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Spatial Coupling of Mass Transit Networks and Business Centers in China's Megacities: A Complex Network Theory Approach

Shiping Wen*

School of Civil Engineering and Architecture, Chongqing University of Science and Technology, 401331 Chongqing, China

* Correspondence: Shiping Wen (wensp@cqust.edu.cn)

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Abstract: As fundamental nodal elements in urban spatial structures, the coupling and coordinated development of urban business centers and urban rail transit contributes to the optimization of these structures. Utilizing complex network theory, a model for the urban rail transit network was constructed. The importance and hub nature of urban rail transit stations were evaluated from different angles, including degree centrality, closeness centrality, betweenness centrality, and eigenvector centrality. These metrics examined the station's degree, closeness to other nodes, number of shortest paths, and centrality of neighboring nodes. The coupling relationship between urban rail transit and urban business centers was taken into account, leading to the creation of a coupling and coordination degree model for urban rail transit stations and urban business centers. An analysis of the spatio-temporal evolution of the coupling relationship between urban rail transit and business centers in Beijing, Shanghai, and Guangzhou from 2000 to 2020 was conducted. The findings indicated an interactive and mutually influencing coupling relationship between the urban rail transit network and urban business centers. Over time, the coupling and coordination degree of urban rail transit stations and urban business centers trended from being uncoordinated towards preliminary, moderate, and good coordination. Spatial heterogeneity existed in the coupling and coordination status of different circles, with the best coupling and coordination conditions being in the core area. There was a degree of variance in the coupling and coordination development situation of rail transit stations and business centers in the core areas of different cities. Among them, Shanghai's core area had the best spatial coupling and coordination development situation, Beijing's core area lagged in business center development compared to the construction of the urban rail transit network, while Guangzhou's core area saw urban rail transit network development lag behind its mature business centers. The application of these research findings aids in promoting sustainable urban development. While this study primarily measured the importance of urban rail transit network stations from the node centrality perspective, future studies could further examine the spatial coupling of urban rail transit and business centers from the viewpoints of accessibility and passenger flow.

Keywords: Urban rail transit; Business centers; Complex networks; Centrality indices; Coupling and coordination degree

1 Introduction

A level of urbanization unprecedented in human history is currently being experienced by China [1]. The urbanization rate in China in 2000 was at 36%, which surpassed 60% for the first time in 2019. Urbanization serves as an essential engine for modernization and economic growth [2, 3], yet rapid urbanization has led to excessive crowding in urban centers, traffic congestion, and environmental pollution [4, 5]. Urban rail transit, characterized by high speed, large capacity, long operating hours, high safety, and environmental friendliness, can balance urban elements such as population, resources, and environment effectively [6]. Therefore, ameliorating the relationship between the development of urban rail transit construction and urban spatial structure can effectively alleviate these urban issues [5, 7].

In fact, urban rail transit networks, as a form of local public good, greatly enhance accessibility, resulting in significant external effects [8]. A pivotal role is played by urban rail transit in the development process of urban spatial structure [9], and it directs the evolution of urban spatial structure through stations. Urban business centers can stimulate the development of surrounding areas and have significant economic benefits, serving as fundamental nodal elements of the urban spatial structure [10]. However, existing research mainly discusses the relationship between the layout of urban rail transit and business centers from the perspective of geographical space structure, while the intrinsic link between urban rail transit network and urban business centers is less revealed from the perspective of network space. In light of this, complex network theory is introduced in this study, and urban rail transit network models are constructed using Beijing, Shanghai, and Guangzhou as examples. The spatiotemporal evolution of the coupling relationship between urban rail transit stations and urban business centers is examined from both network space and geographical space perspectives. The aim is to uncover the inherent mechanism of the coordinated development of urban rail transit and urban spatial structure coupling, hoping to provide theoretical guidance and policy reference for urban sustainable development.

2 Literature Review

Since the 1960s, increasing attention has been paid by researchers to the impact of urban rail transit construction on urban spatial morphology and real estate value. Alonso [11], Muth [12], and Mills [13] proposed the monocentric model of urban spatial structure, suggesting that transportation cost is a crucial factor affecting land value, and improvements in accessibility can lead to a reduction in transportation costs, subsequently causing an increase in land value. Thomson [9] was the first to propose the concept of guiding urban space development through rail transit, asserting that rail transit plays a key role in the formation and development process of urban space. The construction of urban rail transit can cause an increase in the value of commercial land [14–16], and its agglomeration and diffusion forces can affect population distribution [17], thereby guiding the spatial layout of commercial land around stations [18]. The layout of urban business centers can be guided by the construction of urban rail transit, and simultaneously, the development of urban business centers can promote the construction of urban rail transit. Mitchell and Rapkin [19] argued that the mode of urban land use is a major factor determining urban traffic flow, and the spatial layout of urban business centers determines the distribution of passenger flow and transportation demand. Newman and Kenworthy [20] analyzed the relationship between urban land use and transportation systems in 32 major cities worldwide and found that high-density development patterns can promote the development of public transportation systems.

