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Analysis of Land Use Optimization of Metro Station Areas Based on Two-Way Balanced Ridership in Xi'an

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Abstract: With the development of metro systems, the problem of unbalanced ridership into and out of the stations, caused by the singleness of station area development, has become increasingly prominent. Research on land use optimization in metro station areas based on a two-way balance of ridership is proposed. First, the stepwise regression analysis method was used to build a relationship model between ridership and the land use index under the guidance of the two-way balance of ridership. Second, the range was optimized by calculating the land use factors of the metro station area. Finally, the land use of the metro station area was optimized from the perspectives of development intensity and land usage. Taking metro stations in Xi'an as an example, the results show that the land use characteristics of metro station areas are quite different. Under the guidance of the two-way balance of ridership, the current land use values of Daminggongxi Station, Nanshaomen Station, and Tiyuchang Station exceed the optimal value range and can be reduced by more than 2.78%. The current land use values of Chaoyangmen Station, Longshouyuan Station, and Weiyijie Station are within the optimized range. The land use values of Kaiyuanmen Station, Banpo Station, and Fengchengwulu Station are below the optimized range and could be increased by more than 13.7%. In addition, optimizing the development intensity or adjusting the land type is further proposed to ensure that the land use factors of station areas are within the calculated optimal value range. The results provide a reference for the optimization of land use in the Xi'an metro station area.

Keywords: land use; two-way balance of ridership; metro station area; stepwise regression analysis

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1. Introduction

The processes of urbanization and motorization in China have been accelerating in the 21st century, with mismatching problems between the carrying capacity of the city and traffic demand becoming increasingly prominent [1,2]. Due to their characteristics, public metro systems have become an important mode of transportation for people's daily travel. With the gradual development of metro networks, the proportion of metro trips to the total urban public transit trips is continuing to increase. However, the development of metros not only affects residents' travel but also affects the development and land use in metro station areas [3,4]. There is a two-way interactive relationship between station land use and station ridership which promote and restrict each other [5]. On the one hand, whether the land use of station areas is reasonable or not seriously affects the operational efficiency of the metro and affects the distribution of ridership in urban space. On the other hand, for metro stations with many outbound passengers and few inbound passengers, there will be problems with densely populated and overloaded land in the station area. Metro stations with many inbound passengers and few outbound passengers usually represent low land use rates and wasted space resources in station areas [6]. Therefore, optimizing the land use in station areas under the balanced conditions of two-way ridership [7], developing both in harmony [8], and avoiding excessive two-way ridership unevenness [9] have arisen as problems in the development of metro systems.

In theoretical research, the exploration of the relationship between ridership and land use in station areas can clarify the modes of action and the mechanism principle between the two. Qualitative and quantitative research methods can be used to deeply explore the internal motivation mechanisms behind land generating inbound ridership and land attracting outbound ridership. In this way, the perspective of balance between inbound and outbound ridership guides the optimization of station area land reconstruction and enriches the theory and method systems of metro station area land optimization. In a realistic sense, because the Xi'an metro is in the development stage and is not yet a complete network, the impact of metro stations on surrounding land use is still changing. Therefore, on a practical level, research on the land use of metro station areas can provide a basis for the construction and development around the metro station area. The research can guide the optimization and transformation of land use in metro station areas, the imbalance of ridership into and out of the station can be improved, and a reliable basis for further construction around metro stations can be provided.

This research adopted the framework system of "data analysis-model building-threshold calculation-index optimization" to analyze the linear relationship between inbound and outbound ridership and the land use factors of station areas. Models were constructed for the independent variable land use factor and the dependent variable inbound and outbound ridership, so as to obtain the multiple regression equation between inbound ridership, outbound ridership, and land use factors. The aim was to find a balance between the generation and attraction of ridership, reduce environmental pollution, and ensure the social fairness of land development. The conceptual framework of the research is shown in Figure 1. The main contributions of this research are as follows:

- The expansion of theoretical research. Focusing on the basic theory of inbound and outbound ridership and station area land use, we deeply studied the internal mechanism between ridership and land use and enriched the theoretical system of station area land use optimization research.
- Innovation of technical means. Combined with multi-source data (cell phone signaling, built-up area GIS data) for analysis, a data processing model for analyzing ridership distribution was developed. The model focused more on the distribution characteristics of land-generated inbound ridership and attracted outbound ridership.
- Innovation in research methods. Through the study of relevant literature and data analysis, the influence mechanism and relationship model of inbound and outbound ridership and land use factors were established. On this basis, optimization research was carried out, a land use index optimization system under the guidance of the two-way balance of ridership was established, and specific optimization measures for land use in each station area are proposed.

In the remainder of this paper, Section 2 reviews the relevant literature. Section 3 presents the scope of the study and the sources of data collection. Section 4 introduces the model used in this paper, the calculation method of variables, and the calculation method of the suitable value of metro ridership. The findings and discussion are presented in Section 5, and finally, the conclusions of this study are summarized.

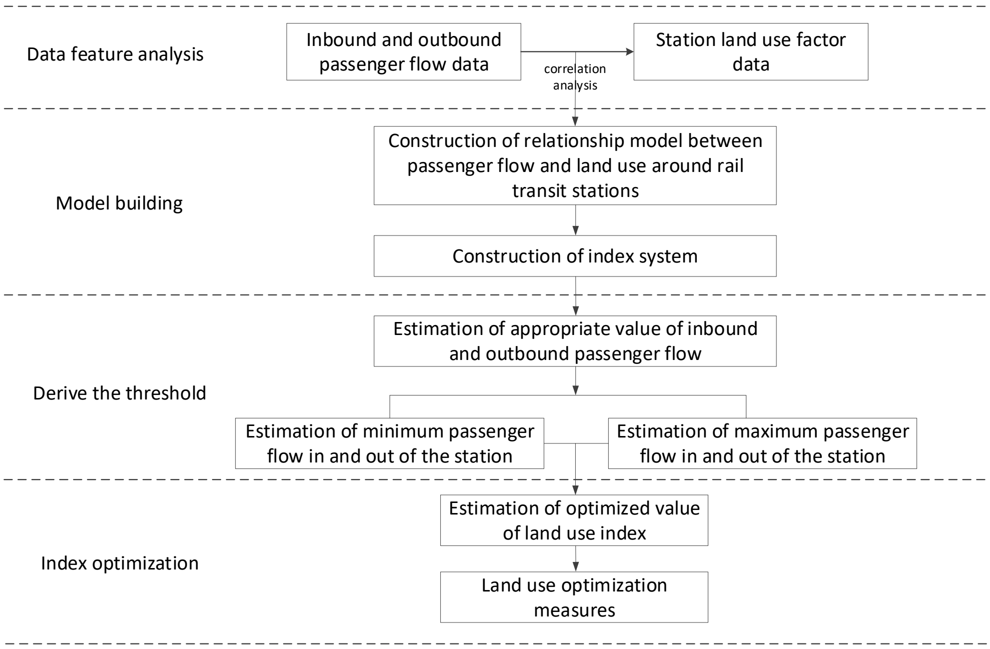


Figure 1. Research conceptual framework.

