Impact of Land Use Along the Line on Passenger Flow of Regional Railways

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Abstract

With the acceleration of regional integration, the trend of Chinese megacities evolving into metropolitan areas and urban agglomerations has become increasingly evident. Traditional transportation modes primarily designed for intra-city travel struggle to meet commuting demands between urban cores and surrounding towns. International experience demonstrates that regional (suburban) railways are crucial for addressing such demands and supporting the integration of metropolitan areas. Consequently, both central and local governments in China have prioritized the development of suburban railways, leading to an unprecedented wave of planning and construction in multiple megacities. However, operational lines often face challenges such as lower-than-expected passenger volumes, low commuting ratios, and severe financial losses.This study selects 16 operational suburban railway ilnes in Beijing, Shanghai, Guangzhou, and international cities (Tokyo, Paris, London, New York) as research subjects. Utilizing quantitative and qualitative analysis methods, it explores key factors influencing passenger flow characteristics of suburban railways. The independent variables include the proportion of construction land, population density, land use functions, distance from the nearest station to the core urban center, and regional total population. Passenger flow intensity of suburban railways serves as the dependent variable. Pearson correlation analysis evaluates relationships between variables, followed by ordinary least squares (OLS) regression to construct interaction models. Finally, the study analyzes the impact of existing territorial spatial planning patterns (e.g., urban layout) and land use characteristics along railway lines on passenger flow and operational feasibility through case studies. The findings aim to provide insights for coordinating suburban railway planning with metropolitan spatial strategies in China.

Keywords: Regional (suburban) railway; Land use along the lines; Territorial spatial planning; Interaction mechanisms; Urban agglomeration

1. Introduction

With the acceleration of China's regional integration process, the trend of gradually evolving megacities into metropolitan areas and metropolitan areas is becoming more and more clear. This trend has brought about profound changes in the urban spatial structure, and the traditional transportation modes that mainly meet the needs of urban travel, such as subways and buses, have been difficult to effectively meet the growing commuting needs between the urban core area and the surrounding towns. International experience shows that urban (suburban) railways play an irreplaceable role in solving such needs and supporting the integrated development of metropolitan areas and metropolitan areas. Suburban railways can not only effectively shorten the time and space distance between the urban core area and the surrounding towns, but also promote the coordinated development of the regional economy and enhance the overall competitiveness. To this end, governments at all levels, from the central to the local level, have generally regarded the development of suburban railways as an important policy priority. In recent years, many of China's megacities and megacities have set off an unprecedented boom in the planning and construction of suburban railways. Cities such as Beijing, Shanghai, and Guangzhou have formulated large-scale suburban railway network plans and invested heavily in their construction. However, the lines that have been opened are generally facing problems such as lower than expected passenger flow, low commuting ratio, and serious operating losses. For example, the actual passenger flow of Shanghai Jinshan Line: about 30,000 passengers per day , commuting proportion: about 40%, operating loss: annual loss of about 200 million yuan; The actual passenger flow of the S2 line of the Beijing suburban railway: about 15,000 passengers per day, the proportion of commuting: about 30%, and the operating loss: the annual loss is about 150 million yuan.

Existing studies have extensively explored the significant impact of land use along the line on the passenger flow of urban rail transit. For example, Cervero's research shows that high-density, mixed-use land use patterns can significantly increase ridership in rail transit[1]. He et al. used spatio-temporal geographic weighting and gradient boosting decision tree models to study the nonlinear relationship between various built environment characteristics and rail transit passenger flow[2]. However, these studies mainly focus on urban rail transit systems, such as subways and light rail, while there are relatively few studies on suburban railways. At present, researchers have paid more attention to other factors in the study of passenger flow on suburban railways. For example, Wang et al. studied the impact of fare policies on passenger flow in suburban railways and found that a reasonable fare strategy can significantly improve passenger flow[3]. Li et al. discussed the influence of suburban railway service frequency and station setting on passenger flow, and found that high-frequency service and reasonable station layout can effectively attract passengers. Zhao et al. took the S2 line of Beijing suburban railway as the research object to explore the linear relationship between job-housing balance and urban commuting time, and few researchers studied the relationship with land use along the line[4]. Finally, the impact of territorial spatial planning on the passenger