Urban rail transit networks are not only complex in structure but also in relationships, representing a typical complex network. As an infrastructure network for passenger flow transportation, they have a significant impact on a city's economy, society, and environment. In studies on the importance of nodes in complex networks, the main indices to measure node importance are degree centrality, closeness centrality [21], betweenness centrality [22, 23], and eigenvector centrality [24]. Crucitti et al. [25] studied the closeness centrality and betweenness centrality of urban road networks and argued that the combined analysis of multiple centrality indices could reflect the centrality of network nodes more reasonably.

In existing research, most scholars focus on the unidirectional influence of urban rail transit and urban business centers [26], with fewer studies on their mutual interaction and even fewer examining their coupling relationship from the perspective of complex networks. This study uses a method combining complex networks and Geographic Information Systems (GIS) to investigate their coupling relationship, expanding the research perspective on urban rail transit networks. Taking Beijing, Shanghai, and Guangzhou, three megacities with a high level of economic development and early commencement of urban rail transit, as examples, the study considers both time and space. Data on urban rail transit and urban business centers from 2000-2020 in these cities are divided into five time sections: 2000, 2005, 2010, 2015, and 2020. Using GIS analysis methods, and according to the latest round of "Urban Master Plan" for Beijing, Shanghai, and Guangzhou, each city is divided into three layers: Central Activity Zone (CAZ), CAZ to Main Urban Area (MUA), and Peripheral Urban Area (PUA). Complex network theory is introduced to construct urban rail transit network models at five time sections, and four node centrality indices, degree centrality, closeness centrality, betweenness centrality, and eigenvector centrality, are extracted as evaluation indices for the importance and hub nature of urban rail transit stations. Commercial facility land scale, commercial facility building area, service population, daily passenger flow, and the number of large-scale commercial facilities are selected as evaluation indices for the scale level of urban business centers. A coupling and coordination degree model is constructed for urban rail transit and urban business centers, revealing the coupling relationship and spatiotemporal evolution between urban rail transit stations and urban business centers.

3 Coupling Mechanism of Urban Rail Transit and Business Centers

The concept of "coupling" originates from physics, referring to the phenomenon where two or more systems or modes of motion influence and unite with each other through various interactions. This dynamic relationship of mutual dependence, coordination, and promotion arises from benign interactions among subsystems [23]. The construction of urban rail transit enhances the accessibility of areas surrounding the stations, which brings substantial external economic benefits. This can attract socially active groups with strong competitive abilities such as businesses to cluster around these stations, consequently influencing the layout of urban business centers. Concurrently, the layout of urban business centers can affect passenger flow distribution. The functional aggregation around the stations provides sufficient passenger demand for the development of urban rail transit, which in turn promotes the development of urban rail transit. Therefore, a coupled relationship exists between urban rail transit and urban business centers, which mutually influence, interact with, and depend on each other. The coupled coordination of urban rail transit and urban business centers can effectively promote sustainable urban development.

The spatial coupling mechanism between urban rail transit and urban business centers, as shown in Figure 1, demonstrates that on one hand, the development of urban rail transit network, as a kind of local public goods, brings huge external effects and greatly enhances accessibility. According to the growth axis theory, improvements in urban transportation infrastructure can effectively guide industries and populations to cluster on both sides of the transportation line. Using the transportation line as the "main axis", an industrial belt gradually forms, driving urban economic development. As commercial land use is characterized by high economic benefits and strong carrying capacity, and can better promote and enhance the development of surrounding areas [24], the construction of urban rail transit, according to the rent competition theory, can attract socially active groups with strong competitive abilities, such as businesses, to gather around the stations, gradually guiding the layout of urban business centers. On the other hand, the development of urban business centers will cause changes in passenger flow distribution. Urban rail transit can reduce commuting costs and extend acceptable commuting distances under certain time constraints. Changes in passenger flow distribution, commuting distance, and commuting costs determine the choice of transportation mode, which in turn influences transportation demand. According to supply and demand theory, increasing the demand for urban rail transit can further promote the development of the urban rail transit network.

Hence, the urban rail transit network and urban business centers have a relationship of mutual interaction and coupled development. From a temporal perspective, the development of the urban rail transit network and the layout of urban business centers must undergo a long period of interaction and influence to form a coupling state. From a spatial perspective, the coupling state manifests as similarity and consistency in the spatial distribution of urban rail transit network stations and urban business centers.