2. Literature Review

Scholars have achieved some results in related research on station ridership and station area land use. The interactive relationship between station land use and ridership has been confirmed by many studies [10–14]. Land use is the dominant factor in metro ridership [11]; optimizing station land use can improve this. Some existing studies have identified important contributions of land use attributes to metro ridership, including density [15,16], land use mix diversity [10], and other related factors. For example, the study by Chan et al. found that during the morning rush hour, for every 10% increase in commercial and administrative office space, the outbound ridership increased by 6% [17]. Cervero et al. found that improving the levels of intensity, diversity, and connection with public transport was an effective means to increase ridership [10]. Combining the actual historical ridership data of Beijing's metro operations, Guang [18] selected discrete indicators such as land use nature, development intensity, and station accessibility as fuzzy indicators for the basis of an in-depth analysis of land use around the station and ridership at the station. Additionally, the relationship between the inbound and outbound ridership of metro stations and land use under the condition of new line access was established. Cai [19], Cheng [20], Tan [21], and others have conducted research from the perspective of a relationship between ridership and land use, established a ridership prediction model for metros, and analyzed land-influencing factors. However, the above studies are based on analyses of the impacts of land use on metro ridership, and less attention has been paid to the impact of metro ridership on station land use.

Research on the impact of metro systems on land use in station areas has mainly focused on land use value [22,23] and land use structure and intensity [24]. From the perspective of metro station ridership, research on the impact of metro stations on land use is still limited. Liu et al. proposed a comprehensive development model of metro station areas based on the two-way balance of ridership in view of the imbalance of station ridership caused by contemporary developments of metro station areas and built an optimization model [25]. Zhang studied the relationship between the two-way balance of public traffic flow and land use in urban public transport corridors, proposed a method of classifying urban public transport corridors according to different development intensities and development methods, and built a two-way traffic flow calculation model and land use adjustment model [26]. Qiao et al. analyzed microscopic pedestrian characteristics and proposed a computing system to analyze the best two-way pedestrian flow [27]. However, quantitative relationships on the impact of metro ridership on station land use are still unclear, such as the impact of ridership on land use mix diversity and land use intensity.

Regarding the modeling relationship between ridership and station area land use, many scholars have constructed different method systems for different land use factors. In recent years, scholars have mostly chosen to use empirical analysis and regression models to explain the relationship between station ridership and land use factors and present optimization suggestions. Scholars have also established direct estimation models based on ordinary least squares (OLS) and partial least squares to reflect the impact of factors in land use types on ridership [17,28]. These multiple regression methods assume that the global parameters are consistent, and consider that each influencing factor has nothing to do with the spatial location and do not consider the difference in its spatial location. Scholars who used empirical analysis, such as Guo [29] and Cui [30], have proposed random equilibrium distribution methods for predicting ridership. Those who utilized regression models, such as Zhang [31] and Sung [32], incorporated land elements as independent variables and ridership as dependent variables to establish multiple regression models, adjusting land elements for different optimization objectives.

In summary, most of the previous studies have focused on the analysis of the total ridership of the station with models that lacked the fine classification of land use and could not accurately reflect the impact of metro ridership on land use. There are few studies on the two-way balance of ridership in the existing literature, and it is difficult to reveal the law of land use under the two-way balance of ridership. Therefore, how to effectively analyze the characteristics of two-way ridership and guide the rational optimization of station area land are some of the current problems. Based on this, in this study, a stepwise regression model was developed from the perspective of the two-way balance of ridership, and an optimization strategy of land use in the station area was explored.

3. Study Area and Data Source

3.1. Study Area

The capital city of Shaanxi Province, Xi'an is an urban area with a high population density in northwestern China. In recent years, considerable progress has been made here in the construction of a metro system. As of December 2021, there are eight metro lines in operation in Xi'an (Lines 1–6, Line 9, and Line 14), with a total operating mileage of 258 km and a total of 154 stations. The metro accounts for more than 50% of urban public transportation. With the expansion of urban scale and the increasing traffic demand, the metro station area, which is the main center of activity for metro ridership, has huge growth potential and needs to be continuously updated and optimized. In addition, the land use of the metro station area is difficult to coordinate with the construction and operation of the metro. The inbound ridership generated by the land and the attracted outbound ridership is unbalanced, resulting in different forms and degrees of influence of ridership on the station area. Lines 1 and 2, the earliest built lines in Xi'an, running through the city from east to west and north to south, are also the backbone lines for the development of Xi'an's metro network. The development of land characteristics along the lines is more stable than on other metro lines. Therefore, this study took the stations of Xi'an metro Line 1 and 2 as candidate research objects. In addition, we further excluded some stations according to the following principles:

- Stations outside the Third Ring Road in Xi'an. The metro station areas outside the Third Ring Road are still in the development and construction stages.
- Metro transfer stations. Transfer stations are affected by the flow of passengers, the different distribution characteristics of ridership at the station, and the complex characteristics of the ridership; the land use of the metro station area is affected by various factors as well, showing different characteristics.
- Stations with abnormal ridership. Similar to Zhonglou Station, Xiaozhai Station, Yongningmen Station, etc., are affected by holidays or flow restriction control measures.

- The selection was according to the administrative region where the site was located. The stations are distributed in different positions in the east, south, west, north, and center of the built-up urban area.

According to the analysis of the land characteristics of the metro station area, it was found that residential, commercial, and public service land are the main land types for the generation and attraction of ridership in the metro station. Therefore, the land use of the selected metro station area should include the most basic functions of work and housing, and the proportions of these three types of land area are relatively large, though there are clear differences between stations. According to the above principles, this study analyzed a total of nine stations: Fengchengwulu Station, Daminggongxi Station, Longshouyuan Station, Nanshaomen Station, Tiyuchang Station, Weiyijie Station, Chaoyangmen Station, Banpo Station, and Kaiyuanmen Station. These sites were the final research objects of this paper, as shown in Figure 2.

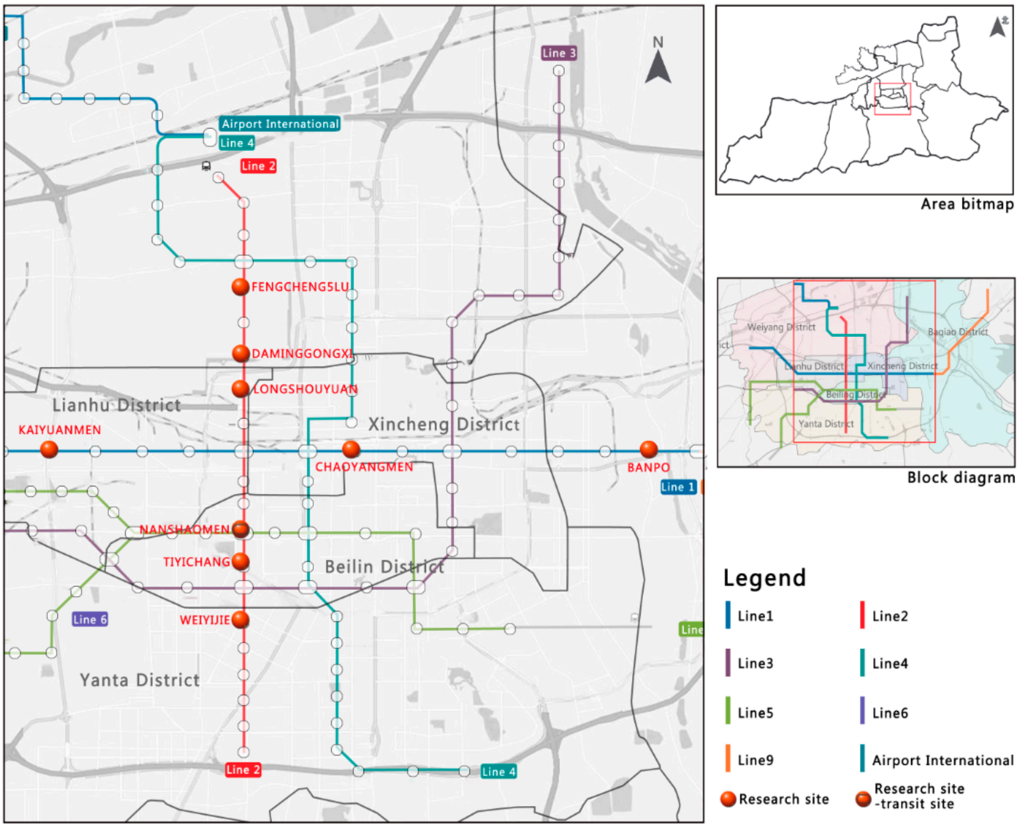


Figure 2. Study area.