flow and feasibility of suburban railways has not been fully studied. At present, the research on territorial spatial planning and transportation mainly focuses on the synergy mechanism and the study of existing land use problems. For example, Hu Gangyu believes that the comprehensive transportation of the metropolitan area should establish a systematic and coordinated planning thinking, break through the traditional "point-axis" backbone channel to lead the spatial structure of the metropolitan area, and emphasize the support of the transportation network for the spatial pattern of the metropolitan network[5]. Deng Maoying evaluated the causes of inefficient stations, and proposed to adjust the land use (such as floor area ratio) around the station through a multi-objective optimization method in the context of territorial spatial planning, so as to improve the scale of passenger flow and achieve sustainable development, so as to provide suggestions for territorial planning. There are few studies to quantify territorial spatial planning to explore whether the existing domestic territorial spatial planning is conducive to improving the passenger flow of suburban railways.

Therefore, the research focus of this study is, first, focusing on suburban railways, breaking through the limitations of traditional studies that only focus on the relationship between land use and passenger flow in urban rail transit systems, and accurately locking the research object on suburban railways, which opens up a new perspective in this field of research. Second, new exploration of territorial spatial planning, the current research on territorial spatial planning and rail transit mostly focuses on exploring the coordination mechanism and providing suggestions for territorial spatial planning through the analysis of the current transportation and land use. In contrast, from the perspective of territorial spatial feasibility, this study deeply explores the rationality of China's planned territorial spatial planning through quantitative analysis, and innovatively takes the increase in suburban railway passenger flow as the verification criterion, which provides a new research idea and verification method for the study of territorial spatial planning.

2. Research Methodology and Subjects

2.1 Research Methods

(1) Pearson correlation analysis

Pearson correlation coefficient is widely used to measure the degree of correlation between two variables X and Y (linear correlation), and its value is between -1 and 1. The Pearson correlation coefficient between two variables is defined as the quotient of the covariance and standard deviation between two variables.

The value is positive if and only if both Xi and Yi fall on the same side of their respective means, and the correlation coefficient is positive if both Xi and Yi tend to be greater than or tend to be less than their respective means. If Xi and Yi tend to fall on the opposite side of their means, the correlation coefficient is negative.

$$\rho_{x,y} = \frac{E(XY) - E(X)E(Y)}{\sqrt{E(X^2) - (E(X))^2}\sqrt{E(Y^2) - (E(Y))^2}} \tag{1}$$

(2) Model Selection--OLS

Ordinary Least Squares (OLS) aims to fit a line by minimizing the sum of squared distances from points to the line, essentially minimizing the sum of squared residuals. This paper uses the OLS linear regression model to fit passenger flow against selected independent variables related to surrounding land use along the route and estimate parameters. Correlation coefficients verify variable relationships, including positive/negative correlation and degree of correlation. The model reveals the intrinsic links between them, expressed as follows:

$$Y_m = \beta_0 + \sum_k \beta_k X_{mk} + \varepsilon_m \tag{2}$$

ym - passenger density of line m
β0 - is a constant
βk - is the regression coefficient between passenger flow and independent variables
Xmk - is the kth independent variable in line m
εm - is the error value of line m

2.2 Study Objects

In this study, 16 urban suburban rail lines in six major international cities, namely Beijing, Shanghai, Guangzhou, Tokyo, Paris and London, were selected for in-depth study (Table 1).

Tab.1. Research objects

Cities	Lines	No. of Stations(Block)	Mileage (km)
Beijing	Huaimi Line	7	144.6
Beijing	S2 Line	6	108.3
Beijing	City Deputy Center Line	6	32.7
Beijing	Tongmi Line	7	83.4
Guangzhou	Metro Line 18	8	58.3
Shanghai	Jinshan Railway	9	56.4
United Kingdom	Crossrail line	41	118
New York	New Haven Line	30	119
New York	Hudson Line	29	119
New York	Harlem Line	38	132
Paris	RER D Line	59	196
Paris	RER E Line	21	56
Paris	RER C Line	86	185.6
Tokyo	JR Chuo Line	32	53.1
Tokyo	Toyoko Line	22	24.2
Osaka	Hankyu Kyoto Main Line	27	45.3

The selection reasons are as follows: ① The cities are globally dense and prosperous metropolises with large urban areas and well - developed suburban transportation networks, offering abundant cases for suburban transportation research. ② Comparative studies, especially with international metropolises like Tokyo, Paris, and London (which have long - standing suburban rail transit development), are possible.

