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Research on the Spatial Spillover Effect of Transportation Infrastructure on Urban Resilience in Three Major Urban Agglomerations in China

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Abstract: The development of transportation infrastructure can ensure the strong recovery and reconstruction function of a city, and it is an important way to build a resilient city. Studying the impact of the transportation infrastructure level on urban resilience is related to the future development of a city. Based on panel data for China's three major urban agglomerations from 2008 to 2019, this paper uses the spatial econometric model to explore the spatial spillover effect of transportation infrastructure on urban resilience. The results show that, due to its spillover effect, intra-regional transportation infrastructure promotes the urban resilience of cities around Beijing–Tianjin–Hebei and the Pearl River Delta, while it only promotes the urban resilience of local cities in the Yangtze River Delta. Inter-regional transportation infrastructure not only inhibits the local urban resilience of Beijing–Tianjin–Hebei but also reduces the urban resilience of surrounding cities. However, the impact on the Yangtze River Delta and the Pearl River Delta is not obvious. To promote the overall resilience level in three major urban agglomerations in China, this paper argues that it is urgently required to improve the quality of urban road traffic facilities and optimize the structure of intercity transportation to promote the development of transportation infrastructure and urban resilience. The implementation of several policies is recommended to efficiently improve the transportation infrastructure and urban resilience in these three major urban agglomerations in China.

Keywords: transportation infrastructure; sustainable transportation; urban resilience; spatial spillover effect; urban agglomeration

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1. Introduction

At present, China's urbanization process is advancing rapidly, and high-quality development is advancing steadily. However, urban development also faces multiple threats, such as frequent climate disasters, continuous economic crises, and serious public health incidents, making it difficult to stabilize the city's internal structure and aggravating the uncertainty surrounding urban development [1]. For example, the novel coronavirus (COVID-19) epidemic emerged at the beginning of 2020, which sounded the alarm in all countries around the world. It warned us that we must enhance cities' ability to resist public safety risks and enhance the resilience of cities in the context of new urbanization. Therefore, also considering the international and domestic situation, in March 2021, the "14th Five-year Plan" was deliberated and adopted by the National People's Congress of the People's Republic of China and the Chinese People's Political Consultative Conference. Its aim is to build a livable, innovative, intelligent, green, humanistic, and resilient city and to build a regional economic layout with high-quality development, thus highlighting that a resilient city has become a new requirement and goal in future urban development.

As an expression of the urban system's adaptability, recovery, and regeneration ability in response to various natural and man-made disasters, urban resilience emphasizes the joint participation and diversified cooperation of various stakeholders, such as residents, communities, enterprises, governments, and non-governmental institutions [2]. This capability is currently becoming a new topic in relevant subject areas, such as social risk management, resilient cities, and urban sustainable development.

The improvement in urban resilience involves many aspects required in the process of urbanization. Among them, urban infrastructure is the key factor for urban disaster response and post-disaster recovery [3]. Research on infrastructure and urban resilience has become one of the hot topics in urban risk planning [4]. As an important part of infrastructure, the development of transportation infrastructure not only plays a key role in the process of new urbanization [5] but also ensures the strong recovery and reconstruction function of a city from the perspective of safe urban development [6], which is an important way to build a resilient city. Therefore, in the national comprehensive three-dimensional transportation network plans outlined in February 2021, emphasis was placed on strengthening the infrastructure network layout, improving the connectivity and network resilience of China's comprehensive transportation network, and becoming a "transportation power." Based on the above, this paper explores the impact of transportation infrastructure on the development of urban resilience.

There is little literature on the relationship between transportation infrastructure and urban resilience, thus requiring greater further in-depth study. On the one hand, the existing research on the factors affecting urban resilience has focused on multi-dimensional perspectives, such as industrial structure [7], system construction [8], the ecological environment [9], and smart city construction [10]. However, as important infrastructure supporting economic and social operation and ensuring people's normal life, transportation facilities lack empirical analysis in the context of urban resilience construction. On the other hand, most of the literature has found that transportation infrastructure has a positive effect on economic development [11], industrial construction [12], enterprise productivity [13], and residents' employment [14]. However, due to the lag of investment in transportation infrastructure and the spatial spillover effect, there is a varying negative effect on economic growth [15], industrial output value [16], industrial agglomeration [17], and total factor productivity [18] in regions with different characteristics. In addition to the traditional transportation infrastructure elements (such as roads and intersections), there is also a series of new infrastructure (such as bike-sharing systems [19,20] and park-and-ride systems [21,22]) that promote the efficiency of urban transportation, thus, also enhancing the efficient operation of the overall urban system, but it is not known whether this can promote the construction of resilient cities. There is also little literature focusing on the impact mechanism of transportation infrastructure on urban resilience from the perspective of resilience construction, which is both of exploratory and practical significance.

Against this backdrop, based on panel data for China's three major urban agglomerations from 2008 to 2019, this article uses the improved entropy method to measure the urban resilience level of each city of China's three major urban agglomerations, introduces transportation infrastructure into research on urban resilience, and uses the spatial econometric model to explore the direct effect and spatial spillover effect of transportation infrastructure on the regional urban resilience of China's three major urban agglomerations.

The remainder of this article is structured as follows. Section 2 discusses the hypotheses development, the model specifications, variable selection, and data sources. Section 3 presents and discusses the empirical results. Finally, Section 4 presents the conclusions and policy implications.

2. Hypotheses Development, Material, and Methods

2.1. Hypotheses Development

On the spatial scale of urban agglomeration, transportation infrastructure is divided into urban individual units and intercity units, which can better distinguish the impact of the development of transportation construction, both within and between cities, on the resilience construction of the whole urban agglomeration [12]. Therefore, this paper divides transportation infrastructure into intra-regional transportation infrastructure and inter-regional transportation infrastructure, analyzes the impact on urban resilience, and puts forward research hypotheses.

Hypothesis 1 (H1). *The construction of transportation infrastructure in the area has a significant impact on the urban resilience of urban agglomerations, but the degree of impact is different in urban agglomerations with different transportation development characteristics.*

Urban internal traffic infrastructure is one of the basic conditions to ensure the daily operation of a city, which will produce economic, social, and environmental benefits and affect the sustainable development of the city [23]. However, improvements in the overall risk resistance system of the urban agglomeration needs to be matched with the regional traffic development of each city within the urban agglomeration for coordinated development. This enables a continuous urban agglomeration to be formed with the central city as the core, radiating and cooperating with the surrounding cities. If the urban road traffic network system is at a low level, improvements in traffic infrastructure will not only significantly enhance the efficient flow of various production factors in the city but will also effectively improve the risk response ability of the overall urban infrastructure. When the region is impacted by natural geological disasters or public health incidents, the multi-level infrastructure network formed by the superposition of the agglomeration effect and the diffusion effect of transportation infrastructure in urban agglomeration will have stronger resilience [24]. However, when the urban road traffic network system develops to a certain extent, with the expansion of the urban scale, the marginal roads in the suburbs will gradually change into trunk roads, and their functions will change, although their original form will not have changed, resulting in the insufficient capacity of traffic roads and increased pressure on the traffic network in urban hot spots. The contradiction between the supply of urban road traffic facilities and urban traffic demand is extremely prominent in this context, inevitably leading to serious road congestion and environmental degradation. It is difficult to give full play to the interconnectivity of the regional traffic system, which will hinder improvements in the overall resilience level of the city and is not conducive to maintaining the vitality of the urban safety system [25].

