Citation: ZHANG Na, JIANG Yuan, TANG Jie, ZHOU Yin, YU Ruhai. Evaluation of the Development Benefits and Fairness of TOD in Megacities: A Case Study of Chengdu[J], Urban Transport of China, 2024 (6).

Evaluation of the Development Benefits and Fairness of TOD in Megacities: A Case Study of Chengdu

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Abstract: Scientifically and reasonably evaluating the benefits and fairness of the TOD development in rail transit is conducive to promoting green and low-carbon travel and optimizing urban resource allocation. Combining the objective element value and subjective perceptive value of station space, a three-dimensional node-place-perception benefit evaluation model is developed, and a TOD development benefits evaluation system with 6 categories and 29 indicators is constructed. Rail transit stations are divided into four categories, namely, fully developed, moderately developed, underdeveloped, and unbalanced development. Based on the different social attributes of groups, including the difference in income level, age, and education level, this paper establishes a set of fairness assessment criteria, and discusses the heterogeneity of TOD development benefits and group distribution and the fairness of TOD to vulnerable groups by combining with the geographically weighted regression model. Taking the megacity of Chengdu as an example, this paper discusses the coordinated development of rail transit station space from the perspective of transportation, land, and people. The evaluation results show that the land development and construction of rail transit station space in Chengdu is relatively balanced, with preferable sensory comfort and fairness. Finally, optimization strategy guidance is given for stations with different characteristics to support the detailed planning of TOD and promote the sustainable and high-quality development of rail transit.
DOI: 10.13813/j.cn11-5141/u.2024.0037-en

Keywords: urban rail transit; TOD; development benefits; fairness; evaluation indicators; node-place-perception model; Chengdu

0 Introduction

Urban rail transit is an important carrier for carrying the efficient and sustainable urban development. The comprehensive development around urban rail transit stations and their station domains has become a common consensus in urban planning and construction, and is a representative approach of the current transit-oriented development (TOD) model guided by public transportation. The TOD comprehensive development project in China's mega cities has been implemented and operated for a long time, and its supporting benefits for urban development, group demand, and so on need to be evaluated. Meanwhile, whether the benefit generated by TOD is shared among different groups fairly is a key livelihood topic worth paying attention to, and the widespread phenomenon of gentrification ① makes it difficult to achieve the original intention of the TOD model. Therefore, it is necessary to conduct research on the benefits and fairness of TOD development, thus providing the optimization strategy and reference for the TOD model of future urban rail transit.

Existing literature has laid a solid foundation for the research on the benefits and fairness of TOD development, and its main research direction and content include two categories. (1) The evaluation system and evaluation analysis of TOD development benefits. It includes the construction of the evaluation system and research on the evaluation model, where the former includes the three-dimensional system of "strength-structure-value" [1], the four-dimensional system of "cost-benefit-land planning-basic information" [2], and the four-dimensional system of "density-diversity-design-benefit" [3]. Although there are differences in the results of the construction of evaluation systems, the common principle is to determine the specific dimension and content around the core purpose and research perspective. The latter, such as the node-place (NP) model [4–5], TOPSIS model [2], and principal component analysis [3], focus on selecting appropriate analysis models based on the evaluation system and data situation. (2) Fairness analysis of rail transit resources. For example, the Gini coefficient [6], potential model [6], spatial fairness index [7], and location entropy [7] are used to evaluate the coverage and distribution matching of the resource conditions such as rail transit stations [6, 8], lines [8–10], and accessibility [8–9] on the elderly population [6], young population [6, 8], and low-income population [9–10]. Existing research on fairness has mostly focused on the station layout, route direction, accessibility coverage, and other aspects, with little mention of the

Received: 2024-06-30

relationship between TOD development benefits and fairness.

As the driver and growth pole of national economic and social development, the mega city plays an important role in the overall development of a country. It is of great significance for promoting regional integration development and playing a leading and radiating role in the region to pay attention to the spatial efficiency of rail transit networks of the mega city. The permanent population of Chengdu has reached 13.34 million, making it the seventh mega city. Meanwhile, as a demonstration area for the new first-tier city and park city, Chengdu is exploring new paths for modern governance of the mega city led by TOD construction of urban rail transit. Taking Chengdu as a typical representative of the mega city, this article combines research results of existing literature and the actual situation of Chengdu to construct an evaluation system and evaluation method of TOD development benefits, conducts comprehensive evaluation, and calculates the fairness of TOD based on spatial distribution data of different groups and proposes optimization strategies.

1 Research overview

As of August 2023, Chengdu has opened 12 rail transit lines of the first three phases (excluding the Rong-2 tram line), including 282 rail transit stations, with a total operating mileage of 558 km, covering the central urban area of Chengdu (12 administrative districts and 2 economic functional districts) and the eastern new district. The daily passenger volume reached 4.275 3 million, with a travel sharing rate of over 60% of public transportation. The station covers 34% of the commuting population within 800 m, ranking second in China.

1.1 Research area and data

Driven by the construction of the Chengdu-Chongqing dual city economic circle and the new development concept of the park city demonstration area, Chengdu vigorously promotes the construction of rail transit and TOD, and proposes to use rail transit to lead urban development. Following the concept of station city integration, industry priority, functional integration, and comprehensive operation, Chengdu aims to build commercial centers, living centers, industrial centers, and cultural landmarks around rail transit stations, and become a global TOD model city. As of December 2023, Chengdu has started 24 projects for rail transit TOD (including 23 in the central urban area), covering 14 districts in Chengdu where rail transit lines have been opened. This article selects the central urban area of Chengdu as the research scope, with a total area of 4 062 km^2, including 279 rail transit stations in the first three phases (see Fig. 1).

The dataset used in this article mainly includes rail transit line and station data provided by Chengdu Rail Transit Group Co., Ltd., built environment data (plot data, building data, road network data, POI data, etc.), travel data (bus stop data, shared bicycle order data, etc.), Baidu population portrait data, and street view data of the Baidu map. The specific description is shown in Tab. 1.

1.2 Research content

Research was conducted on the benefits and fairness of TOD development from three aspects, and the research framework is shown in Fig. 2. Firstly, a comprehensive evaluation method for evaluating the TOD development benefits in urban rail transit was constructed. This method divided the spatial value of station domains into three dimensions: the spatial energy level, functional layout, and experiential perception, and selected 29 indicators for measurement. Through an improved node-place-perception model, the TOD development benefits were divided into four types: fully developed, moderately developed, underdeveloped, and unbalanced development. Secondly, based on the differences in the social attribute of different groups, including income, age, and the education level, a set of fairness evaluation criteria was constructed, and a regression model was used to explore the heterogeneity of TOD development and group distribution, as well as the fairness issues for vulnerable groups. Finally, taking Chengdu as an example, the evaluation method and fairness evaluation criteria were applied to provide optimization and improvement suggestions for the typical TOD station, providing effective reference for detailed TOD planning and equal supply of public services.

