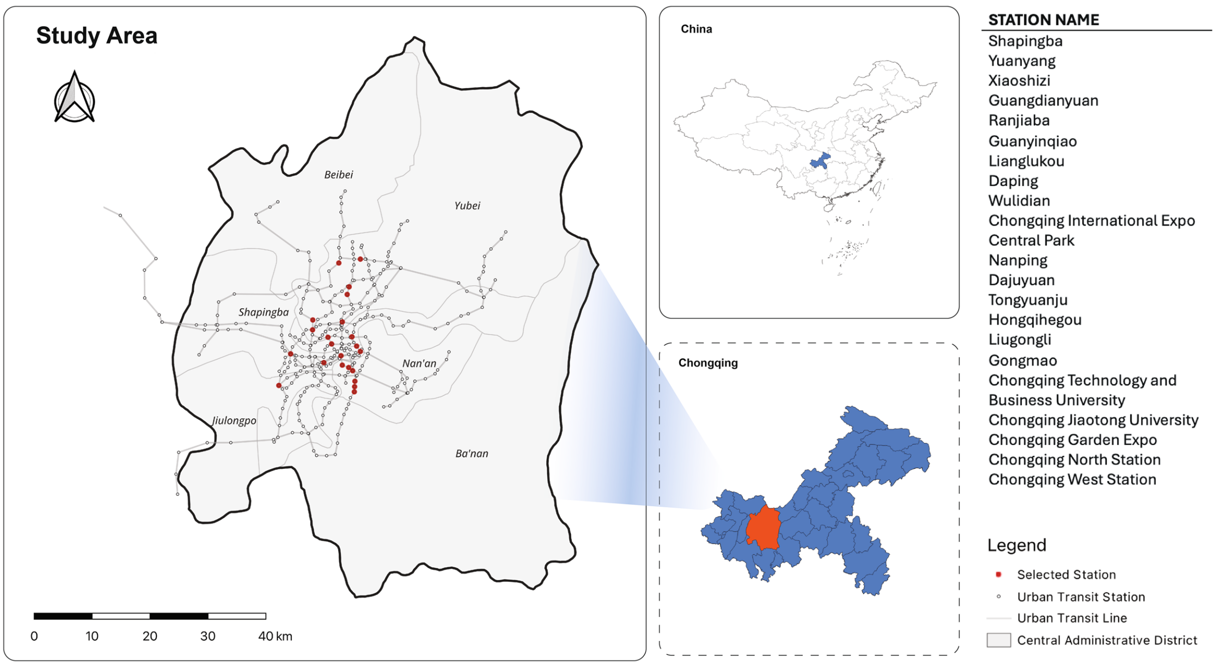

FIGURE 1
Study area: identified stations in central administrative district of Chongqing.

enjoyment, and directness of reaching a station for individuals. This includes considerations like directness of pathways, density of POIs along the route, availability of shading. Each indicator is normalized to vary between 0 and 100. We illustrate the model structure in Figure 2 and detail the indicators in the subsequent sections.

TABLE 2 Data types and sources used in this study.

Data type	Source
Street network; Sidewalks	OpenStreetMap (2023)
Urban Transit lines and stations	Chongqing Transport Bureau (2023)
Point of Interest	Gaode Map Place API (2023)
Building footprint; Building height	Gaode Map (2023)
Streetview Images	Baidu Streetview (2023)
Population; Employment	Bureau of Statistics of Chongqing (2022)
Land use	Bureau of Statistics of Chongqing (2022)

3.2.1 Node dimension

Following existing scholarship, we assess node values based on criteria such as the proximity of other transit stations, the quantity and coverage of bus stops, and the connectivity of the station to urban road networks (Gonçalves and Portugal, 2008; Vale, 2015; Zhang et al., 2019; Dou et al., 2021; Su et al., 2022). We exclude accessibility by bicycle in this calculation because commuting by bicycle is less than 1% of the modal share in Chongqing, a trend commonly observed in other mountainous cities as well. Node indicators are listed in Table 3.

3.2.2 Place dimension

Previous studies typically apply catchment areas for each station to measure the place index (Vale, 2015; Jeffrey et al., 2019). The distance threshold for the place index is not universally standardized and

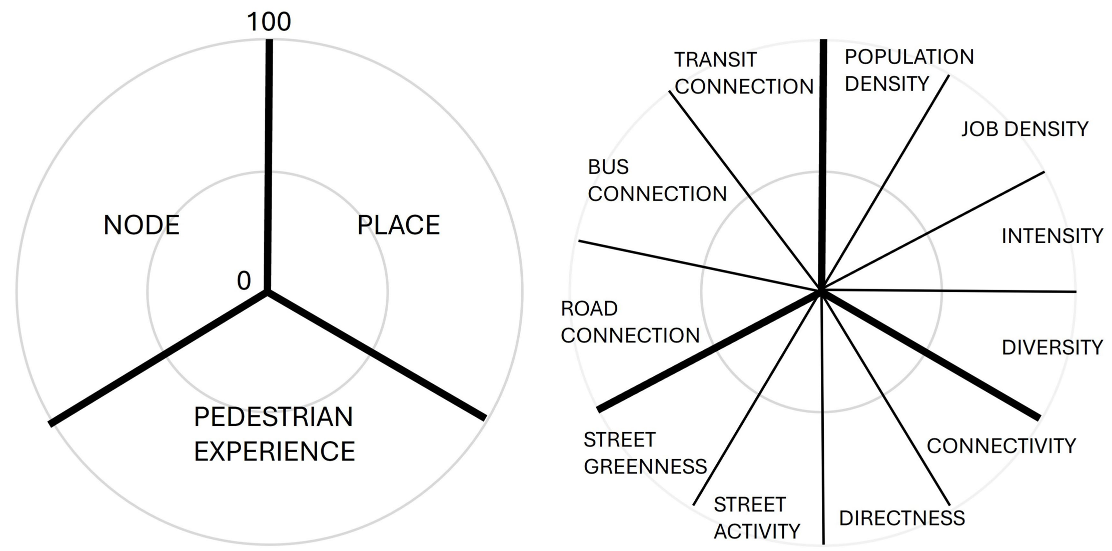

FIGURE 2
A station area assessment model structure.

TABLE 3 Indicators of the node dimension and calculation methods.

