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Urban Resilience and Transportation Infrastructure Level in the Yangtze River Delta

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The development of urban resilience is inseparable from the construction of urban infrastructure. As an important lifeline of the city, transportation infrastructure is an important part of improving urban resilience. Studying the coordinated development degree of urban resilience and transportation infrastructure level is related to the future development of the city. On the basis of measuring the urban resilience and transportation infrastructure level in the Yangtze River Delta, this study uses the coupling coordination model and spatial autocorrelation model to explore the spatiotemporal evolution trend of the coupling coordination between urban resilience and transportation infrastructure level. The results show that first, the average development levels of urban resilience and transportation infrastructure are at the middle and lower levels, showing a spatial pattern of "high in the southeast and low in the northwest." Second, the degree of coupling coordination fluctuates and rises and is in the transition stage from mild imbalance to primary coordination. Finally, the degree of coupling coordination is spatially positively autocorrelated, and the degree of agglomeration shows a stable development trend, but the difference of coordinated agglomeration between cities is expanding. To enhance the security and sustainable competitiveness of the Yangtze River Delta, this study argues that it is urgent to establish the concept of resilient urban development and promote the integration of urban agglomeration transportation infrastructure to promote the coordinated development of urban safety systems and infrastructure. Suggestions were recommended to efficiently improve the urban resilience and transportation infrastructure level in the Yangtze River Delta.

Keywords: urban resilience, transport infrastructure, coupling coordination, spatial autocorrelation, Yangtze River Delta

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1 INTRODUCTION

At present, China's urbanization process has rapidly advanced, and its high-quality development is advancing steadily. However, the phenomena of population expansion and traffic congestion make it difficult to stabilize the internal urban structure and aggravate the uncertainty of urban development (Wang et al., 2015). In October 2020, the Fifth Plenary Session of the 19th CPC Central Committee deeply analyzed the international and domestic situation and pointed out that China is facing a profound and complex development environment challenge. It should enhance risk awareness and strive to build a resilient city. In March 2021, the "14th Five-Year Plan" deliberated and adopted by "The National People's Congress of the People's Republic of China" and "Chinese People's Political

Consultative Conference" clearly proposed to promote the construction of new cities, comply with the new concepts and trends of urban development, and build a livable, innovative, smart, green, humanistic, and resilient city, which puts forward new requirements and goals for the development of cities in the future. As an expression of the adaptability, recovery, and learning ability of the urban system in response to various natural and man-made disasters, urban resilience is composed of various human and natural systems such as urban economy, society, ecology, and infrastructure (Zhao et al., 2020). This complex coupling system process emphasizes multiple cooperation of different stakeholders such as community, enterprise, and government. The composite system formed by it has become a hot topic to be studied urgently, such as urban sustainable development and the coupling mechanism of the man–land system.

The improvement of urban resilience can start from many aspects needed in the process of urbanization and then promote the high-quality development of the city. Among them, adequate, reliable, and stable urban infrastructure is the key factor for cities to respond to emergencies and is an important part of improving urban resilience (Wei 2020). As one of the important infrastructures, the development level and spatial distribution of transportation infrastructure play a key role in the process of urbanization (Huang et al., 2020). The construction of large-scale public infrastructure dominated by transportation infrastructure investment has driven China to steadily promote the development of new urbanization (Gan et al., 2021; Zhang et al., 2021); it can ensure the strong recovery and reconstruction function of the city from the perspective of the urban safety system development (Zhang and Feng 2019). Based on the aforementioned impact of transportation infrastructure on urbanization, this research will study the internal relationship between urban resilience and transportation infrastructure level and analyze the current situation of urban development through the coupling coordinated development degree of urban resilience and transportation infrastructure level.

