Research on the Development Mechanism of Urban Rail Transit in China Based on the Geodetector

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Abstract. Urban rail transit is a vital component of urban public transportation, which has created considerable economic benefits and social values in the process of urban development. At present, numerous cities in China have constructed multiple rail transit lines, making it crucial to study the influencing factors of spatial heterogeneity and the development mechanisms of rail transit. This paper applies the Geodetector to explore the influence of diverse economic, social, and natural conditions on the spatial heterogeneity of rail transit. Among them, the main single factor affecting the construction of urban rail transit in China is gross regional product, with a q-value of 0.5216 ($p<0.05$), and the main interactive factor is the combination of gross regional product and built-up area, with a q-value of 0.6379, presenting a two-factor or nonlinear enhancement effect in their interaction. In addition, this study probes into four core development mechanisms of rail transit, namely the economic support mechanism, demand-driven mechanism, spatial constraint mechanism, and natural condition regulation mechanism, and puts forward a series of policy suggestions for the planning, construction, and operation of rail transit, which provides certain reference value for the research on urban rail transit.

Keywords: Geodetector; Urban rail transit; Development mechanism; Influencing factors; Spatial heterogeneity

1 Introduction

In recent years, with the continuous improvement of the urbanization level in China, the construction process of urban rail transit has been further accelerated. By the end of 2019, 37 cities in mainland China had completed the construction of rail transit systems, with the total length of operating lines reaching 5180.6 kilometers [1]. Most first-tier and new first-tier cities have built dense rail transit networks, which not only facilitate people's travel but also bring certain economic benefits to the cities. In the planning stage, the land appreciation benefit of the planned area covered by rail transit is significant; during the construction period, it can improve the regional employment rate and boost economic growth. In the operation stage, rail transit effectively enhances regional accessibility, stimulates the development and utilization of land, and optimizes the urban spatial layout [2]. Meanwhile, the opening and operation of rail transit is conducive

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to the development of urban underground space, and alleviates the problems of urban traffic congestion and environmental quality deterioration to a certain extent [3,4]. Therefore, exploring the influencing factors of rail transit construction is of practical significance for optimizing urban planning, formulating transportation policies, and promoting urban economic development.

The factors influencing the construction of urban rail transit involve population, economy, spatial urbanization, and other aspects. Xia et al [5] found that there is a trend of first rising and then falling between regional urbanization and rail transit in Beijing, among which the level of economic urbanization exerts the greatest impact. Li et al [6] integrated data such as user information and points of interest in Guangzhou and found that the number of station entrances and exits and transfer simulation points are positively correlated with rail transit passenger flow, while bus transfer stations and parking lots have no significant correlation with passenger flow. However, most existing studies only focus on a single city, which has certain one-sidedness and limitations. In addition, the development of urban rail transit has temporal and spatial heterogeneity. Temporally, the construction of rail transit is divided into the accelerated evolution stage, growth stage, deceleration stage, and late low-speed evolution stage [7]. Spatially, the construction of rail transit in the central urban area is relatively complete, while that in the outer suburbs is relatively backward [5].

Therefore, this study expands the research scale from a single city to the national level and analyzes the driving mechanism of urban rail transit construction from a macro perspective. It is conducive to deepening the understanding of the theoretical development stage of rail transit, providing empirical evidence from China for constructing a more universal investment theory of transportation infrastructure, and offering decision-making references for the planning and approval of rail transit at the national level.

2 Data and Methods

2.1 Data Sources

This study selects the length of under-construction urban rail transit lines as the explained variable to measure the scale of rail transit construction. This indicator can directly reflect the construction progress and network expansion scale of urban rail transit in each city. The data are derived from the China Urban Construction Statistical Yearbook from 2010 to 2024, with the unit of kilometers. Seven explanatory variables are selected from six dimensions, including economic development, population scale, fiscal capacity, urban form, natural environment, and transportation demand, in this paper, as shown in Table 1. Finally, a total of 64 cities were included in this study, among which the missing values of variables were handled by deletion.

2.2 Geodetector

The Geodetector is an important tool for detecting spatial differentiation, that is, the extent to which an independent variable factor explains the dependent variable [8]. The q-value reflects the explanatory power of the independent variable X on the spatial differentiation of the dependent variable Y, as shown in Eq. (1). L represents the total number of variable layers, Nh and N represent the sample size of layer h and the total sample size respectively, and σ_h^2 and σ2 represent the variance of the research object in layer h and the overall variance of the research object respectively. The value range of q is between 0 and 1. The larger the q-value and the closer it is to 1, the stronger the explanatory power of X on Y, and vice versa.