Hypothesis 2 (H2). *The construction of inter-regional transportation infrastructure has a negative (inhibitory) effect on the direct effect of the urban resilience of urban agglomerations, but its spatial spillover effect is different in urban agglomerations with different transportation development characteristics.*

The investment in and construction of inter-regional transportation infrastructure represented by highway transportation have always been important tools to promote economic and social development in China [26]. Today, with the rapid development of urbanization in China, ordinary citizens are moving to cities that seem to offer a better life and provide opportunities to find a better job, while rich people living in more developed cities are leaving their place of residence to seek peace, escape from the suburbs, and live in a better ecological environment. This change in mentality among the above groups promotes the planning and construction of transportation infrastructure because the inter-regional transportation infrastructure can indeed reduce transportation costs, save time costs, and promote interaction with surrounding cities [27]. However, compared with individual cities, urban agglomerations, as a form of spatial organization in the mature stage of urban development, have developed to a certain stage, and the traffic volume of passengers and freight is among the highest in the country. Due to the characteristics of public welfare and externality, however, the construction of inter-regional infrastructure at this stage is still dominated by government investment, and the investment cycle of infrastructure construction is one of long, excessive investment, slow renewal frequency, and lagging development, which is more prominent in urban agglomerations that have formed a basic highway network [28]. As a result, during holidays and social emergencies in recent years, the traffic and transportation conditions have been constrained by traffic flow, traffic capacity, and other constraints, resulting in serious congestion. Since the cities within the urban agglomeration are no longer isolated subjects, these external shocks can quickly pass through the network of the urban agglomeration, which can easily produce a chain effect and amplification effect [29]. This weakens the adjustment and recovery ability of urban agglomeration systems in dealing with risks, which hinders the resilience of urban infrastructure and the construction of overall urban resilience. In addition, inter-regional transportation infrastructure has typical externalities and network characteristics between cities. The development of local urban transportation infrastructure can improve the urban resilience of surrounding cities through the urban construction demonstration effect and the network effect [30], while the transfer of labor, capital, and other resources to core cities, on the contrary, exerts downward pressure on the resilience construction of surrounding underdeveloped cities [31].

2.2. Econometric Model

Before the application of spatial econometric analysis, the basic model of the urban resilience of the transportation infrastructure of three major urban agglomerations in China is constructed, as shown in Equation (1):

$$\begin{aligned} URRES_{it} = \alpha + \beta_1 INTRATRA_{it} + \beta_2 INTERTRA_{it} + \beta_3 INDSTR_{it} + \\ \beta_4 POPDEN_{it} + \beta_5 EMINC_{it} + \beta_6 FINAN_{it} + \beta_7 INNO_{it} + \varepsilon_{it} \end{aligned} \quad (1)$$

where: subscript i represents the regional city; subscript t indicates the time (year); $UrRes_{it}$ denotes the dependent variable, which represents the urban resilience level of the cities in region i in year t; $IntraTra_{it}$ and $InterTra_{it}$ indicate independent variables, representing the level of intra-regional transportation infrastructure and inter-regional transportation infrastructure of regional cities in year t, respectively; $IndStr_{it}$, $PopDen_{it}$, $EmInc_{it}$,$Finan_{it}$, and $Inno_{it}$ are the control variables, which, respectively, represent the industrial development structure, population density, urban employee income, financial development level, and regional innovation level of regional cities in year t; α denotes a constant term; and ϵ_{it} is a random error term.

2.3. Variable Design

2.3.1. Core Explanatory and Dependent Variables

The core explanatory variable in this paper is the level of transportation infrastructure. On the one hand, in China's transportation infrastructure, road transportation within the city occupies the prime position among all transportation modes, whether in terms of construction mileage or cumulative passenger and freight transportation, and the exchange of human and material resources among various regions of the urban agglomeration is mainly through the basic transportation mode of road transportation. On the other hand, it is difficult to obtain the mileage data for railways, waterways, and shipping at the prefecture level, and the three major urban agglomerations in China are located on a plain with relatively flat landforms. The road network and highway network can be used as a better standard to measure the level of transportation infrastructure. Considering the above two aspects, this paper mainly refers to the work of Demurger [32], Xie and Wang [12], and Jiang and Yin [33], among other scholars, and uses traffic density for measurement purposes. The level of intra-regional traffic infrastructure (*INTRATRA*) is measured by urban road density, i.e., the length of urban roads divided by the urban administrative area, while the road length per square kilometer of each city measures the level of intra-regional traffic infrastructure.

The dependent variable in this paper is the urban resilience level (*URRES*). The level of urban resilience is a composite evaluation measure involving many aspects. To accurately evaluate the urban resilience level of the three major urban agglomerations in China, this paper constructs the urban resilience level evaluation index system based on the actual development of the three major urban agglomerations and follows the principles of comprehensiveness, systematization, and operability. Based on the existing research of scholars, such as Chen and Xia [34], Zhang and Li [35], and Ma and Shen [36], from the perspective of ensuring the stability of the urban internal system, this paper specifically decomposes urban resilience into four primary indicators: urban economic resilience; urban social resilience; urban ecological resilience; and urban infrastructure resilience. Urban economic resilience is the basis and driving force for the regulation and control of urban economic construction. Urban social resilience measures the rational distribution of urban social resources and the intensity of effective information communication. Urban ecological resilience reflects the sustainable development degree of the urban ecosystem as a spatial service carrier. Finally, urban infrastructure resilience is an important factor to ensure the resilience of human and urban ecological systems. This paper also selects 20 secondary indicators to construct the urban resilience evaluation index system, as shown in Table 1. The 20 secondary indicators selected cover the main aspects of urban economy, urban society, urban ecology, and urban infrastructure, and the dimensions of urban development, represented by the four primary indicators, can be aggregated to form the urban internal system, which is recognized by most scholars [31–33]. Therefore, the 20 secondary indicators selected in this paper can be aggregated to represent overall urban resilience.

Table 1. Evaluation index system for the urban resilience level.

Target Layer	Criterion Layer	Index Layer	Index Unit and Nature	Index Meaning
Urban resilience	Urban economic resilience	GDP per capita	Yuan (+)	Economic strength per capita
		Amount of foreign capital actually used in the current year	Ten thousand U.S. dollars (+)	Status of foreign economic exchanges
		Local general public budget revenue	Ten thousand yuan (+)	Government financial strength
		Savings deposit balance of urban and rural residents	Ten thousand yuan (+)	Residents’ financial capital strength
		Number of industrial enterprises above designated size	Number (+)	Industrial development strength
		Total retail sales of social consumer goods	Ten thousand yuan (+)	Market activity
	Urban social resilience	Number of beds in hospitals and health centers	Number (+)	Medical assistance guarantees the capability
		Number of students in ordinary colleges and universities	Persons (+)	The popularization of risk education
		Social security index	% (+)	Social insurance protection capacity
		Urban registered unemployment rate	% (−)	Social stability

Table 1. *Cont.*

Target Layer	Criterion Layer	Index Layer	Index Unit and Nature	Index Meaning
	Urban ecological resilience	Park green area per capita	m^2 (+)	Environmental conservation status
		The green coverage rate of built-up area	% (+)	Urban greening status
		The comprehensive utilization rate of general industrial solid waste	% (+)	Waste utilization efficiency
		Centralized treatment rate of a sewage treatment plant	% (+)	Wastewater treatment efficiency
		Harmless treatment rate of domestic waste	% (+)	Environmental renovation efficiency
	Urban infrastructure resilience	Drainage pipeline density in the built-up area	km/km^2 (+)	Urban drainage status
		Annual electricity consumption	10,000 kWh (+)	City power supply status
		Gas penetration rate	% (+)	City gas supply status
		Number of Internet users	Ten thousand households (+)	The city's external liaison
		Number of buses per 10,000 people in municipal districts	Vehicle (+)	Urban evacuation capacity

Note: The "social security index" is the ratio of the total number of employees participating in basic pension insurance, basic medical insurance, and unemployment insurance to the permanent population [37].