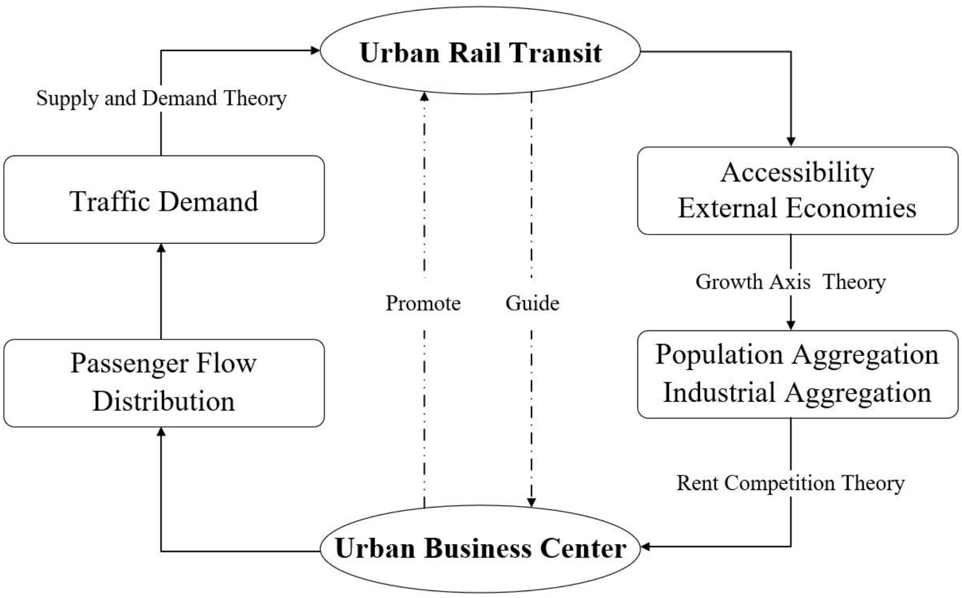

Figure 1. Spatial coupling mechanism of urban rail transit and urban business centers

4 Scope of Research

Rapid development has been observed in the field of urban rail transit in China since the year 2000. By the end of 2020, the total length of urban rail transit lines in operation in China had reached 7,970 kilometers. The operational urban rail transit systems presently encompass subway, monorail, maglev, tram, and intercity rapid transit. Beijing, Shanghai, and Guangzhou, as mega-cities in China, are the core cities of the Beijing-Tianjin-Hebei, Yangtze River Delta, and Pearl River Delta urban agglomerations, respectively. The combined length of their urban rail transit lines accounts for 35% of the country's total. The main modes of urban rail transit, such as subway and maglev, in Beijing, Shanghai, and Guangzhou are chosen for study in this research, focusing on the spatiotemporal evolution of the coupling relationship between urban rail transit stations and city business centers.

Following the research of Xu et al. [16], data of urban rail transit stations and surrounding business centers within a 400-meter radius in Beijing, Shanghai, and Guangzhou from 2000 to 2020 is collected for this research. This longitudinal dataset is divided into five time periods: 2000, 2005, 2010, 2015, and 2020. To study spatial heterogeneity, according to the Urban Master Plans of Beijing (2016-2035), Shanghai (2017-2035), and Guangzhou (2017-2035), each city is divided into three zones: the core area (CAZ), from the core area to the main urban area (CAZ-MUA), and the urban periphery (PUA). The research examines the coupling and coordination relationship between urban rail transit and city business centers in these three zones.

5 Data and Methods

5.1 Spatial Distribution Data of Urban Rail Transit and Business Centers

Geographic Information System (GIS) analysis method is employed to divide the urban areas of Beijing, Shanghai, and Guangzhou into three zones: CAZ, CAZ-MUA, and PUA. The spatial layout data of urban rail transit and city business centers for these three cities is extracted for five time periods: 2000, 2005, 2010, 2015, and 2020. Centering on the stations, the spatial data and size-grade data of the business centers within a 400-meter radius around these stations are also collected (Table 1).

Table 1. The number of urban rail transit station under different business center grading

City	Year	CAZ				CAZ-MUA				PUA			
		St	Mc	*Rc*	Cc	St	Mc	Rc	Cc	St	Mc	Rc	Cc
Beijing	2000	25	4	7	14	14	3	1	10				
	2005	25	4	11	10	33	3	1	29	6			6
	2010	40	7	15	18	84	3	10	71	49			49
	2015	55	10	14	31	160	4	18	138	67			67
	2020	64	12	13	39	211	5	25	181	127			127
Shanghai	2000	23	15	2	6	21	2	2	17				
	2005	27	17	3	7	46	2	5	39				
	2010	57	30	7	20	156	8	21	127	31		4	27
	2015	67	30	18	19	191	10	25	156	45		9	36
	2020	68	31	18	19	260	18	24	218	81		15	66
Guangzhou	2000	16	5	1	10								
	2005	36	5	6	25	3			3				
	2010	80	13	8	59	38		1	37	14		1	13
	2015	94	14	9	71	41		2	39	14		1	13
	2020	106	16	9	81	69	2	3	64	57		2	55

Note: St represents the total number of urban rail transit stations within the circle scope, Mc represents the number of urban rail transit stations with municipal-level business centers within a 400-meter radius, Rc represents the number of urban rail transit stations with district-level business centers within a 400-meter radius, and Cc represents the number of urban rail transit stations with community-level business centers within a 400-meter radius.

5.2 Selection of Urban Rail Transit Network Indicators

Based on the complex network analysis method, urban rail transit network models for five time periods are constructed. Degree centrality, closeness centrality, betweenness centrality, and eigenvector centrality are chosen as indicators for assessing the importance and hub nature of urban rail transit stations.

