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Evaluation of the Coordination Between TOD Development Level and Urban Vitality at Urban Rail Transit Stations: A Case Study of Rail Transit Micro-Centers in Beijing

WANG Jing[1], LU Xianqiao[2], LU Huapu[3]

1. School of Architecture and Urban Planning, Beijing University of Civil Engineering and Architecture, Beijing 100044, China;
2. Beijing Municipal Institute of City Planning & Design, Beijing 100045, China;
3. Institute of Transportation Engineering, Tsinghua University, Beijing 100084, China

Abstract: Promoting the in-depth integrated development of urban rail transit stations and urban spatial structures is a critical path for achieving high-quality growth in mega-cities. Based on the node-place model, this paper proposes a method for evaluating the coordination between the Transit-Oriented Development (TOD) level and urban vitality at urban rail transit stations from both micro and macro perspectives. The proposed method incorporates walkability and urban vitality into the evaluation model and employs spatial coordination assessment, evaluation matrix analysis, and correlation analysis to evaluate the coordination between the current TOD development and urban spatial structures at urban rail transit stations. Using 31 rail transit micro-centers in Beijing as a case study, this paper evaluates the coordination between TOD development level and urban vitality. The results indicate that TOD development level and urban vitality at urban rail transit stations exhibit a distinct core-periphery structure. Based on coordination characteristics and developmental trends, urban rail transit stations are categorized into four types: vitality-coordinated, vitality-leading, vitality-cultivating, and vitality-lacking. There are significant variations in the coordination between TOD development level and urban vitality across these station types. Additionally, this paper reveals a positive correlation between TOD development level and urban vitality; however, the coordination between the node index and urban vitality is relatively weak, indicating an insufficient synergy between transit supply and urban vitality and inadequate stimulation of the transit supply volume on urban vitality. **DOI:** 10.13813/j.cn11-5141/u.2024.0603-en

Keywords: urban rail transit; TOD; node-place-walkability; urban vitality; rail transit micro-centers; Beijing

0 Introduction

The Transit-Oriented Development (TOD) concept, guided by public transportation, has promoted the further development of rail transit stations and surrounding areas, attracting more resources and making the rail transit stations the core nodes of urban development [1]. Promoting the coordinated development of rail transit stations and the urban spatial structure to form a positive interactive relationship is increasingly regarded as a key path to solving urban traffic congestion and achieving sustainable urban development. Beijing is a typical mega city in a developing country. During the rapid urbanization process, the city’s scale has grown rapidly and land use has expanded rapidly, but transportation infrastructure construction often lags behind urban expansion, especially the insufficient support and guidance of the public transportation system for the development of the urban spatial structure. Although the mileage and network density of Beijing’s rail transit have been increasing in recent years, the contradiction between transportation and urban development still exists due to the unreasonable spatial structure and functional layout of the city. This phenomenon is also common in other major cities in developing countries, which affects the promotion and implementation of the TOD concept. Therefore, an in-depth exploration of the synergy between the urban rail transit stations and urban spatial structure can provide an important evaluation basis for policy formulation and investment priority determination.

Most existing studies have evaluated the coordination between urban rail transit station transportation and land use from a micro perspective [2–8], ignoring the impact of the macro-level urban spatial structure on station classification. There is a close coordination between urban rail transit and the urban spatial structure, which can promote the integration of transportation facilities with the overall development of the city, thereby enhancing the overall efficiency and sustainability of urban space. From the perspective of the urban spatial structure, there are differences in the collaborative mode and goal between regions with different functions and vitality, and the “divide and rule” of urban rail transit stations must consider the factor of the urban spatial structure. Therefore, it is necessary to evaluate the coordination between the development level of micro-level TOD urban rail transit stations and the macro-level urban spatial structure, which is conducive to achieving coordinated

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and integrated development of urban rail transit and the urban spatial structure through the reasonable and effective method.

The node-place (NP) model proposed by Bertolini [9] is a commonly used TOD evaluation model, which is mainly used to evaluate the coordination between node traffic and place functions in the station areas. However, the NP model and its derivative models rarely consider the interaction between the surrounding area (hereinafter referred to as the “station area”) of the micro-level stations and the macro-level urban spatial structure [10–13]. Meanwhile, urban vitality can provide a macro perspective for the collaborative evaluation model as a core element of urban spatial structure characteristics. Therefore, this article proposed a method for the collaborative evaluation of the TOD development level and urban vitality of urban rail transit stations from a micro and macro collaborative perspective based on the NP model. At the micro-level, the node-place-walkability model was used to describe the TOD development level of urban rail transit stations. At the macro-level, the impact of the NP model on the urban spatial structure was evaluated using the urban vitality indicator. The indicators of a collaborative evaluation model and quantitative node value dimension of the hierarchical classification matrix, the place value dimension, the walkability dimension, and the urban vitality dimension were constructed. This paper took 31 rail transit micro-centers in the List of Rail Transit Micro-Centers in Beijing (First List) as an example to conduct spatial collaborative evaluation, evaluation matrix analysis, and correlation analysis between the TOD development level and urban vitality of urban rail transit stations, so as to explore the coordination between the TOD development level and urban spatial structure of urban rail transit stations, providing a more comprehensive and in-depth theoretical and practical basis for urban sustainable development and high-quality development of urban rail transit.