Both international and local scholars have been committed to comprehensively and systematically expanding the role of urban resilience and transportation infrastructure in promoting sustainable and balanced urban development and promoting the process of urbanization. However, there are few studies on the relationship between urban resilience and transportation infrastructure. In addition, there is a lack of studies to deeply explore the relationship between them. On the one hand, the existing research on the factors affecting urban resilience focused on multidimensional perspectives such as economic development (Xu and Zhang 2019), system construction (Eakin et al., 2017), ecological environment (Wang et al., 2021), and infrastructure guarantee (Rehak et al., 2019). However, as one of the important infrastructures, transportation infrastructure lacks empirical analysis with urban resilience. On the other hand, the existing studies have investigated the coupling mechanism between transportation infrastructure and economic growth (Lai et al., 2020), industrial development (Liu et al., 2021), urbanization construction (Sun and Cui 2018), and tourism development (Zhang et al., 2022), but few studies focused on the discussion from the perspective of urban resilience construction, and there is a lack of analysis on the action mechanism of transportation factors in urban resilience construction. To sum up, scholars at home and abroad have made fruitful achievements in the research of urban resilience and transportation infrastructure, but they pay less attention to the relationship between urban resilience and transportation infrastructure level of urban agglomeration, so it is urgent to strengthen theoretical and practical exploration.

Based on the research of scholars, the research on the coupling coordination and temporal and spatial evolution mechanism of urban resilience and transportation infrastructure development not only has extremely important academic significance and theoretical value but also a beneficial exploration under the framework of urban resilience development planning and modern transportation infrastructure construction and development planning. It has important guiding and decision-making significance for subsequent cities to implement the new urbanization strategy and sustainable development. Therefore, this study uses the entropy method to measure the urban resilience level and transportation infrastructure level of 41 prefecture-level cities in the Yangtze River Delta from 2008 to 2018 and the coupling coordination model and spatial autocorrelation model to explore the spatiotemporal change trend and spatial agglomeration form of coupling coordination between urban resilience and the transportation infrastructure level. Taking the Yangtze River Delta as the research object, this study is mainly based on the following two considerations:

(1) The urban system of cities in the Yangtze River Delta is complex, but due to the differences between the ability to resist risks and the development stage of urbanization, there are significant regional differences in urban resilience and the urbanization level in the Yangtze River Delta (Lu et al., 2022). To explore the coordinated development relationship between urban resilience and the transportation infrastructure level in the Yangtze River Delta, we can try to find out the differences between regional urban resilience and new urbanization development from the perspective of transportation infrastructure to provide a reference for building a new city with the perfect transportation system and strong overall resilience and improve the overall comprehensive strength of the Yangtze River Delta.
(2) At present, the Yangtze River Delta has formed a "Trinity" comprehensive transportation hub system of comprehensive transportation hub clusters, hub cities, and hub ports and stations. Exploring the coordinated evolution process between urban resilience and the transportation infrastructure level in the Yangtze River Delta is conducive to comprehensively promoting the construction of transportation infrastructure within and between cities, forming an interconnected and collaborative management transportation infrastructure system and supporting and ensuring the integrated development of the Yangtze River Delta.

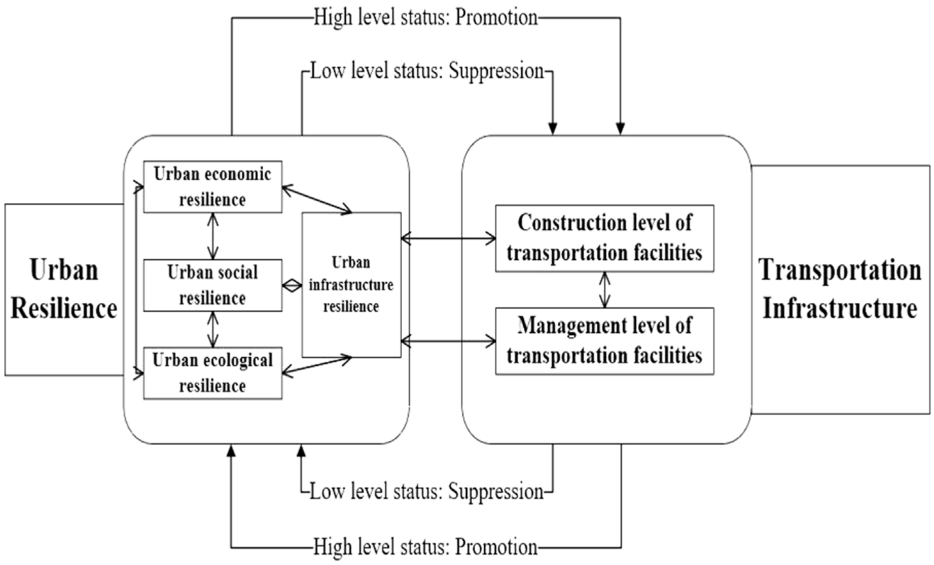

FIGURE 1 | Coupling coordination mechanism between urban resilience and the transportation infrastructure level.