Indicator description	Description	Calculation method
N1: Transit Coverage	Accessibility by transit	$N1 = \frac{Na}{Ncq}$ (1) N_a: Number of transit stations within 20 min of travel. N_{cq}: Total number of transit stations.
N2: Feeder Transport	Accessibility by bus, evaluated by number of stops and number of directions served	$N2 = N_l \sum_{1}^{n} L_i$ (2) N_l: Number of directions served. n: Number of transit station entrance/exit. L_i: Number of connecting bus stops at entrance/exit i.
N3: Motorway Access	The amount of road length per unit area.	$N3 = \frac{L}{Sd}$ (5) L: Total length of roads (km) S_d: Comprehensive development areas based on a station radius length of 800 m

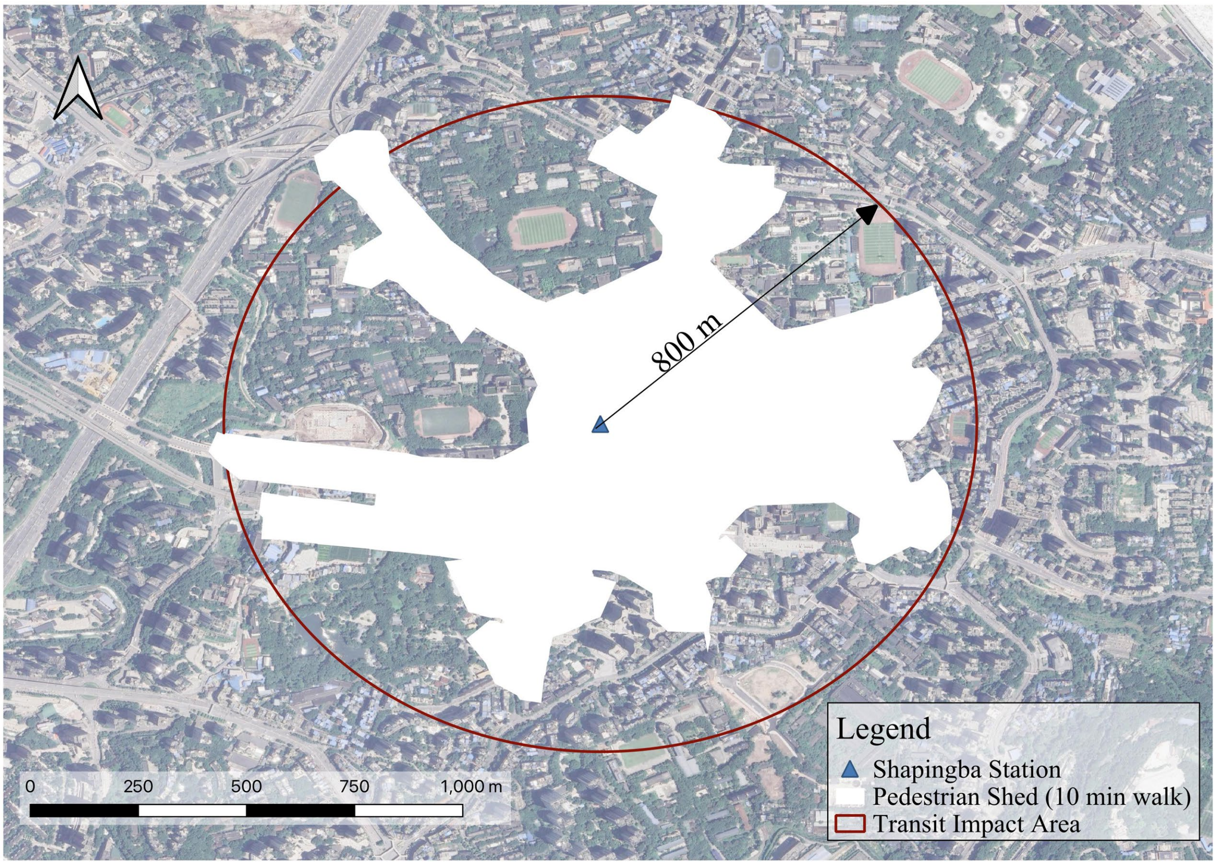

FIGURE 3
Illustration of ped-shed area and TIA.

commonly ranges from 5 to 10 min of walking, roughly equivalent to a 400–800 m walking distance (Frank et al., 2005, 2006; Zemp et al., 2011; Jun et al., 2015; Lyu et al., 2016; Li et al., 2019). Walkability extends beyond straight distances, particularly in mountainous cities. Factors such as steep walking slopes and irregular pedestrian networks significantly influence the distances most people are willing to walk. This study applies a circular area with a radius of 800 m as the transit impact area (TIA) and a network catchment area within 10 min of walking as the pedestrian sheds (Ped-Shed) area, drawing from Vale (2015). We aim to account for the ease of access when evaluating the vibrancy, richness, and liveability of urban places by comparing the actual accessible area to the maximum theoretical coverage. The Ped-Shed is determined using the GaoDe Map Distance API for an accurate representation of real-world accessibility in the given location. Figure 3 illustrates the TIA with the actual accessible Ped-Shed area at Shapingba station.

We use four indicators to describe the place dimension: population density, employment density, development intensity and land use mix. Having access to high-density land uses and the opportunity to engage in a variety of activities provides favorable conditions for both land use and transport development (Dittmar and Poticha, 2004; Cao et al., 2006; De Vos et al., 2013). Place indicators are listed in Table 4.

3.2.3 Pedestrian experience dimension

Evaluating pedestrian accessibility in mountainous areas differs from that in flat cities due to terrain challenges. Areas theoretically accessible can become inaccessible due to significant detours, long stairs, or elevation differences that disrupt direct connections. To empirically represent pedestrian experiences in accessing transit stations, we introduced indicators including parcel connectivity, pedestrian directness, street activity, and street greenery (Table 5). Parcel connectivity measures the ratio of directly connected parcels within walking distance. Pedestrian directness measures the ratio of actual walking distance to Euclidean distance, with lower values indicating fewer detours (Stangl, 2019). The street activity index comprehensively measures the number and density of POIs along streets (Yue et al., 2017). Street greenery refers to the percentage of visible greenery from specific vantage points, collected from Baidu Streetview images, reflecting the amount of vegetation in the urban environment (Long and Liu, 2017). These metrics help us understand how pedestrians navigate around stations, reflecting their experiences in terms of comfort, effort, and aesthetics.

3.3 Analyze patterns and develop a typology of stations

After we obtain the 11 indicator values for all stations, we create a rose diagram for each station. The diagram visualizes the 11 indicators in a circular layout, with each indicator ranging from 0 to 100. We then develop our typology of stations based on their node,

TABLE 4 Indicators of the place dimension and calculation methods.

Indicator description	Description	Calculation
P1: Population density	The square root of the product of the population density within TIA and ped-sheds	$P1 = \sqrt{\left(\frac{(H_t + W_t - HW_t)}{S_t}\frac{(H_p + W_p - HW_p)}{S_p}\right)}$ (6) H: Number of residents in TIA (H_t) and ped-shed (H_p) W: Number of workers in TIA (W_t) and ped-shed (W_p) HW: Local workforce residents in TIA (HW_t) and ped-shed (HW_p) S_t: Area of TIA of each station S_p: Area of ped-shed of each station
P2: Employment density	The square root of the product of the job density within PIA and ped-sheds	$P2 = \sqrt{\left(\frac{W_t W_p}{S_t S_p}\right)}$ (7) W: Number of workers in TIA (W_t) and ped-shed (W_p) S_t: Area of TIA of each station S_p: Area of ped-shed of each station
P3: Development intensity	The density of urban fabric based on FAR	$P3 = \sqrt{\left(\frac{\sum_{i=1}^{m} f_i S_i \sum_{i=1}^{n} f_i S_i}{S_t S_p}\right)}$ (8) f_i: Building heights. S_i: Building ground area. m: Number of buildings in TIA. n: Number of buildings in ped-shed.
P4: Degree of functional mix	Measure of the diversity of different land use types	$P4 = \frac{-\sum_{j=1}^{J} p_j \ln p_j}{\ln J}$ (9) p_j: The proportion of built-up area for each land use type within the total built-up area of TIA J: Total number of land use types

place and pedestrian experience profiles. Principal Components Analysis (PCA), a data reduction technique and multivariate statistical method, is used to extract synthetic variables or factors from the original set. This approach assumes that the original data can be represented as a linear combination of "artificial" variables corresponding to latent factors. We performed a Hierarchical Clustering on Principal Components (HCPC) to identify groups of similar observations in the dataset and enhance cluster interpretation by leveraging the reduced, informative components from PCA. This study conducted factor and cluster analysis using R, specifically with the factoextra and FactoMineR packages.