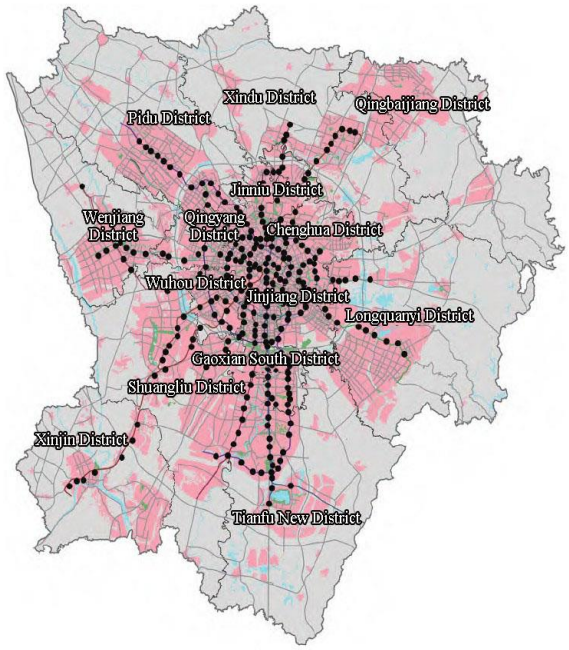

Fig. 1 Study area and the distribution of rail transit stations

Tab. 1 Data set

Data type	Data set	Number of data entries	Data field
Rail transit data	Rail transit station data	282	Station name, station latitude and longitude, and the line to which the station belongs
	Entry and exit data of rail transit stations	1 390	Station name, entrance and exit names, and latitude and longitude of the entrance and exit
	Rail transit line data	12	Name of the rail transit line, length of the rail transit line, and start and terminal of the rail transit line
	Bus station data	12 627	Station name and station latitude and longitude
	Shared bicycle order data	18 983 258	Order No., start time of the order, start latitude and longitude of the order, end time of the order, and end latitude and longitude of the order
Built environment data	Site data	1 627 396	Block type, block latitude and longitude, and block area
	Building data	613 915	Building type, building latitude and longitude, and building area
	Road network data	62 593	Road section type and road section length
	Greenway data	4 025	Greenway type and greenway length
	POI data	1 212 500	Facility type and facility latitude and longitude
	Business area	39	Business area level, business area latitude and longitude, and area of the business area
Population data	Population portrait data	486 965	Age, education level, work type, income level, and consumption level
Other data	Street view data	1 424 000	Year of street view collection, and street view latitude and longitude

2 Research method

2.1 Node-place-perception model

The node-place (NP) model was proposed by Professor Bertolini at the University of Amsterdam in 1996 [11] to analyze the development dynamics and complexity of transportation hub areas. Wherein, the node represents the accessibility of the transportation hub in large public transportation network, and the place represents the land use efficiency of the transportation hub in the urban physical space. The two have a certain coupling relationship, which has important reference value for interpreting the coordination relationship between transportation and land use and evaluating the spatial development benefits of the station domain. The classic NP model divides the transportation hub area into four categories: (1) The stress type, where both the node value and place value are strong; (2) The balance type, located in the middle area of the spindle shape, where the node value and place value promote each other and develop in a balanced manner; (3) The dependence type, with low node value and place value, mutual dependence and mutual loss; (4) The unbalance type, located outside the spindle shape, which is further divided into the unbalanced node (where the node value far exceeds the place value) and the unbalanced place (where the place value far exceeds the node value).

After the emergence of the NP model, many scholars have extensively explored the application direction of the model, which has now become the mainstream method for TOD evaluation and classification. Zemp et al. [12] and Chorus et al. [13] classified 1 700 rail transit stations in Switzerland and 1 200 rail transit stations in the Tokyo metropolitan area respectively using the conventional NP model, and explored and identified the impact of different factors such as the passenger flow, distance from the central business district, and the labor force size on the station. In recent years, some scholars have realized the limitations of the conventional NP model in the practical environment, and extended and improved the model by introducing a third dimension, such as the design level (compactness and walkability) [14–15], guidance level (distance between work and residence) [16], traffic level (passenger flow) [17–18], etc., enriching the semantic interpretability of the NP model and increasing its generalization ability in different regional characteristics.

Focusing on the comprehensive benefits of TOD, this article divided the development benefits of rail transit station space into three dimensions, namely, the macro location energy level in urban space—the spatial level, the mixed efficiency of land use and function—the functional layout, and the design friendliness level from a human sensory perspective—experiential perception. The three dimensions depict the potential value of station space in the TOD model from different perspectives. Combining the NP model, this paper constructs a three-dimensional spindle model for evaluating the TOD development benefits, i.e., the node-place-perception model (see Fig. 3). Its classification is similar to that of the conventional NP model: (1) Fully developed (the stress type), which means that the spatial

energy level, functional layout, and experiential perception are all strong; (2) Moderately developed (the balance type), located in the middle area of the spindle, with balanced development of the spatial energy level, functional layout, and experiential perception, which can promote each other; (3) Underdeveloped (the dependence type), weak spatial level, functional layout, and experiential perception, with mutual dependence and mutual loss; (4) Unbalanced development (the unbalance type), located outside the spindle shape, which is further divided into three categories: spatial energy level unbalance (the spatial energy level is far lower than the other two aspects), functional layout unbalance (the functional layout level is far lower than the other two aspects), and experiential perception unbalance (the experiential perception level is far lower than the other two aspects).