2 MECHANISM ANALYSIS OF THE RELATIONSHIP BETWEEN URBAN RESILIENCE AND THE TRANSPORTATION INFRASTRUCTURE LEVEL

As a place for the reproduction of modern human beings, ensuring the safe operation of human society is one of the important functions of urban resilience. The construction of a safe and resilient city with high efficiency and sustainable competitiveness is related to the overall definition of social stability. As an important part of the construction of an urban safety system, transportation infrastructure has a strong interaction with urban resilience.

Different degrees of urban resilience have different effects on the construction and development of transportation infrastructure. Specifically, it has different effects on the development of transportation infrastructure through urban capital investment and urban safety systems. In a city with a high level of resilience, it has various financial support for the safe operation of the overall urban system. To continue to maintain and further improve its emergency preparedness and response capabilities against natural and man-made disasters, large-scale investment in the construction of various infrastructure, including the transportation industry, is an important measure to enhance the city's hard power. It not only promotes the integrated construction of the transportation system but also ensures the reliable operation of the high-level and resilient urban system. However, when the city is at a low level of resilience due to the rise of various risk factors of urban safety prevention and control compared with cities with high resilience levels, there is a lack of effective risk response and recovery capabilities to maintain the orderly exchange status of materials and energy inside and outside the city. If a strong natural disaster occurs, it will bring a lot of tests to the resilience of urban infrastructure, especially the transportation guaranteed ability of the transportation infrastructure, which restricts the construction of transportation infrastructure and causes the urban safety system construction in the medium and long term to be of no fundamental improvement.

Different levels of transportation infrastructure development have different effects on urban resilience construction. Specifically, urban safety systems and urban infrastructure resilience have an impact on the overall resilience of the city. Under the low-level transportation network system, the acceptance capacity of traffic roads is insufficient, which makes it difficult to give full play to the connectivity of regional transportation systems. The importance of urban safety risk management and urban infrastructure resilience is at a low level, which brings great challenges to the basic conditions and development environment of urban resilience development and then hinders the effective development of the overall urban resilience. When the transportation infrastructure is at a high level, the transportation infrastructure significantly enhances the efficient flow of the city's internal space to a large extent, which not only stimulates the vitality of urban development and promotes the deep integration of urban elements and resources but also effectively improves the risk response ability of the overall urban infrastructure and improves the self-stability and adaptability of the urban system. Then, it has an important driving force for the improvement of the overall resilience level of the city.

Therefore, urban resilience and the transportation infrastructure level interact and influence each other. Urban resilience and the transportation infrastructure level at different development levels have different effects on the sustainable development of the overall urban system. The coupling coordination mechanism of urban resilience and the transportation infrastructure level is shown in **Figure 1**.

TABLE 1 | Evaluation index system of urban resilience and the transportation infrastructure 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 used in the current year	Ten thousand U.S. dollars (+)	The status of foreign economic exchanges
		Local general public budget revenue	Ten thousand yuan (+)	Government financial strength
		Balance of savings deposits 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 level
	Urban social resilience	Hospital, number of beds in health centers	Number (+)	Medical assistance guarantees the capability
		Number of students in ordinary colleges and universities	Person (+)	Popularization of risk education
		Social security index	% (+)	Social insurance protection capabilities
		Registered urban unemployment rate	% (-)	Social stability
	Urban ecological resilience	Park green area per capita	m^2 (+)	Environmental conservation status
		Green coverage rate in built-up areas	% (+)	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	The density of drainage pipes in a 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 relations
		The number of buses per 10,000 people in the municipal area	Vehicle (+)	Urban evacuation capacity
Transportation infrastructure system	Transport infrastructure construction level	Highway traffic mileage	Km (+)	Highway development status
		Highway density	Km/100 km^2 (+)	
		Road length for installation of street lamps	Km (+)	Urban road development status
		Urban road density	Km/km^2 (+)	
		City road area	10,000 m^2 (+)	
		Urban road area rate	% (+)	
		Number of bridges	Number (+)	City carrying scale
	Transport infrastructure, management level	Transportation, employees in warehousing and postal industry	10,000 people (+)	Manpower investment intensity
		Transportation expenditure in local finance	100 million yuan (+)	Government investment intensity
		Transportation, fixed asset investment in warehousing and postal industry	100 million yuan (+)	Project investment intensity

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 [34].