Most of the literature research results show that the service range of metro stations is mainly between 400 m and 800 m [32–34]. China's "Guidelines for Planning and Design of Areas Along Urban Rail Lines" defines a metro station area as "an area that is about 500–800 m away from the station and can reach the station entrance within about 15 min' walk, and is closely related to the rail function". Therefore, considering that the metro network in Xi'an is not yet perfect, the density of the network is low, and there is high popularity of shared bicycles, the metro station domain referred to in this study was defined as the built-up urban area with the station at the center and a radius of 800 m, in concentric circles, which is influenced by the station's ridership.

3.2. Data Source

The main data of this study included metro station area land use, cell phone signaling data, and long-term station ridership forecasts. Among them, the land use data were based on high-definition satellite images (Baidu map (5 November 2019 baidu.com)), on-site field surveys and measurements, and statistics from a GIS database of built-up areas within the Third Ring Road of Xi'an in 2017. Land use data are mainly used to calculate a series of characteristic indicators of the built environment, such as the land use nature and building area of the metro station area. Cell phone signaling data came from 2G, 3G, and 4G user data of Xi'an Unicom users, which are records generated by active and passive interactions between cell phones and base stations. The time period selected for cell phone signaling data followed two principles: one was to avoid special periods such as holidays; the second ensured that the daily collection period covered the complete operation time, which was one continuous week. Therefore, this study collected the cell phone signaling data of passengers at metro stations for one continuous week (5 to 12 November 2019) to calculate the number of inbound and outbound passengers at metro stations. The long-term station ridership forecast data comes from Xi'an Rail Transit Group Company Limited and is used to estimate the appropriate value of ridership at metro stations.

4. Methodology

According to the characteristics of the obtained data and the research purpose, the methods used in this paper included three aspects: a regression analysis model, the construction of a variable set, and the estimation of suitable values.

4.1. Regression Analysis

Regression analysis models are some of the most effective and intuitive models used by scholars to study the relationship between multiple land use factors and the ridership of metro stations. Based on previous research experience, this study used a stepwise multiple linear regression model to construct a relationship between land use factors and ridership. Using stepwise multiple linear regression models is an optimal approach; every time a new variable is introduced into the model, it is necessary to check whether the independent variables in the original model still have statistical significance. Independent variables with insignificant partial regression sums of squares are excluded. In this way, variables are introduced and eliminated until no new variables are introduced, and old variables are not deleted. Therefore, the model retains the most significant important variables and the prediction accuracy is high. Moreover, the stepwise multiple linear regression can correct for multicollinearity to a certain extent, resulting in a relatively simple model with fewer variables.

Stepwise multiple linear regression is often used to describe random linear relationships between the dependent variable, y, and multiple independent variables, x. The model equation is shown in (1):

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k + \delta \tag{1}$$

where $x_1, \ldots, x_k$ is a set of independent variables, y is the dependent variable, $\beta_0, \ldots, \beta_k$ is the regression coefficient, and δ is the error term.

4.2. Building a Variable Set

The interaction relationship between land use and ridership in the metro station area has been clarified. However, different scholars have constructed different sets of independent variables for land factors. The total land area can be used as a quantitative index to describe the scale of land use. The traffic volume per unit area of buildings of different natures is different. When the land area is fixed, the larger the plot ratio, the larger the building area, and the greater the inbound ridership. Thus, the plot ratio affects the size of the building, and the size of the building directly determines the basic degree of inbound and outbound ridership.

For the mixed diversity of buildings and land use, the higher the degree of mixing, the more complex and richer the functions of the station area, and the more it can meet the needs of people's daily life. Under the premise of satisfying people's travel purposes, people are more inclined to choose a shorter commuting distance to avoid long-distance travel by metro, thereby reducing the inbound ridership in station areas. Although with a greater diversity of buildings and land use, more people's desire to travel can be stimulated, the motivation of people to take the metro in station areas is reduced. Therefore, the degree of mixing is an external constraint that generates inbound ridership and is a direct influencing factor.

Therefore, this study drew on the extant literature and combined actual data to construct land use factors, including the total land area, total building area, average building density, average plot ratio, building mix diversity, and land mix diversity. Among them, the total land area is the land within a radius of 800 m from the metro station. The total construction area is the area of the plots within an 800 m radius from the metro station. The average building density describes the vacant land ratio and building density of the station area and is the area of the building footprint/total area of the station area. The average plot ratio describes the land development intensity of the same type of land in the affected area of the site, and the value is the total construction area of the same type of land/the area of the same type of land. The variables and statistics of the nine stations are presented in Table 1.

Table 1. The variables and statistics of the nine stations.

Variables		Min	Max	Mean	SD
Land characteristics	Total land area (X1) (ten thousand m^2)	170.01	247.89	216.76	25.88
	Total building area (X2) (ten thousand m^2)	215.61	618.16	429.85	126.22
	Average building density (X3)	0.26	0.42	0.32	0.565
	Average plot ratio (X4)	1.05	2.95	1.99	0.563
	Building mix diversity (X5)	1.12	1.52	1.28	0.133
	Land use mix diversity (X6)	1.46	1.95	1.71	0.165
Traffic characteristics	Outbound ridership (y1)	475	2900	1822	1143.8
	Inbound ridership (y2)	482	4164	1622	779.1
	Metro sharing rate (X7)	20.61%	24.57%	22.16%	1.31%

Building mix diversity describes the richness and complexity of buildings in the station area, The model equation is shown in (2):

$$B = -\sum_{i=1}^{n} K_i ln K_i \quad (2)$$

Land use mix diversity describes the richness and complexity of land use within a station area, The model equation is shown in (3):

$$L = -\sum_{i=1}^{m} P_i ln P_i \quad (3)$$

where L is the mixed diversity of land use, m is the variety in land use types, and P_i is the proportion of the ith land use type. B is the mixed diversity of the buildings, n is the number of building types, and K_i is the proportion of the ith building type.

The ridership characteristics survey of the research object refers to the distribution of ridership within the station area, i.e., the inbound and outbound ridership, excluding the inbound and outbound ridership and the transit ridership outside the station area. When filtering the raster data of cell phone signaling, we performed the following operations to exclude out-of-range ridership and other transit ridership.

Screening of inbound ridership: cell phone signaling with a starting point within the station area and an end point at the station was selected as site ridership generated by the land, i.e., the inbound ridership.

Screening of outbound ridership: cell phone signaling with a starting point at the station and an end point within the station area was selected as site ridership attracted by the land, i.e., the outbound ridership.

Through the cell phone signaling database of traffic travel modes in Xi'an within the Third Ring Road, the grid data of the starting point O of the traffic occurrence within the station area were taken as the place of traffic occurrence, and the grid data of the end point D of the traffic occurrence within the station area were used as the grid data. The grid data were used as the traffic termination point to filter out the total traffic trips in the station domain grid, combined with the metro trips within each station domain. The rail traffic sharing rate of each station could then be calculated; the sharing rate directly reflects the relationship between the station area rail traffic volume and the total travel volume, The model equation is shown in (4):

$$t = Q_{train}/Q_{all} \tag{4}$$

where t is the sharing rate and Q_{train} is the actual number of metro trips. Additionally, Q_{all} is the number of trips made by all modes of transportation.