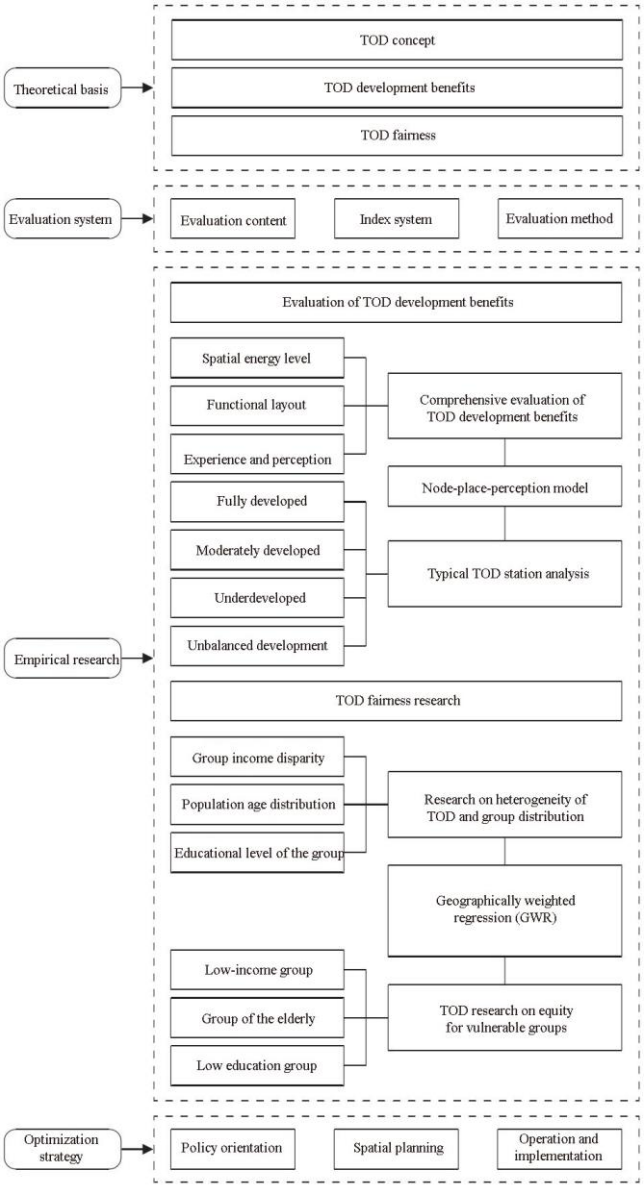

Fig. 2 Research framework

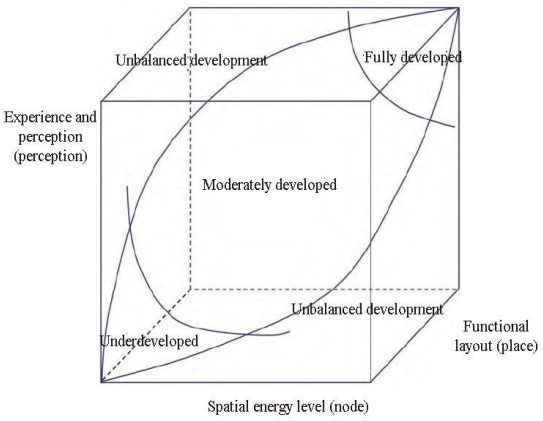

Fig. 3 Node-place-perception model

Based on the three dimensions of the node-place-perception model, this paper constructed a TOD development benefit evaluation system consisting of 29 indicators in six categories. The main basis for selecting indicators is: (1) To measure the efficiency level of the spatial energy level dimension through the centrality of rail transit stations in the rail transit network and the importance of their location in the urban physical space; (2) To measure the efficiency level of functional layout dimensions through the built environment and functional matching around rail transit stations, namely, the land development indicator and facility density indicator; (3) To measure the benefit level of the experiential perception dimension by the experience and feelings brought by the surrounding environment of the rail transit station, including the street view quantification indicator and connection efficiency indicator (see Tab. 2). Considering that the average distance between rail transit stations in Chengdu is 1.5 km, this article set the threshold for the spatial range of the station domain to 1 km, and weighted summary of the indicators of each dimension were performed using the entropy method [19].

2.2 Fairness research

Fairness research has always been an important perspective in the field of urban studies. Under the people-oriented development orientation in the new era, its research perspective has gradually shifted from spatial balance to human fairness. In addition to emphasizing balanced distribution in space, it needs to pay attention to the balance of interests between differentiated groups [20–21]. With the implementation of the TOD model, the land value has been released, which has promoted the increase of the residential price and regional economic growth, and further led to fundamental changes in the urban functional pattern, social class, and transportation mode of surrounding areas. Meanwhile, many unfair phenomena have emerged. Research has found that the vicinity of TOD stations is more prone to gentrification [22], as convenient rail transit creates a premium effect on surrounding residential areas, leading to the replacement of low- and middle-income families by

Tab. 2 TOD development benefit evaluation system

Dimension	Category	Indicator	Indicator description
Spatial energy level (node)	Network centrality	Degree centrality	It reflects the degree of adjacency between the station and surrounding stations
		Betweenness centrality	It reflects the ability of the station to transmit information in the line network topology
		Closeness centrality	It reflects the centrality of the station in the line network topology
		Eigenvector centrality	It comprehensively reflects the importance of the station in the line network topology
		Number of stations reachable in 30 min	It reflects the traffic accessibility of the station in the rail transit line network
	Importance of location	Distance from the (sub) center of the city/km	Shortest distance from each station to the (sub) center of the city
		Number of large business areas	Number of large business areas within a radius of 1 km around the station
		Number of park attractions	Number of park attractions within a radius of 1 km around the station
		Number of transportation hubs	Number of transportation hubs within a radius of 1 km around the station
		Number of class A hospitals	Number of class A hospitals within a radius of 1 km around the station
		Number of colleges and universities	Number of colleges and universities within a radius of 1 km around the station
Functional layout (place)	Land use efficiency	Mixing degree of land use	Mixed entropy of AOI for different land use classifications
		Mixing degree of functions	Mixed entropy of POI for different functional classifications
		Plot ratio/%	Proportion of the total building area to the net land area within a radius of 1 km around the station
		Building coverage/%	Proportion of the building floor area to the total area within a radius of 1 km around the station
		Land use ratio/%	The proportion of the area of different types of land (commercial, industrial, residential, and public services) to the total area within a radius of 1 km around the station
	Functional diversity	Density of parks and green spaces/(piece·km^{-2})	Ratio of the number of park and green facilities to the total area within a radius of 1 km around the station
		Density of public service facilities/(piece·km^{-2})	Ratio of the number of public service facilities to the total area within a radius of 1 km around the station
		Employment density/(piece·km^{-2})	Ratio of the number of job positions to the total area within a radius of 1 km around the station
		Density of commercial and business facilities/(piece·km^{-2})	Ratio of the number of commercial and business facilities to the total area within a radius of 1 km around the station
		Residential density/(piece·km^{-2})	Ratio of the number of residential facilities to the total area within a radius of 1 km around the station
Experience and perception (perception)	Sensory friendliness	Pedestrian friendliness/%	Proportion of pedestrian pixel points in street view images within a radius of 1 km around the station
		Green looking ratio of the street/%	Proportion of green plant pixels in street view images within a radius of 1 km around the station
		Sky open degree	Ratio of the sky area to the ground area in street view images within a radius of 1 km around the station
		Number of entrances and exits in the station/piece	Number of entrances and exits set in rail transit stations
	Convenience of connection	Road network density/(km·km^{-2})	Road network density within a radius of 1 km around the station
		Greenway density /(km·km^{-2})	Greenway density within a radius of 1 km around the station
		Bus station density/(piece·km^{-2})	Bus station density within a radius of 1 km around the station
		Taking and returning ratio of shared bicycles	Ratio of the number of shared bicycles taken to that of shared bicycles returned within a radius of 1 km around the station

high-income families. However, affluent groups are more inclined to use private cars rather than public transportation [23]. Many cities have attracted low-income residents to TOD areas by providing affordable housing and social security housing to ensure social fairness in public transportation services [24–25]. Some countries have even implemented policies for equitable transit-oriented development (ETOD) [26–27] to ensure that citizens who need public transportation the most benefit, including people of color, low-income families, the elderly, people with disabilities, and families with limited or no access to vehicles.

In the research methods related to TOD fairness in China and abroad, Delmelle et al. [28] explored the fair distribution of the Colombian rapid transit system about the socio-economic class of the community. The results showed that the middle-income group had the greatest opportunity to walk into the rapid transit system, while the corresponding opportunities for the highest and lowest socio-economic classes were the most limited. Sandoval et al. [29] compared the TOD of MacArthur Park in Los Angeles with that of Fruitvale Village in Oakland and found that public resources such as culture, politics, finance, and architecture could be

fully integrated by establishing the TOD community, thereby enhancing the willingness of low-income groups to participate in community revitalization. Li [30] quantified the gentrification phenomenon in the TOD area of Beijing using multi-level nested regression and other methods and conducted empirical research on the fairness of TOD in Beijing by combining the coverage of different groups. Xu [31] analyzed the fairness of TOD in Nanjing by measuring the mixed degree of residential supply and the accessibility of facilities through an information entropy model. Overall, research on TOD fairness in China and abroad mainly focuses on aspects such as housing fairness, transportation accessibility, facility supply and demand matching, employment provision, and care for vulnerable groups, and proposes targeted optimization measures and strategies through quantitative analysis of relevant indices and models or qualitative research on policy implementation.