A complex network can be represented as G=(V, E), where V represents the set of all nodes in the network, and E represents the set of all edges [27]. The urban rail transit network can be abstracted into a complex network, where the nodes of the network are the urban rail transit stations, and the construction of the edges of the network mainly has two methods: L-space and P-space [28], as shown in Figure 2. In the L-space method, an edge exists between two adjacent nodes on the same line, reflecting the geographical information of the urban rail transit stations. The P-space method posits that an edge exists between two stations if there is a direct line between them, effectively reflecting the transfer status of the urban rail transit stations. Due to the fast operation speed of urban rail transit, it is more reasonable to have an edge between two directly reachable stations. In this research, the P-space method is chosen to construct the network, assuming the network to be undirected and disregarding the weights of the edges.

The urban rail transit networks for Beijing, Shanghai, and Guangzhou from 2000 to 2020 are subdivided into five temporal cross-sections: 2000, 2005, 2010, and 2015. The P-space (P-space) method is utilized for constructing the urban rail transit network models for these five time periods. The urban rail transit network models for these three cities are presented in Figures 3- 5. In these figures, the size of the nodes represents the betweenness centrality; the larger the node, the higher its betweenness centrality.

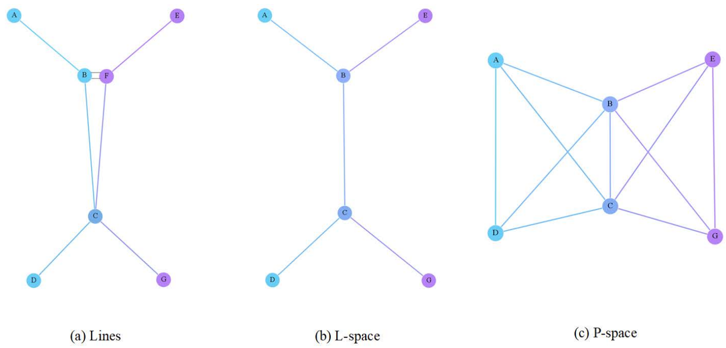

Figure 2. Construction methods of urban rail transit network models: L-space and P-space: (a) Schematic diagram of urban rail transit lines with two lines (blue and purple) (Station B and Station F are connected by a platform and can be reached on foot); (b) Urban rail transit network model constructed by L-space method; (c) Urban rail transit network model constructed by P-space method.

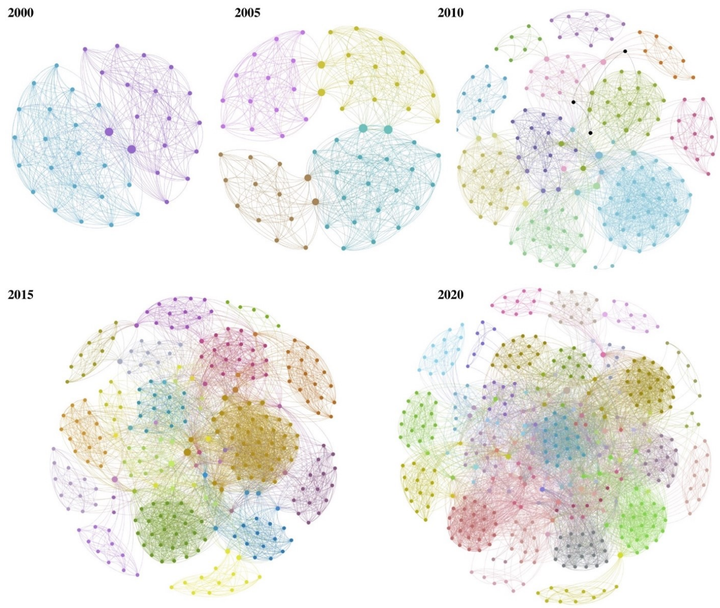

Figure 3. Urban rail transit network model for five time cross-sections of Beijing

Table 2. Importance indicators of complex network nodes

Indicator name	Meaning of the indicator
Degree centrality	The most direct measure of node centrality; the greater the node degree, the higher its degree centrality
Closeness centrality	Reflects the closeness of a node to other nodes; the closer it is to other nodes, the higher its closeness centrality
Betweenness centrality	Measures the importance of a node by the number of shortest paths passing through it
Eigenvertor centralit	The importance of a node depends on the centrality of its neighbor nodes

Between 2000 and 2020, the number of nodes and edges in the urban rail transit network of each city in Beijing, Shanghai, and Guangzhou has been consistently increasing, with the network becoming increasingly complex. Simultaneously, the degree centrality, closeness centrality, betweenness centrality, and eigenvector centrality of the network nodes are changing, indicating that the importance and hub nature of the same station in the urban rail transit network are constantly changing with the network's evolution. As a result, the degree centrality, closeness centrality, betweenness centrality, and eigenvector centrality of the nodes in the urban rail transit network are extracted as indicators for measuring the importance and hub nature of urban rail transit stations. In an undirected network without considering edge weights, the importance indicators of complex network nodes are as shown in Table 2.