4.3. Estimation of a Suitable Value of Metro Ridership

The suitable value of metro ridership refers to the design of inbound or outbound ridership for a metro station under ideal conditions. The two-way balance of ridership means that, in an ideal state, the inbound ridership is equal to the outbound ridership. Based on this premise, this study took the metro demand generated by existing land as the lower limit of the suitable value of the constraint ridership and took the long-term maximum supply of metro stations as the upper limit of the suitable value for the constraint ridership to determine the two thresholds to solve the metro problem. The contradiction between demand and supply thus guides the optimization of land use.

The current state of land use determines the most basic traffic demand; thus, the metro demand generated by the current land was used as the minimum value for estimating the appropriate value for metro ridership. Secondly, the maximum supply of the long-term development of the metro determined the maximum suitable value of metro ridership. The specific equation is shown in (5):

$$y_{S\ min} \leq y_1 = y_2 \leq y_{S\ max} \tag{5}$$

where $y_{S\ min}$ is the metro demand generated by the current land use, $y_{S\ max}$ is the maximum supply for the long-term development of the metro, y_1 is the outbound ridership, and y_2 is the inbound ridership.

Estimation of the long-term inbound (outbound) ridership of the metro, $y_{S\ max}$

This study explored the relationships between inbound ridership, outbound ridership, and land use; thus, the weighted values of inbound and outbound ridership in long-term peak hours were used as the inbound and outbound ridership in peak hours. Then, the daily average of inbound and outbound ridership, using the inbound and outbound ridership during peak hours, was calculated. Under the guidance of the two-way balance of ridership, the inbound and outbound ridership were considered to be equal, and the directional unbalance coefficient should have tended to 1. Under the guidance of the two-way balance of ridership, the inbound and outbound ridership were considered to be equal. Therefore, the daily average ridership into and out of the station was multiplied by a factor of 0.5 to determine the maximum supply for long-term development, $y_{S\ max}$.

Average daily inbound and outbound ridership, The model equation is shown in (6):

$$D = \frac{F_1 + F_2}{PHR} \tag{6}$$

The largest supply for the long-term development of the metro, The model equation is shown in (7):

$$y_{S\ max} = D \times 0.5 \tag{7}$$

where D is the average daily inbound and outbound ridership, F_1 is the outbound ridership during long-term peak hours, F_2 is the inbound ridership during long-term peak hours, and PHR is the peak hour traffic ratio.

Estimation of the current inbound (outbound) ridership of the metro, $y_{S\ min}$

Using the classic original unit method in the field of transportation, ridership forecasting of the current metro station ridership was performed. For each land use or building type, the ridership generated and attracted per unit area was different. Therefore, the occurrence rate and attraction rate of the unit land area or unit building area of different uses were used to calculate the current ridership of the metro station.

Current metro inbound ridership, The model equation is shown in (8):

$$\sum P_i = S_i \times p_i \times t \tag{8}$$

Current metro outbound ridership, The model equation is shown in (9):

$$\sum A_i = S_i \times a_i \times t \tag{9}$$

where P_i is the amount of ridership generated by the land area or building area of class i, A_i is the amount of ridership attracted by land area or building area of class i, S_i is the land or building area of class i, p_i is the land or building of class i traffic generation rate, t is the metro sharing rate, a_i is the traffic attraction rate of i-type land or building, and P_i and A_i are values from the reference table of traffic travel rates for different construction projects in Xi'an.

Under the guidance of the two-way balance of ridership, it is considered that the inbound ridership is equal to the outbound ridership, the model equation is shown in (10) and the metro demand generated by the existing land is obtained as $y_{S\ min}$:

$$y_{S\ min} = \frac{\sum P_i + \sum A_i}{2} \tag{10}$$

where $\sum P_{\mathrm{i}}$ is the current inbound ridership and $\sum A_i$ is the outbound ridership.

5. Results and Discussion

5.1. Relationship Model between Ridership and Land Use Factors

Before building the regression model, the correlations between average daily station ridership, attracted station ridership, and the land use factors in the station area were analyzed. By screening out the relevant land use indicators that influence ridership, the interaction mechanisms of each station area generating and attracting station ridership and land use were explored. At the same time, there may be multicollinearity among the independent variables; therefore, the multicollinearity test was carried out among the independent variables. Through the analysis of indicators, the correlation of each indicator was determined to be poor. In order to better discuss the relationship between land use and ridership, the study did not exclude independent variables.

In this study, IBM SPSS Statistics Version 28 software was used to solve the stepwise regression model, X1 to X7 were imputed step by step, and the coefficients after linear regression of the respective variables were obtained. According to the results of the model, the average building density of X3 and the sharing rate of X7 were not found to be significant independent variables; thus, they were not included in the final model results. The final model results are presented in Table 2 which shows the fit of the multiple regression model.

Table 2. Stepwise multiple linear regression of station inbound and outbound ridership.

Land Use Factors	Estimated Coefficient	Standard Error	Standardized Coefficient	T-Value	*p*-Values
Intercept	−37.38 (−31.51)	0.50 (0.30)		−74.10 (−106.22)	0.009 (0.006)
Total land area (lnx1)	1.57 (1.51)	0.12 (0.07)	0.20 (0.20)	12.88 (21.00)	0.049 (0.030)
Total building area (lnx2)	1.40 (1.03)	0.11 (0.06)	0.46 (0.35)	13.15 (16.27)	0.048 (0.039)
Average plot ratio (x4)	0.81 (0.95)	0.06 (0.04)	0.47 (0.57)	12.88 (25.84)	0.049 (0.025)
Building mix diversity (x5)	0.76 (0.83)	0.06 (0.03)	0.11 (0.12)	13.55 (25.04)	0.047 (0.025)
Land use mix diversity (x6)	0.57 (0.84)	0.04 (0.02)	0.10 (0.15)	15.38 (38.34)	0.041 (0.017)
R^2			0.988 (0.979)		
Adjusted R^2			0.994 (0.979)		
Sum of Squares			7.582 (7.027)		
df			7 (7)		
Mean Square			1.090 (1.015)		
F			19,095.882 (51,432.081)		
P			0.006 (0.003)		

5.2. Estimation of Optimal Values of Land Use Factors in Station Areas

Through the analysis, it can be seen that the total land area X1, total building area X2, average plot ratio X4, building mix diversity X5, and land use mix diversity X6 are the key factors affecting ridership into and out of the station. The total station land area was taken as a given condition and no optimization study was performed for the total land area. Under the premise of X1, X2 was affected by X4; therefore, X4 was optimized first, then X2 was optimized for the nature of the land.

Through the constraints of the appropriate value of ridership into and out of the station, the minimum and maximum values of the metro ridership were obtained. Land-use-related factors were calculated using relational models. The calculation results for the average plot ratio, building mix diversity, total building area, and land use mix diversity are shown in Table 3.