This article focused on the service coverage of TOD for differentiated groups, including those with different income levels, ages, and educational levels. The specific definitions of each group are shown in Tab. 3. Referring to the method of sorting out the correspondence between the TOD station type and passenger flow level [17], this paper established a correspondence table between vulnerable groups and TOD development benefits to assist in judging the relative fairness of rail transit station construction. Combined with the regression analysis model, the correlation between the income level, age, and education level and the spatial level, functional layout, and experiential perception of rail transit stations was explored, providing references for the scientific planning of rail transit TOD and the maximization of public and social benefits.

According to the ETOD concept, TOD stations with good development benefits should be equipped with supportive facilities to accommodate special social groups. Therefore, this article proposed the TOD fairness evaluation criteria for differentiated groups (see Tab. 4), where the group ratio is summarized based on the current situation in Chengdu.

Tab. 3 Classification basis of group characteristics

Differentiation factor	Differentiation group	Specific definition
Income level/ (CNY·month^{-1})	Low-income group	<2 500
	Middle-income group	2 500–<30 000
	High-income group	≥30 000
Age	Underage group	<18
	Adult group	18–65
	Elderly group	>65
Education level	Low education group	Senior high school or below
	Medium education level group	Junior college
	Highly educated group	University and above

Tab. 4 Correspondence of TOD fairness evaluation for different groups

Differentiated group		Fully developed	Moderately developed	Underdeveloped	Spatial energy level unbalance	Functional layout unbalance	Experiential perception unbalance
Low-income group (< CNY 2 500·month^{-1})	More (>60%)						
	Moderate (45%–60%)						
	Less (<45%)						
Low education level group (senior high school and below)	More (>60%)						
	Moderate (45%–60%)						
	Less (<45%)						
Elderly group (> 65 years old)	More (>3%)						
	Moderate (1%–3%)						
	Less (<1%)						

Note: Green, yellow, and orange represent relative fairness, relatively moderate, and relative unfairness, respectively.

This article used the GWR model to analyze the correlation between the differentiation factor (the income level, age, and education level) and TOD development benefits. Compared with the ordinary least squares (OLS) method, the GWR model can establish regression equations for each geographical element and reflect the non-stationarity of correlation in space through the regression coefficient matrix [32]. Assuming there are n geographical entities, m impact factors, and the calculation formula for the GWR model is

$$Y_i = \beta_0(u_i, v_i) + \sum_{j=1}^{m} \beta_j(u_i, v_i) X_{ij} + \varepsilon_i ,$$

where Y_i is the representation value of the i-th geographical entity (i.e., the TOD benefit index), $i = 1, 2, \cdots, n$; X_{ij} is the j-th impact factor of the i-th geographical entity, $j = 1, 2, \cdots, m$; (u, v) is the spatial coordinate of the geographic entity; β is a spatial geographic location function, commonly used as a Gaussian kernel function; ε_i is the regression residual of the i-th geographical entity.

3 Evaluation of TOD development benefits in Chengdu

3.1 Basic situation of benefits

Based on the TOD development benefit evaluation system, the TOD development benefit index of 279 rail transit stations in the central urban area of Chengdu was obtained, including the spatial level index, functional layout index, and experiential perception index (see Fig. 4).

The indices of the three dimensions of the rail transit stations within the second ring road of Chengdu are relatively high, especially the functional layout index, which ranks in the top 20%. It reflects that the resource investment around the stations is relatively concentrated, mainly, in the core urban areas (i.e., Wuhou District, Qingyang District, Chenghua District, Jinjiang District, Jinniu District, and Gaoxin South District). The surrounding built environment level and land development efficiency of stations at the middle and terminal of the line decrease with the increasing distance from the city center. From the perspective of the spatial energy level index, transfer stations exhibit a higher level among stations on the same line, thanks to their high network centrality and betweenness centrality, and their transportation supply level and passenger flow intensity are higher than those of ordinary stations. From the perspective of the experiential perception index, most of the rail transit stations in the core urban area have good sensory friendliness and convenient connections, and there are a few stations in the peripheral areas, such as Century City Station, Cuqiao Station, and Longquanyi Station, with higher sensory values than surrounding stations, indicating that the rail transit stations located in the center of the area have significant advantages in the quality of the surrounding transportation environment and street space.

3.2 TOD classification of rail transit stations

Based on the node-place-perception model, the TOD classification of rail transit in central urban areas of Chengdu was obtained (see Fig. 5). And 72% of the rail transit stations are moderately developed, with only a few fully developed or underdeveloped, indicating that the overall construction effect of Chengdu's rail transit is good, and the layout of the rail transit network is matched with the urban built environment. The stations of unbalanced development are mainly of spatial energy level unbalance, and there are relatively few stations with functional layout and experiential perception unbalance. It indicates that the spatial energy level of Chengdu's rail transit stations is generally lower than the functional layout level and experiential perception level, that is, the construction level of Chengdu's rail transit network generally lags behind its urban development level and resource allocation efficiency, and there is still room for further refinement and adjustment of the rail transit network.