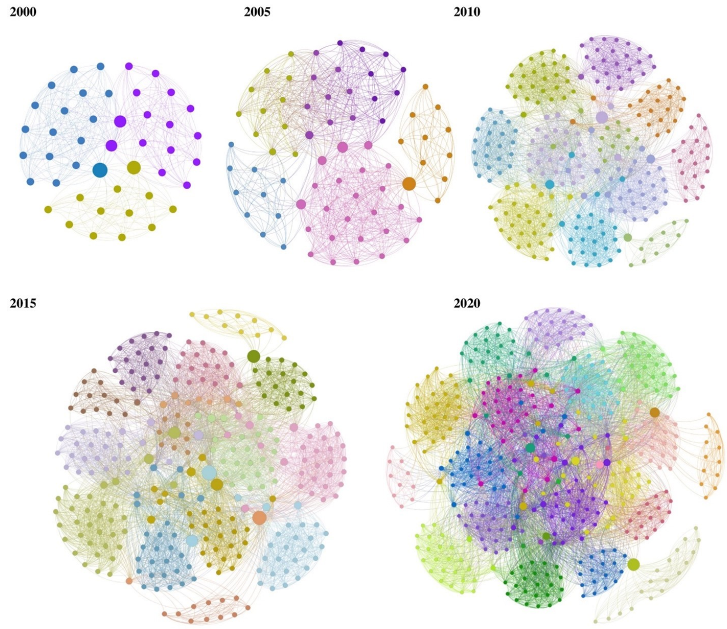

Figure 4. Urban rail transit network model for five time cross-sections of Shanghai

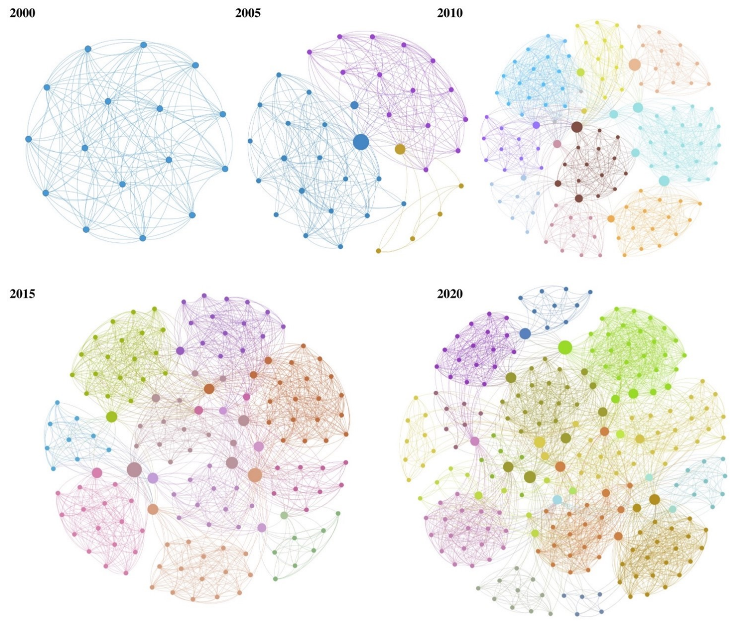

Figure 5. Urban rail transit network model for five time cross-sections of Guangzhou

5.3 Selection of Urban Commercial Center Indicators

Based on the "Urban Commercial Center Level Division", urban commercial centers are divided into three levels according to the scale of commercial facility land use, commercial facility construction area, service population, daily passenger flow, and the number of large commercial facilities: City-level commercial centers, regional commercial centers, and community-level commercial centers. Accordingly, the chosen indicators for measuring urban commercial centers include the scale of commercial facility land use, commercial facility construction area, service population, daily passenger flow, and the number of large commercial facilities.

5.4 Research Methodology

The coupling coordination degree model is referenced to study the coupling and coordination relationship between urban rail transit stations and urban commercial centers. The specific steps are as follows:

5.4.1 Preprocessing the data with the utility function

Assuming a subsystem has *n* samples and *m* evaluation indicators, *i*=1, 2, . . . , *n*; *j*=1, 2, . . . , *m*. x_{ij} represents the *j*th index value of the ith sample, and let γ, δ be the upper and lower limits of x_{ij}, i.e., $\gamma = \max(x_{ij}), \delta = \min(x_{ij})$. Then the utility function of x_{ij} to the subsystem can be expressed as:

$$u_{ij} = \begin{cases} (x_{ij} - \delta)/(\gamma - \delta), u_{ij} \text{ is a positive utility} \\ (\gamma - x_{ij})/(\gamma - \delta), u_{ij} \text{ is a negative utility} \end{cases} \tag{1}$$

Here, u_{ij} represents the utility contribution of x_{ij} to the subsystem, and the greater u_{ij}, the greater its utility contribution to the subsystem.

5.4.2 Using the entropy method to calculate the weights of each index

In order to eliminate artificial subjective factors, the entropy method, an objective weighting method, is used to calculate the weights of each index. As the entropy method requires the use of a logarithmic function when determining weights, and u_{ij} cannot be 0, when u_{ij}=0 appears, it is assigned a value of 0.001 without affecting the order of utility.