In addition, this paper uses the entropy method within the objective weighting evaluation method to assign the index weight of urban resilience levels. To ensure that the results include the comparison between different years, referring to the practice of Yang and Sun [38], time variables are added to the entropy method.

2.3.2. Control Variables

To further improve the accuracy of the model, this paper selects industrial development structure (*INDSTR*), population density (*POPDEN*), urban employee income (*EMINC*), financial development level (*FINAN*), and regional innovation level (*INNO*) as control variables:

- Industrial development structure (*INDSTR*) has the characteristics of an automatic stabilizer. In the face of a fluctuating economic environment, it can self-repair the regional economic system through a diversified industrial environment and mechanism [7], using the secondary and tertiary industries to account for this. This variable is measured by the proportion of GDP.
- Population density (*POPDEN*) represents the effect of urban population agglomeration. Its growth can benefit the city itself through the expansion of the consumer market, but it will also adversely affect surrounding cities through resource outflow [31]. This variable is measured by permanent population density.
- Urban employee income (*EMINC*) can improve the living standards of urban residents, enhance the ability of social individuals to resist risks, and achieve high-quality urbanization [39]. This variable is measured by the average salary of on-the-job employees.
- Financial development level (*FINAN*) not only helps the rapid development of the real economy but also helps companies resist external shocks, which, in turn, drives the re-allocation of resources and industrial transformation and upgrading [40]. This variable is measured by the balance of various loans of financial institutions at the end of the year.

- Regional innovation level (*INNO*) is a major factor that affects the resilience of a city in many aspects. It can promote the development quality of surrounding cities through its regional diffusion and spatial spillover [41]. This variable is measured by the number of patent applications in each city.

To overcome the problems of collinearity and heteroscedasticity that may be caused by the model, the core explanatory variables and the above five control variables are processed in logarithm form.

2.4. Data Selection and Source

This article is based on the "Opinions on Establishing a More Effective New Mechanism for Regional Coordinated Development [41]", the "Outline of the Yangtze River Delta Regional Integration Development Plan", and the "Guiding Opinions on Deepening the Pan-Pearl River Delta Regional Cooperation". The planning scope of the large urban agglomeration includes 14 cities in the Beijing–Tianjin–Hebei urban agglomeration, encompassing Beijing, Tianjin, Hebei, and Anyang in Henan, the Yangtze River Delta urban agglomeration with 41 cities in the four provinces and the cities of Jiangsu, Zhejiang, Anhui, and Shanghai, and the Pearl River Delta urban agglomeration, which includes "Guang Fo Zhao" (Guangzhou, Foshan, Zhaoqing), "Shen Guan Hui" (Shenzhen, Dongguan, Huizhou), and "Zhu Zhong Jiang" (Zhuhai, Zhongshan, Jiangmen). The 2008–2019 panel data for "City" is the measurement unit. The original data for the sample come from the 2009–2020 China Urban Statistical Yearbook, the China Urban Construction Statistical Yearbook, the Statistical Yearbook of each city, and the National Economic and Social Development Statistical Bulletin. Individual missing data were filled in by interpolation. The descriptive statistics of the variables are shown in Table 2.

Table 2. Descriptive statistics.

Variable	Variable Description	Observations	Mean	Std Deviation	Minimum	Maximum
URRES	Urban resilience	768	0.3168	0.1190	0.1074	0.7592
INTRATRA	Intra-regional transportation infrastructure	768	2.6241	1.2221	−0.1482	6.4793
INTERTRA	Inter-regional transportation infrastructure	768	4.8122	0.3117	3.5940	5.4157
INDSTR	Industrial development structure	768	4.5111	0.0721	4.2400	4.6049
POPDEN	Population density	768	6.4447	0.7571	4.4663	8.8143
EMINC	Urban employee income	768	10.8528	0.4030	9.8720	12.0622
FINAN	Financial development level	768	17.0226	1.2612	14.0217	20.4198
INNO	Regional innovation level	768	9.0077	1.5807	4.3307	12.4742

2.4.1. Spatial Autocorrelation Test

Whether to add spatial effects based on Equation (1) depends on whether the dependent variables have spatial autocorrelation characteristics. Due to the proximity between regions, the emergence of certain economic phenomena may affect the economic activities of the neighboring spatial regions. If the regional spatial dependence between economic activities is ignored, the accuracy of the model parameter estimation may be affected [42], which makes it important to examine the spatial correlation between regions. Spatial autocorrelation is a spatial data analysis method that assesses whether a series of data has spatial dependence on spatial units, reflecting the degree of spatial agglomeration of the subject under a certain index. The specific steps are as follows.

(1) Selection of the spatial weight matrix

The construction of the spatial weight matrix is an important prerequisite for investigating the regional spatial correlation. The spatial weight matrix can reflect spatial dependence and spatial interaction. The commonly used spatial weight matrix has three types: spatial adjacency weight matrix; geographic distance weight matrix; and economic distance weight matrix. Taking into account the characteristics of transportation infrastructure and urban resilience, the impact of transportation construction and urban resilience activity diffusion is only weakly related to spatial proximity. Areas with similar transportation infrastructure levels and urban resilience development levels are closer to each other. Mutual economic exchanges are more frequent, and spatial correlations are more likely to be formed. Therefore, this paper uses the reciprocal of the intercity administrative center distance multiplied by the reciprocal of the actual intercity GDP average difference as the "economic geographic distance" between regions to construct the spatial weight matrix. The economic geographical distance weight matrix contains both geographical and economic factors. It is assumed that the spatial interaction is determined by the distance between the locations of the regional administrative centers of the units and the closeness of economic activities between the two places. The closer the distance, the greater the weight assigned, which considers the actual impact environment of relevant indicators [43]. The specific calculation formula for the economic geographic distance weight matrix W_{ij} is:

$$W_{ij} = \begin{cases} \frac{1}{d_{ij}} \times \frac{1}{|\overline{Y_i} - \overline{Y_j}|} & (i \neq j) \\ 0 & (i = j) \end{cases} \quad (2)$$

where: d_{ij} represents the distance between the two points of the regional administrative center of unit i and unit j; and Y_i and Y_j are the average values of the real GDP per capita of the i-th unit and the j-th unit, respectively. Accordingly:

$$\overline{Y_i} = \frac{1}{t_1 - t_0 + 1} \sum_{t_0}^{t_1} Y_{it} \quad (3)$$

where Y_{it} is the real GDP per capita of the i-th unit in year t.