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N_{\sigma^2}} \tag{1}$$

In addition, it can also be used to identify the interaction between different factors, that is, to judge whether the joint action of two factors (X1 and X2) will enhance or weaken the explanatory power of the dependent variable Y. The specific method is to judge the values of q(X1), q(X2), and q(X1∩X2), as shown in Table 2. However, different hierarchical methods and the number of layers of the original tool may lead to uncertainty in the output results. In this regard, this study adopts the optimal parameter GD model to achieve more accurate, flexible, and efficient spatial analysis [9].

Table 1. Explanatory variables and their descriptions

Variable Name	Variable Symbol	Unit	Definition and Measurement Description
Gross regional product	X1	100 million RMB	Measures the urban economic development level and reflects the material foundation for rail transit construction
Floating population	X2	10,000 people	Reflects the urban population attraction and the new commuting demand
Local general public budget revenue	X3	100 million RMB	Measures the local government's fiscal strength and affects the investment feasibility of rail transit
Built-up Area	X4	Square kilometers	Characterizes the physical development boundary and spatial scale of the city
Annual average temperature	X5	°C	Controls the impact of climatic conditions on construction, operation, and travel modes
Annual precipitation	X6	Millimeters	Controls the impact of natural geographical conditions on rail transit construction
Motor vehicle ownership	X7	10,000 vehicles	Reflects the urban motorization level and road traffic pressure

Table 2. Explanatory variables and their descriptions

Criterion	Interaction Effect
q(X1∩X2)＜Min(q(X1),q(X2))	Nonlinear weakening
Min(q(X1),q(X2))＜q(X1∩X2)＜Max(q(X1),q(X2))	Single-factor nonlinear weakening
q(X1∩X2)＞Max(q(X1),q(X2))	Two-factor enhancement
q(X1∩X2)=q(X1)+q(X2)	Independence
q(X1∩X2)＞q(X1)+q(X2)	Nonlinear enhancement

3 Results

3.1 Data Analysis

As shown in Table 3, the TOP 10 cities' average rail transit line length exceeds 154km (Beijing first with 297.99km, 36 times that of bottom-tier cities), mostly megacities with early, sustained investment. The last 10 cities (mostly third-tier) have average length <22km (Kunshan 6.00km, Haining 8.26km), reflecting lagging development in small and medium-sized cities.

Table 3. Ranking of the Top 10 and Bottom 10 Cities by Average Length of Newly Built Urban Rail Transit Lines in China

Rank	City	Average Line Length (km)	Rank	City	Average Line Length (km)
1	Beijing	297.99	55	Xiangtan	21.25
2	Guangzhou	265.89	56	Huai'an	20.70
3	Shanghai	223.17	57	Dujiangyan	20.08
4	Chongqing	219.14	58	Jiaxing	13.79
5	Chengdu	216.64	59	Mengzi	13.35
6	Shenzhen	212.97	60	Tianshui	12.92
7	Nanjing	203.44	61	Zhangzhou	9.83
8	Hangzhou	169.16	62	Sanya	8.46
9	Tianjin	160.03	63	Haining	8.26
10	Wuhan	154.95	64	Kunshan	6.00

3.2 Single Factor Effect

As can be seen from Figure 1, the q-value of X1 is 0.5216, which is the largest among the seven influencing factors, indicating that gross regional product has the strongest explanatory power for the spatial differentiation of rail transit construction and is the dominant factor affecting the construction of rail transit lines. The q-values of X3, X4, and X7 are close, which are 0.4456, 0.4341, and 0.4328, respectively, showing that local general public budget revenue, built-up area, and motor vehicle ownership are also important factors affecting the length of rail transit lines. The q-value of X2 is 0.2181, meaning that the floating population has a certain explanatory power for the length of rail transit lines, but is not a decisive factor. The q-values of X5 and X6 are 0.0786 and 0.0216, respectively (the q-value of X6 is not shown in the figure), indicating that climatic factors such as temperature and precipitation have a small impact on the length of rail transit lines, which may indirectly affect the development of rail transit through construction and construction conditions.