The weight of u_{ij}:

$$P_{\mathrm{j}}(i) = u_{ij}/\sum_{i=1}^{n} u_{ij} \tag{2}$$

Information entropy:

$$e_j = -k \times \sum_{i=1}^{n} [P_{\mathrm{j}}(i) \times \ln P_{\mathrm{j}}(i)], \quad k = 1/\ln n \tag{3}$$

Information entropy redundancy:

$$\mathrm{d}_j = 1 - e_j \tag{4}$$

The weight of the *j*th index:

$$\lambda_{\mathrm{j}} = \mathrm{d}_j/\sum_{j=1}^{m} \mathrm{d}_j \tag{5}$$

5.4.3 Using the weighted average method to obtain the comprehensive evaluation index value of the *i*th sample

$$u_i = \sum_{j=1}^{m} \lambda_j \times u_{ij} \tag{6}$$

5.4.4 Coupling coordination degree model

There are two subsystems in the coupling system of urban rail transit network and urban commercial center, and a coupling coordination degree model of the two subsystems is built.

Coupling function:

$$\mathrm{C} = 2 \times \sqrt{u_1 \times u_2}/(u_1 + u_2) \tag{7}$$

where, the larger *C* is, the higher the coupling degree of the two subsystems. However, when the indicators of the two subsystems are low, the coupling degree might be high. Therefore, to solve this problem, the coordination degree needs to be further calculated.

$$
\begin{cases} D = \sqrt{C \times T} \\ T = \alpha u_1 + \beta u_2 \end{cases} \tag{8}
$$

where, D is the coordination degree, T is the comprehensive evaluation index of the system, α, β respectively reflect the importance of the two subsystems to the entire system. Since urban rail transit can guide the layout of urban commercial centers, and the development of urban rail transit requires the support of urban commercial centers, this study assumes that the urban rail transit network and the urban commercial center are equally important, i.e., α=β=0.5. Based on the research findings of predecessors, and considering the coupling and coordination characteristics of urban rail transit network and urban commercial center, the coupling coordination degree evaluation criteria are set as shown in Table 3.

Table 3. Evaluation criteria for coupling coordination degree

Phase	Coupling coordination degree (D)	Coupling coordination situation
First phase (start-up period)	$0 < D \leq 0.4$	Not coordinated
Second phase (transition period)	$0.4 < D \leq 0.6$	Preliminarily coordinated
Third phase (development period)	$0.6 < D \leq 0.8$	Moderately coordinated
Fourth phase (mature period)	$0.8 < D \leq 1$	Well cordinated

6 Research Results and Discussion

6.1 Research Results

The analysis of the coupling and coordination degree of urban rail transit stations and urban business centers within the urban areas of Beijing, Shanghai, and Guangzhou is shown in Figure 6. Since 2000, the number of urban rail transit stations has shown a rapid growth trend, with the largest growth in Shanghai and Guangzhou between 2005 and 2010, and Beijing maintaining a large and stable growth rate since 2005. In terms of the coupling and coordination between stations and business centers, although a considerable proportion of stations remain uncoordinated, the total number of stations with preliminary coordination, medium coordination, and good coordination is increasing with the changes in the spatial layout of urban rail transit stations and urban business centers. The empirical analysis results of the three cities show that the construction of urban rail transit networks guides the spatial layout of urban business centers, and the spatial layout of urban business centers will also promote the construction of urban rail transit networks. The relationship between urban rail transit networks and urban business centers is one of mutual interaction and influence.

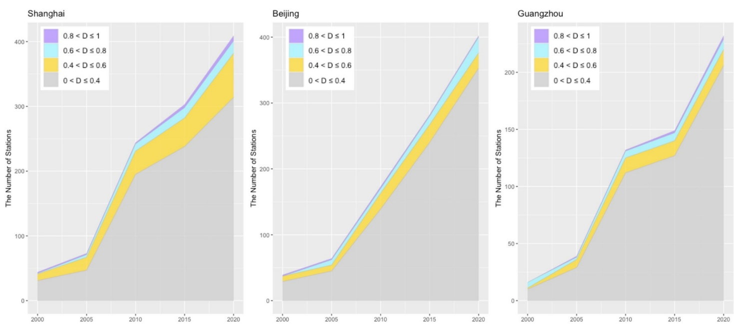

Figure 6. Distribution of urban rail transit stations based on coupling coordination degree

The results of the coupling coordination degree of urban rail transit stations and business centers in different layers of Beijing, Shanghai, and Guangzhou are shown in Figures 7-9.

The analysis of the coupling coordination degree between urban rail transit stations and urban business centers in the core area (CAZ) shows a continuous increase in the number of stations in the core area, with Beijing and Guangzhou maintaining a relatively large growth rate between 2015 and 2020, while Shanghai's growth rate slowed down during the same period. The number of stations with preliminary coordination, medium coordination, and good coordination between urban rail transit stations and urban business centers is increasing, with the proportion of such stations in the total number of stations in the core area of Shanghai being the largest, while that in Guangzhou is the smallest.