(2) Calculation of global Moran's I statistics

This paper uses the global Moran's I statistic to test the spatial autocorrelation degree of the urban resilience index for the three major urban agglomerations in China. The specific formula is as follows:

$$I = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij}(X_i - \overline{X})(X_j - \overline{X})}{s^2 \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij}} \quad (4)$$

where: n is the total number of units studied; w_{ij} is the value of the elements in the i-th row and j-th column of the spatial weight matrix W; X_i and X_j are the index values of the i-th unit and the j-th unit; X is the average value of the index; and s^2 is the variance of the index, which is:

$$\overline{X} = \frac{1}{n} \sum_{i=1}^{n} X_i,\ s^2 = \frac{1}{n} \sum_{i=1}^{n} (X_i - \overline{X}) \quad (5)$$

The range of Moran's I index is [–1, 1]. If $I \in [-1, 0]$, this indicates that the index has a negative spatial correlation; if $I \in [0, 1]$, this indicates that the index has a positive spatial correlation; if $I = 0$, this indicates that the index has no spatial autocorrelation, i.e., spatial random distribution.

The significance of the spatial correlation coefficient is tested by the standardized Z-statistic, and the expression is:

$$Z = \frac{I - E(I)}{\sqrt{VAR(I)}} \quad (6)$$

where: $E(I)$ is the expected value of Moran's I; and $VAR(I)$ is the variance of Moran's I.

2.4.2. Spatial Panel Model Setting

The general form of the spatial panel model uses the following three models, and the established expressions are as follows:

(1) Spatial lag model (SLM):

$$\begin{aligned} URRES_{it} &= \alpha\iota + \rho WURRES_{it} + \beta_1 INTRATRA_{it} + \beta_2 INTERTRA_{it} + \beta_3 INDSTR_{it} \\ &+\beta_4 POPDEN_{it} + \beta_5 EMINC_{it} + \beta_6 FINAN_{it} + \beta_7 INNO_{it} + \mu_n + \nu_t + \varepsilon_{it} \end{aligned} \tag{7}$$

(2) Spatial error model (SEM):

$$\begin{aligned} URRES_{it} &= \alpha\iota + \beta_1 INTRATRA_{it} + \beta_2 INTERTRA_{it} + \beta_3 INDSTR_{it} \\ &+\beta_4 POPDEN_{it} + \beta_5 EMINC_{it} + \beta_6 FINAN_{it} + \beta_7 INNO_{it} + \mu_n + \nu_t + \varphi_{it} \end{aligned} \tag{8}$$

$$\varphi_{it} = \lambda W \varphi_{it} + \varepsilon_{it}$$

(3) Spatial Durbin model (SDM):

$$\begin{aligned} URRES_{it} &= \alpha\iota + \rho WURRES_{it} + \beta_1 INTRATRA_{it} + \beta_2 INTERTRA_{it} + \beta_3 INDSTR_{it} \\ &+\beta_4 POPDEN_{it} + \beta_5 EMINC_{it} + \beta_6 FINAN_{it} + \beta_7 INNO_{it} + \theta_1 W \times INTRATRA_{it} \\ &+\theta_2 W \times INTERTRA_{it} + \theta_3 W \times INDSTR_{it} + \theta_4 W \times POPDEN_{it} + \theta_5 W \times EMINC_{it} \\ &+\theta_6 W \times FINAN_{it} + \theta_7 W \times INNO_{it} + \mu_n + \nu_t + \varepsilon_{it} \end{aligned} \tag{9}$$

where: ι is the unit column vector of order $n \times 1$; W is the $n_t \times n_t$ spatial weight matrix, which is composed of t $n \times n$ block matrix spatial weight matrices W_{ij}; μ_n is an $n \times 1$ dimension individual fixed effect column vector; ν_t is a $t \times 1$ dimension time fixed effect column vector; φ_{it} is an independent identically distributed disturbance term with a mean value of 0 and a variance of σ^2; and ρ, α, β, θ, and λ are the parameters that the model needs to estimate.

Regarding the choice of SLM, SEM, or SDM in the spatial panel model, Elhorst [44] proposed that the Lagrange multiplier (LM) test and robust LM test should be performed in the absence of spatial effects to select a suitable spatial panel model. Anselin et al. [45] proposed the following criteria: if it is found that the LM (lag) is statistically more significant than the LM (error), and the robust LM (lag) is significant but the robust LM (error) is not significant, then SLM can be selected as the appropriate spatial econometric model. If the LM (error) is statistically more significant than the LM (lag), and the robust LM (error) is significant but the robust LM (lag) is not significant, then choose SEM as the appropriate spatial econometric model. If it appears that both the LM (lag) and the LM (error) pass the test at the specified significance level, SDM is temporarily selected as the predetermined spatial econometric model, and then SDM is performed separately according to the likelihood ratio (LR) test and compared with SLM, SDM, and SEM to determine the preliminary spatial econometric model.

Similar to general panel models, spatial panel models also include fixed effects models and random effect models. Regarding the choice of a fixed effects model or random effects model, Baltagi [46] provided a Hausman test that can be used to test the random effects versus fixed effects for the preliminarily determined spatial econometric model. If the null hypothesis is rejected, then we tend to accept the fixed effects model instead of the random effects model. If the fixed effects model is selected, the final spatial econometric model is determined by considering the individual fixed effects, time fixed effects, and individual time double fixed effects based on the LR test, respectively.

3. Results and Discussion

3.1. Results of the Spatial Autocorrelation Test

Table 3 shows the global Moran's I index for China's three major urban agglomerations in each year from 2008 to 2019. According to the test results, the global Moran's I index for the urban resilience level in each year is greater than 0, in which the corresponding normality Z-statistics for the Beijing–Tianjin–Hebei urban agglomeration and the Yangtze River Delta urban agglomeration pass the significance test at the 1% level, and the Pearl River Delta urban agglomeration passes the significance test at the 5% or 10% level in most years. It can be seen that the three urban agglomerations strongly reject the original assumption that there is no spatial autocorrelation in the level of urban resilience, showing instead that there is strong positive spatial autocorrelation.

Table 3. Moran's *I* index for the urban resilience of three major urban agglomerations in China from 2008 to 2019.

Year	Beijing–Tianjin–Hebei Urban Agglomeration	Yangtze River Delta Urban Agglomeration	Pearl River Delta Urban Agglomeration
2008	0.445 ***	0.604 ***	0.197 **
2009	0.459 ***	0.602 ***	0.159 *
2010	0.430 ***	0.551 ***	0.117
2011	0.444 ***	0.573 ***	0.160 *
2012	0.447 ***	0.576 ***	0.154 *
2013	0.444 ***	0.566 ***	0.195 **
2014	0.492 ***	0.549 ***	0.161*
2015	0.477 ***	0.545 ***	0.157 *
2016	0.420 ***	0.586 ***	0.144 *
2017	0.348 ***	0.539 ***	0.136 *
2018	0.316 ***	0.520 ***	0.185 *
2019	0.347 ***	0.531 ***	0.132

Note: ***, **, and * represent significance at the 1%, 5%, and 10% level, respectively.