3. Data sources and descriptive statistics

3.1 Data sources

Percentage of 500 m construction land: Basemap in GIS authors' self-mapping; Population density within 1000 m: global 1000 m population density raster data; 500 m land use function: Google Maps, GIS authors' self-mapping; Passenger traffic: Google, Ministry of Transportation and Communications of the People's Republic of China, Statista, UCI.

Zong, Erkai [6], Zhang, Yuejin [7] and other scholars proposed that the 500 m radiation paradigm along the line covers nearly 16% of the residential and employment population in the urban core area attracts more than half of the passenger traffic of the urban railways, so that the surrounding 500 m range is identified as the direct impact area; Anderson, R [8], Tatem, A. J [9], Zhao, J [10], & Deng, W. Batty, M[11] and other scholars believe that the use of 1000m population raster data in the study of land use along rail transit has the advantages of moderate data accuracy, data availability, matching the influence range of rail transit, high data processing efficiency, and high validity of statistical analysis. Therefore, this paper takes 500m and 1000m as the research scope.

3.2 Percentage of land used for construction

With the support of GIS software and using Basemap satellite map as a reference, a buffer zone (Buffer) of 500 meters along the line was constructed to distinguish the built-up land from the non-built-up land (as shown in Fig. 3). In the quantitative analysis, it was found that there are significant differences in the percentage of built-up areas along domestic and international municipal railroads. Specifically, the percentage of built-up area along the Toyoko Line in Japan is as high as 97%, while that along the Huaimi Line of the Beijing Suburban Railway is relatively low at 31% (as shown in Fig.1).

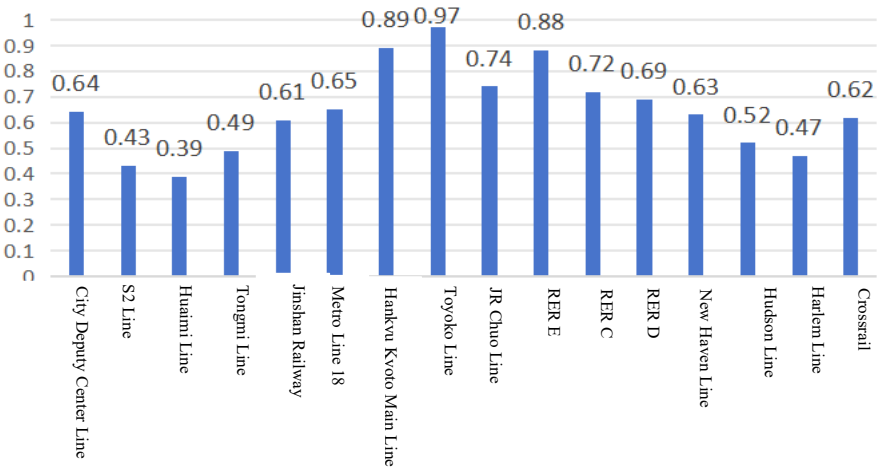

Fig. 1. Proportion of built-up area

3.3 Land use functions

Within 500 meters along the current alignment, the main land types include six categories: residential, commercial office, industrial warehousing, public service facilities, roads and municipal transportation facilities, and agricultural, forestry and watersheds. Based on a large number of studies and analyses [6], the degree of influence of these land use types on rail transit passenger flow is classified into two categories of Influence Degree I (medium-high) and Influence Degree II (low) (as shown in Table 2). Using GIS and remote sensing techniques, combined with Google Maps calibration, we identified the land use types along each line and calculated the ratio of the area of the land use of Impact DegreeI to Impact Degree II land use (as shown in Fig. 2). The results show that the impact intensity of the site layout along the three lines in Japan on passenger flow is generally high, with the highest impact intensity of 4.12 for the Toyoko line.