4 Results

4.1 Station assessment result

Our factor analysis (orthogonal, varimax rotation), results in 2 interpretable factors, with an eigenvalue larger than 1 and explaining 60% of total variance. Factor 1 has strong loadings for place indicators including population and employment density (P1, P2) and development intensity (P3). Factor 2 has strong loadings for indicators on connections including motorway access (N3) and pedestrian directness (W2). Based on these factors, an HCPC is conducted, resulting in 5 interpretable groups of stations, as shown in Figure 4.

Stations in Cluster 5 have high development density and well-connected road networks compared to overall means across all clusters. Place variables (P1, P2, P3) and motorway access (N3) are most significantly associated with Cluster 5. Cluster 4 is significantly associated with street greenness (W4), land use mix (P4), and street activity (W3), indicating a pedestrian-friendly built environment. Cluster 3 is strongly influenced by node values but are less influenced by land use diversity (P4), with stations in this category strong in transportation functions. Stations in Cluster 2 features low place variables and a lack of parcel connectivity (W1). These stations are relatively new, suggesting opportunities to enhance land use development in their surrounding areas. Cluster 1 only includes Chongqing West Station, a unique example with low N1 (transit coverage) and a pedestrian-unfriendly environment. This station, operational since 2018, primarily serves regional rails and has limited transportation and pedestrian connections. We summarize the values of 11 indicators in our NPW (node, place, pedestrian) model in Figure 5.

The Chongqing Comprehensive Transportation Plan (2021–2035) categorizes urban transit stations into four functional types—Urban Center Stations, General Urban Stations, Transport Hub Stations, and Special Control Stations—based on their locations and functions within the transportation system. In this study, we blend these typologies to determine the stations that fall into different intersections and to gain insights into station-specific development characteristics. Table 6 presents a cross-tabulation of the station classifications.

These crosstabulations provide detailed insights into station-specific accessibility characteristics, which are not fully captured by

TABLE 5 Indicators of the pedestrian experience dimension and calculation methods.

W1: Parcel Connectivity	The ratio of directed connected parcels within walking distance.	$W1 = \frac{N_e}{N_E}$ (3) N_e: Number of parcels that are directly connected from the entrance/exit of a transit station. N_E: Number of parcels covered within 10 min of walking
W2: Pedestrian Directness	The ratio of Euclidean distance to actual walking distance, high value means less detours.	$W2 = \frac{nr}{\sum_1^n l_i}$ (4) n: Number of destinations r: Euclidean distance from the station to each destination l_i: Walking distance to each destination
W3: Street Activity Index	A comprehensive measure of number/density of POIs along the streets	$W3 = \ln\left(\rho_P M_P\right)$ (10) ρ_P: POI density. M_P: POI diversity.
W4: Street green view index		$W4 = P_{GLR}$ P_{GLR}: Street greenery coverage. The percentage of greenery visible from a particular vantage point on a street

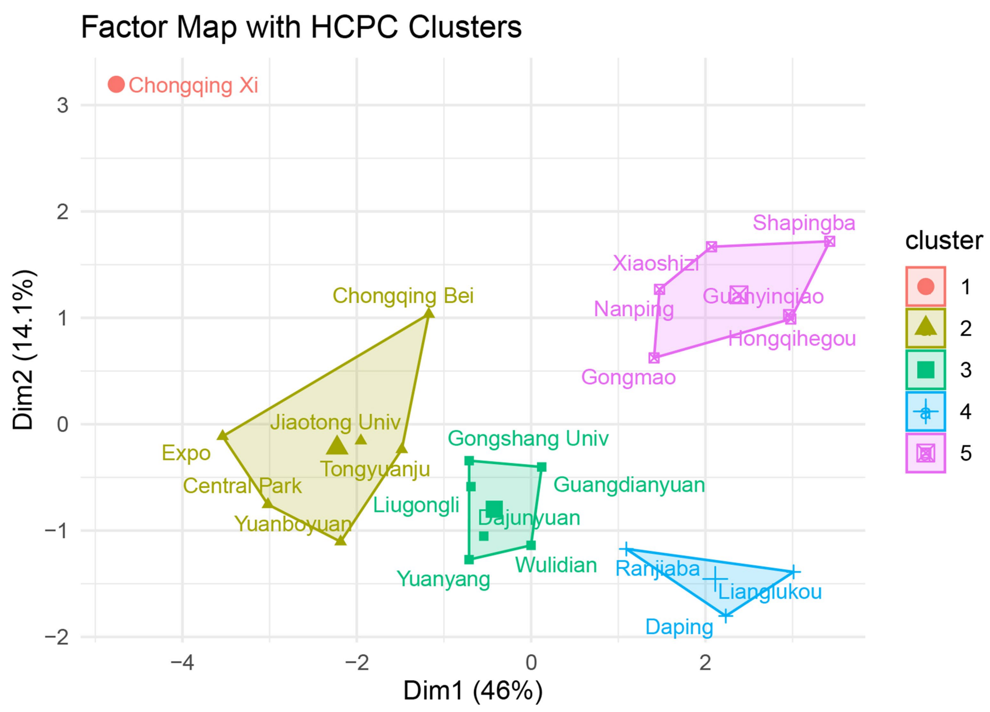

FIGURE 4
HCPC clustering results.

standard node-place analyses. There is a noticeable overlap among the strong stations: Type 5 stations almost exclusively fall under urban stations, while Types 4 and 3 are mostly general urban stations with moderate to strong network functions. Special control stations, though vaguely defined in the municipal plan, typically refer to stations that are not commercial hubs but are crucial for accessing new and emerging city landmarks like the new Expo Center or the Garden Expo Park. Interestingly, both major transit hub stations, Chongqing North and Chongqing West, exhibit low development and pedestrian experience, indicating that while they serve significant transit functions, they are not conducive to pedestrian activities.