3.2. Results and Analysis of Spatial Regression Model

According to the above spatial autocorrelation test, it is necessary to add spatial effects to Equation (1) for analysis. Using Stata 15.0 software, panel econometric estimation is carried out under the spatial interaction effect. As shown in Tables 4–6, SLM, SEM, and SDM models are constructed using the maximum likelihood method (MLE) to regress the three spatial models of three major urban agglomerations in China.

Table 4. Estimation and test results of three spatial econometric models for the Beijing–Tianjin–Hebei urban agglomeration.

Variable	SLM	SEM	SDM
INTRATRA	0.004 (0.24)	−0.002 (−0.11)	0.004 (0.19)
INTERTRA	−0.054 * (−1.75)	−0.027 * (−1.82)	−0.049 *** (−3.43)
INDSTR	0.389 ** (2.28)	0.245 (1.60)	0.336 ** (2.29)
POPDEN	0.077 (1.51)	0.083 *** (2.60)	0.109 *** (4.77)
EMINC	−0.054 (−1.37)	0.013 (0.32)	−0.018 (−0.50)
FINAN	0.008 (0.57)	−0.005 (−0.31)	−0.016 (−1.05)
INNO	0.027 ** (2.28)	0.037 ** (2.56)	0.038 *** (2.76)
Constant term	−1.455** (−2.02)	— —	— —
Observations	168	168	168
Log L	372.909	442.396	453.218
R^2	0.744	0.697	0.755
Individual fixed effect	Not controlled	Controlled	Controlled

Table 4. *Cont.*

Variable	SLM	SEM	SDM
Time fixed effect	Not controlled	Controlled	Controlled
Moran's *I* (error)		11.099 ***	
LM test (error)		97.849 ***	
Robust LM test (error)		20.746 ***	
LM test (lag)		98.632 ***	
Robust LM test (lag)		21.528 ***	
Hausman test (fixed versus random effects)	7.420	19.480 **	8.70×10^9 ***
LR test (individual fixed effect)	—	53.830 ***	24.650 *
LR test (time fixed effect)	—	208.610 ***	100.170 ***
LR test (SDM versus SLM)		21.640 ***	
LR test (SDM versus SEM)		160.620***	

Notes: () represents the statistical value of the *t*-test, calculated using robust standard error; ***, **, and * represent significance at the 1%, 5%, and 10% level, respectively.

Table 5. Estimation and test results of three spatial econometric models for the Yangtze River Delta urban agglomeration.

Variable	SLM	SEM	SDM
INTRATRA	0.012 (1.28)	0.012 (1.28)	0.013 *** (3.11)
INTERTRA	−0.003 (−0.19)	−0.003 (−0.20)	−0.006 (-0.56)
INDSTR	0.192 ** (2.09)	0.194 ** (2.10)	0.157 ** (2.47)
POPDEN	−0.046 *** (−3.12)	−0.046 *** (−3.16)	−0.032 *** (−2.58)
EMINC	0.005 (0.28)	0.004 (0.26)	0.008 (0.57)
FINAN	−0.003 (−0.43)	−0.003 (−0.41)	−0.006 (−1.09)
INNO	0.009 ** (2.31)	0.010 ** (2.31)	0.007 ** (2.47)
Observations	492	492	492
Log L	1358.320	1358.264	1365.883
R^2	0.093	0.096	0.319
Individual fixed effect	Controlled	Controlled	Controlled
Time fixed effect	Controlled	Controlled	Controlled
Moran's *I* (error)		11.677 ***	
LM test (error)		124.895 ***	
Robust LM test (error)		41.514 ***	
LM test (lag)		96.606 ***	
Robust LM test (lag)		13.224 ***	
Hausman test (fixed versus random effects)	15.500 *	19.540 **	35.580 ***
LR test (individual fixed effect)	120.500 ***	129.100 ***	111.260 ***
LR test (time fixed effect)	1005.010 ***	1004.750 ***	915.840 ***
LR test (SDM versus SLM)		15.130 **	
LR test (SDM versus SEM)		15.240 **	

Notes: () represents the statistical value of the *t*-test, calculated using robust standard error; ***, **, and * represent significance at the 1%, 5%, and 10% level, respectively.

Table 6. Estimation and test results of three spatial econometric models for the Pearl River Delta urban agglomeration.

Variable	SLM	SEM	SDM
INTRATRA	−0.018 * (−1.90)	−0.020 * (−1.87)	−0.026 ** (−2.14)
INTERTRA	−0.007 (−0.24)	−0.008 (−0.26)	−0.018 (−1.03)
INDSTR	−0.198 (−1.63)	−0.214 (−1.46)	−0.501 * (−1.75)
POPDEN	−0.074 (−0.94)	−0.085 (−1.06)	−0.150 * (−1.71)
EMINC	0.011 (0.29)	0.016 (0.41)	0.025 (1.02)
FINAN	0.002 (0.06)	0.001 (0.04)	0.012 (0.53)
INNO	0.027 ** (2.56)	0.028 *** (2.69)	0.032 *** (3.08)
Observations	108	108	108
Log L	291.069	291.433	293.526
R^2	0.410	0.439	0.362
Individual fixed effect	Controlled	Controlled	Controlled
Time fixed effect	Controlled	Controlled	Controlled
Moran's *I* (error)		6.092 ***	
LM test (error)		22.198 ***	
Robust LM test (error)		2.269	
LM test (lag)		44.833 ***	
Robust LM test (lag)		24.905 ***	
Hausman test (fixed versus random effects)	235.070 ***	31.330**	—
LR test (individual fixed effect)	22.320***	23.250 ***	24.050 *
LR test (time fixed effect)	73.150 ***	58.920 ***	49.640 ***
LR test (SDM versus SLM)		4.910	
LR test (SDM versus SEM)		4.190	

Notes: () represents the statistical value of the *t*-test, calculated using robust standard error; ***, **, and * represent significance at the 1%, 5%, and 10% level, respectively.

The LM test and the robust LM test for the Beijing–Tianjin–Hebei urban agglomeration and the Yangtze River Delta urban agglomeration are significant at the level of 1%, indicating that a spatial econometric model should be established, and SDM should be initially determined as the ideal model. The subsequent LR test and Hausman test show that the fitting degree of the SDM model is better under individual time double fixed effects. Finally, the LR test for SLM, SEM, and SDM shows that it is significant at the level of 1%. SDM is, thus, rejected and returns to SLM or SEM, indicating that SDM does not need to be simplified to SLM or SEM, and SDM is further determined as the ideal model.

The robust LM test for the Pearl River Delta urban agglomeration is not significant in the SEM model but it passes the significance level of 1% in SLM, indicating that a spatial econometric model should be established, and SLM should be tentatively determined as an ideal model. The subsequent LR test and Hausman test show that the fitting degree of the SLM model is better under individual time double fixed effects. Finally, the LR test for SLM, SEM, and SDM reveals that they do not pass the significance level of 10%, and the assumption that SDM returns to SLM or SEM cannot be rejected, indicating that SDM should be simplified to SLM or SEM. Through comprehensive judgment, SLM is, therefore, determined as the ideal model.

Accordingly, the spatial Durbin model with individual time double fixed effects is adopted in the Beijing–Tianjin–Hebei urban agglomeration and the Yangtze River Delta urban agglomeration, and the spatial lag model with individual time double fixed effects is adopted in the Pearl River Delta urban agglomeration for parameter estimation.