1 Construction of an evaluation system

Urban rail transit and the urban spatial structure interact with each other. At the macro level, there is a significant coordination effect between the urban form and urban rail transit network planning. The introduction and expansion of urban rail transit not only improve urban transportation efficiency, promote economic growth, and improve the land value along the route but also guide the re-layout of the urban spatial structure, which helps to form a multi-center structure and effectively alleviate the pressure on the central area of a city. At the micro level, the urban spatial structure has an impact on urban rail transit, where factors such as the residential population density, employment density, and land use mixing affect the use efficiency and effectiveness of urban rail transit significantly [14]. Urban rail transit greatly improves regional transportation convenience, enhances station accessibility, and gathers more people and capital. The micro-level elements of suitable TOD transportation service facilities, building density, and land use in the station area have a synergistic and mutually reinforcing effect on the urban spatial structure. Therefore, an evaluation system for the coordination between the TOD development level and urban vitality of urban rail transit stations is constructed at both macro and micro levels (see Fig. 1).

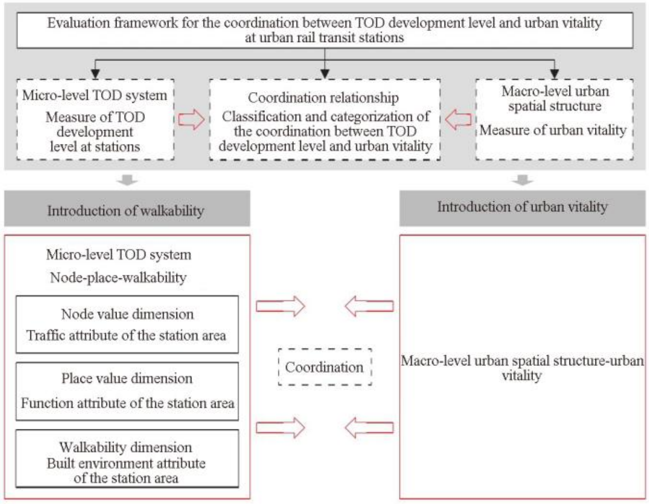


Fig. 1 Evaluation framework for the coordination between TOD development level and urban vitality at urban rail transit stations

1) Measure of the TOD development level of urban rail transit stations

The NP model aims to promote the coordinated coupling of node and place functions of the station area, which mainly focuses on transportation supply and land use characteristics of the place, lacking consideration for the built environment of the station area. However, the built environment of the station domain is closely related to people’s travel experience and widely regarded as one of the key influencing factors in TOD development. Therefore, the NP model should be combined with the evaluation of the built environment characteristics of the station area to comprehensively evaluate the TOD development level of urban rail transit stations. In addition, it is one of the important directions for TOD development to create a good walking environment, and a large number of studies on the relationship between the built environment and walking [15–21] indicate that the measure of the walkability of the station area should be included in the model. According to the study on the impact of the “5D” elements of the built environment on walkability [20], namely the reasonable distance, destination accessibility, high density, diversity, and good design, the station area walkability can be used to evaluate all dimensions of the built environment impacting travel. Therefore, this article extended the walkability dimension in the NP model so that the impact of the walking environment on urban rail transit stations is reflected, thus forming a measurement method for the TOD development level of urban rail transit stations based on “node-place-walkability”.

2) Measure of urban vitality

Previous studies show that urban vitality is a comprehensive reflection of multiple aspects such as the economy, society, culture, and space in the urban system. A station area with high urban vitality usually means more diverse land use, denser population distribution, richer social activities, and more convenient transportation connections. Urban vitality is regarded as a comprehensive indicator used to evaluate the importance of a station area in a city [21–22]. Therefore, urban vitality can serve as a core element of urban spatial structure characteristics, providing a macro perspective for the coordinated evaluation model, so that the evaluation is not limited to the station area, but the perspective is expanded to the entire urban system. We can better understand the interactive relationship between the station area and the entire city, as well as how this interactive relationship affects the implementation of the TOD concept by introducing the dimension of urban vitality. It is an important step in improving the accuracy and comprehensiveness of TOD evaluation for urban rail transit stations to incorporate urban vitality into the coordinated evaluation model.

2 Evaluation indicators and model

2.1 Selection of evaluation indicators

The evaluation indicators for the coordination between the TOD development level and urban vitality of urban rail transit stations were selected at both macro and micro perspectives (see Fig. 2).

Macro-level classification is a classification and evaluation of the urban vitality dimension to assess the vitality level of each station area. Based on existing literature research, the uniqueness of indicators, and the availability of publicly available data, this article selected the passenger flow at stations, nighttime activity, and future planning as indicators to evaluate urban vitality, and avoids cross-cutting and mutual influence between dimensions through correlation testing. Specifically, the passenger flow of stations is an important representative of the vitality of urban rail transit stations; nighttime activities, including population density and economic activity at night, are important manifestations of urban vitality; and future planning uses the proportion of core land (industrial and residential) area in planned land to represent the amount of industrial land and population that can be carried within the region, which is an important source of urban vitality.

Micro-level classification is a measure system for the TOD development level of urban rail transit stations constructed in three dimensions: node value, place value, and walkability. Among them, the node value dimension mainly considers three indicators: the carrying capacity of a station, station network centrality, and transfer convenience of a station; The place value dimension mainly considers three indicators: the land development level, mixed use of land, and the land value; The walkability dimension selects three indicators: the road texture, facility accessibility, and pedestrian network accessibility. Finally, urban rail transit stations are classified through indicator processing, correlation testing, standardization, weight determination, and three-dimensional (3D) model clustering.