Tab. 2. Classification of land use for the intensity of impact on rail transit passenger flow

Impact intensity	Land use classification
Site I (medium-high)	Type II residential (multi-, medium-, and high-rise settlements), commercial offices, public service facilities (hospitals, schools, and various exhibition halls), parks and squares
Site II (low)	Industrial warehousing, Class I residential (low-rise settlements), Class III residential (shantytowns and dilapidated buildings), rural construction land

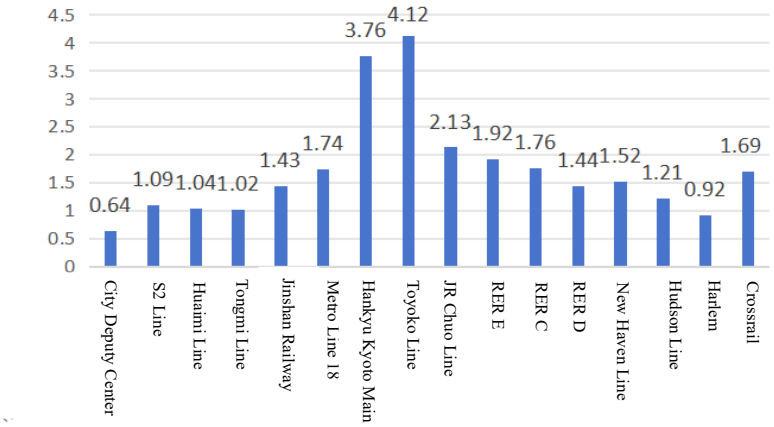

Fig. 2. Land use within 500 m along each line

3.4 Population density

The metrics were calculated mainly by using global 1km accuracy population raster data, converting it to vector data in GIS software, and constructing a linear buffer zone of 1km range along the line. The average value of population density within this buffer zone was calculated , and it was found that the highest population density of 23,100 people/KM² was found along the Japanese Toyoko Line. (as shown in Figure 3).

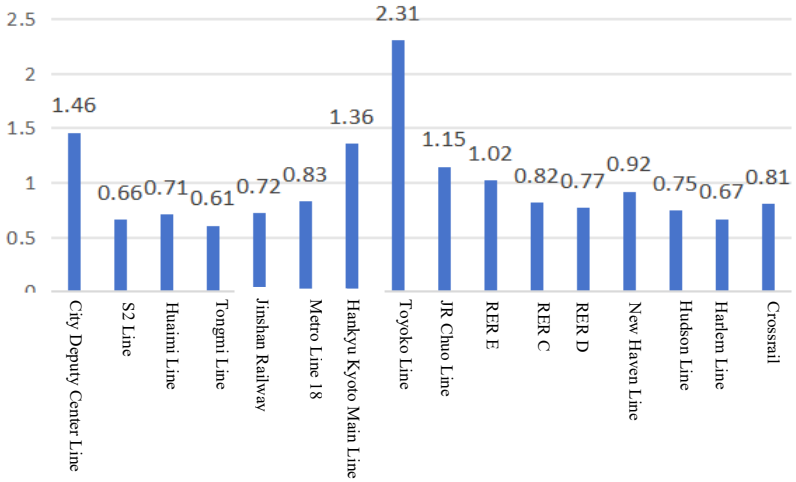

Fig. 3. Population density

3.5 Passenger density

In terms of passenger density, foreign municipal railroads generally perform well, with the annual passenger density of most lines exceeding 100,000 passengers per kilometer, including Japan's Toyoko Line, which is as high as 16.18 million passengers per kilometer per year. In contrast, the passenger density of domestic municipal railroads is generally lower, only Guangzhou Metro Line 18 and Shanghai Jinshan Railway perform better, with 545,000 and 207,000 passengers per kilometer per year, respectively.

Tab. 3. Passenger density of suburban railway lines

City	Opening Time	Data Year	Route	Passenger Flow Density
Beijing	2017	2023	City Deputy Center Line	0.9
Beijing	2008	2023	S2 Line	2.5
Beijing	2017	2023	Huaimi Line	0.5
Beijing	2020	2023	Tongmi Line	0.3
Shanghai	2012	2023	Jinshan Railway	20.7
Guangzhou	2021	2023	Metro Line 18	42.3
Osaka	1907	2018	Hankyu Kyoto Main Line	432.2
Tokyo	1926	2018	Toyoko Line	1618
Tokyo	1889	2018	JR Chuo Line	221.1
Paris	1852	2018	RER ELine	90.2
Paris	1979	2018	RER CLine	75.4
Paris	1981	2018	RER DLine	74.0
New York	1876	2019	New Haven Line	32.8
New York	1864	2019	Hudson Line	12.4
New York	1931	2019	Harlem Line	11.9
London	2015	2017	Crossrail	56.2