Considering the spatial spillover effect, the regression coefficient of each variable parameter cannot simply reflect the degree of influence of the independent variables on the dependent variables. Therefore, following Lesage and Pace [47], the total effect affecting urban resilience is decomposed into a direct effect and an indirect effect by using the partial differential method. Specifically, the direct effect represents the influence of the explanatory variables in the region on the dependent variable in the region, the indirect effect represents the influence of the explanatory variable in the neighboring region on the dependent variable in the region, i.e., spatial spillover effect, and the total effect is the sum of the direct effect and indirect effect. Tables 7–9 list the direct effect, indirect effect, and total effect of each explanatory variable in the SDM model with individual time double fixed effects and some indicators to judge the goodness of fit of the regression results.

Table 7. The three effect results for each variable in the SDM model with individual time double fixed effects in the Beijing–Tianjin–Hebei urban agglomeration.

Variable	Direct Effect	Indirect Effect	Total Effect
INTRATRA	−0.009 (−0.31)	0.083 * (1.91)	0.074 (1.49)
INTERTRA	−0.037 ** (−2.27)	−0.094 ** (−2.06)	−0.131 *** (−3.33)
INDSTR	0.253 * (1.80)	0.705 * (1.96)	0.958 *** (2.67)
POPDEN	0.098 *** (3.69)	0.081 (1.01)	0.179 ** (2.39)
EMINC	0.007 (0.19)	−0.188 *** (−2.65)	−0.181 *** (−3.32)
FINAN	−0.014 (−1.08)	−0.005 (−0.10)	−0.019 (−0.35)
INNO	0.037 * (1.90)	0.004 (0.20)	0.041 (1.48)
Observations		168	
Log L		453.218	
R^2		0.755	

Notes: () represents the statistical value of the *t*-test, calculated using robust standard error; ***, **, and * represent significance at the 1%, 5%, and 10% level, respectively.

Table 8. The three effect results for each variable in the SDM model with individual time double fixed effects in the Yangtze River Delta urban agglomeration.

Variable	Direct Effect	Indirect Effect	Total Effect
INTRATRA	0.013 *** (3.19)	−0.010 (−0.92)	0.003 (0.25)
INTERTRA	−0.006 (−0.51)	−0.004 (−0.16)	−0.010 (−0.35)
INDSTR	0.164 *** (2.67)	−0.070 (-0.54)	0.094 (0.78)
POPDEN	−0.032 *** (−2.69)	0.003 (0.10)	−0.029 (−0.99)
EMINC	0.008 (0.60)	−0.039 (−1.11)	−0.031 (−0.84)
FINAN	−0.006 (−1.12)	0.015 (0.91)	0.009 (0.54)
INNO	0.007 ** (2.32)	0.016 *** (2.89)	0.022 *** (4.20)
Observations		492	
Log L		1365.883	
R^2		0.319	

Notes: () represents the statistical value of the *t*-test, calculated using robust standard error; *** and ** represent significance at the 1% and 5% level, respectively.

Table 9. The three effect results for each variable in the SDM model with individual time double fixed effects in the Pearl River Delta urban agglomeration.

Variable	Direct Effect	Indirect Effect	Total Effect
INTRATRA	−0.019 ** (−2.00)	0.005 * (1.80)	−0.014 ** (−1.99)
INTERTRA	−0.006 (-0.20)	0.003 (0.31)	−0.003 (-0.16)
INDSTR	−0.196 (−1.58)	0.054 (1.49)	−0.142 (−1.57)
POPDEN	−0.080 (−1.05)	0.023 (1.01)	−0.058 (−1.04)
EMINC	0.009 (0.26)	−0.004 (−0.35)	0.006 (0.22)
FINAN	0.005 (0.16)	−0.001 (−0.01)	0.005 (0.22)
INNO	0.027 ** (2.44)	−0.008 * (−1.93)	0.019 *** (2.58)
Observations		108	
Log L		291.069	
R^2		0.410	

Notes: () represents the statistical value of the *t*-test, calculated using robust standard error; ***, **, and * represent significance at the 1%, 5%, and 10% level, respectively.

It can be found from Tables 7–9 that, in terms of core explanatory variables, the indirect effect of intra-regional traffic infrastructure on the urban resilience of the Beijing–Tianjin–Hebei urban agglomeration is significantly positive, passing the significance test at the 10% level, but the significance of the direct effect and the total effect is not strong. The direct effect on the urban resilience of the Yangtze River Delta urban agglomeration is significantly positive, passing the significance test at the 1% level, but the significance of the indirect effect and the total effect is weak. The direct effect and total effect on the urban resilience of the Pearl River Delta urban agglomeration are significantly negative, passing the significance test at the 5% level, and the indirect effect is significantly positive, passing the significance test at the 10% level. This shows that, while developing the local internal traffic construction, the internal cities of Beijing, Tianjin, and Hebei can also promote improvements in the resilience level of cities in adjacent areas; in particular, the traffic construction level and resilience management level of cities around Beijing and Tianjin have been strengthened under the vigorous development of Beijing and Tianjin. Compared with Beijing–Tianjin–Hebei and the Pearl River Delta, the Yangtze River delta accounts for the majority of cities with a low degree of internal traffic development, which is mostly in the initial development stage. As a result, the development of intra-regional traffic infrastructure can quickly improve the urban resilience of local cities. There are few cities in the Pearl River Delta and, in recent years, road development in these cities has led to increased pressure on the traffic network, resulting in serious traffic congestion and forming a "congestion effect." Although the internal traffic construction of neighboring cities can alleviate the traffic of local cities and promote improvements in local resilience, the huge impact caused by the degree of congestion is still not conducive to the resilience construction of local cities. The above validates H1.

The direct effect, indirect effect, and total effect of inter-regional transportation infrastructure on the urban resilience of the Beijing–Tianjin–Hebei urban agglomeration are significantly negative, passing the significance test at the 5% and 1% levels. However, for the Yangtze River Delta urban agglomeration and the Pearl River Delta urban agglomeration, the three effects of inter-regional transportation infrastructure on urban resilience are less significant, the symbols of the regression coefficients are mostly negative, and only the indirect effects for the Pearl River Delta are positive. This shows that, although the development of highway transportation can reduce the cost of factor transportation and promote the interconnection of urban transportation networks, for the interior of urban agglomerations, it also brings high land prices, high labor costs, and crowded urban transportation to economically developed cities and surrounding cities, which will cause additional costs for urban resilience construction activities. Increasing the pressure on urban carrying capacity and adjustment and recovery capacity in the face of risks is not conducive to the resilience construction of local and neighboring cities, resulting in a decline in the overall resilience level of the city. This shows that the highway transportation construction has exceeded the needs of the economic development of the local urban agglomeration at this stage, and there are problems, such as excessive investment in the industry and the structure of the transportation system, which have a significant impact on the sample of the Beijing–Tianjin–Hebei urban agglomeration. The above verifies H2.

In terms of control variables, the direct, indirect, and total effects of the industrial development structure on the urban resilience of the Beijing–Tianjin–Hebei urban agglomeration are significantly positive, passing the significance test at the 10% and 1% levels. The direct effect on the urban resilience of the Yangtze River Delta urban agglomeration is significantly positive, passing the significance test at the 1% level, but the significance of the indirect effect and the total effect is weak. The results of the three effects on the urban resilience of the Pearl River Delta urban agglomeration are not significant. This shows that, if the industrial structure of the urban agglomeration is continuously optimized, transformed, and upgraded, this can give better play to its competitive advantages, optimize the resource allocation within and between industries, and form the optimal production scale effect. This not only improves the resilience of local cities but also promotes the development of resilience construction in neighboring cities and enhances the urban economic and industrial resilience, which is more significant in the Beijing–Tianjin–Hebei urban agglomeration.