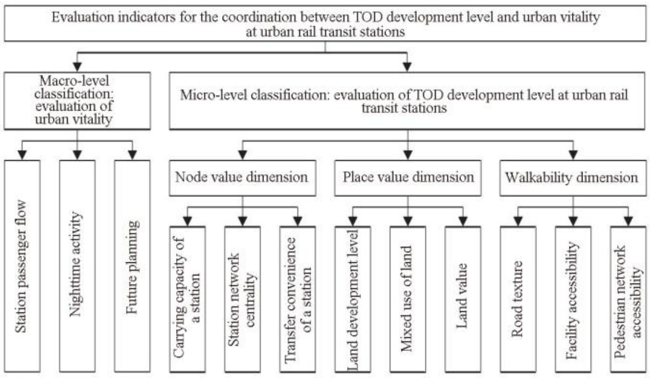


Fig. 2 Evaluation indicators for the coordination between TOD development level and urban vitality at urban rail transit stations

2.2 Classification-categorization matrix coordination evaluation model

A coordination evaluation model was constructed based on clustering analysis to obtain the types of urban rail transit stations. The node-place-walkability classification results were taken as the *x*-axis, and the urban vitality level was taken as the *y*-axis. The macro-level classification results and micro-level classification results were constructed through the matrix quadrant, so as to gain a deeper understanding of the correlation between urban rail transit stations and the urban spatial structure, and identify the coordination between the TOD development level and urban vitality of urban rail transit stations based on the quadrant position (see Fig. 3).

3 Cases of rail transit micro-centers in Beijing

3.1 Research object and data source

To promote the integrated development of urban rail transit and cities and enhance the vitality of station surroundings, Beijing proposed the construction of an urban rail transit micro-center with the rail transit station as the core at the end of 2020. A rail transit micro-center refers to an urban spatial area that is fully integrated and interactive with rail transit stations, which has high accessibility, intensive land use, diverse urban functions, and a sense of place and recognition. It has five characteristics: vitality sharing, complex diversity, efficient intensification, convenient accessibility, and pleasant space, where vitality shaping is an important goal. The approval of the List of Rail Transit

Micro-Centers in Beijing (First Batch) states that the rail transit micro-centers will be based on forming dynamic centers in the future with composite functions, high quality, and serving the people in Beijing, and achieve organic integration with the urban public service center system and various levels of urban life service circles. Therefore, the evaluation of the coordination between the TOD development level of urban rail transit stations and urban vitality will be beneficial for guiding the policy formulation and implementation effect evaluation of rail transit micro-center construction, guiding the development of rail transit micro-center construction.

Tab. 1 Overview of 31 built and operational rail transit micro-centers in Beijing

Urban area		Quantity	Station as rail transit micro-center	
			Transfer station	General station
Central urban area	Haidian District	3	Mudanyuan	Wudaokou and Liudaokou
	Chaoyang District	2	Shilihe	Dongdaqiao
	Fengtai District	6	Jingfengmen, Caoqiao, Xingong, and Lize Financial Business District	Fengtai South Road and Yushuzhuang
	Shijingshan District	2	Jin'anqiao	New Shougang
Outlying area	Yizhuang New City	5	Ciqu	Beishenshu, Ciqu North, Rongchang East Street, and Tongji South Road
	Daxing District	1		Daxing New City
	Fangshan District	2		Liangxiang University Town and Liangxiang Nanguan
	Changping District	4	Huoying	Huilongguan East Street, Shahe University Park, and Life Science Park
Sub center	Tongzhou District	6	Huazhuang	Wansheng West, Wansheng East, Qunfang, Gaoloujin, and Jiahuihu

The List of Rail Transit Micro-centers in Beijing (First Batch) designates 71 stations as the construction areas for rail transit micro-centers, including 17 railway passenger stations and 54 subway stations (hereinafter referred to as “urban rail transit stations”). This article selected 31 urban rail transit stations that have been built and put into use as of February 2023 as the research object (see Tab. 1).

When we study the impact range of urban rail transit stations, pedestrian catchment area (PCA) is often used for measurement, usually represented by a circular buffer zone. This article used a 10-minute walking time threshold and an average walking speed standard of 1.3 $m \cdot s^{-1}$ to set the pedestrian attraction range of urban rail transit stations as an 800 m buffer zone.

The multi-source data used in this article mainly includes the urban rail transit stations and line data of Beijing, points of interest (POI) around a station, urban rail transit network data, road vector data, and passenger flow data of urban rail transit stations (see Tab. 2).

Tab. 2 Multi-source data information

Data type	Number	Field	Source
Urban rail transit station	458	Station name, latitude, and longitude	OpenStreetMap
Urban rail transit line	520	Line name, latitude, and longitude	Amap
Operation of urban rail transit station		Station operation timetable	Official websites of Beijing Subway, BJMTR, and Beijing Metro Operation Administration Corporation
Bus station	3 637	Line name, latitude, and longitude	Amap
Bus line	6 253	Line name, latitude, and longitude	Amap
POI of urban rail transit station surroundings	46 521	Name, type, latitude, and longitude	Bigemap
Building	43 755	Height, type, area, and location	OpenStreetMap
Road network	20 716	ID, classification, and length	OpenStreetMap
Residential district	605	Name and housing price	Website of Homelink
Passenger flow of urban rail transit station	62	Date, in and out quantity	Research project of coordination between transportation and land in Beijing
Nighttime lighting	31	Average value of light brightness	NPP-VIIRS satellite data
Planning land use	31	Proportion of various types of land use	Beijing Municipal Commission of Planning and Natural Resources

Note: The year of the planned land data is 2020; the year of the passenger flow data for urban rail transit stations is March 2022, and the year of the remaining data is 2023.