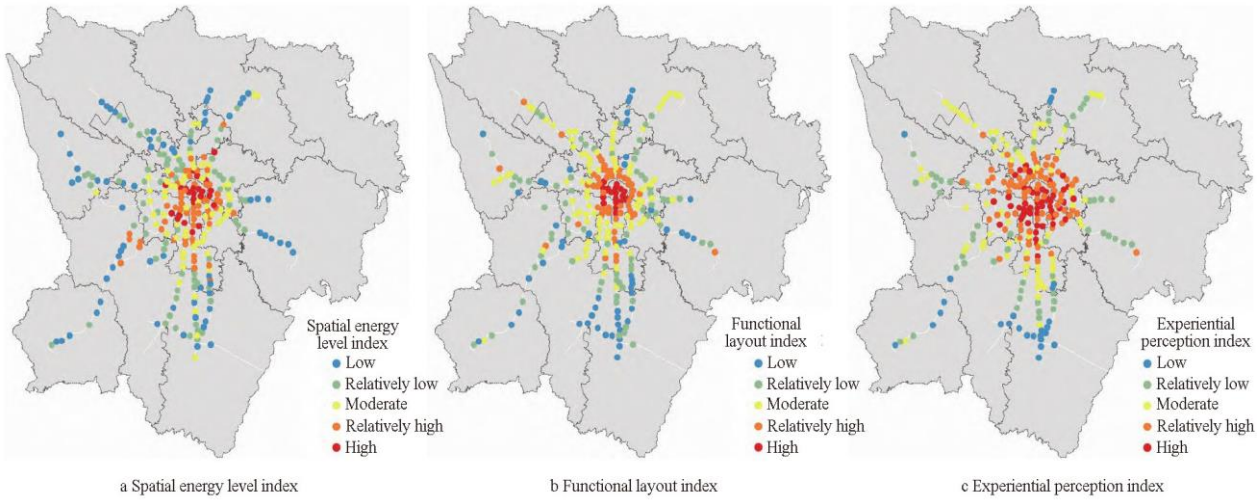

Fig. 4 TOD development benefit index of rail stations in Chengdu central area

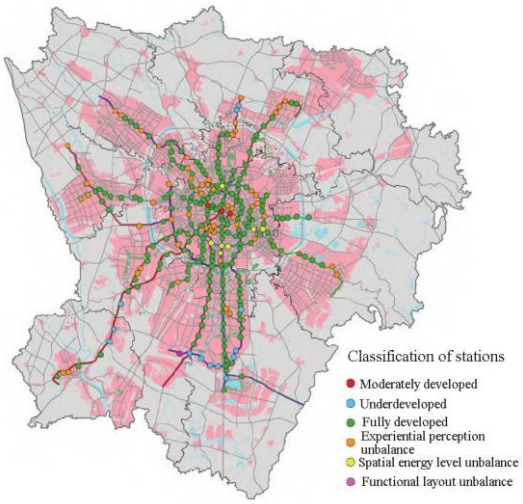

Fig. 5 Spatial distribution of TOD classification results of rail stations in Chengdu central area

From the perspective of spatial distribution: (1) The fully developed stations are located in the old city area, namely, Tianfu Square Station, Chunxi Road Station, and Provincial Hospital of Chengdu University of Traditional Chinese Medicine Station, all of which are multi-line transfer stations with the centrality of 6, 4, and 6, respectively. They undertake the functions of the political and cultural center, commercial center, and residential center of the city, and the spatial level, functional layout, and experiential perception level of these stations are relatively high, with relatively small potential for further development of their station domain space. (2) There are 15 underdeveloped stations, mainly located at the middle and rear ends of the line, and their geographical locations are often at the junction of administrative regions, with relatively insufficient resource allocation and construction, and there is great potential for optimization and improvement in all aspects. (3) There are eight stations with functional layout unbalance, which are mainly core hub stations in the main urban area, including South Railway Station, Chengdu East Railway Station, and North Station Xi'erlu Station. Their spatial level is relatively high, but in contrast, the functional layout and experience perception levels are insufficient, and it is necessary to increase the supply of supporting facilities and resources in the station domain space to improve passengers' travel experience. (4) There are many stations with spatial energy level unbalance, such as Longquanyi Station, Huangtianba Station, and Financial City Station, all of which are regional center stations. The station domain space undertakes important political, cultural, and commercial functions, but the transportation convenience is insufficient. Nearly 80% of the stations with spatial energy level unbalance are non-transfer stations. In future network planning, new line transfers can be considered to improve the level of interconnection. (5) The only station of experiential perception unbalance is Lanjiagou Station, indicating that the sensory friendliness around Chengdu's rail transit stations is good, and can match the location of the station. The allocation of public resources in the surrounding area is relatively sufficient, and the quality of the streets and the convenience of connections have reached a qualified level.

4 TOD fairness assessment of Chengdu

4.1 Fairness and heterogeneity based on differentiated group characteristics

Based on Baidu's 2022 population profile data, combined with the definitions in Tab. 4, this paper derived the distribution pattern of differentiated groups as shown in Fig. 6. The distribution of differentiated groups in the central urban area is uneven, generally scattered, but there are also some clustering effects, and most of the clustering areas are close to the subway station, with a high correlation between group distribution and rail transit.

From the perspective of the income level, low-income groups mainly gather in the old residential areas within the second ring road near Baiguolin Station and Southwest University of Finance and Economics Station in Qingyang District, as well as the first ring road block near Liangjiaxiang Station in Jinniu District, mainly consisting of practitioners of the middle and low-end service industry (see Fig. 6a). The high-income group mainly gathers near the Qingjiang West Road Station and Cultural Palace Station of subways in the Qingyang District, as well as the blocks near the Dayuan business area and Financial City business area of Gaoxin South District, with practitioners of the middle and high-end service industry as the main group (see Fig. 6c). From an age perspective, there is no clear pattern in the distribution of minors and adults, but the elderly population is mainly concentrated in the old neighborhoods within the second ring road (see Fig. 6f), as this area has convenient living infrastructure. From the perspective of the education level, the low education group is mainly concentrated in areas with developed industries, where typical areas are the neighborhoods near factories in the high-tech western district and the area near the North Railway Station (see Fig. 6g). The distribution pattern of highly educated groups is consistent with that of high-income groups, but more concentrated in high-tech zones and the Tianfu New District (see Fig. 6i).

Based on Tab. 4 and the distribution of the population, the fairness evaluation results of TOD in the central urban area of Chengdu are obtained (see Fig. 7). The fairness of coverage for vulnerable groups in Chengdu's central urban rail transit stations is relatively good, where 87% of stations are relatively fair and moderate, and only a few stations experience unfairness. Based on the TOD classification of rail transit stations, it is found that the development of fully developed stations (the Tianfu Square Station, Chunxi Road Station, and Provincial Hospital of Chengdu University of Traditional Chinese Medicine Station) is relatively fair.

Within a radius of 1 km around the stations, the proportion of low-education and low-income groups exceeds 50%, and the proportion of elderly groups exceeds 3%, indicating that the three stations with the most concentrated land resource development in Chengdu have achieved equalization of public interests, providing convenient living service facilities and transportation services for people from all walks of life. Underdeveloped stations and stations of functional layout unbalance are mostly relatively fair and moderate stations, with a low proportion of vulnerable groups around the stations and no vicious cycle of resource scarcity and poverty concentration. Similarly, the moderately developed stations mostly belong to relatively moderate stations, which further confirms the positive role played by Chengdu's rail transit construction in social fairness.