The direct and total effects of population density on the urban resilience of the Beijing–Tianjin–Hebei urban agglomeration are significantly positive, passing the significance tests at the 1% and 5% levels, but the significance level of the indirect effect is weak. The direct effect on the urban resilience of the Yangtze River Delta urban agglomeration is significantly negative, passing the significance test at the 1% level, but the significance of the indirect effect and the total effect is not strong. The three effect results for the urban resilience of the Pearl River Delta urban agglomeration failed to pass the 10% significance test. The possible reason is that, in the face of urban agglomerations with different degrees of development, the population density needs to be within a certain reasonable range to be conducive to urban construction and management. The data comparison shows that the population density of Beijing, Tianjin, and Hebei is low, while the population density of the Yangtze River Delta and the Pearl River Delta is relatively high. The population density growth of the Beijing–Tianjin–Hebei urban agglomeration is conducive to pooling market factors, expanding local market potential and enhancing urban economic resilience. The high population density in the Yangtze River Delta and the Pearl River Delta will lead to the growth of resource demand and tension in energy supply. In the face of sudden social events, this will entail some risks in maintaining the operation of the social system and lead to a decline in urban resilience.

The indirect and total effects of urban employee income on the urban resilience of the Beijing–Tianjin–Hebei urban agglomeration are significantly negative, passing the significance test at the 1% level, but the positive significance level of the direct effect is not high. However, for the Yangtze River Delta urban agglomeration and the Pearl River Delta urban agglomeration, the three effects of urban employee income on urban resilience are less significant, the direct effect is positive (promotion) and the indirect effect is negative (inhibition). This shows that the growth of the local labor income level within the urban agglomeration has a limited effect on improving the resilience level of local cities but will inhibit the resilience level of adjacent cities. This is due to the population siphon effect of large- and medium-sized cities, especially in the Beijing–Tianjin–Hebei urban agglomeration. Giving the labor population a high wage income that differs from small cities leads to concentration in developed areas, resulting in the lack of personnel corresponding to urban safety risk management in adjacent cities, which has a certain negative impact on urban resilience.

The regression results for the three effects of the financial development level on the three major urban agglomerations in China do not pass the 10% significance test. This shows that, although the development scale and efficiency of the financial-related industries in the three urban agglomerations are in the leading position in the country, their role in gathering social idle funds and regulating macroeconomic leverage has not significantly promoted improvements in resilience in urban management and construction.

The direct effect of the regional innovation level on the urban resilience of Beijing–Tianjin–Hebei urban agglomeration is significantly positive, passing the significance test at the 10% level, but the positive significance level of the indirect effect and the total effect is not strong. For the Yangtze River Delta urban agglomeration and the Pearl River Delta urban agglomeration, most of the regression results for the three effects of regional innovation level on urban resilience have strong positive significance, with most passing the significance test at the 5% level. However, the indirect effect of the Pearl River Delta urban agglomeration on urban resilience is negative and significant, passing the significance test at the 10% level. This shows that improvements in the innovation level can promote the flow of innovation elements, enhance the economic vitality of an innovative society, and enhance the economic resilience of local cities. However, the scientific research level of most cities in the Beijing–Tianjin–Hebei urban agglomeration is far lower than that of Beijing and Tianjin, and the technological progress of Beijing and Tianjin has a weak effect on the resilience of surrounding cities. Moreover, in the Pearl River Delta urban agglomeration, most of the innovative factor resources are concentrated in Guangzhou and Shenzhen. The strong factor siphon effect harms the resilience management of surrounding cities and hinders improvements in the resilience of adjacent cities.

3.3. Robustness Test

To further test the robustness of the above spatial regression results, this paper, on the one hand, replaces the spatial weight matrix in the spatial econometric model with the economic distance weight matrix to test whether there is still a significant spatial spillover effect between transportation infrastructure and urban resilience under different weight matrices; on the other hand, by excluding control variables, specifically by excluding the weak significance level of the financial development level (*FINAN*) from the previous results, the spatial regression model is constructed again to test the model's resilience.

The economic distance weight matrix is constructed by using the reciprocal of the difference in the average real per capita GDP between cities as the "economic distance" between regions. The economic distance weight matrix W_{ij} is calculated by the following formula:

$$W_{ij} = \begin{cases} \frac{1}{\left|\overline{Y_i} - \overline{Y_j}\right|} & (i \neq j) \\ 0 & (i = j) \end{cases} \tag{10}$$

where $\overline{Y_i}$ and $\overline{Y_j}$ are the average values of real GDP per capita over the years for the i-th unit and the j-th unit, respectively.

Tables 10–12 report the economic distance matrix and the robustness test results after excluding the financial development level. It can be seen that, compared with the regression results of the original model, the direct, indirect, and total effects of the core explanatory variables and control variables on urban resilience have not changed significantly, and their significance level is relatively stable. This shows that the above spatial regression results are sufficiently robust.

Table 10. Robustness test results for the three effects in the Beijing–Tianjin–Hebei urban agglomeration.

Variable	Economic Distance Matrix			Eliminating the Control Variable *FINAN*		
	Direct Effect	**Indirect Effect**	**Total Effect**	**Direct Effect**	**Indirect Effect**	**Total Effect**
INTRATRA	−0.012 (−0.83)	0.091 * (1.73)	0.079 (1.31)	−0.008 (−0.59)	0.076 * (1.89)	0.068 (1.49)
INTERTRA	−0.025 ** (−2.16)	−0.197 *** (−2.93)	−0.222 *** (−3.52)	−0.038 ** (−2.39)	−0.092 ** (−2.40)	−0.130 *** (−3.80)
INDSTR	0.374 ** (2.13)	0.958 ** (2.34)	1.332 ** (2.52)	0.214 (1.57)	0.708 ** (2.12)	0.922 *** (2.82)
POPDEN	0.097 *** (5.05)	0.086 (0.93)	0.183 ** (2.03)	0.106 *** (3.94)	0.085 (0.95)	0.191 ** (2.24)
EMINC	0.002 (0.06)	−0.328 *** (−3.14)	−0.326 *** (−3.36)	0.001 (0.01)	−0.183 *** (−2.77)	−0.183 *** (−3.43)
FINAN	−0.018 (−0.95)	−0.011 (−0.21)	−0.029 (−0.47)	—	—	—
INNO	0.033 (1.19)	0.028 (0.92)	0.060 (1.61)	0.035 *** (3.03)	0.006 (0.38)	0.041 ** (2.24)
Observations		168			168	
Log L		451.939			452.686	
R^2		0.658			0.791	

Notes: () represents the statistical value of the *t*-test, calculated using robust standard error; ***, **, and * represent significance at the 1%, 5%, and 10% level, respectively.

Table 11. Robustness test results for the three effects in the Yangtze River Delta urban agglomeration.