3.3 Interactive Factor Effect

Figure 2 shows the results of the pairwise interaction of the seven influencing factors obtained by the Geodetector. The red dots indicate that the interaction type of the two factors is nonlinear enhancement, and the yellow dots indicate that the interaction type is two-factor enhancement. The size of the dots reflects the strength of the interaction, that is, the q-value after the interaction, and the larger the dot, the stronger the interaction. It can be seen from the figure that the interaction between X1 and X4 is the strongest, reflecting that the combination of gross regional product and built-up area is the most critical factor affecting the length of rail transit lines, and their joint action has the strongest explanatory power for it. The improvement of the economic development level is often accompanied by the expansion of the built-up area, which in turn promotes the construction of rail transit. The interaction intensity between X2 and X5, X2 and X6, and X5 and X6 is very small, reflecting that the pairwise interaction of the floating population, average temperature, and precipitation has a small impact on the length of rail transit lines. In addition, all pairwise interactions of the factors in the figure show two types: nonlinear enhancement and two-factor enhancement, that is, the influence of any two factors on the dependent variable Y after interaction is greater than their single effect. This shows that the length of rail transit lines is the result of the joint action of multiple factors, and the explanatory power of a single factor is limited.

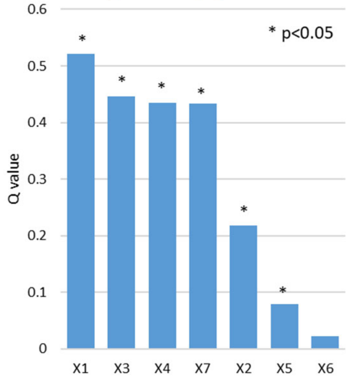

Fig. 1. Single factor effect

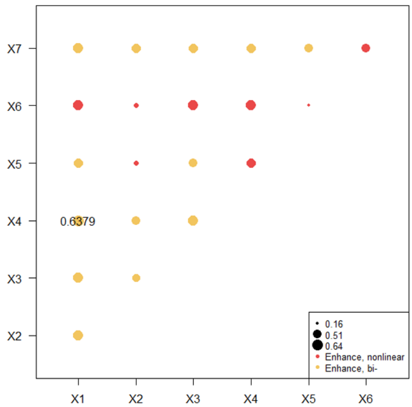

Fig. 2. Interactive factor effect

4 Discussion

Gross regional product and local fiscal revenue are core factors affecting rail transit spatial heterogeneity, as they determine the government's investment capacity for rail transit construction. Fiscal capacity is a prerequisite for project launch and continuation, while land appreciation benefits from Transit-oriented development (TOD) are key to balancing rail transit investment [10]. High construction, maintenance, and operation costs of rail transit depend on strong urban economic strength and sufficient fiscal revenue. Cities with sound economic development can build multi-center, networked rail transit networks, while less developed cities can only prioritize core urban areas and control line length. Floating population growth and rising motor vehicle ownership reflect increasing travel demand pressure. Population density and employment spatial distribution determine passenger flow intensity, and commuting corridors between high-density residential areas and employment centers drive rail transit coverage and extension [1]. By 2019, 66 Chinese cities had over 1 million cars, nearly half with over 2 million [1], worsening traffic congestion and pollution—for example, Beijing's annual indirect congestion loss accounts for 5% of its gross regional product [5]. Rail transit alleviates this by reducing private car use and improving travel efficiency. Built-up area and urban spatial structure affect rail transit layout and costs. Built-up area expansion promotes new line construction or extension to connect new and original urban areas, but increases costs due to building demolition and pipeline avoidance. Urban spatial structure (monocentric or multi-center) essentially frames the rail transit network [11]. Annual average temperature and precipitation have indirect impacts on rail transit via construction difficulty. Extreme temperatures reduce efficiency and increase material and maintenance costs, while excessive precipitation raises tunnel flood control pressure and project complexity.

To address rail transit development challenges, policy suggestions are proposed: establish differentiated investment and financing policies and diversified fund guarantees, such as using TOD land appreciation to subsidize operations [10]; integrate rail transit into territorial space planning to solve "station-city separation" [12]; promote standardization and intelligence, strengthen dispatching systems and power supply; and enhance climate-adaptive design for safety.

This study has limitations: 64 sample cities may not cover all urban rail transit characteristics, and explanatory variables (economic, social, and natural) lack in-depth consideration of policy and technological factors, which can be supplemented in future research.

5 Conclusion

Based on Geodetector results, Chinese urban rail transit construction is jointly affected by natural, economic, and social factors. Economic factors are the dominant factor. Social factors reflect travel demand and regional connections, promoting and spatially restricting rail transit. Natural factors restrict construction but not line length. Urban rail transit network planning should comprehensively consider these factors to exert its driving effect on urban social and economic development and promote high-quality urban development.

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