4. Analysis of Impact Factors

4.1 Correlation analysis

Tab. 4. Results of Pearson correlation analysis

	relevance								
	1	2	3	4	5	6	7	8	9
1Passenger density	1								
2Population density	.892**	1							
3Site Function	.905**	.750**	1						
4Construction Land Ratio	.735**	.750**	.830**	1					
5Area	-0.171	-0.123	-0.313	-.506*	1				
6Gross Domestic Product	0.406	0.327	0.408	0.273	.541*	1			
7Population	.663**	.612*	.627**	0.339	0.239	.520*	1		
8Nearest Distance to Center	-0.399	-0.393	-.498*	-.613*	0.138	-.634**	-0.144	1	

4.2 Regression analysis

Fig. 4 reveals that the percentage of construction land, land use function and population density have a linear relationship with passenger density, and the residual distribution conforms to normal distribution with good variance alignment. Therefore, the conditions for the use of OLS model are met and regression analysis will be performed to construct the model.

The data in Tab. 5 shows that the F-value is 51.367 accompanied by a p-value significantly less than 0.05, indicating that the constructed multiple linear regression model passes the overall test of significance and is effective in explaining the changes in the dependent variable. For deeper understanding, the significance and strength of the role of the respective variables need to be further explored.

Tab. 5. Results of OLS regression analysis

	Unstandardized coefficient		Standardized coefficient		Significance	
	B	Std err	Beta	t	p	VIF
(Const)	-174.136	119.413		-1.458	0.173	
Percentage of built-up land (X1)	-569.674	245.981	-0.365	-2.316	0.041	5.369
Land use function (X2)	218.818	44.222	0.801	4.948	0.000	5.666
Population density (X3)	376.117	75.852	0.624	4.959	0.000	3.427
Population (X4)	-0.030	0.034	-0.096	-0.876	0.400	2.623
Adjust R2	0.931					
F	51.367					
significance	.000b					
D-W Value	2.202					