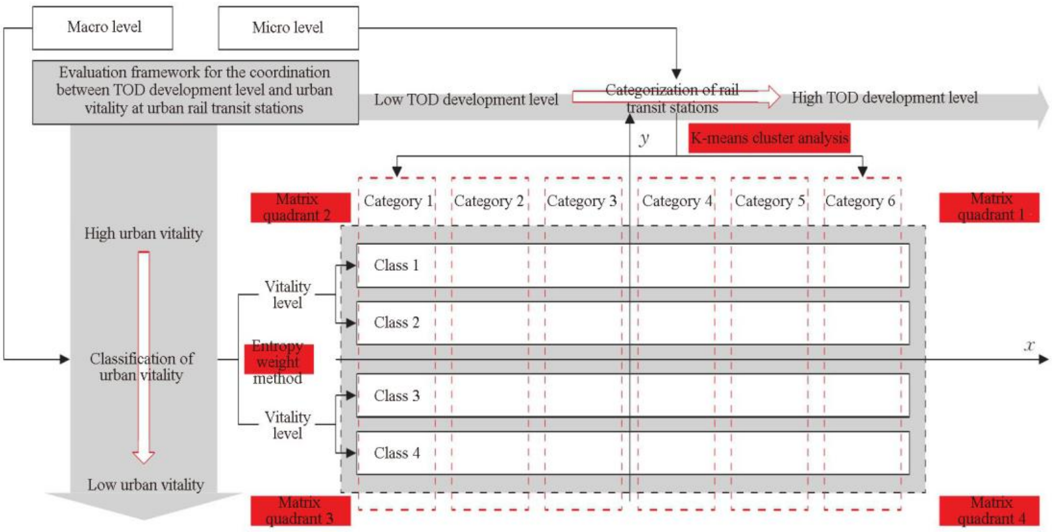


Fig. 3 Classification-categorization matrix coordination evaluation model

3.2 Evaluation indicators and calculation method

Referring to relevant research in China and abroad [23–30], and based on data availability and regional applicability, this article screened indicators from four dimensions: the node value, place value, walkability, and urban vitality, and determined a total of 21 indicators (see Tab. 3).

3.3 Evaluation method

This article used the information entropy weighting method to integrate indicators at classification and categorization levels, which avoids the subjectivity of manual weighting. In the classification and evaluation of the TOD development level of urban rail transit stations, the K-means clustering method was used to obtain the corresponding types of urban rail transit stations. The specific method and results were based on the classification study of rail transit micro-center stations in Ref. [31].

Tab. 3 Classification-categorization matrix coordination evaluation indicators

Level	Dimension	Basic indicator	Sub indicator	Indicator description
Categorization	Node value (*N*)	Station bearing capacity	$N1 =$ Number of entrances and exits at the station	Number of entrances and exits at the station
			$N2 =$ Number of service directions at the station	The number of directions for the terminal station is 1; the number of directions for non-transfer stations (excluding terminal stations) is 2; for the transfer station with an additional line that can be transferred each time, the direction increases by 2
		Station network centrality	$N3 =$ Betweenness centrality of urban rail transit network	Proportion of the shortest path length through the station to the total network path length
			$N4 =$ Closeness centrality of urban rail transit network	Reciprocal of the average distance between a station and other stations
			$N5 =$ Average distance between urban rail transit stations	Average distance between a station and adjacent stations
		Convenience of station transfers	$N6 =$ Number of bus stations in the station area	Number of bus stations in the station area
			$N7 =$ Convenience of bus transfers	Number of bus lines within 200 m around a station
	Place value (*P*)	Land development level	$P1 =$ Building development intensity	Proportion of the total area of above-ground buildings in the station area in the total area of the station area
			$P2 =$ Building density	The proportion of the base area of above-ground buildings in the station area in the total area of the station area
		Mixed land use	$P3 =$ Mixed degree of land use functions	POI land use mixing degree calculated based on the Shannon diversity index method
			$P4 =$ Number of facilities in the place	Number of POIs in the station area
		Land value	$P5 =$ Surrounding housing price	Average price of second-hand residential properties in the station area
	Walkability (*W*)	Road texture	$W1 =$ Density of road network	The ratio of total length of road network in the station area to the area of the station area
		Facility accessibility	$W2 =$ Revised pedestrian index for commercial service facilities	Commercial service facility accessibility calculated by the WalkScore method
			$W3 =$ Revised pedestrian index for public service facilities	Public service facility accessibility calculated by the WalkScore method
			$W4 =$ Revised pedestrian index for living service facilities	Living service facility accessibility calculated by the WalkScore method
			$W5 =$ Revised pedestrian index for park and green space service facilities	Park and green space service facility accessibility calculated by the WalkScore method
		Pedestrian network accessibility	$W6 =$ Pedestrian network accessibility of stations	Calculate BtA800c (pedestrian traffic volume measured at an intermediate angle of 800 m) using spatial syntax software sDNA and take the average value
Classification	Urban vitality (*V*)		$V1 =$ Daily average station passenger flow	The daily average number of passengers entering and leaving the station within a month
			$V2 =$ Nighttime light index	Average nighttime light value throughout the year
			$V3 =$ Future planning vitality	Proportion of the core land (industrial land) area in planned land use

Note: This article used the average scores of the node value dimension (*N*), place value dimension (*P*), and walkability dimension (*W*) indicators, namely, the average NPW value, to reflect the level of TOD development.

4 Research results

4.1 Classification of urban rail transit stations and categorization of urban vitality

The TOD development level of 31 urban rail transit stations was divided into six types from high to low: the pressure type, node imbalance type, balance type, balance type-low walkability, development type-low walkability, and subordinate type-low walkability (see Tab. 4). The urban vitality of urban rail transit stations was divided into four levels, where the urban vitality decreases from level 1 to level 4 (see Fig. 4).