(1) Average plot ratio

From the analysis of the relational model, it can be seen that the average plot ratio had an obvious positive correlation with the inbound and outbound ridership. Table 3 shows that the development intensity of Daminggongxi Station, Nanshaomen Station, and Tiyuchang Station exceeded the optimized upper limit. Fengchengwulu Station, Kaiyuanmen Station, and Banpo Station did not reach the optimal lower limit, whereas Longshouyuan Station, Weiyijie Station, and Chaoyangmen Station were all within the optimal value range. The level of the average plot ratio of the station area represents the level of development intensity: the higher the development intensity, the higher the land development benefit. Therefore, when the average plot ratio of the station area exceeded the appropriate value, the upper limit of the appropriate value was taken as the lower limit of optimization, and the current plot ratio was used as the upper limit of the guide average plot ratio. When the average plot ratio was lower than the appropriate value, the appropriate value was adopted as the standard to guide the average plot ratio. When the average plot ratio of the station area conformed to the appropriate value, the current plot ratio was taken as the lower limit of optimization and the upper limit of the appropriate value as the upper limit of the guide average plot ratio. Except for Daminggongxi Station, Nanshaomen Station, and Tiyuchang Station, the average plot ratios of other stations can be increased.

Table 3. Optimum value ranges of the average plot ratio, total building area, building mix diversity, and land use mix diversity.

Stations		Fengchengwulu	Daminggongxi	Longshouyuan	Nanshaomen	Tiyuchang	Weiyijie	Kaiyuanmen	Chaoyangmen	Banpo
Current value	X_4	1.79	2.59	2.06	2.95	2.31	1.69	1.7	1.75	1.05
	X_2	339.91	618.15	481.53	501.71	573.61	392.65	344.43	401.04	215.61
	X_5	1.14	1.13	1.23	1.28	1.45	1.32	1.3	1.52	1.18
	X_6	1.5	1.75	1.74	1.77	1.82	1.57	1.46	1.95	1.84
Y1 Outbound ridership optimization value range	X_4	2.19–3.48	0.98–2.27	1.19–2.48	1.58–2.87	0.66–1.95	1.5–2.79	1.97–3.26	0.99–2.28	2.22–3.51
	X_2	493.65–1642.03	138.24–459.83	215.38–716.42	139.96–465.55	122.37–407.06	328.62–1093.07	442.05–1470.38	197.58–657.21	644.38–2143.37
	X_5	1.6–3.08	0.71–0.77	0.24–1.72	0.29–1.19	0.45–1.03	1.11–2.58	1.61–3.09	0.65–2.13	2.53–4.01
	X_6	1.96–3.41	0.07–1.39	0.77–2.22	0.22–1.68	0.06–1.4	1.35–2.81	1.76–3.22	1.09–2.55	3.17–4.62
Y2 Inbound ridership optimization value range	X_4	2.11–3.63	0.46–1.99	0.83–2.36	1.31–2.83	0.15–1.67	1.24–2.77	1.84–3.36	0.77–2.29	2.47–3.99
	X_2	407.94–978.14	182.20–436.88	238.60–5721.17	194.96–467.46	165.49–396.79	303.06–726.68	372.46–893.06	229.16–549.47	488.34–1170.92
	X_5	1.48–3.08	0.12–0.49	0.06–1.55	0.45–1.15	0.35–0.77	0.85–2.46	1.45–3.05	0.49–2.1	2.68–4.29
	X_6	1.95–4.09	0.24–0.9	0.03–2.16	0.54–1.6	0.22–0.92	0.93–3.07	1.65–3.79	0.58–2.72	3.84–5.97

(2) Building mix diversity and land use mix diversity

From the regression equation analysis, it can be seen that there was a positive correlation between the building mix diversity, land use mix diversity, and ridership into and out of the station. For the development of station land, a higher mix diversity can also bring greater land use benefits and improve urban vitality. Therefore, according to the appropriate mix diversity, the station area building mix diversity and land use mix diversity were further determined. When land use mix diversity was higher than the suitable value, the upper limit of the suitable value was used as the lower limit of optimization, and the current mix diversity was used as the upper limit of optimization. When the mix diversity was lower than the suitable value, the upper and lower limits of the suitable value were adopted as the guiding standards. When the station area mix diversity conformed to the appropriate value, the current mix diversity was used as the lower limit of optimization, and the upper limit of the appropriate value was used as the upper limit of the guiding mix diversity.

It can be seen from Table 3 that the building mix diversity and land use mix diversity of Daminggongxi Station, Nanshaomen Station, and Tiyuchang Station exceeded the optimized upper limit. Fengchengwulu Station, Kaiyuanmen Station, and Banpo Station did not reach the optimal lower limit, whereas Longshouyuan Station, Weiyijie Station, and Chaoyangmen Station were all within the optimal value range. Notably, except for Daminggongxi Station, Nanshaomen Station, and Tiyuchang Station, the mix diversity of the rest stations needs to be improved. Therefore, according to the current situation of each station, increasing the number and scale of functional types of land and buildings could effectively increase the functional diversity of urban land, stimulate vitality, and promote use efficiency. However, due to the different actual land use and construction statuses of each station area, some station areas can increase their mix diversity, though some station areas are not suitable for increasing their mix diversity.

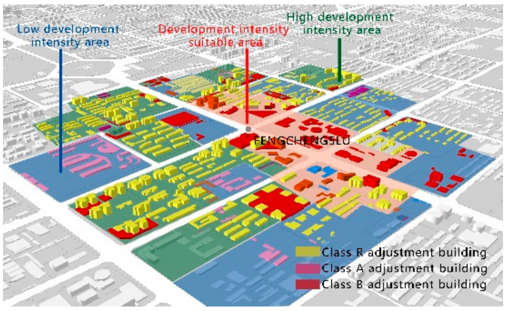
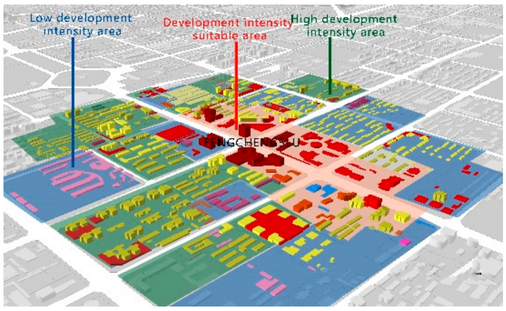
According to the regression model, the optimal threshold ranges of average plot ratio, building mix diversity, and land use mix diversity were analyzed. Therefore, the next step was to optimize the land use of the station area from the perspectives of development intensity and the adjustment of land use properties.

5.3. Optimizing Measures for Land Use in Station Areas

Two threshold ranges are closely associated with the measures for optimal land use: objective theoretical calculations and land use optimization measures. The current development intensity (plot ratio) of each station area was compared with the optimization range, and, according to the difference between the average plot ratio of each station area and the value of the optimization range, the plot could be divided into areas with a low development intensity, areas with a suitable development intensity, and areas with a high development intensity (the intensity division of each station is shown in Figure 3). The formulation of optimization measures in this study followed the principle of stock planning. On the basis of the current stock, local update optimization is proposed for different plots.

(1) Development intensity optimization

When the land use layout of the station area was carried out, the land development intensity of the core area of the station area could be improved; the schematic diagram is shown in Figure 4. This advocates for the construction of comprehensive service facilities with a high plot ratio and the implementation of joint development. In adjusting the land use structure, it is recommended that the station area should be arranged from the inside to the outside, such as commercial, catering and entertainment, office, residential, and other functions, focusing on the compounding of functions, and integrating and improving the comprehensive service function of the station area. By properly controlling the development volume of peripheral areas and balancing the total development volume of the whole area, the land use of the whole station area presents a circle-level decreasing mode centered on the station.