Variable	Economic Distance Matrix			Eliminating the Control Variable *FINAN*		
	Direct Effect	**Indirect Effect**	**Total Effect**	**Direct Effect**	**Indirect Effect**	**Total Effect**
INTRATRA	0.012 *** (2.98)	−0.007 (−0.53)	0.005 (0.39)	0.014 *** (3.15)	−0.010 (−0.81)	0.004 (0.30)
INTERTRA	−0.005 (−0.40)	−0.026 (−1.01)	−0.031 (−1.03)	−0.006 (−0.51)	0.002 (0.06)	−0.004 (−0.13)
INDSTR	0.161 *** (2.67)	−0.040 (−0.28)	0.121 (0.93)	0.147 ** (2.53)	−0.021 (−0.19)	0.126 (1.28)
POPDEN	−0.040 *** (−3.48)	0.001 (0.01)	−0.039 (−1.22)	−0.031 *** (−2.61)	−0.003 (−0.09)	−0.034 (−1.13)
EMINC	0.006 (0.48)	−0.047 (−1.28)	−0.040 (−1.05)	0.006 (0.46)	−0.039 (−1.18)	−0.032 (−0.95)
FINAN	−0.004 (−0.69)	0.026 * (1.72)	0.023 (1.43)	—	—	—
INNO	0.006 ** (2.21)	0.014 ** (2.28)	0.020 *** (3.50)	0.007 ** (2.43)	0.016 *** (3.11)	0.023 *** (4.34)
Observations		492			492	
Log L		1365.879			1364.949	
R^2		0.310			0.288	

Notes: () represents the statistical value of the *t*-test, calculated using robust standard error; ***, **, and * represent significance at the 1%, 5%, and 10% level, respectively.

Table 12. Robustness test results for the three effects in the Pearl River Delta urban agglomeration.

Variable	Economic Distance Matrix			Eliminate the Control Variable FINAN		
	Direct Effect	Indirect Effect	Total Effect	Direct Effect	Indirect Effect	Total Effect
INTRATRA	−0.017 * (−1.70)	0.007 (1.64)	−0.010 * (−1.71)	−0.018 * (−1.70)	0.005 * (1.58)	−0.013 * (−1.67)
INTERTRA	−0.009 (−0.29)	0.004 (0.33)	−0.004 (−0.26)	−0.009 (−0.30)	0.003 (0.40)	−0.005 (−0.25)
INDSTR	−0.188 (−1.49)	0.081 (1.48)	−0.107 (−1.47)	−0.190 (−1.53)	0.054 (1.40)	−0.136 (−1.54)
POPDEN	−0.078 (−0.96)	0.035 (0.95)	−0.043 (−0.96)	−0.080 (−1.06)	0.023 (1.02)	−0.057 (−1.06)
EMINC	0.015 (0.42)	−0.008 (−0.47)	0.008 (0.38)	0.011 (0.33)	−0.003 (−0.36)	0.008 (0.32)
FINAN	0.003 (0.10)	−0.001 (−0.07)	0.002 (0.12)	—	—	—
INNO	0.025 ** (2.23)	−0.011 ** (−2.22)	0.014 ** (2.15)	0.028 ** (2.51)	−0.008 ** (−1.97)	0.020 *** (2.66)
Observations		108			108	
Log L		294.218			291.065	
R^2		0.380			0.426	

Notes: () represents the statistical value of the *t*-test, calculated using robust standard error; ***, **, and * represent significance at the 1%, 5%, and 10% level, respectively.

4. Conclusions and Policy Implications

4.1. Conclusions

The overall urban resilience of the three major urban agglomerations in China has a positive spatial autocorrelation, showing an obvious agglomeration trend. In terms of explanatory variables, the intra-regional transportation infrastructure has a positive effect on the urban resilience of cities in Beijing–Tianjin–Hebei and the Pearl River Delta due to the spatial spillover effect, while this only affects the resilience construction of local cities for the urban agglomeration of the Yangtze River Delta. For the Beijing–Tianjin–Hebei urban agglomeration, the inter-regional transportation infrastructure inhibits the urban resilience development of local cities. Moreover, the spatial spillover effect has a negative impact on the urban resilience level of surrounding cities, but the impact on the Yangtze River Delta and the Pearl River Delta agglomerations is not obvious. At the same time, in terms of control variables, this paper finds that industrial development structure, population density, urban employee income, and regional innovation level have different degrees of direct effects and spatial spillover effects on the urban resilience of the three urban agglomerations, thus showing regional heterogeneity.

4.2. Policy Implications

Based on the above research conclusions, this paper puts forward the following policy recommendations:

1. Improve the quality of urban road traffic facilities and promote the interconnection of intercity road facilities. This paper finds that the development of urban internal traffic infrastructure promotes the urban resilience of local and neighboring cities. Therefore, focusing on the construction of urban road traffic should become the focus of the construction of an urban risk prevention system in the future. In urban transport development planning, in order to improve the connection strength of the road traffic network to improve the city's ability to resist disaster risks, it is necessary to deepen our understanding of the concept of urban resilience construction and connotative development characteristics, formulate scientific and reasonable road transport system quality improvement schemes, build large-scale public transport infrastructure (such as bus rapid transit, subways, etc.), deepen road transport cooperation between

developed and underdeveloped areas in urban agglomerations, and expand intercity road traffic coverage.

2. Optimize the structure of intercity transportation and promote the construction of new transportation infrastructure, such as intercity light rail and high-speed railways. In this paper, the construction level of inter-regional transportation infrastructure takes the highway density as the main measurement index but, in practice, railways, waterways, and shipping will also affect the development of the intercity transportation network. The inter-regional traffic infrastructure has an adverse impact on the construction of urban resilience, which shows that the operation state of highway transportation is too saturated at this stage, causing a series of negative problems, such as urban traffic congestion and increasing traffic pressure. There are deficiencies in the construction of an urban safety system that affect the operational efficiency of the overall traffic network of urban agglomerations. Therefore, it is necessary to accelerate the establishment of an efficient transportation system represented by intercity light rail and high-speed railways, further enhance the attraction of other transportation modes, optimize the passenger transportation and cargo transportation structure in the transportation network, promote the diversified development of transportation infrastructure, formulate appropriate urban congestion control policies, and improve the resilience of urban infrastructure construction.
3. Promote the transportation connection and cross-regional cooperation of urban agglomerations and promote the coordinated development of urban safety and transportation systems. From the perspective of economic development, urban agglomerations are divided into developed cities and underdeveloped cities. We should make full use of their regional complementarity, give full play to the influence and radiation of core cities, drive the development of surrounding cities with core cities, and subsequently promote the regional integrated development of urban agglomerations. This should be accomplished while ensuring that core cities, such as Beijing, Tianjin, Shanghai, Nanjing, Suzhou, Hangzhou, Guangzhou, and Shenzhen, in the three major urban agglomerations continue to strengthen the construction of urban three-dimensional transportation networks and deepen the urban safety and resilience system. These cities can provide policy support and financial assistance to the less developed areas in the urban agglomerations and improve the transportation system in the less developed areas, thus improving the accessibility and connectivity of intercity transportation networks. This will promote the orderly and free flow of resource elements between cities, drive the resilient development level of multiple areas (such as economy, society, ecology, and infrastructure) in the urban system, promote the overall balanced and coordinated development of developed and underdeveloped cities in the urban agglomeration, and realize the development of more resilient urban agglomeration.

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