The type of urban rail transit stations and the distribution of urban vitality levels are shown in Fig. 5. Overall, the TOD development level and urban vitality of most urban rail transit stations in the central area of the city are relatively high, but in the peripheral areas of the city at the end of the lines, both are relatively low for most urban rail transit stations. In terms of the TOD development level of urban rail transit stations, stations in the city center usually have high accessibility and efficient land use, attracting a large population and industrial agglomeration. These stations usually have complete transportation infrastructure and diversified land use functions, providing residents with convenient and comfortable travel and living environment. In contrast, due to the insufficient transportation infrastructure and land use planning, the TOD development level of urban rail transit stations in the peripheral areas of a city at the end of the line is relatively low. In terms of urban vitality, due to the concentration of population and industries, central urban rail transit stations usually have high urban vitality. These areas have rich cultural, educational, and commercial resources, attracting a large number of people and logistics. In contrast, due to sparse population and industrial distribution, urban rail transit stations located at the end of the line in peripheral areas have relatively low urban vitality.

Overall, Beijing presents a clear core-periphery structure in terms of the TOD development level and urban vitality in urban rail transit stations. However, some urban rail transit stations located at the end of the line in peripheral areas, such as Huilongguan East Street, Jin'anqiao, and Gaojinlou, also have a high level of TOD development and urban vitality. These urban rail transit stations are usually located in large residential areas, urban sub-centers, or important transportation hubs, with high accessibility and land use efficiency. They also possess a certain degree of urban vitality. The development of these areas provides new directions and opportunities for the future urban planning and construction of Beijing.

4.2 Classification-categorization matrix coordination evaluation

The conventional NP model method cannot identify the fit between stations and the urban spatial structure, while the classification-categorization matrix coordination evaluation model can effectively identify the degree of match between the TOD development level of urban rail transit stations and urban vitality, thereby determining the fit between the TOD development level of urban rail transit stations and the urban spatial structure. This article conducted a cross-analysis between the types of urban rail transit stations and the level of urban vitality, forming a 6 × 4 cross matrix. According to the coordination characteristics and development trend, urban rail transit stations in different quadrants were classified into four types: the vitality-coordinated type, vitality-leading type, vitality-cultivating type, and vitality-lacking type (see Fig. 6).

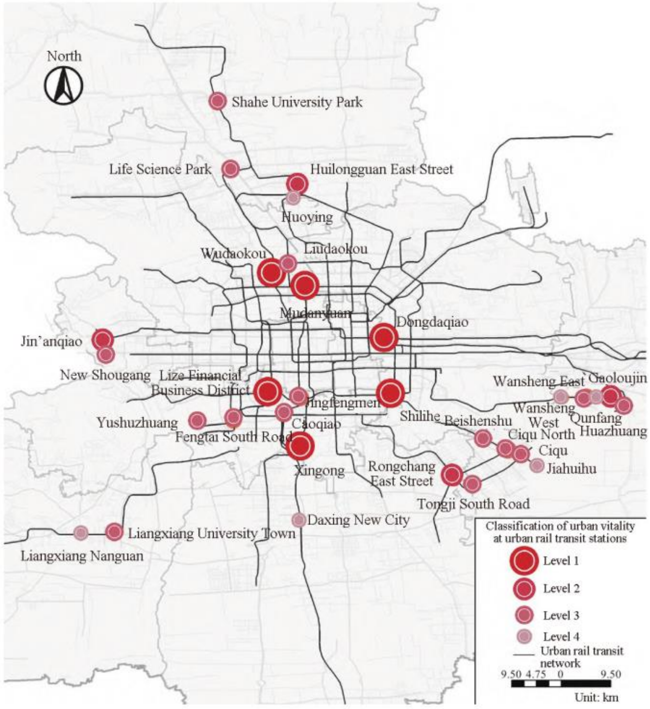


Fig. 4 Classification of urban vitality at urban rail transit stations

Tab. 4 Urban rail transit station types and average values by dimension

Urban rail transit station type	Number	Station	Average value by dimension		
			Node value	Place value	Walkability
Pressure type	1	Dongdaqiao	0.65	0.75	0.78
Node imbalance type	1	Shilihe	0.88	0.57	0.56
Balance type	7	Wudaokou, Mudanyuan, Liudaokou, Fengtai South Road, Jingfengmen, and Caoqiao	0.54	0.54	0.39
Balance type-low walkability	5	Lize Financial Business District, Jin'anqiao, Rongchang East Street, Huilongguan East Street, and Huoying	0.52	0.47	0.17
Development type-low walkability	12	Gaoloujin, New Shougang, Wansheng East, Huazhuang, Ciqu North, Tongji South Road, Beishenshu, Liangxiang University Town, Life Science Park, Yushuzhuang, Qunfang, and Liangxiang Nanguan	0.30	0.32	0.15
Subordinate type-low walkability	5	Ciqu, Shahe University Park, Wansheng West, Daxing New City, and Jiahuihu	0.25	0.16	0.07