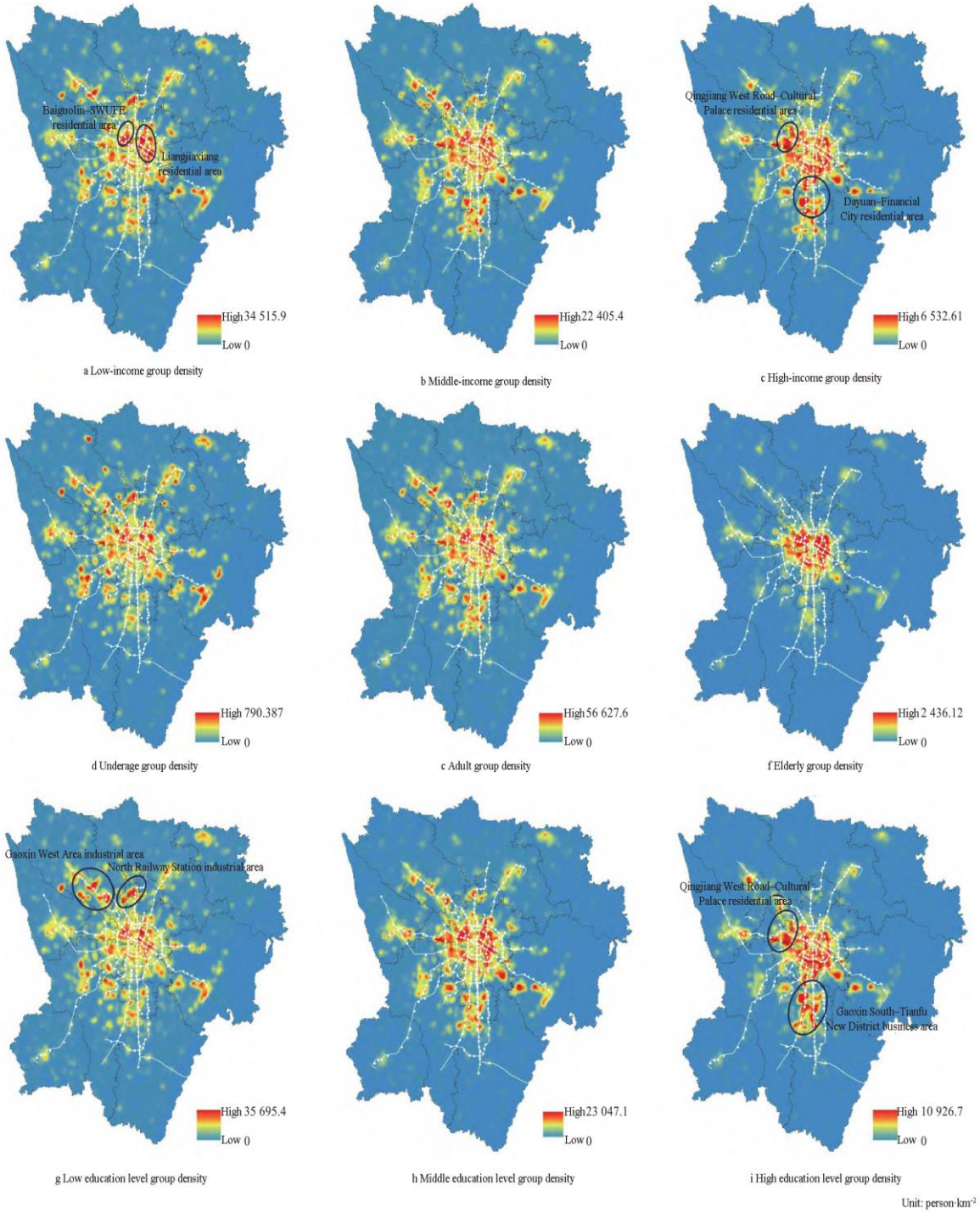

Fig. 6 Distribution characteristics of differentiated social groups

In addition, the relatively unfair stations are mainly distributed at the end of the rail transit line and in the high-tech southern area and are at the two extremes of unfairness. Most of the stations at the end of the line belong to spatially unbalanced stations, located in the old cities of various regions. Compared with the areas within the Chengdu Ring Expressway, their resource development and transportation convenience are insufficient and they gather a large number of low-income and low-education groups (accounting for more than 65%). They have difficulty accessing the rich public services in the city center, and their participation and contribution to urban development and construction are relatively low. The stations in the Gaoxin South District are mainly moderately developed stations with relatively efficient resource development, including the Jiaozi business area, the Dayuan business area, and the Tianfu Third Street business area. The housing premiums around the stations are too high, and the inclusiveness of vulnerable groups is insufficient. The proportion of low-income and low-education groups is less than 45%, indicating a certain gentrification phenomenon.

4.2 Fairness of TOD services for vulnerable groups

A correlation analysis was conducted between the normalized proportion of vulnerable groups within 1 km of rail transit stations and the TOD development benefit index (see Fig. 8). The proportion of low-income and low-education groups was negatively correlated with the TOD development benefit index, and that of elderly people was positively correlated with the TOD development benefit index. It indicates that the TOD development has a slight degree of residential exclusion for groups with labor but lower education levels, and a certain degree of residential attraction for retired elderly groups. It suggests that there is still room for optimization and improvement in the fairness protection of vulnerable groups in Chengdu's TOD.

From the perspective of the evaluation dimension of TOD development benefits, the benefit index of the experiential perception dimension has the strongest correlation with vulnerable groups, followed by the correlation of the functional layout dimension, and the benefit index of the spatial level dimension has the weakest correlation with vulnerable groups. It indirectly reflects that micro-level design and optimization from a human perspective have the most significant promoting effect on TOD fairness. For example, measures such as increasing cycling greenways and bus connections can create a "last kilometer" high-quality travel space, which can effectively enhance the willingness of low-income groups in the surrounding area to take rail transit. However, the promotion effect of strategic development and construction at the macro level on TOD fairness is relatively weak, as the improvement of the level and function of rail transit stations often leads to a rapid increase in the surrounding housing price and consumption level, weakening the participation ability of vulnerable groups.

To further explore the spatial heterogeneity of the relationship between TOD fairness and TOD development benefits, this paper used a geographical weighting regression model to quantitatively analyze the correlation between the proportion of vulnerable groups within 1 km of rail transit stations and TOD development benefits. The model adopts the Gaussian kernel function and Akaike Information Criterion (AIC), with a global $R^2 = 0.73$, $MSE = 0.21$, and the correlation coefficients of various groups are shown in Fig. 9.

Fig. 9 shows that the spatial distribution of the correlation between various groups and TOD development benefits is extremely uneven, especially in some stations where low-income groups show a positive correlation with TOD development benefits. For example, the correlation between the transfer station Shenxianshu Station and the TOD development benefit evaluation in all three dimensions is greater than 0, and that between the transfer station Wuqing South Road Station and the TOD development benefit evaluation in all three dimensions is less than 0. It indirectly reflects that the gathering of low-income groups at Shenxianshu Station has a smaller impact on the overall TOD benefit of the central urban area than at Wuqing South Road Station. To promote TOD fairness, it is appropriate to increase protective facilities to guide low-income groups to gather near rail transit stations with a GWR coefficient greater than 0. The low education group shows a negative correlation with the three dimensions of TOD development benefit evaluation at different stations, while the elderly group shows a positive correlation with all three dimensions of TOD development benefit evaluation at different stations, indicating that Chengdu has considered elderly friendliness in the TOD construction of rail transit, but lacks tolerance for groups with low education level.