<table>
<tr><th>Stations</th><th>Current situation</th><th>Optimized</th></tr>
<tr><td>Feng-
chengwulu</td><td>
</td><td>
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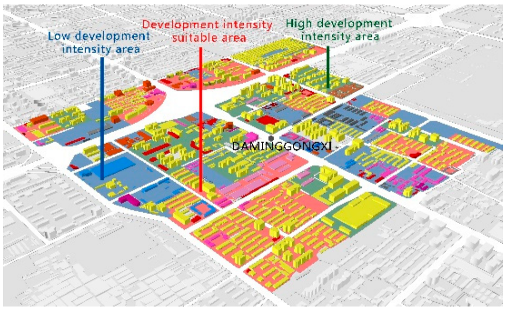
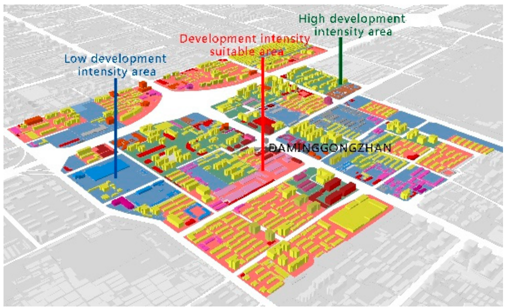
gongxi</td><td>
</td><td>
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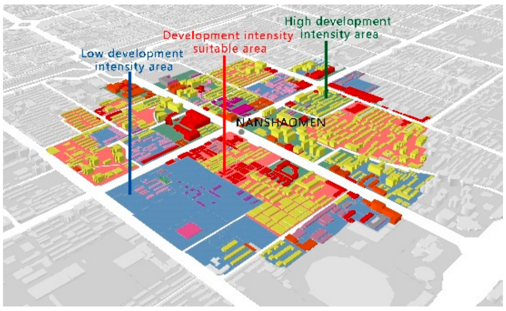
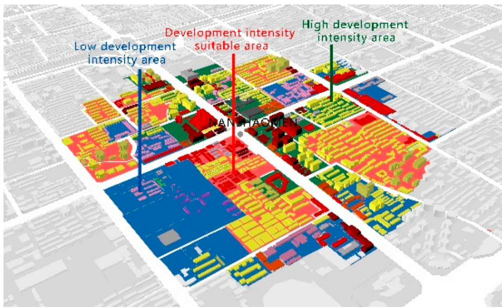
<tr><td>Nansha-
omen</td><td>
</td><td>
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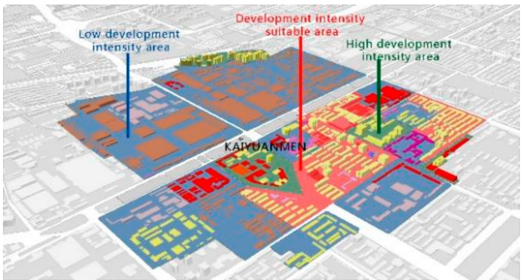
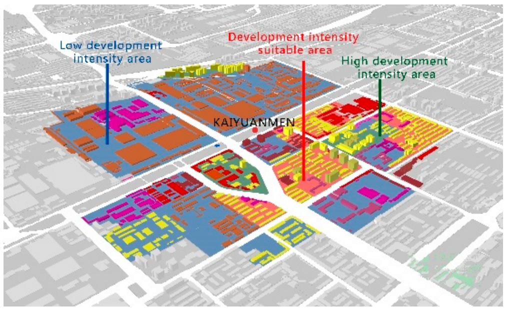
<tr><td>Kaiyanmen</td><td>
</td><td>
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Figure 3. *Cont.*

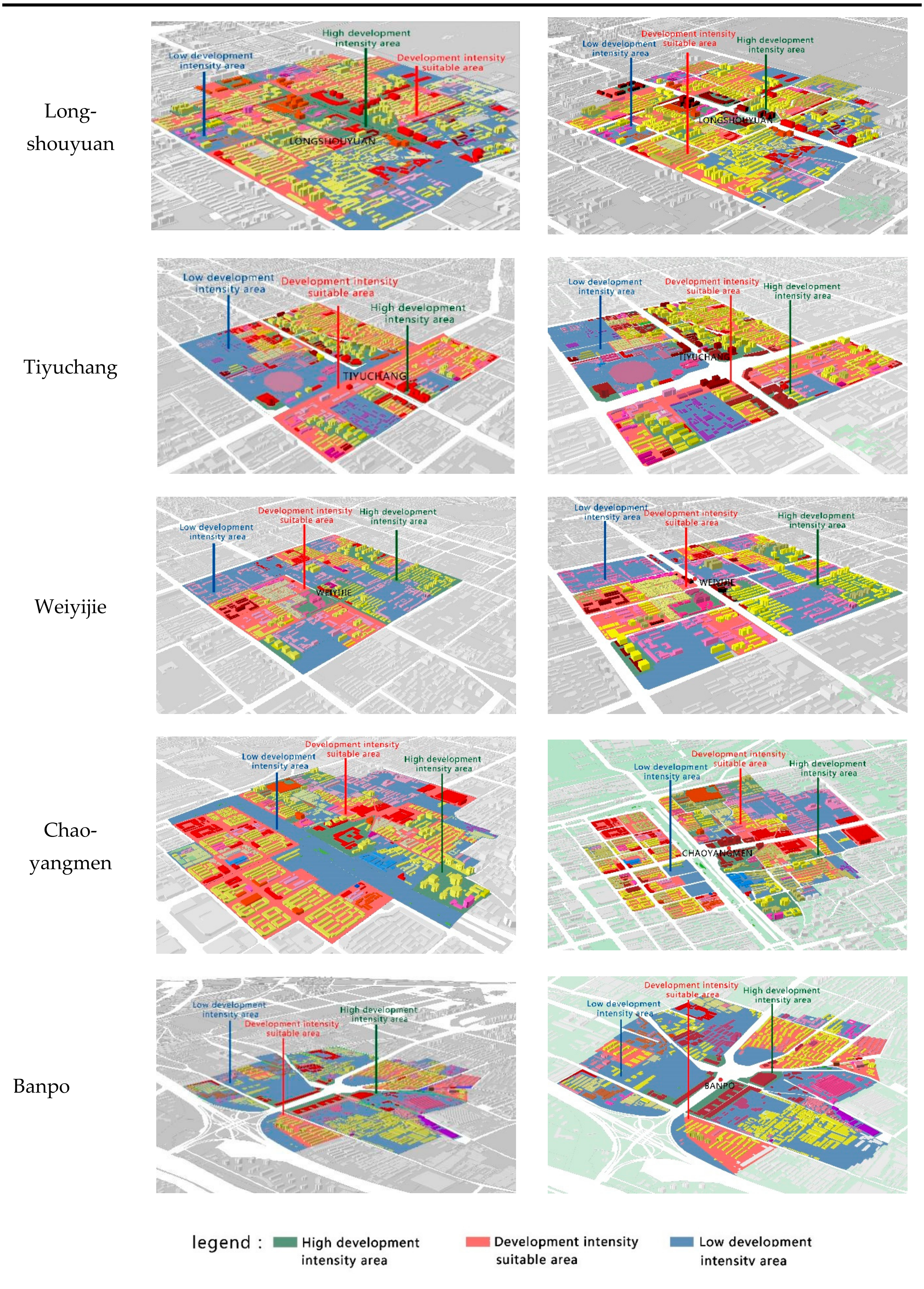


Figure 3. The development intensity zoning of each station and the spatial intention before and after optimization.