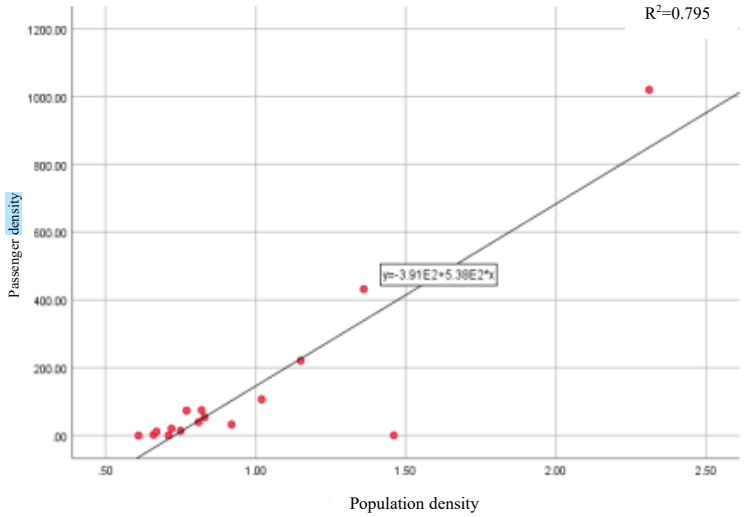

Fig. 4a. Scatter distribution

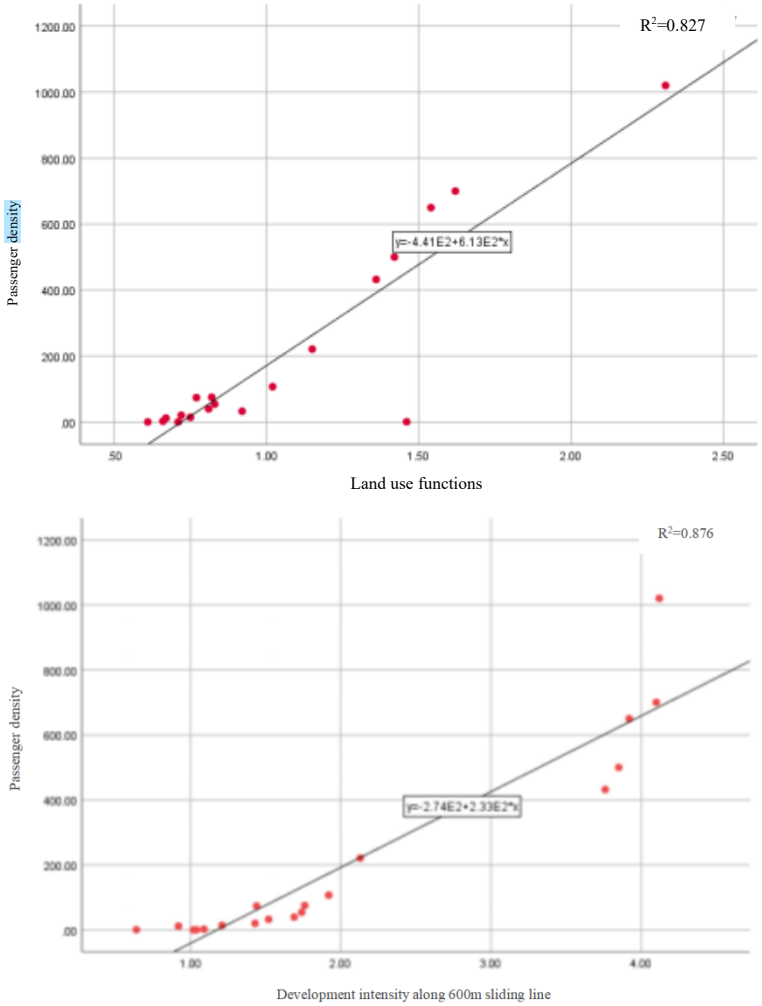

Fig. 4b. Scatter distribution

Tab.5 data shows all independent variables have VIF<10, indicating no significant covariance issue. With R^2 = 0.949, independent variables explain 94.9% of the dependent variable's variation, showing excellent model fit. The D - W value of 2.202 is in the desired range, confirming no autocorrelation. The t - test p - values (0.041, 0.000, 0.000) of the three independent variables are ≤ 0.05, showing significant effects on the dependent variable. Thus, the OLS regression model based on these variables is statistically valid, as shown below:

$$Y=-174.136-569.674X1+218.818X2+376.117X3 \quad (3)$$

4.3 Conclusion

After analyzing data from 16 routes, eight independent variables (Table 4) were studied. Population density, land use function, construction land proportion, and city population and passenger density are significantly positively correlated ($p<0.01$), with coefficients 0.892**, 0.905**, 0.735**, and 0.663** respectively.

Linear regression shows standardized coefficients: construction land share (-0.365), land use function (0.801), and population density (0.624). Construction land share is negatively correlated; for each standard deviation increase, the dependent variable drops by 0.365 standard deviations. Land use function has a strong positive correlation, with a 0.801 coefficient meaning a one-standard-deviation improvement raises the dependent variable by 0.801 standard deviations. Population density also has a positive correlation, with a 0.624 coefficient showing its positive effect. Overall, land use function is the main factor affecting the dependent variable, more so than population density, while construction land ratio has the opposite effect.

Suburban rail construction in Chinese cities marks the shift to integrated metropolitan areas, aligning with the “dual - carbon” strategy. Correlation and regression show that dynamic land use and dense population are key for high suburban rail patronage. But there's a gap between China's current land use, planning, and population distribution and the ideal for efficient suburban rail operation.

5. Exploring the causes

The purpose of this chapter is to explore the core causes of the differences in the development of municipal suburban railroad lines at home and abroad, but the causes of the formation of differences are very complex. According to the existing literature, including Liu L [12],Lu Yuan. [13] , it is revealed that the spatial planning layout of foreign metropolitan areas tends to be polycentric and functionally mixed, with which the complementary suburban railroad system effectively drives the balanced growth of the region, whereas domestic cities such as Beijing and Shanghai face the limitations of monocentric densification and urban-rural binary grouping structure, and the potential of the suburban railroad has not been fully released. Further, the analysis of Lin Xiongbin [14], Curtis C [15] pointed out that in the integrated land development and financing mechanism, foreign countries use PPP and other models are more mature, which helps to promote the project quickly and financially sustainable, on the contrary, the domestic need for mechanism innovation and policy flexibility enhancement. Therefore, the main cause of the differences is the difference between spatial planning concepts and policy synergy mechanisms.