We visualize our blended station topologies based on NPW model in Figure 6. We have five categories: urban stations with high development and average pedestrian experience, urban stations with average development and high pedestrian experience, suburban stations with average development and average pedestrian experience, suburban stations with average centrality, low development and low pedestrian experience, and transportation hubs with low development

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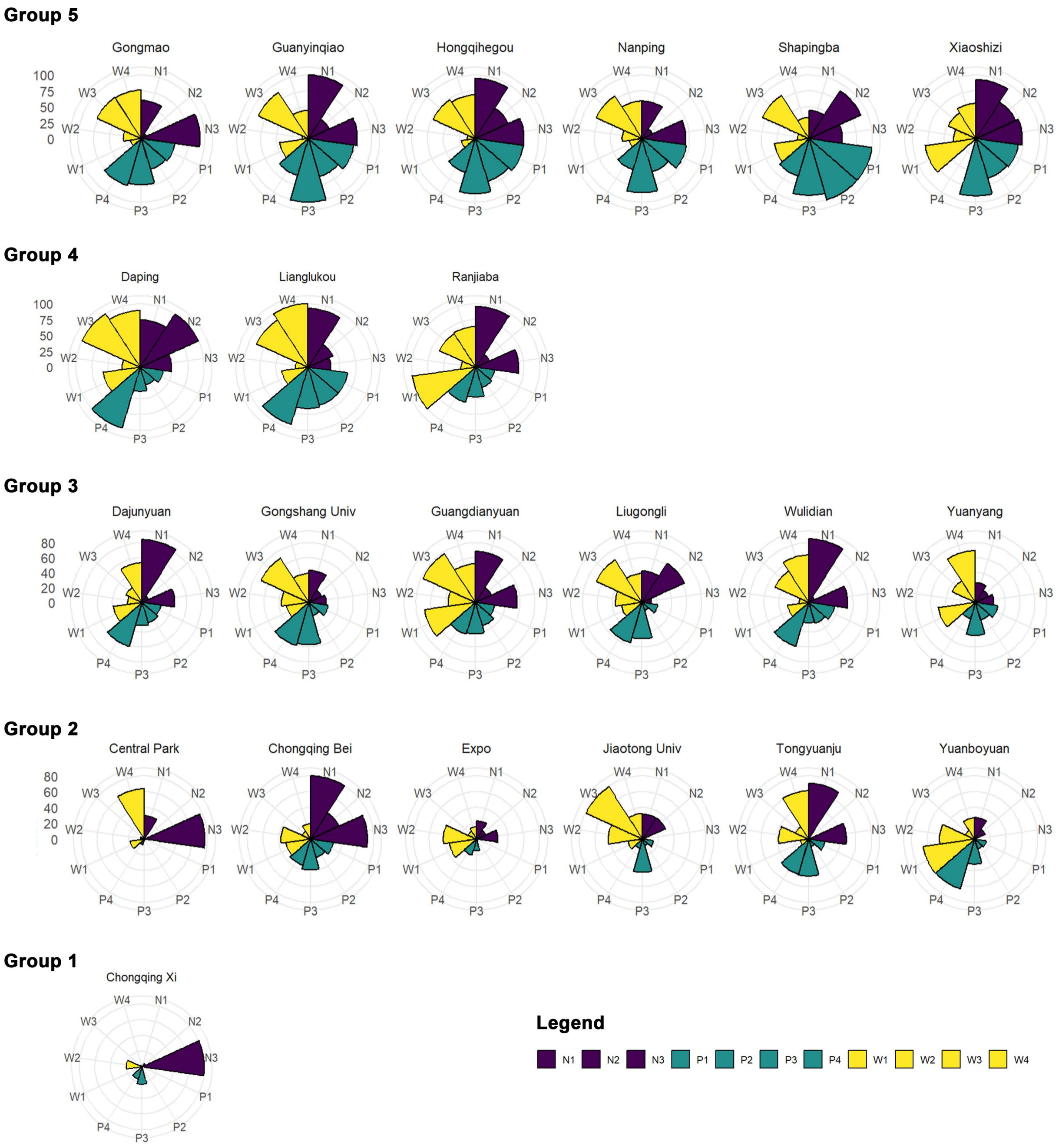

FIGURE 5
Indicator values for station profiles.

and low pedestrian environment. Each category diversifies the land use and pedestrian development opportunities for stations.

4.2 Practical implication on four stations

In order to clarify what the station-specific development opportunities may mean for planning practice, this section discusses the characteristics of four stations, each belonging to one category from our NPW typology. We describe how the additional pedestrian experience dimension sheds light on targeted and prioritized planning recommendations. We also relate our findings to the objectives of transportation and land use planning policies in mountainous cities.

4.2.1 Shapingba Station

Located in one of the central business districts (Sanxia Plaza) in Chongqing, Shapingba Station belongs to Cluster 5 in NPW typology. Loop Line, Line 1, and Line 9 intersect at this station. The area surrounding the station has been well-developed, with a relatively high level of land development and an integrated transportation system, including comprehensive bus connections. Additionally, the station has been further enhanced with the recent completion and

TABLE 6 Cross-table of cluster categories and station types in the local plan.

	Urban Center Stations	General Urban Stations	Special Control Stations	Transport Hub Stations
High centrality, high development, average pedestrian experience	Shapingba, Xiaoshizi, Guanyinqiao, Hongqihegou, Nanping	Gongmao		
High centrality, average development, high pedestrian experience	Daping, Lianglukou	Ranjiaba		
Average centrality, average development, average pedestrian experience		Guangdianyuan, Liugongli, Wulidian, Yuanyang, Gongshang Univ.	Dajuyuan	
Average centrality, low development, low pedestrian experience		Jiaotong Univ., Tongyuanju	Yuanboyuan, Expo, Central Park	Chongqing North
Low centrality, low development, low pedestrian experience				Chongqing West

operation of the Shapingba high-speed rail hub and its superstructure. The passenger traffic in and out of this station is expected to grow. Figure 7 depicts the population density, employment distribution, street POI distribution, and sidewalk distribution within the station's impact area.

Table 7 presents the indicator values of Shapingba Station. The population and job density of Shapingba Station are the highest among all stations in this study. The indices for street activity and pedestrian directness are also on the higher end.

Shapingba Station has high development density and well-connected road networks, surpassing the average level across all clusters. Land use in the station's vicinity has been maximized, and additional development could potentially lead to conflicts due to limited available space. However, implementing urban design strategies to upgrade the walking environment of existing spaces can mitigate these challenges and foster sustainable growth. This may involve creating pedestrian-friendly paths, improving park-and-ride connections, enhancing streetscapes, and integrating green infrastructure.

4.2.2 Guangdianyuan Station

Located in the rapidly developing Yubei District in the northern suburb of Chongqing, Guangdianyuan Station is a Line 6 station that was completed and put into operation in December 2014. Commercial offices and research use dominate the surrounding land use. Figure 8 depicts the population density, employment distribution, street POI distribution, and sidewalk distribution within the station's impact area. Table 8 presents the indicator values.

Guangdianyuan Station falls within cluster 3 and primarily serves the Guangdian Industrial Park, which situates away from the main urban area of Chongqing. Consequently, the station is serviced by only one transit line, with limited bus routes available, resulting in lower feeder transport convenience and node values. While the area boasts a large catchment area, its functional diversity is limited, mainly comprising commercial offices and research facilities, with moderate population and employment density. Pedestrian paths are generally favorable, with no significant slopes or detours. Thus, fully leveraging transportation and land use opportunities will be critical for future station development, including enhancing land use diversity and intensity, and ensuring pedestrian connections.

4.2.3 Central Park station

Central Park station was initially conceived to serve long-distance commuters from two of Chongqing's planned new towns—Airport New Town and Yuelai New Town in the northern part of Chongqing. Currently, Central Park station only serves Line 10. The area around the station is still under development, with minimal land development and limited pedestrian services. Additionally, the station does not provide transfers to any bus lines. The station is classified into Cluster 2 in our model. Analysis of population density, job distribution, POI and sidewalk distribution within the station's influence area can be seen in Figure 9.