3 INDEX SYSTEM CONSTRUCTION, DATA SOURCES, AND RESEARCH METHODS

3.1 Index System Construction

To accurately evaluate the coupling coordination relationship between urban resilience and the level of transportation infrastructure in the Yangtze River Delta, this study follows the principles of comprehensiveness, systematization, and operability to construct an evaluation index system for urban resilience and transportation infrastructure. Drawing on the existing research works by Chen and Quan (2021) and Feng et al. (2020), from the perspective of ensuring the stability of the urban internal system, urban resilience is specifically decomposed into urban economic resilience, urban social resilience, urban ecological resilience, and urban infrastructure resilience. A total of 20 secondary indicators are selected to construct the urban resilience evaluation index system; based on the existing research works by Jiajing and Chaolong (2018); Xibin et al. (2017), starting from the two aspects of the development and application of transportation infrastructure, the transportation infrastructure level is decomposed into two first-level indicators of the construction level and management level, and a total of 10 second-level indicators are selected to construct the transportation infrastructure evaluation index system. The system is shown in **Table 1**.

In this study, the comprehensive score evaluation of urban resilience and the transportation infrastructure level is carried out by the entropy method. The entropy method belongs to the objective weighting method, which determines the index weight through the difference between the original data of each index. In the process of determining the weight coefficients of different indicators, the entropy method avoids the influence deviation caused by human subjective factors and can objectively reflect the importance of each indicator in the comprehensive evaluation system. Therefore, the entropy method is used to determine the weight of each index and the comprehensive score of urban resilience and the transportation infrastructure level.

3.2 Data Selection and Source

Based on the planning scope of the "Outline of the Yangtze River Delta Regional Integrated Development Plan" released in December 2019, 41 cities in Jiangsu, Zhejiang, Anhui, and Shanghai are taken as the research objects, and the relevant data of each city from 2008 to 2018 were selected to comprehensively measure and deeply explore the coordination relationship between the evaluation systems. The original data of the evaluation indicators are obtained from the 2009–2020 China Urban Statistical Yearbook, China Urban Construction Statistical Yearbook, the statistical yearbooks of provinces and cities in the Yangtze River Delta region, and the National Economic and Social Development Statistical Bulletin. Individual missing data are filled in by interpolation.

3.3 Research Method

3.3.1 Entropy Method

The entropy method belongs to the objective weighting method, which determines the index weight through the difference between the original data of each index. In the process of determining the weight coefficients of different indicators, the entropy method avoids the influence deviation caused by human subjective factors and can objectively reflect the importance of each indicator in the comprehensive evaluation system (Zhou and Liu 2020). Therefore, the entropy method is used to determine the weight of each index and the comprehensive score of urban resilience and the transportation infrastructure level. The specific steps are as follows:

(1) Index selection: If there are m prefecture-level cities and N indexes in the cross-sectional data of a horizontal system, X_{ij} is the jth index value of the ith city.

(2) Dimensionless processing: Due to the different dimensions and specific orders of magnitude of each index, this study adopts the method of range standardization to dimensionless original data. The details are as follows:

For positive indicators:

$$X_{ij}' = \frac{X_{ij} - min\, X_{ij}}{max\, X_{ij} - min\, X_{ij}}. \tag{1}$$

For negative indicators:

$$X_{ij}' = \frac{max\, X_{ij} - X_{ij}}{max\, X_{ij} - min\, X_{ij}}. \tag{2}$$

In **Eqs 1**, **2**, $X_{ij}^{`}$ represents the jth index value of the ith city after dimensionless treatment.