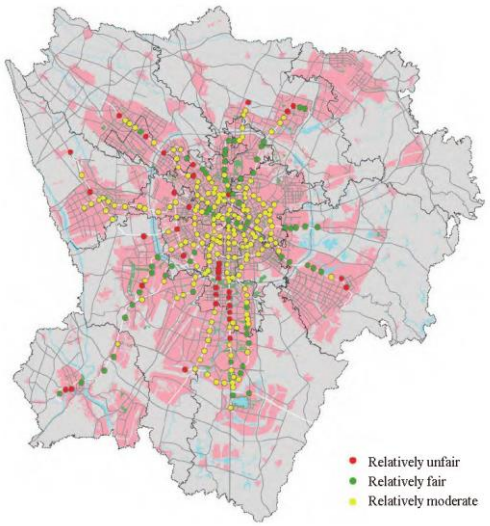

Fig. 7 Evaluation results of TOD fairness for different groups in Chengdu central area

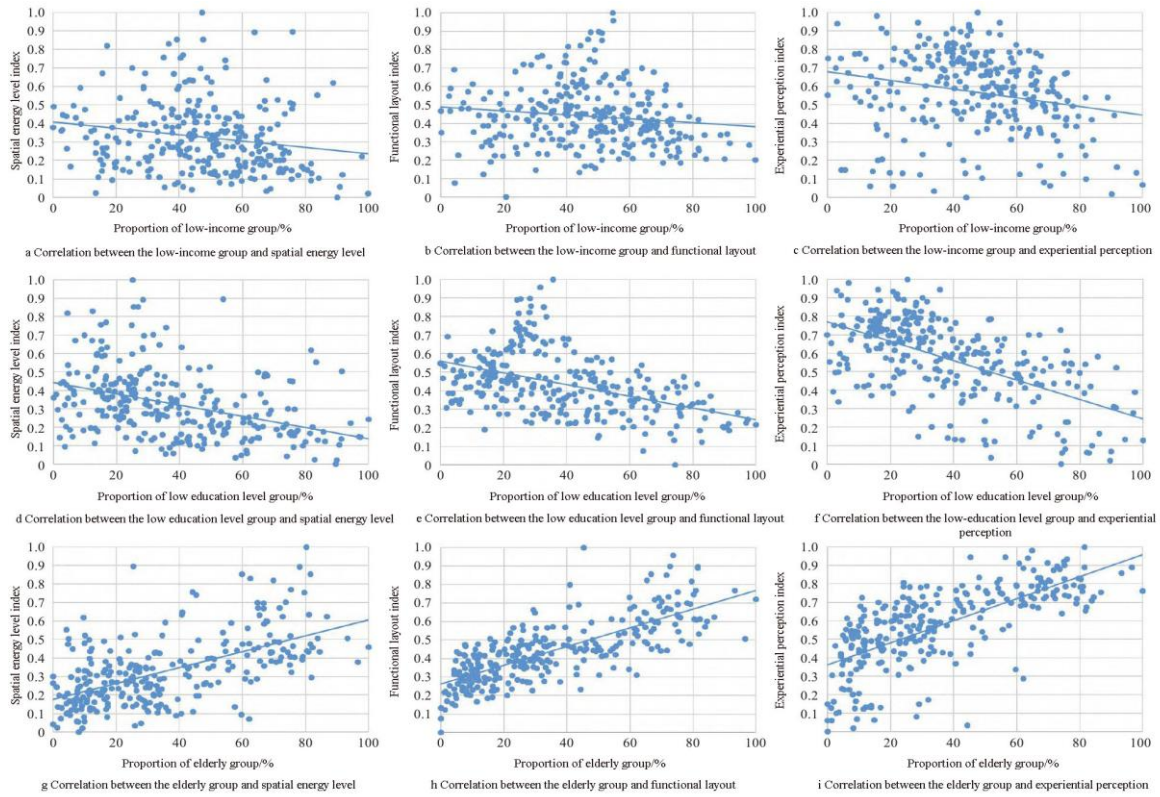

Fig. 8 Correlation analysis between the proportion of vulnerable groups and TOD development benefit index within 1 km of rail transit station

5 Optimization strategy

Based on the TOD development benefits and fairness evaluation results of Chengdu's rail transit stations, this article proposed optimization strategies for typical stations with different characteristics.

1) Fully developed stations

The fully developed stations such as the Tianfu Square Station, Chunxi Road Station, and Provincial Hospital of Chengdu University of Traditional Chinese Medicine Station are located in the city center, surrounded by cultural symbolic buildings and city-level business areas, and have a high tolerance for vulnerable groups, making them relatively fair stations. According to subway card swiping records, the daily passenger flow at the three stations in 2022 reached 80 000, 120 000, and 70 000, respectively, indicating a high travel demand. It is recommended to use urban design methods to conduct micro update of the station domain space based on the historical and cultural characteristics of Chengdu, adjust the capacity of transportation facilities to meet the peak traffic distribution needs of the region, avoid large-scale construction activities and maintain the existing development level and guarantee facilities, and avoid further congestion caused by the excessive attraction of the passenger flow. Meanwhile, non-motorized transportation interchange should be optimized to improve the micro circulation efficiency of the urban non-motorized transportation system and transportation network.

2) Moderately developed stations

There are a large number of moderately developed stations, accounting for over 70%, mainly located in urban and regional centers with mature functions and high level of transportation organization. The space covers urban business areas, residential areas, scientific research and teaching areas, and tourist attractions, and the transportation operation capacity matches the level of land development. Take Tianfu Third Street Station and Tianfu Fifth Street Station of subway line 1 as an example. Their current land development intensity is relatively high, adjacent to the Dayuan business area, Tianfu Software Park, Yintaicheng, Ganghuitiandi and other business areas. However, the public infrastructure and affordable housing around the stations are lacking, resulting in a low proportion of vulnerable groups and insufficient fairness in the coverage of vulnerable groups by rail transit. According to the single-day entry card swiping records in 2022, the average daily passenger flow at the two stations was relatively high, with 90 000 and 60 000, respectively. However, the number of entrances and exits at the stations was insufficient (only 4), and they were not directly connected to commercial office buildings or shopping malls underground. It is suggested to accelerate the TOD

integration of stations and cities and promote the development of new lines, add pedestrian and cycling-friendly places and diversified residential options based on the positioning of the central dynamic area, and enhance the overall experience and comfort of the region.