The construction of Central Park Station was primarily driven by TOD and occurred before the comprehensive development of the surrounding parcels. These parcels are yet to be fully developed, showing sparse population and job density, inadequate street activity, and the lowest feeder transport and development intensity among all 22 stations. However, this offers an excellent opportunity to shape a balanced, well-developed area and create the most suitable pedestrian system for the location from the outset. Given that Central Park Station is still in its early development stage, it is crucial to align subsequent infrastructure development with its intended purpose and support the ongoing parcel planning and development processes (Table 9).

4.2.4 Chongqing North Station

Chongqing North Station is adjacent to the Chongqing North Railway Station, which is the largest passenger transportation center in Southwest China and Chongqing's primary high-speed rail hub. Consequently, this metro station serves as a transfer hub for multiple metro lines: Loop Line, Line 3, Line 4, and Line 10, making it a pivotal transportation node. The southern square area of the Chongqing North Railway Station is part of an existing developed area, with the surrounding land primarily used for transportation facilities such as bus terminals and long-distance bus stations, complemented by commercial and residential areas. The northern square area has recently expanded and is currently under development. Analysis of population density, job distribution, POI and sidewalk distribution within the station's influence area can be seen in Figure 10.

Chongqing North Station exemplifies a location where prioritizing node functions is crucial. Its role as a transportation hub restricts

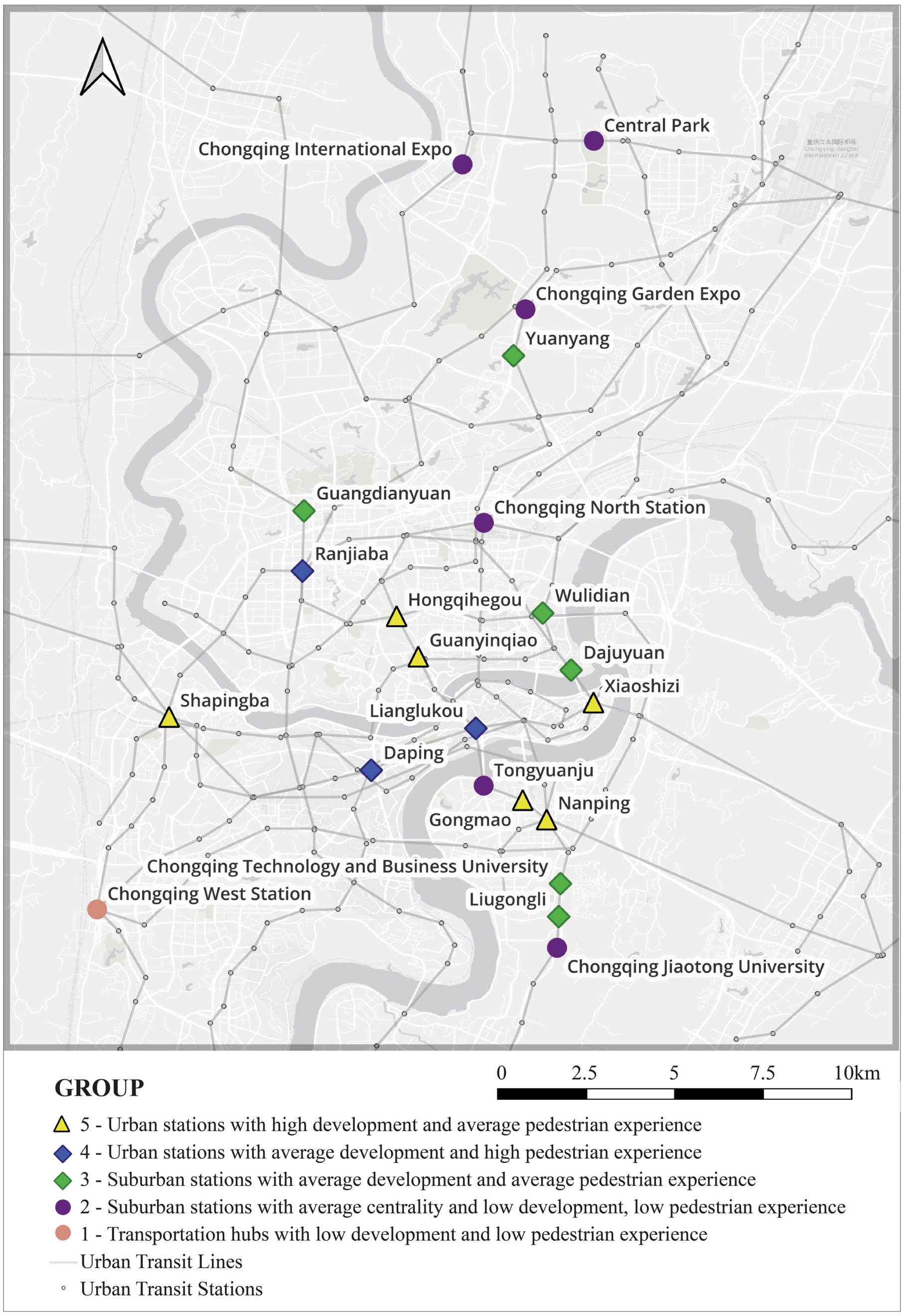

FIGURE 6
Urban transit station group map.

extensive land development due to limited space and suitability. To enhance connectivity, we can improve the pedestrian system by adding greenery, establishing convenient connections with local buses and guidance systems, and enhancing street-level commercial activities (Table 10).

5 Discussion

This research aims to introduce an empirical framework tailored for assessing urban transit stations in mountainous cities. Mountainous cities present distinct challenges when it comes to transportation and land use development, particularly due to their intricate road network layouts and pedestrian detours resulting from terrain elevation. Insufficient pedestrian infrastructure can hinder the connection of certain land parcels, making them impractical or unattractive for development. These challenges can be reflected using the node-place model framework combined with pedestrian-specific indicators. Our new model allows us to better categorize different urban transit station areas according to their respective realized pedestrian benefits.