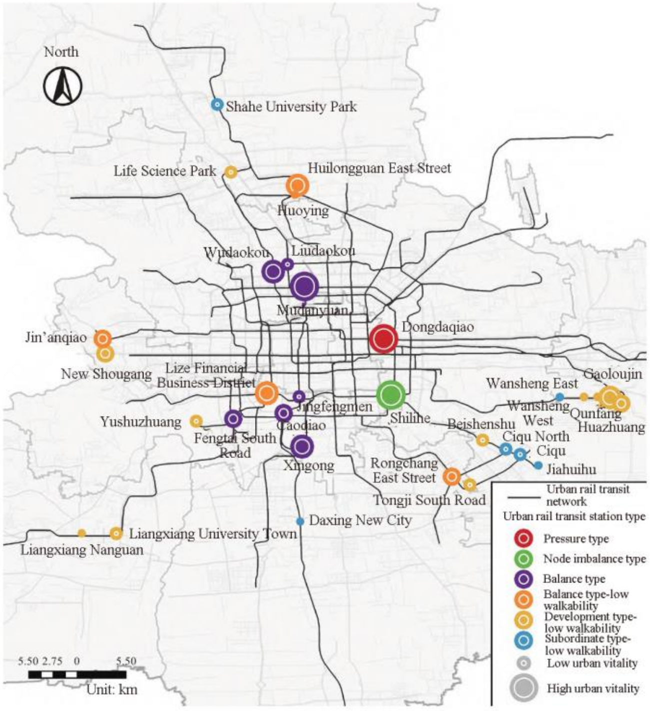


Fig. 5 Distribution of urban rail transit station types and urban vitality levels

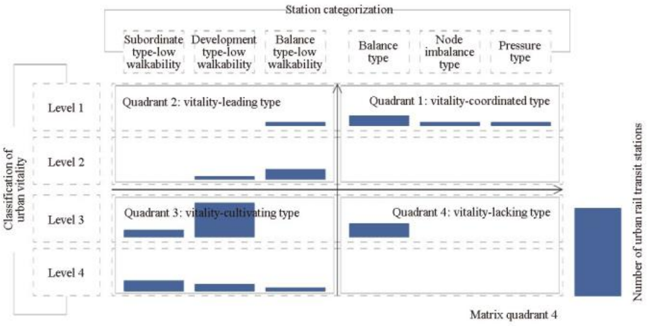


Fig. 6 Identification of urban rail transit station types based on classification-categorization matrix coordination evaluation

Note: The height of the bar chart represents the number of urban rail transit stations of this intersection type, and the upper right corner represents the urban rail transit stations with the highest level of urban vitality and the best TOD development level.

4.2.1 Vitality-coordinated type

The vitality-coordinated urban rail transit stations not only create good TOD development results but also have good urban vitality. Pressure type and node imbalance type stations belong to this category (see Tab. 5), which are mainly located in the central area of Beijing. For example, the Dongdaqiao station of the level 1–pressure type (*NPW* average = 0.73, urban vitality index = 0.71) and the Shilihe station of the level 1–node imbalance type (*NPW* average = 0.67, urban vitality index = 0.71) show good coordination between the TOD development level and urban vitality. It is worth noting that these stations have some problems. For example, due to the high concentration of people and logistics, urban rail transit stations face significant traffic pressure, which can easily lead to congestion. In addition, excessive concentration of land use functions may lead to a decline in environmental quality and living conditions. Therefore, in future urban planning and development, it is necessary to pay attention to balancing the relationship between transportation, land use, and urban vitality. On the one hand, we can alleviate the traffic pressure and improve travel efficiency by optimizing traffic organization and layout of transportation facilities; on the other hand, we focus on environmental protection and improvement of living conditions, providing residents with a comfortable and livable urban environment.

The urban vitality value of the level 1–balance type stations in vitality-coordinated urban rail transit stations is slightly higher than the TOD development level, demonstrating good coordination between the TOD development level and urban vitality. Stations of this type are mostly located in mature residential areas, with densely populated and prosperous commercial activities in the surrounding areas, providing a continuous passenger flow for the stations. Meanwhile, in the planning and design of such stations, passengers' travel needs are fully considered, and good coordination is formed with surrounding land and transportation facilities, where the Wudaokou and Mudanyuan Stations are typical representatives of such stations. As an important node of Beijing Subway Line 13, the Wudaokou Station not only connects multiple important commercial districts and residential areas but also closely connects with surrounding non-motorized vehicle lanes, sidewalks, and other road traffic facilities, providing passengers with convenient and comfortable travel experience. In addition, as the starting station of Subway Line 19, the Xingong Station undertakes the important task of commuting passenger flow between the southern urban and suburban areas of Beijing. The coordination between land use and transportation in the station area has shown remarkable performance, not only providing passengers with fast and convenient travel services but also further enhancing the attractiveness and convenience of urban rail transit stations through measures such as optimizing surrounding transportation organization and improving supporting facilities.

Tab. 5 Classification-categorization types and indicator levels of vitality-coordinated urban rail transit stations

Station	Classification-categorization type	*NPW* average	Urban vitality index
Dongdaqiao	Level 1–pressure type	0.73	0.71
Shilihe	Level 1–node imbalance type	0.67	0.71
Mudanyuan	Level 1–balance type	0.56	0.72
Xingong	Level 1–balance type	0.45	0.59
Wudaokou	Level 1–balance type	0.51	0.61

4.2.2 Vitality-leading category

Although the vitality-leading urban rail transit stations have good urban vitality, their TOD development has not reached the corresponding level, that is, the TOD development level does not match the urban vitality significantly (see Tab. 6). For example, the Lize Financial Business District Station (*NPW* average index = 0.37, urban vitality index = 0.63), which is classified as level 1–balance type–low walkability, has high urban vitality due to the strong commercial atmosphere, dense employment and residential population in the surrounding area. However, due to the implementation of some regional planning in the station area, the connectivity of the pedestrian network and accessibility of facilities in the station area are poor. To enhance the TOD development level of urban rail transit stations, an efficient and convenient pedestrian network system can be constructed, and its transportation connection system can be continuously improved to improve the traffic conditions in the station area, thereby enhancing the overall traffic efficiency of the station. Level 2–balance type–low walkability stations also exhibit the same situation, such as Huilongguan East Street Station (*NPW* average = 0.35, urban vitality index = 0.53). As a large residential area surrounding the station, it has many commercial, cultural, and entertainment facilities, attracting people and logistics gathering. However, the road network of large residential areas makes walkability at a low level, which affects the TOD development level of urban rail transit stations. For such stations, the pedestrian network and facility accessibility can be optimized to improve the level of walkability and provide residents with a more comfortable and convenient travel environment.