Accordingly, this study selects Tokyo and Beijing as samples to explore in detail the causes of the differences in spatial planning concepts

and models and synergistic mechanisms, and to analyze the Tokyo model as a guide for the planning of suburban railroads and the efficient use of land in China.

Tab. 6. Comparison of indicators between the Tokyo metropolitan area and Beijing Metropolitan Area

Indicators	Beijing	Tokyo Metropolitan Area
Spatial planning concepts and models	Single Center Cluster	Multi-center corridor type
Synergistic Mechanism of Railway Transportation and Land Use Policies	Land ownership - government-led and centralized planning	Private land ownership - government-private sector cooperation

5.1 Differences in spatial planning concepts

The Beijing Urban Master Plan (2016 - 2035) uses a "multi - cluster" model. In this model, ecological space networks with the city. As a result, much non - construction land passes through suburban railroads when connecting clusters, causing inefficient land use along the routes.In contrast, Tokyo adopts a "multi - corridor" model. Here, ecological and urban spaces are distributed in a finger - like pattern. The city expands along major transport routes, especially rail lines, creating high - intensity residential and commercial areas along these corridors.

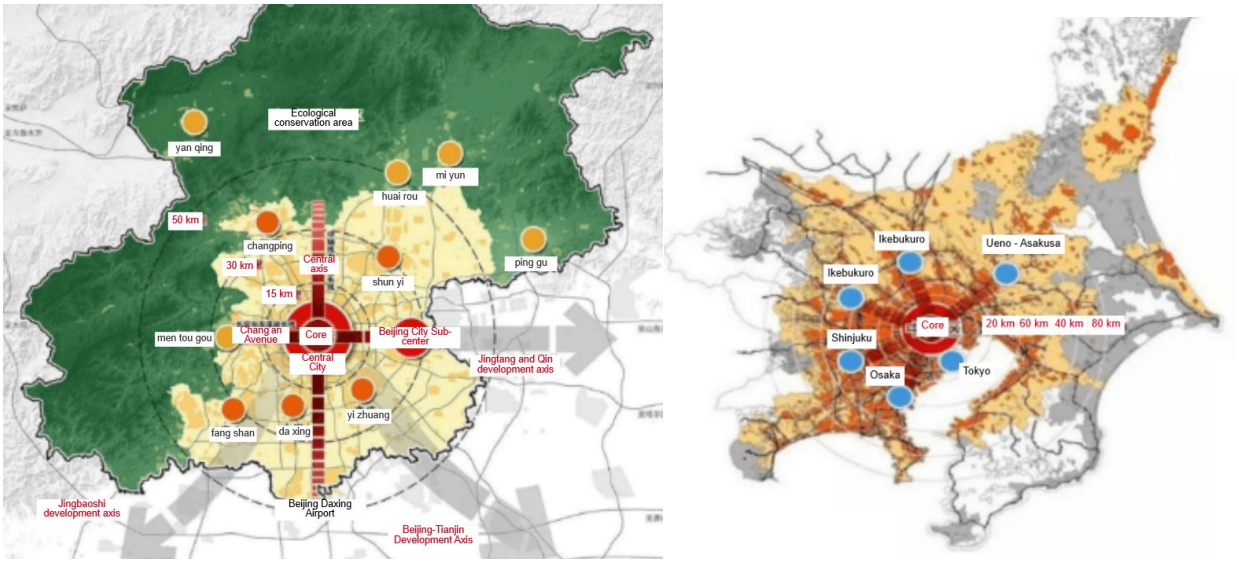

Fig. 5. Urban development structure of Beijing and Tokyo

An analysis of the land use planning around the S2 line of the Beijing Metropolitan (Suburban) Railway shows (e.g., Fig. 6) that eco-land occupies a significant proportion of the area, while the ratio of built-up land to non-built-up land is about 1.4, a phenomenon that reveals a certain degree of disconnection between the planning of the Metropolitan Suburban Railway and the land use planning. On the contrary, in the case of the JR Chuo Line in Tokyo, the land use planning along the line significantly favors high-density development, with a ratio of built-up land to non-built-up land of approximately 4.2, and the urban planning is closely coordinated with the suburban railroad layout.