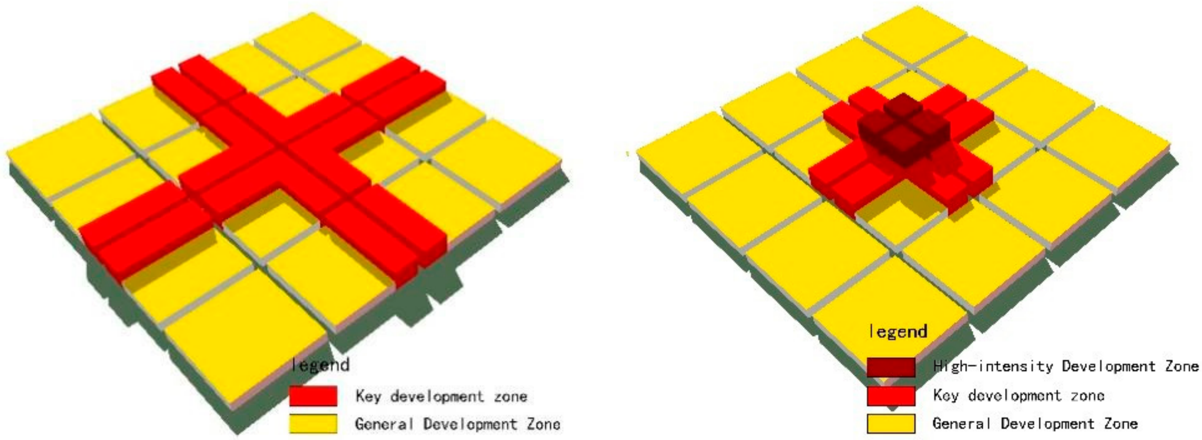


Figure 4. Schematic diagram of development intensity optimization.

For areas with low development intensity, the main types of land use are old residential areas (or low-intensity residential areas), urban villages, industrial land, schools, squares, green spaces, and land to be developed. Due to the special functions of school land and industrial land, the development intensity should not be too high. Squares and green space provide ample open space for a city. Therefore, the recommendations herein are mainly aimed at the renovation of old residential areas and urban villages. On the one hand, the plot ratio is increased, and on the other hand, the living environment is improved to enhance the image of the city, optimization plans is shown in Table 4. According to the optimization value of development intensity, it is suggested that Fengchengwulu Station should increase the plot ratio of such land to above 2.11, Daminggongxi Station should at least be kept above 2.27, Nanshaomen Station should be increased to above 1.31, Kaiyuanmen Station should be increased to above 1.97, Weiyijie Station should be increased to above 1.69, Chaoyangmen Station should be increased to 1.75 or above, and Banpo Station should be increased to 2.22 or above, optimization plan for the development intensity of each station is shown in Figure 5.

Table 4. Areas with low development intensity and optimization plans for the development intensity at each station.

Land classification	Fengchengwulu	Daminggongxi	Nanshaomen	Kaiyuanmen	Longshouyuan	Tiyuchang	Weiyijie	Chaoyangmen	Banpo
A	Remain	Remain	Remain	Increase	Increase	Remain	Increase	Remain	Remain
B	Increase	Increase	Remain	Increase	Increase	Increase	Increase	Increase	Increase
G		Remain	Remain			Increase			Remain
M	Remain	Remain		Remain	Remain				
R	Increase	Increase	Increase	Increase	Increase		Increase	Increase	Increase
S		Remain	Remain						
U	Remain	Remain	Remain	Remain					

A, land for public administration and public service facilities; B, land for commercial service facilities; G, land for green space and squares; M, industrial land; R, residential land; S, land for roads and transportation facilities; U, land for utilities.

For areas with suitable development intensity, the main land types were newly constructed residential quarters, some commercial land, and public service land. This kind of land has good environmental and building qualities and it is recommended to maintain the original state and not transform it.

For areas with high development intensity, the main types of land use are commercial land distributed along both sides of main roads. Although this type of land has a high development intensity, it is in line with its own business format and urban construction standards and the original development intensity value should be maintained. The other type is mostly new construction projects with good construction quality and complete corresponding equipment and facilities; in this case, the original development intensity value should also be maintained. However, to strengthen the aggregation effect of the site, it is recommended that individual commercial land should be subjected to increased construction intensity, although the value of the plot ratio should not exceed 3.99, optimization plan for the development intensity of each station is shown in Figure 6.

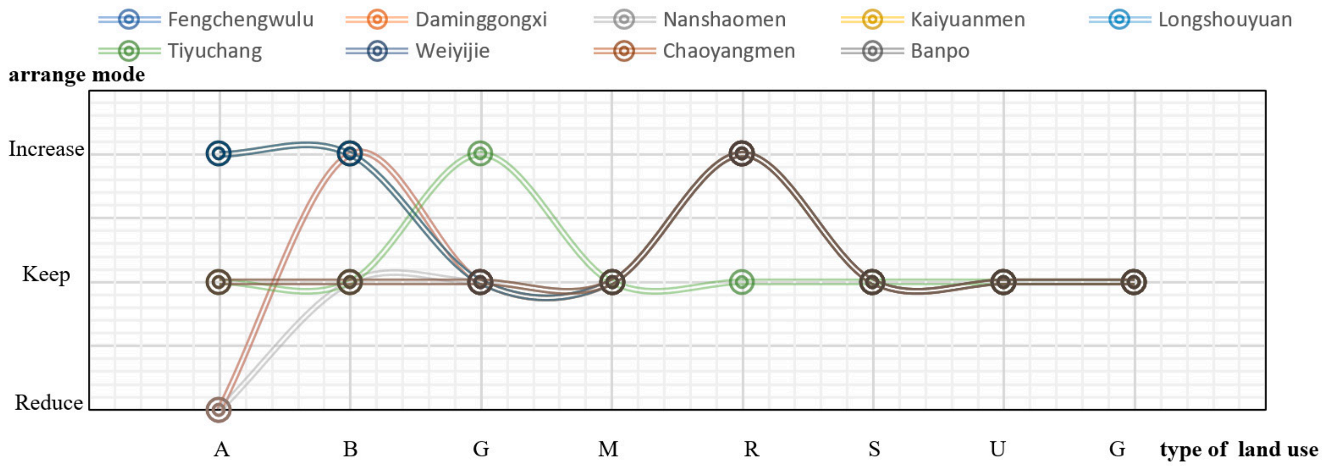


Figure 5. Areas with low development intensity; diagram of the optimization plan for the development intensity of each station.

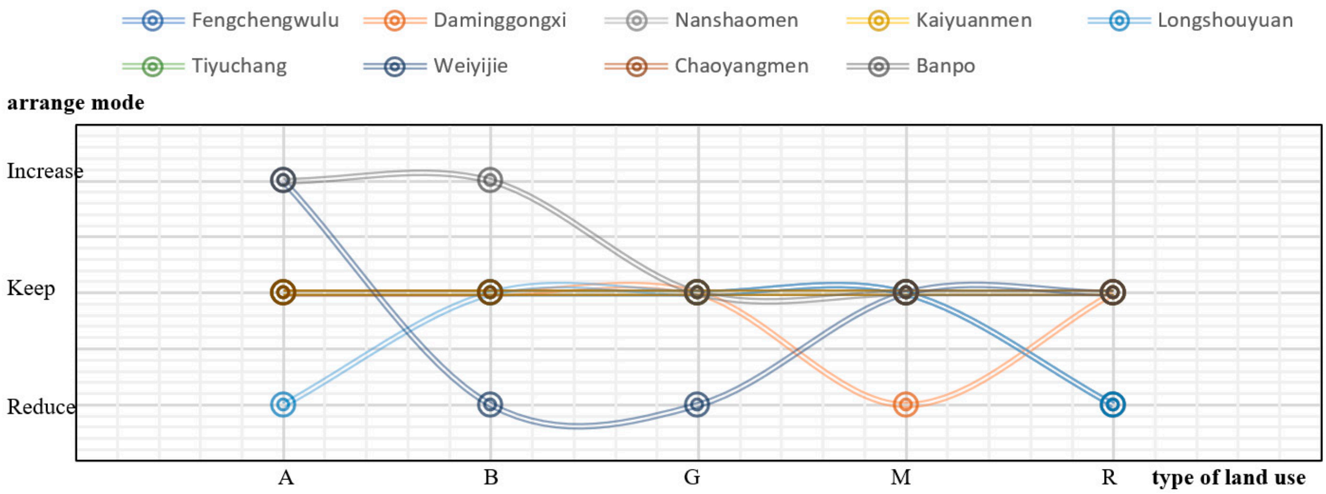


Figure 6. Areas with high development intensity; diagram of the optimization plan for the development intensity of each station.