Level 2–development type–low walkability stations in the vitality-leading urban rail transit stations show obvious mismatching characteristics between the TOD development level and urban vitality. For example, the Gaoloujin Station (*NPW* average = 0.25, urban vitality index = 0.50) has good urban vitality, but its TOD development level is insufficient. This type of station is usually located in the outskirts of the city, with a large number of characteristic industries in the surrounding area, and population density units with a large number of job opportunities. Therefore, such stations should focus their industrial functions on urban rail transit stations and become important functional clusters in the city.

Tab. 6 Classification-categorization types and indicator levels of vitality-leading urban rail transit stations

Station	Classification-categorization type	*NPW* average	Urban vitality index
Lize Financial Business District	Level 1–balance type–low walkability	0.37	0.63
Jin'anqiao	Level 2–balance type–low walkability	0.45	0.43
Rongchang East Street	Level 2–balance type–low walkability	0.40	0.41
Huilongguan East Street	Level 2–balance type–low walkability	0.35	0.53
Gaoloujin	Level 2– development type–low walkability	0.25	0.50

4.2.3 Vitality-cultivating category

The TOD development level and urban vitality level of vitality-cultivating urban rail transit stations are relatively low (see Tab. 7), such as the Daxing New City Station (*NPW* average = 0.16, urban vitality index = 0.17) and Jiahuihu Station (*NPW* average = 0.07, urban vitality index = 0.15). These stations are usually located at the end of an urban rail transit line or in relatively remote areas. Due to insufficient transportation infrastructure and station development or incomplete planning and implementation, the functional benefits of the stations are still at a low level, resulting in relatively low TOD development and urban vitality. The low value of such station locations and walkability indicates great potential for future development, and dynamic evaluation of the planning and implementation of these station areas should be emphasized. In future urban planning and development, it is necessary to strengthen attention and support for these stations, improve the accessibility and convenience of urban rail transit stations through optimizing transportation organization and land use planning, attract more population and industrial clusters, and promote station development.

Level 4–balance type–low walkability stations in vitality-cultivating urban rail transit stations present another mismatching feature, namely, there is a significant difference between the level of TOD development and that of urban vitality. For example, as a special type of station, the Huoying Station (*NPW* average = 0.36, urban vitality index = 0.17) will be positioned as a comprehensive transportation hub in the future, serving as a transfer station for Subway Line 8 and Line 13. The TOD development level has a high node value, but due to incomplete planning and implementation, the station's traffic supply level has not effectively driven the vitality of the station area, and there are still a large number of medium and low-efficiency land uses in the station area. Therefore, compared with the TOD development level, the urban vitality of the Huoying Station is at a lower level. More attention needs to be paid to these types of stations, taking the construction of comprehensive transportation hubs as an opportunity to reactivate the inefficient use of land in the city, optimize transportation functions to guide multiple urban functions to gather here, and promote urban renewal. It can not only improve travel and enhance service functions, but also shape a more attractive urban landscape image, thereby optimizing the urban spatial structure in multiple dimensions and creating a vibrant city center.

4.2.4 Vitality-lacking category

Level 3–balance type stations in vitality-lacking urban rail transit stations exhibit a clear mismatch feature between the TOD development level and urban vitality. These stations have a better TOD development level but a lower level of urban vitality (see Tab. 8). For example, the Jingfengmen

Station (NPW average = 0.51, urban vitality index = 0.29) and Liudaokou Station (NPW average = 0.48, urban vitality index = 0.32), the surrounding areas of these stations generally have mature living facilities and convenient public transportation, and the residents in this area are highly dependent on urban rail transit for travel. Although these types of stations have been given priority in construction, their ability to lead the urban spatial structure is insufficient. In future planning, its vitality should be activated to increase the proportion of core land, making the advantages of TOD development transform into urban vitality.

Tab. 7 Classification-categorization types and indicator levels of vitality-cultivating urban rail transit stations