The significance of our typology lies in its ability to reflect the diverse development statuses and needs of stations within a city. Unlike the traditional urban and suburban classifications, our

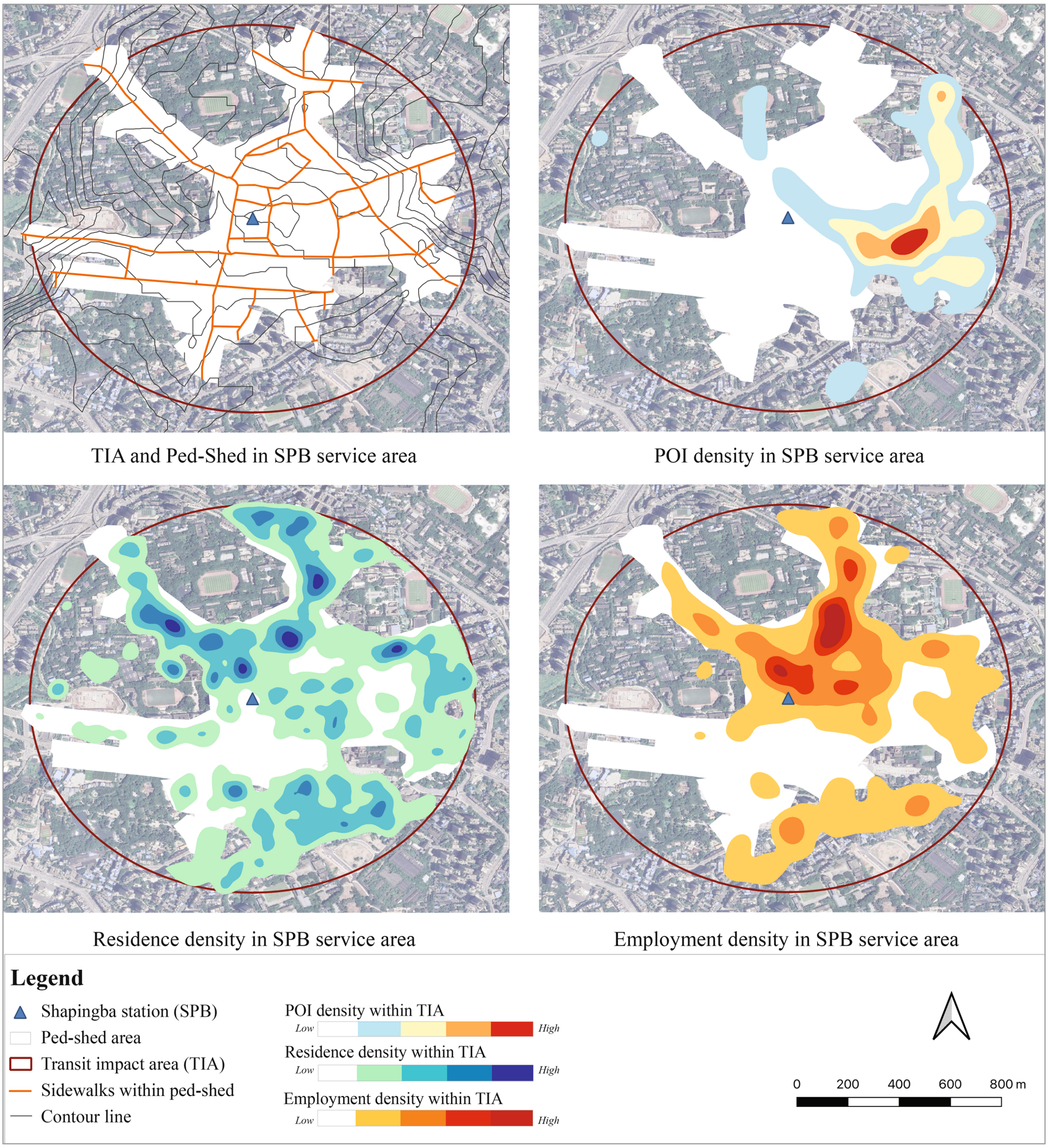

FIGURE 7
Shapingba Station analysis maps.

typology reveals that stations located within the same urban/suburban areas exhibit varied characteristics and requirements. For instance, while Gongmao, Ranjiaba, and Guangdianyuan are all classified as general urban stations, their strengths and priorities differ as shown by the rose diagram. Ranjiaba excels in pedestrian accessibility, Gongmao has fully developed parcels, and Guangdianyuan requires improvement in land use mix.

Furthermore, the additional dimension of pedestrian experience evaluation proves valuable in a mountainous city. Stations near the commercial core of the old city, such as Shapingba, Daping, Xiaoshizi, and Guanyinqiao, are characterized by high node and place values. However, Daping is more pedestrian-friendly, whereas Shapingba, despite being busy, has limited space and could benefit from pedestrian system improvements. Without considering this dimension, opportunities for enhancing the pedestrian experience at these stations might be overlooked.

We would also like to emphasize the importance of bus connections in station areas. Our indicator system includes feeder transport (N2), which evaluates the number and frequency of connected buses. The mean value of N2 across the 22 stations is 31 (out of 100), with 60% of the stations scoring below this mean. Many suburban stations lack immediate ground transport

TABLE 7 Indicator values for Shapingba Station.

Node	N1	Transit coverage	44.2
	N2	Feeder Transport	89.7
	N3	Motorway Access	52.8
Place	P1	Population density	100
	P2	Employment density	100
	P3	Development intensity	89.4
	P4	Degree of Mix	61.1
Pedestrian Experience	W1	Parcel Connectivity	55.1
	W2	Pedestrian Directness	82.1
	W3	Street activity	80.7
	W4	Street green view	33.2