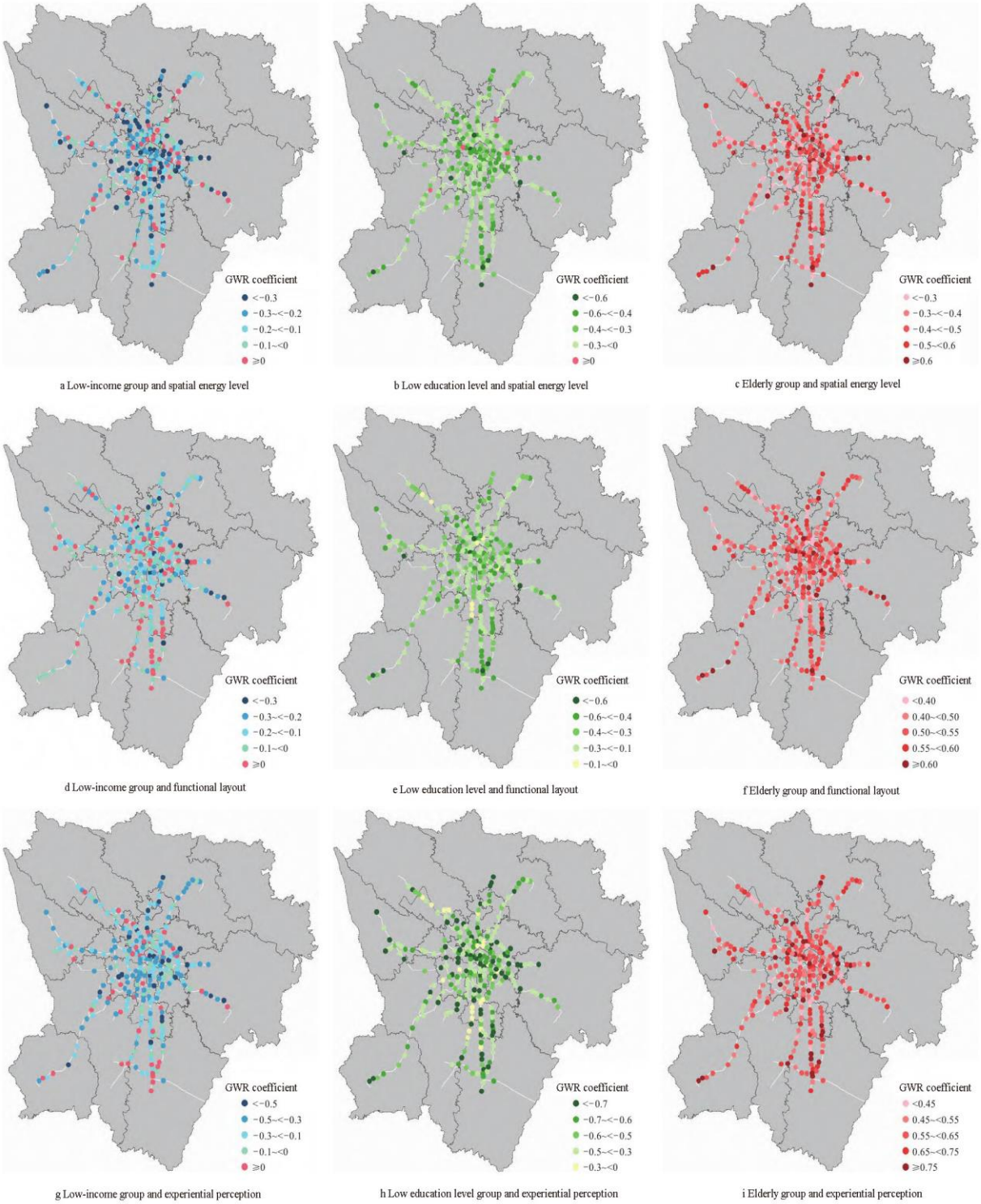

Fig. 9 Analysis results of GWR model

3) Underdeveloped stations

Underdeveloped stations include the Liaojiawan Station, Xinjin Station, Xinglonghu Station, and Sancha Station. Most of these stations are located at the boundaries of the administrative region and only pass through one rail transit line. Affected by the timing of rail transit construction and the

lag in urban development, the surrounding development has just begun, with insufficient passenger flow, a relatively small proportion of vulnerable groups, and moderate TOD fairness. The accessibility of the current rail transit can be utilized to drive commercial and economic development, and development goals can be reasonably set in combination with TOD functional positioning (for example, the Longdengshan Station will be developed into a new economic vitality zone in Chengdu, and Qinhuangsi Station, located adjacent to the Western International Expo City, will be developed into an urban-level business area of the Tianfu New Center). The construction of commercial supporting facilities around the rail transit station can be improved to gather population, and it will be developed in conjunction with neighboring stations to create a regional center and enhance the economic value of the station domain.

4) Stations with unbalanced development

One-third of stations with unbalanced development are relatively unfair stations, and their optimization strategies mainly focus on strengthening interaction and coordination to promote sustainable development of station domain space. ① The stations with unbalanced spatial energy level, represented by Longquan Station and Huangtianba Station, are located at the end of subway line 2 and line 9, respectively. They are relatively unfair stations with a high proportion of vulnerable groups and the direction of optimization and improvement is to improve the convenience of transportation facilities. In future line planning, we should consider adding new lines or expanding the coverage of rail transit stations by adding connections to other modes of transportation to improve the connectivity level of the area. Meanwhile, commercial facilities and quality residential buildings should be increased to increase the proportion of high-income groups. ② The stations of unbalanced functional layout are represented by the South Railway Station and Chengdu East Railway Station, both of which belong to the two major railway passenger hubs in Chengdu and are transfer stations for two lines, with relatively moderate fairness. According to subway card swiping records, the daily average passenger flow at the two stations reaches 80 000 and 50 000, respectively, with severe congestion during commuting hours. The South Railway Station is adjacent to the Kaide business area and Tongzilin area, with high efficiency in surrounding land development. The optimization strategy mainly focuses on increasing public buses and non-motorized transportation connections to alleviate the pressure of the pedestrian flow, and can further increase the supporting public service facilities, build a “15-minute living circle”, promote work-life balance, reduce traffic pressure, and improve the convenience of life. The proportion of commercial and residential land around Chengdu East Railway Station is relatively low and the land value of the station domain space has not played a matching role. It is urgent to strengthen the influence of the surrounding area and attract business models to gather together. ③ The only station with unbalanced experiential perception is Lanjiagou Station, located at the end of subway line 6 in the Shuangliu District. The surrounding urban construction is still ongoing, and the quality of street space is poor. The proportion of low-education groups exceeds 70%. It is suggested that in future planning and construction, commercial and residential development should be combined with urban design in this area, with a focus on integrated block design to enhance the value of the venue and increase experiential comfort. In addition, it is possible to consider integrating the tourism resources around the stations and opening up a rapid transit connecting line to the Yong’an Lake City Forest Park and Maojiawan Forest Park, thereby effectively improving the attractiveness of the passenger flow and economic development potential of the stations.

6 Conclusion

With the emergence of governance challenges in mega cities, the contradiction between transportation, land, and people has become increasingly prominent and the TOD construction of rail transit has become an important path for urban renewal and development. To comprehensively evaluate the TOD development benefits of rail transit stations and the fairness of services for differentiated groups, this paper proposed a node-place-perception model and fairness evaluation criteria, achieving the integration and unity of the objective element value and subjectively perceived value in station domain space. Based on the evaluation model, rail transit stations were classified into fully developed, moderately developed, underdeveloped, and unbalanced development. The impact of the classification on fairness was explored and targeted optimization strategies were formulated.

A case study was conducted on the rail transit stations in the central urban area of Chengdu. The results showed that over 70% of the stations were moderately developed, and over 80% of the stations had good TOD fairness evaluation results, indicating that the efficiency of spatial land development and construction in the rail transit station domain in Chengdu is high, and the overall experience comfort is also high. The core of optimization and improvement lies in exploring the development potential of the station domain based on TOD classification, advocating for micro updates of station space, enriching the supply of public supporting resources, and enhancing the attractiveness of station space to various groups.

The TOD development benefit and fairness evaluation model proposed in this article still has directions for optimization. In the future, more refined indicators such as the land development cost, land transfer value, residential sales price, and rental price will be considered for inclusion. Meanwhile, the evaluation method proposed in this article

has universality and can explore the development characteristics of rail transit stations in different regions and even cities in the future, providing theoretical support for promoting the high-quality integrative development of rail transits and cities.

① It refers to an old district where low-income people were originally gathered, but after renewal, the land price and rent has increased, attracting high-income people to move in and replace the original low-income population.

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