The analysis of the coupling coordination degree between urban rail transit stations and urban business centers in the area from the core to the main urban area (CAZ-MUA) shows that the number of stations in this layer is growing rapidly. However, the proportion of stations with preliminary coordination, medium coordination, and good coordination among the total number of stations is relatively small, and the proportion of uncoordinated stations is relatively large.

The analysis of the coupling coordination degree between urban rail transit stations and urban business centers in the peripheral area (PUA) shows that the number of stations in this layer will increase significantly between 2015 and 2020. However, in terms of coupling and coordination between urban rail transit stations and urban business centers, only a few stations in Shanghai are in a preliminary coordinated state, while almost all stations in Beijing and Guangzhou are in an uncoordinated state.

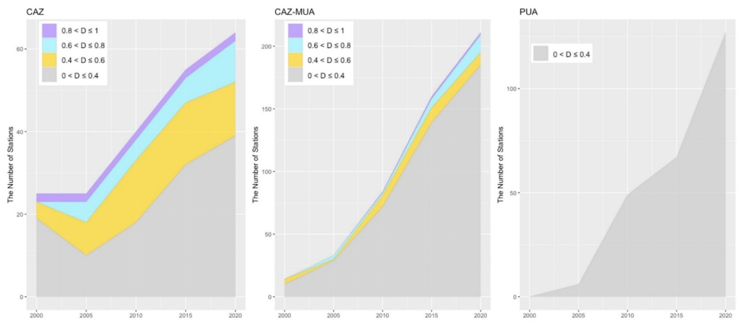

Figure 7. Distribution of urban rail transit stations in different layers of Beijing based on coupling coordination degree

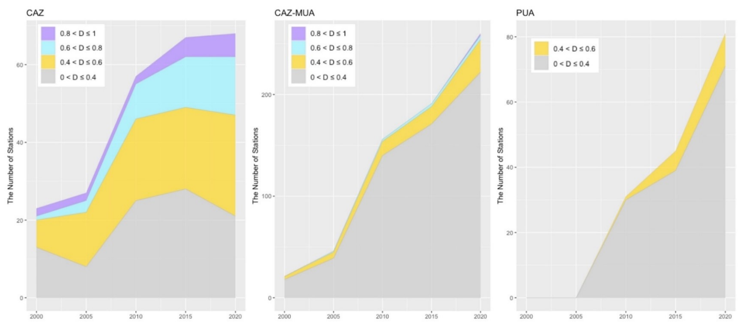

Figure 8. Distribution of urban rail transit stations in different layers of Shanghai based on coupling coordination degree

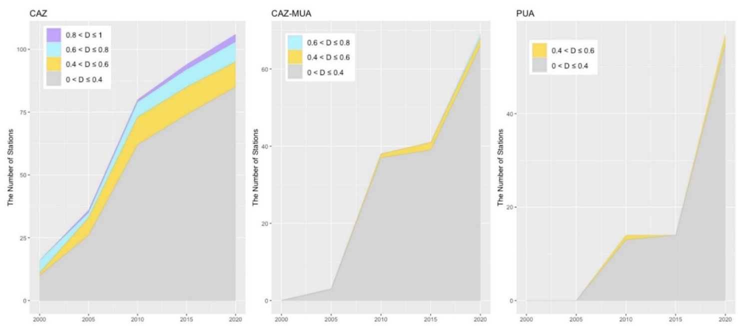

Figure 9. Distribution of urban rail transit stations in different layers of Guangzhou based on coupling coordination degree

6.2 Discussion

The research results within the urban areas of Beijing, Shanghai, and Guangzhou present common characteristics: since 2000, the number of urban rail transit network stations in the three cities has increased significantly.

Simultaneously, with the changes in the spatial layout of urban rail transit stations and urban business centers, the total number of stations with preliminary coordination, medium coordination, and good coordination has been continuously increasing. This is because the relationship between urban rail transit and urban business centers is one of mutual interaction and influence. From a temporal perspective, the development of urban rail transit networks and the layout of urban business centers require a lengthy period of interaction and influence to form a coupled state. From a spatial perspective, the coupled state manifests as the similarity and consistency in the spatial distribution of urban rail transit network stations and urban business centers.

The research results of the coupling coordination analysis of urban rail transit stations and urban business centers in different layers show that the overall coupling coordination degree in the core area (CAZ) is higher than that in the area from the core to the main urban area (CAZ-MUA) and the peripheral area (PUA). The core area is an essential carrier of core urban functions. In the core area, urban business center development is relatively mature, and the development of urban business centers promotes the construction of urban rail transit. The core area is also the first region to open urban rail transit, further guiding the spatial layout of urban business centers.