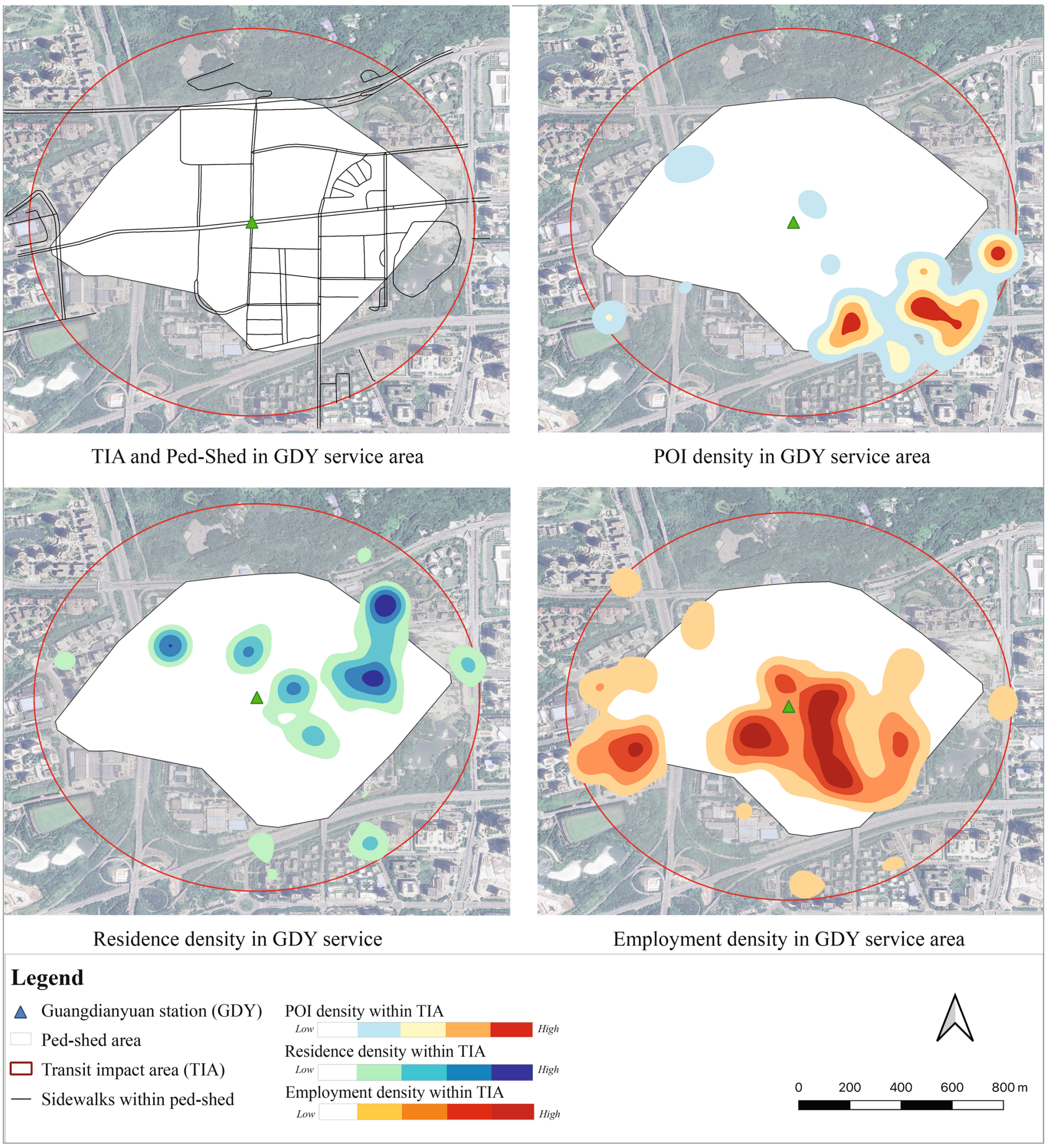

FIGURE 8
Guangdianyuan Station analysis maps.

TABLE 8 Indicator values for Guangdianyuan Station.

Node	N1	Transit coverage	68.4
	N2	Feeder Transport	23.7
	N3	Motorway Access	56.4
Place	P1	Population density	26.1
	P2	Employment density	32.6
	P3	Development intensity	42.5
	P4	Degree of Mix	44.4
Pedestrian Experience	W1	Parcel Connectivity	68.9
	W2	Pedestrian Directness	63.6
	W3	Street activity	67.5
	W4	Street green view	51.7

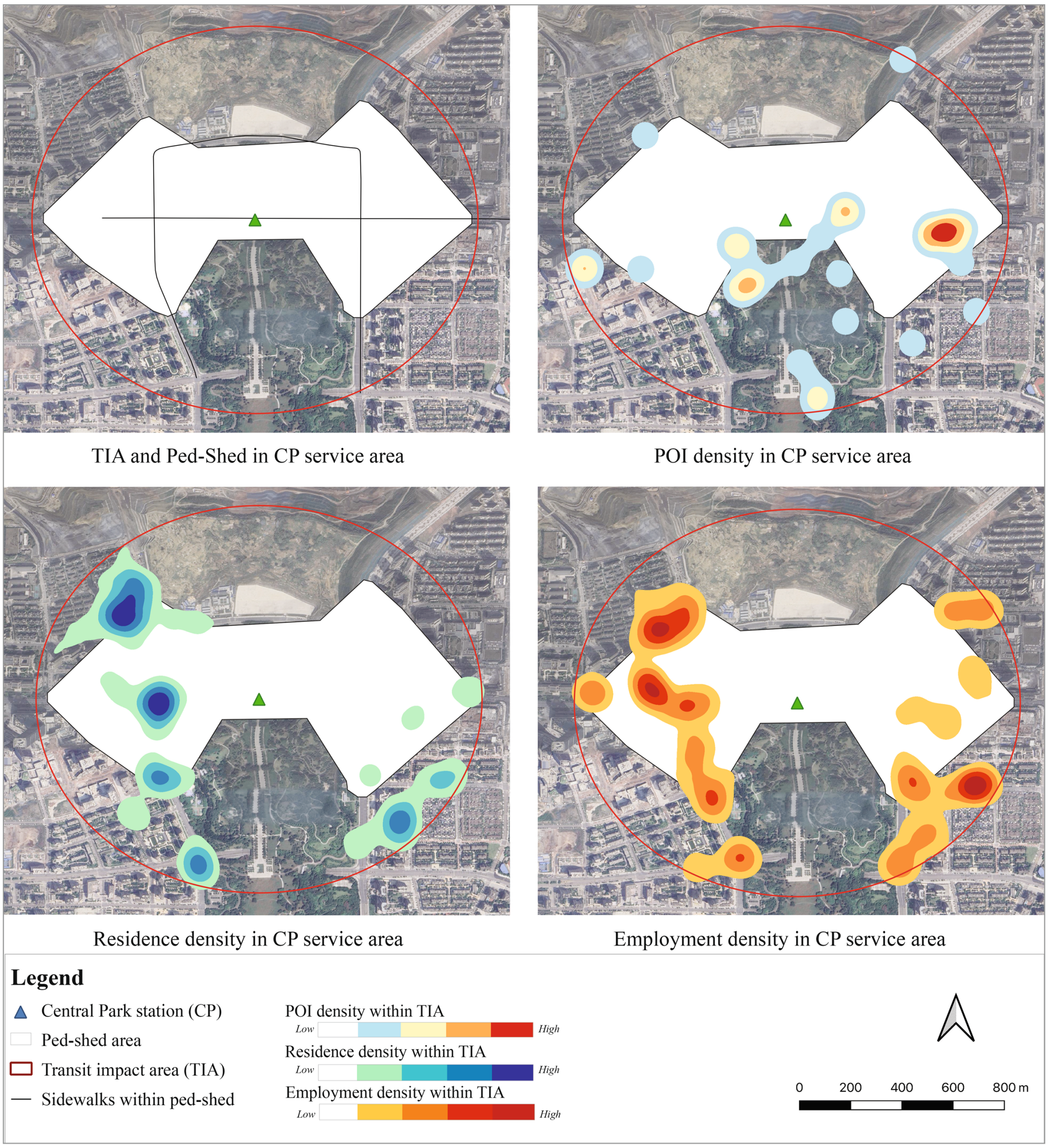

FIGURE 9
Central Park Station analysis maps.

TABLE 9 Indicator values for Central Park Station.

Node	N1	Transit coverage	29.5
	N2	Feeder Transport	0
	N3	Motorway Access	76.6
Place	P1	Population density	1.2
	P2	Employment density	1.4
	P3	Development intensity	0
	P4	Degree of Mix	7.3
Pedestrian Experience	W1	Parcel Connectivity	18.2
	W2	Pedestrian Directness	94.5
	W3	Street activity	0
	W4	Street green view	63.5

TABLE 10 Indicator values for Chongqing North Station.

Node	N1	Transit coverage	80
	N2	Feeder Transport	39.6
	N3	Motorway Access	72.3
Place	P1	Population density	28.8
	P2	Employment density	24.2
	P3	Development intensity	69.4
	P4	Degree of Mix	74.9
Pedestrian Experience	W1	Parcel Connectivity	31.3
	W2	Pedestrian Directness	62.6
	W3	Street activity	11.9
	W4	Street green view	19.1

connections, placing them at the lower end of the station assessment. Central Park, Expo, and Chongqing West stations are notable examples of this issue. Enhancing bus services, particularly feeder buses to transit stations, can promote sustainable urban development and should be a key focus for Chongqing's future growth and infrastructure planning.