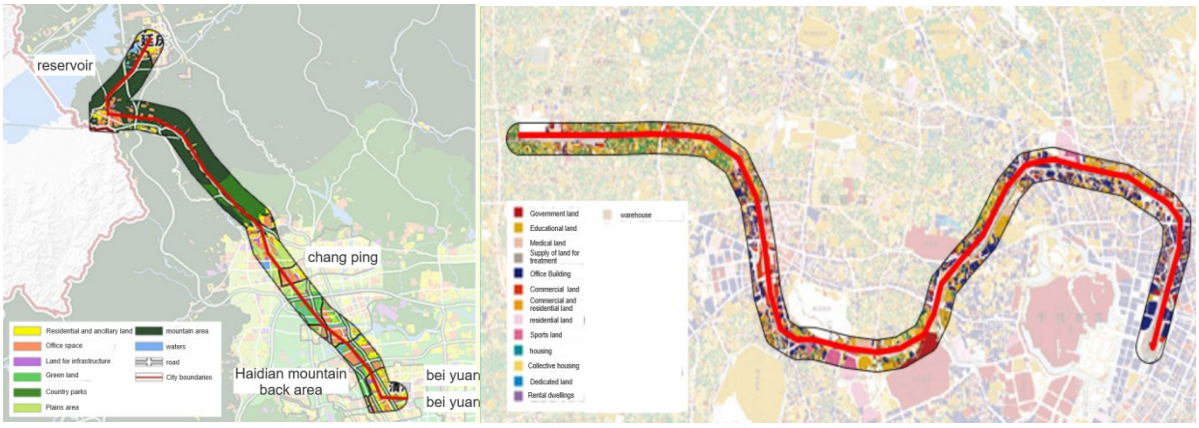

Fig. 6. Land use planning along the Beijing S2 Line and Tokyo JR Chuo Line

5.2 Differences in Policy Synergy Mechanisms

A comparison of the synergistic mechanisms of rail transportation and land use in Tokyo and Beijing reveals notable differences. In Tokyo, due to private land ownership and the Railway Promotion Law, rail companies can efficiently develop commercial and residential properties along rail lines. This results in high synergy between transportation and land use, spurring economic growth, population mobility, and regional integration, creating a dynamic cross - boundary metropolitan area.

Conversely, Beijing's "cluster" development, constrained by administrative boundaries, separates rail construction from land

management. Railway - adjacent land is often managed independently by different cities, limiting the synergy between the two. This restricts immediate response and comprehensive development potential.

In light of this, future territorial spatial planning should use policy design to optimize land use and population distribution along routes, promoting spatial synergy led by suburban rail. Although suburban rail is included in the latest territorial planning, some limitations may bring uncertainty to the system's expansion and effectiveness. This is a crucial issue for in - depth discussion in current planning.

6. Conclusion

Based on the results obtained above, it is shown that the ratio of land use in built-up areas, population density, and land use functions have important impacts on suburban passenger flows. Compared with the Tokyo metropolitan area, the extensive and large-scale construction of suburban railroads in mainland China, where the population and land use in the metropolitan area are still mainly clustered and lack of high-density spatial corridors, may have potential operational risks; and secondly, the mechanism of synergy between suburban railroads and the surrounding land use is imperfect, and lack of coordination between different parties leads to the lack of synchronization between railroad planning and land use planning. Therefore, when planning and constructing suburban railroads, the following aspects should be emphasized:

(1) Optimize the spatial planning layout of the metropolitan area and strengthen the “corridor-type” development mode.

Transform the traditional cluster development pattern. Referring to Tokyo's experience, establish high-density and multi-functional rail transit corridors in conjunction with the current planning of suburban railroads, and efficiently utilize the land along the routes, so as to encourage the suburban railroads to guide the development of the urban layout.

(2) Driving the synergistic development of Beijing's rail transit and land with legislation and collaboration

The key to optimizing rail-land synergy mechanisms lies in legislative innovation and cross-border cooperation. Drawing on Tokyo, it is proposed that regulations be enacted to support rail companies in prioritizing the development of land along rail lines and promoting integrated development. Build a cross-district coordinating body to integrate resources and synchronize planning and implementation. Integrate the market mechanism, implement PPP mode, and utilize the land appreciation to feed the rail project.

(3) Optimize line planning and siting [16]

Urban suburban railroad lines are preferentially located in highly developed and densely populated areas, avoiding non-urbanized areas, aiming at relying on sufficient passenger base, realizing accurate matching between the lines and the surrounding land and population, and maximizing the attractiveness of passengers.

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