Due to the different development patterns of the three cities, the research results also exhibit certain differences. Beijing, as the capital of China, is the political center, cultural center, international communication center, and science and innovation center of China. The core area of Beijing carries the functions of the capital's core area, so the development of urban business centers in Beijing's core area lags behind the construction of urban rail transit networks. In contrast, Guangzhou, an international trade center in China, has a mature urban business center in its core area, but the construction of urban rail transit networks in Guangzhou's core area lags behind the development of urban business centers. Shanghai, a globally renowned financial center, has a mature urban business center in its core area and a rapidly developing urban rail transit network, resulting in better coupling coordination development between urban rail transit stations and business centers in Shanghai's core area.

In existing studies, some scholars have taken Shanghai as an example to study the spatial coupling relationship between urban rail transit and urban public activity center systems, and proposed the "spatial coupling consistency degree" as an indicator to evaluate the spatial location distribution consistency of rail transit stations and commercial centers [10]. Other researchers, based on GIS network analysis methods, have selected centrality (betweenness centrality), proximity, and directness as indicators to measure road traffic network characteristics. They studied the impact of street traffic network centrality on large-scale commercial retail outlets and commodity trading markets in the central urban area of Changchun, and believed that road traffic network centrality (betweenness centrality) has a decisive impact on the spatial distribution of commercial outlets [29].

Based on previous research, this paper uses a combination of complex network and Geographic Information System (GIS) methods. Four node centrality indicators - degree centrality, closeness centrality, betweenness centrality, and eigenvector centrality - are selected as evaluation indicators for the importance and hub of urban rail transit stations. The evaluation indicators for the scale and level of urban commercial centers are determined based on commercial facility land scale, commercial facility building area, service population, daily passenger flow, and the number of large-scale commercial facilities. By constructing a coupling coordination degree model between urban rail transit and urban commercial centers, the coupling coordination relationship between urban rail transit stations and urban commercial centers is revealed from both temporal and spatial dimensions, expanding the research perspective of urban rail transit networks.

7 Conclusion and Implications

7.1 Conclusion

The construction of urban rail transit networks and the development of urban commercial centers form an interactive and mutual influence in a coupling relationship. On one hand, the establishment of urban rail transit influences the spatial layout of urban commercial centers. The development of an urban rail transit network greatly improves accessibility and yields substantial external effects. The enhancement in accessibility and externalities encourages population concentration along urban rail transit lines, subsequently influencing the location choices of urban social activities. Owing to its high capacity, commercial land use gradually attracts urban commercial centers towards the surrounding areas of urban rail transit stations. Conversely, the evolution of urban commercial centers further stimulates the construction of the urban rail transit network. Spatial layout changes in urban commercial centers result in shifts in passenger flow distribution, while urban rail transit reduces commuting costs and increases the acceptable commuting distance within a given time constraint. Alterations in passenger flow distribution, commuting distance, and commuting costs determine the choice of transportation, thereby influencing transport demand and promoting the construction of the urban rail transit network.

As time progresses, the coupling coordination degree between urban rail transit stations and urban commercial centers evolves from non-coordination to preliminary coordination, moderate coordination, and eventually well-coordination. This progression reflects that the development of an urban rail transit network and the layout of urban commercial centers require substantial time for interaction and mutual influence to reach a coupling state. The coupling coordination development between urban rail transit stations and urban commercial centers exhibits regional heterogeneity, with different stages of coupling coordination development observed among different circles of stations and commercial centers. Urban rail transit stations and commercial centers within the core area (CAZ) exhibit the best coupling coordination development, indicating that the urban rail transit network and urban commercial center system mutually support and influence each other most fully in the urban core area.

7.2 Practical Implications

Since 2000, China's urban rail transit has been developing at an unprecedented scale and speed. Urban rail transit has a significant impact on urban development, and the urban rail transit network is expected to achieve a larger scale and higher density. The development of urban rail transit will profoundly affect the layout of urban commercial centers, and the growth of urban commercial centers will further support the development of urban rail transit. Hence, while expanding the scale of the urban rail transit network and developing urban commercial centers, attention should be paid to the coupling coordination development of urban rail transit and urban commercial centers.

Due to historical factors and early urban planning, commercial centers in some cities are excessively concentrated in the core area (CAZ). This high concentration of commercial centers may result in over-intense land use in the urban core area, which is unfavorable for the comprehensive utilization of urban resources and places significant pressure on traffic infrastructure, thereby hindering urban sustainable development. To improve the layout of urban commercial centers, it is suggested to gradually improve the construction of the urban rail transit network outside the urban core area, using the construction of the urban rail transit network to guide and promote the development and adjustment of the spatial layout of commercial centers.

7.3 Limitations and Future Research Directions

This study focuses on the spatial importance and nodality of urban rail transit stations and the scale of urban commercial centers when investigating their coupling coordination relationship. By introducing complex network and GIS analysis methods from temporal and spatial dimensions, a complex network model and a coupling coordination degree model are constructed to analyze the coupling coordination relationship between urban rail transit stations and urban commercial centers spatially. The importance of urban rail transit stations can also be examined from aspects such as accessibility and passenger flow, which can serve as directions for deepening research on the coupling coordination relationship.

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Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Confilict of interest

The authors declare that they have no conflicts of interest.

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