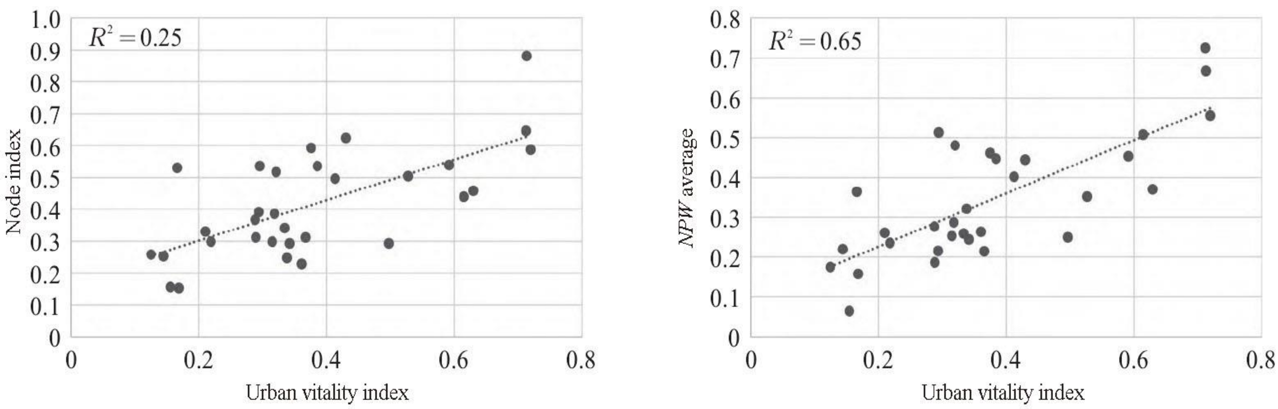
Station	Classification-categorization type	NPW average	Urban vitality index
Ciqu	Level 3–subordination type–low walkability	0.22	0.29
Shahe University Park	Level 3–subordination type–low walkability	0.19	0.29
New Shougang	Level 3–development type–low walkability	0.26	0.36
Wansheng East	Level 3–development type–low walkability	0.24	0.22
Huazhuang	Level 3–development type–low walkability	0.22	0.37
Ciqu North	Level 3–development type–low walkability	0.28	0.29
Tongji South Road	Level 3–development type–low walkability	0.25	0.31
Beishenshu	Level 3–development type–low walkability	0.29	0.32
Liangxiang University Town	Level 3–development type–low walkability	0.24	0.34
Life Science Park	Level 3–development type–low walkability	0.26	0.33
Yushuzhuang	Level 3–development type–low walkability	0.32	0.34
Wansheng West	Level 4–subordination type–low walkability	0.18	0.12
Daxing New City	Level 4–subordination type–low walkability	0.16	0.17
Jiahuihu	Level 4–subordination type–low walkability	0.07	0.15
Qunfang	Level 4–development type–low walkability	0.22	0.14
Liangxiang Nanguan	Level 4–development type–low walkability	0.26	0.21
Huoying	Level 4–balance type–low walkability	0.36	0.17

Tab. 8 Classification-categorization types and indicator levels of vitality-lacking urban rail transit stations

Station	Classification-categorization type	NPW average	Urban vitality index
Liudaokou	Level 3–balance type	0.48	0.32
Fengtai South Road	Level 3–balance type	0.45	0.38
Jingfengmen	Level 3–balance type	0.51	0.29
Caoqiao	Level 3–balance type	0.46	0.37

4.3 Correlation analysis between TOD development level and urban vitality of urban rail transit stations

Through the correlation analysis between the TOD development level of urban rail transit stations and urban vitality (see Fig. 7), it was found that the average NPW value is strongly correlated with the urban vitality index, with a significant positive correlation (R^2 = 0.65), indicating that the implementation of the TOD concept in urban rail transit stations can effectively drive the urban vitality of the station area. The correlation between the node index and the urban vitality index is weak (R^2 = 0.25), indicating insufficient coordination between the transportation supply and urban vitality. On the one hand, although the construction of the transportation infrastructure brings new connections and accessibility to cities, without matching urban activities and land use planning, the transportation infrastructure is difficult to fully unleash its potential. On the other hand, it indicates that some urban rail transit stations' existing transportation system focuses too much on the demand for motor vehicles and ignores the needs of pedestrians and cyclists, resulting in insufficient urban vitality. Overall, it reflects that the construction of 31 urban rail transit stations is still in its early stages, with incomplete transportation infrastructure and a lack of land use in the station area. The TOD development level can effectively drive the urban vitality of the station area, which confirms the development potential of these urban rail transit stations.



a Station node index and urban vitality index b NPW average and urban vitality index

Fig. 7 Correlation analysis between TOD development levels and urban vitality at urban rail transit stations

5 Summary and discussion

This article evaluated the coordination between the TOD development level and urban vitality of 31 urban rail transit stations in Beijing from the perspectives of micro and macro coordination. The main conclusions are as follows:

1) The TOD development level and urban vitality of urban rail transit stations show a clear core-periphery structure, but some urban rail transit stations located at the end of the line in peripheral areas have a high TOD development level and urban vitality, indicating that these local areas may become important nodes leading the development of the urban spatial structure in the future.

2) The coordination evaluation results of the classification-categorization matrix show that there are significant differences in the coordination level between the rail transit micro-centers. Vitality-coordinating type urban rail transit stations usually have good transportation services, efficient land use, and strong urban vitality. On the contrary, vitality-lacking and vitality-leading urban rail transit stations exhibit a mismatch between the TOD development level and urban vitality, requiring targeted planning and improvement. Vitality-cultivating urban rail transit stations need to strengthen planning and guidance, and improve station accessibility and convenience.

3) There is a clear positive correlation between the TOD development level of urban rail transit stations and urban vitality, but the correlation between the node index and urban vitality is weak, indicating insufficient coordination of urban vitality by the transportation supply and the insufficient stimulation intensity of urban vitality by the transportation supply quantity.

Overall, in future urban planning and development, the coordinated relationship between the TOD development level of urban rail transit stations and urban vitality should be fully considered, and scientific and reasonable policy measures should be formulated to improve and enhance urban vitality. Macroscopically, we should promote the refined development of urban rail transit stations based on the level of urban vitality, create differentiated station clusters, and construct urban functional clusters around urban rail transit stations to optimize the urban spatial structure. At the micro level, based on the coordinated state between the TOD development level and urban vitality, the overall coordination level of urban rail transit stations can be improved by optimizing the pedestrian network and facility accessibility, improving the non-motorized transportation system, strengthening the diversified functions of urban rail transit stations, optimizing public services, etc., thus achieving a virtuous cycle of urban transportation and urban development.

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