This study introduces an empirical station assessment tool that can be adapted for use in other mountainous regions outside of China. For areas facing terrain challenges that influence pedestrian experience, this study provides a set of indicators for evaluation. However, when applying this assessment model to other locations, it is essential to consider the unique urban characteristics of these cities and make necessary adjustments to improve the model's accuracy and relevance.

There are also several limitations that should be acknowledged when interpreting the study findings. First, the transportation and land use indicators used in this study are derived from previous research conducted in flat cities. The calculation methods, such as for land use mix, may differ in mountainous cities and require refinement. Second, more indicators such as perceptions of safety, the width and quality of sidewalks could be incorporated into the model. The indicators used in our empirical model are based on available data and the situations of Chongqing and thus may not include all. Therefore, this model is a contribution to the broader node-place literature rather than a comprehensive solution. Studies in evaluating transit stations provide a wide range of perspectives for land use planning practices. This study specifically contributes to the perspective of walking in mountainous cities.

6 Conclusion

In this paper, we leverage existing node-place modelling literature to develop a multi-dimensional station assessment methodology specifically suited for mountainous cities. We introduced new indicators including parcel connectivity, pedestrian directness, street activity, and street greenery, to capture the distinct challenges of mountainous urban environments, thus augmenting the existing model with the dimension of pedestrian experience. We structured our indicators in a rose diagram. This approach allows for differentiated station profiles that provide detailed insights into station-specific accessibility dynamics. By refining local classifications from urban-suburban to five more detailed categories describing the level of land use development and pedestrian friendliness, we gain a deeper understanding of the development opportunities of each station that standard node-place analyses often overlook. Finally, we present four case studies from Chongqing to demonstrate how our analyses inform planning practically and propose targeted development plans for these stations.

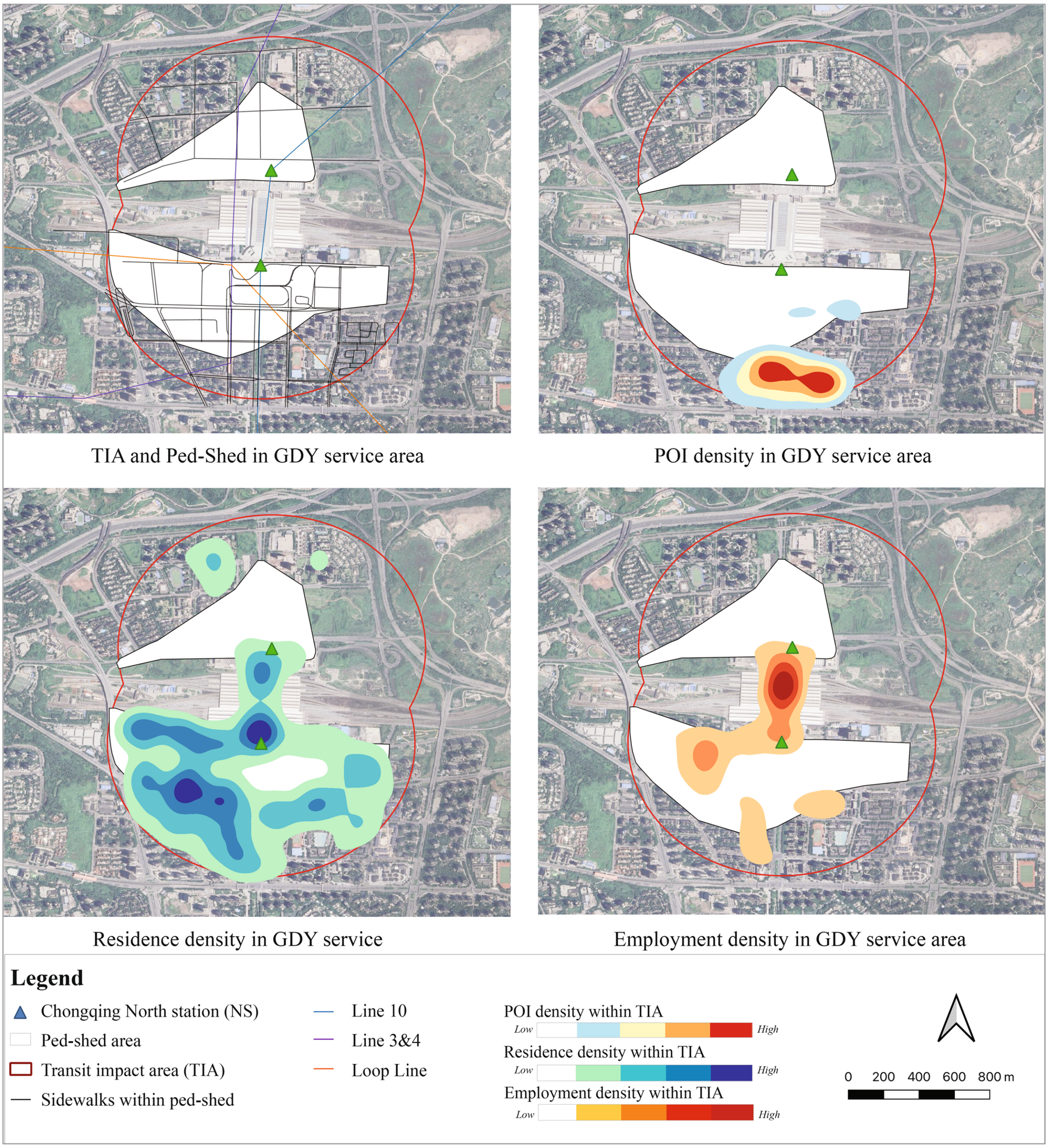

FIGURE 10
Chongqing North Station analysis maps.

For the stations studied, core development strategies identified in this research include strategically improving street view and vitality, enhancing direct connections between transit station entrances and adjacent parcels, establishing a coherent, safe, convenient, and comfortable pedestrian system, and strengthening feeder bus systems. These findings are valuable for other mountainous cities and indicate an important direction for future transportation and land use research.

Building on prior studies that primarily focused on plain cities, this study makes three contributions (Bertolini, 1999). It explores the possibility of integrating pedestrian experience into the traditional node-place evaluation framework, thus expanding the scope of analysis beyond conventional metrics (Bertolini, 2008). It focuses on the unique challenges of walkability in mountainous cities and developed indicators to measure them, thereby broadening the application of node-place models (Bertolini and Spit, 1998). It compares stations situated in varied locations and at different development stages, shedding light on the subtle influence of development opportunities and priorities outcomes.

A next step in this research will consist of a qualitative validation of the usefulness of this model. We could conduct surveys, interviews, or field observations to evaluate the development opportunities surrounding station areas and compare stations across different categories. Given the increasing importance of integrating transport and land use in Chongqing, a strategic approach would be to foster collaboration among public transport operators, the Chongqing Government, and other stakeholders to advocate for healthy, liveable and sustainable city development.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found at: https://www.openstreetmap.org/.

Author contributions

YY: Conceptualization, Data curation, Methodology, Writing – original draft. SY: Conceptualization, Supervision, Writing – original draft. CC: Conceptualization, Methodology, Software, Writing – original draft, Writing – review & editing. YT: Visualization, Writing – review & editing. WL: Data curation, Writing – original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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