(2) Optimization of land use properties

By comparing the status quo with the optimized development intensity, the land types that can be replaced by that of station land are proposed.

Third-class residential land dominated by urban villages or old residential areas is characterized by a high building density and incomplete basic service facilities. The environment is good, mainly low-rise residential land, and commercial facilities are arranged along the street. Each site covers such land and needs to be replaced optimally.

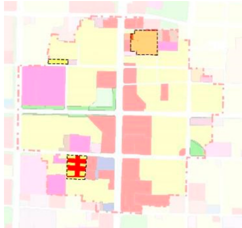
For commercial land in areas with low development intensity, such as old commercial areas with low building density, it is recommended to transform them into high-intensity commercial land by adjusting various indicators of land use in the station area until they meet the above optimized value range. Stations including Daminggongxi Station and Kaiyuanmen Station need to be optimized.

For mixed commercial and residential plots with high construction and development intensity, it is recommended to reduce the construction intensity and convert them into second-class residential land with higher environmental quality, reduce the amount of commercial land, and add a small amount of green land.

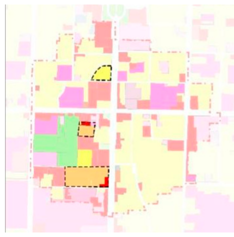
The results of the adjustment and optimization of the land use properties of each station area in this study are shown in Figure 7.

Before optimization

Daminggongxi, current land use.



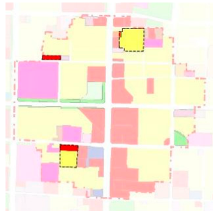
Fengchengwulu, current land use.



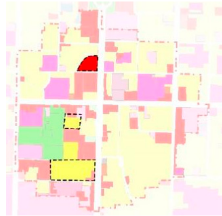
Nanshaomen, current land use.

After optimization

Daminggongxi, optimized land use.



Fengchengwulu, optimized land use.

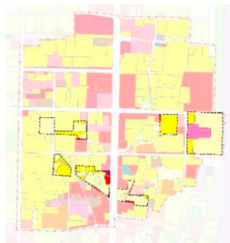


Nanshaomen, optimized land use.

Before optimization

Tiyuchang, current land use.

Weiyijie, current land use.

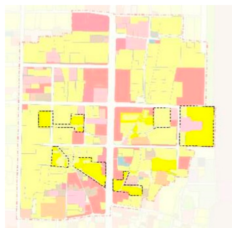


Longshouyuan, current land use.

After optimization

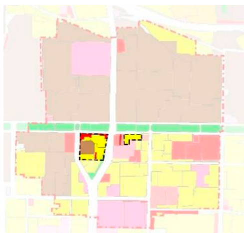
Tiyuchang, optimized land use.

Weiyijie, optimized land use.

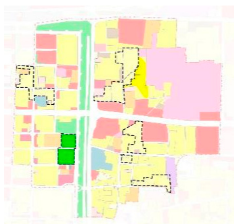


Longshouyuan, optimized land use.

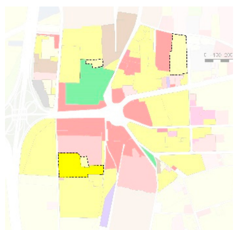
Before optimization



Kaiyuanmen, current land use.



Chaoyangmen, current land use.



Banpo, current land use.

Figure 7. *Cont.*

After optimization

Kaiyuanmen, optimized land use. Chaoyangmen, optimized land use. Banpo, optimized land use.

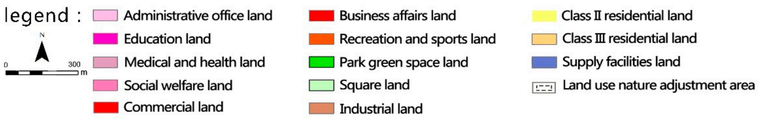


Figure 7. Optimization map of the land use for each station.

6. Conclusions

This study aimed to further understanding of the problem of unbalanced ridership into and out of metro stations caused by the single development of the station area. From the perspective of the two-way balance of ridership, thorough research of the relevant literature, and multi-source data analysis, the relationship model between land use and ridership into and out of the Xi'an metro station area is established. On this basis, optimization research was carried out, a land use optimization system under the guidance of a two-way balance of ridership was established, and specific optimization measures for land use in each station area are proposed. A scientific and effective station area land use optimization method system has been developed to provide a reliable reference for the optimization of urban metro station area land use. The main conclusions of "one model, two thresholds, and two schemes" are as follows.

A stepwise regression model between ridership and land use in Xi'an was constructed. Using IBM SPSS Statistics Version 28, a stepwise multiple linear regression model of inbound ridership, outbound ridership, and land use factors is established. The land use factors are summarized as the total land area, total building area, average plot ratio, average building density, building mix diversity, land use mix diversity, and a relationship between inbound and outbound ridership.

The optimal range of each factor of land use in the station area under the balance of inbound and outbound ridership was obtained by calculation. Based on the two-way balance orientation of ridership, the current ridership and the maximum ridership of the metro in the future were calculated to estimate the appropriate value of ridership into and out of the station. At the same time, a relational model was used to calculate the land use factors, and the optimal range of the intensity and mix diversity was obtained.

A land use optimization scheme has been proposed from the perspective of adjusting the development intensity and the nature of land use. On the one hand, from the perspective of development intensity optimization, by dividing the station area into areas with higher development intensity areas, suitable areas, and lower development intensity areas, the optimal value range of land use factors was obtained, and the optimization direction of the development intensity of various types of land is proposed. The optimized spatial morphology of the station domain has also been graphically expressed. On the other hand, from the perspective of land use property optimization, the land use property categories and adjustment schemes that need to be optimized are proposed.

It is a tedious and complicated task to explore the relationships between the ridership of metro stations and the factors of land use in station areas and so there are still some limitations in this research. For example, when analyzing the characteristics of ridership, the proportional expansion of some cellphone signaling data was used to reflect the proportional relationship of the relevant data for the whole population in Xi'an. Certain errors in this process need to be further investigated and corrected. In addition, this study did not consider station classification; the relationship between ridership and land function should be different for different types of stations. The next step is to study the land use optimization scheme for different types of stations, further expanding the content of the research object. In addition to the macro indicators discussed in this study, the built environment characteristics in the station area can be further analyzed and discussed, considering some micro-level indicators (connection facilities, street facilities, and environmental elements) as well. Secondly, the specific optimization measures proposed in this study for each station may have some personal subjectivity. In the future, various conditions, such as construction status, scientific research, daily operation management, and residents' demands could be more comprehensively analyzed and additional objective and effective optimization measures could be proposed.

Author Contributions: M.Z.: Conceptualization, Writing—original draft. H.T. and B.L.: Methodology, Formal analysis. Y.D.: Data curation, Visualization. Y.L.: Supervision, Project administration. J.W. and K.L.: Formal analysis, Data curation. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to ownership rights.

Conflicts of Interest: The authors declare no conflict of interest.

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