(3) Determination of standardized index weight, that is, to determine the contribution rate of the city I to all cities in the jth index after standardization. The formula is shown in **Eq. 3**:

$$P_{ij} = \frac{X_{ij}'}{\sum_{i=1}^{m} X_{ij}'}. \tag{3}$$

(4) Entropy calculation: Calculate the entropy of the jth index. The formula is shown in **Eq. 4**:

$$e_j = -\frac{1}{\ln(m)} \sum_{i=1}^{m} P_{ij} \ln\left(P_{ij}\right). \tag{4}$$

(5) Information utility value calculation: Calculate the information utility value of the jth index. The formula is shown in **Eq. 5**:

$$d_j = 1 - e_j. \tag{5}$$

(6) Determination of information utility value weight, that is, to determine the contribution rate of the jth index information utility value to the overall index. The formula is shown in **Eq. 6**:

$$W_j = \frac{d_j}{\sum_{j=1}^{n} d_j}. \tag{6}$$

(7) Calculation of comprehensive evaluation index: Finally, calculate the comprehensive evaluation index of city I in a system, and the formula is shown in **Eq. 7**:

$$U_i = \sum_{j=1}^{n} W_j X_{ij}' \tag{7}$$

3.3.2 Coupling Coordination Degree Model

The concept of coupling degree originated from the category of physics. It refers to the interconnected influence of two or more systems under the action of internal and external factors, which can reflect the degree of interdependence and mutual restriction between systems (Yao et al., 2019). As mentioned previously, there is a correlation between urban resilience and the level of transport infrastructure. Therefore, the coupling degree between them is calculated and the interactive relationship between them is analyzed.

The coupling model in this study is as follows:

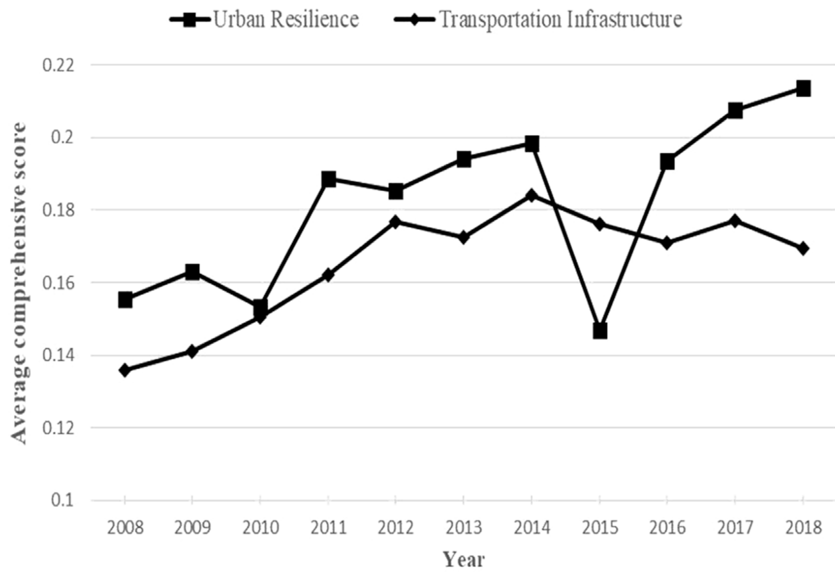

FIGURE 2 | Evolution trend of the average comprehensive score of urban resilience and the transportation infrastructure level in the Yangtze River Delta.

$$C = \sqrt[2]{\frac{U_1 \times U_2}{\left(\frac{U_1+U_2}{2}\right)^2}}. \tag{8}$$

In **Eq. 8**, C is the coupling degree of urban resilience and the level of transportation infrastructure; U_1 is the comprehensive evaluation index of urban resilience; and U_2 is the comprehensive evaluation index of the transportation infrastructure level.

However, the degree of coupling can only judge the strength of the coupling effect between systems, and the coupling degree model cannot reflect the synergistic effect of the development of the two when comparing time and space. For example, when the two evaluation indexes are very low, it is easy to appear a state of high coupling, and high coupling and high development levels have completely different connotations. Therefore, the coordination degree model is introduced to reflect the interaction between the two systems and to measure the coordination degree between urban resilience and the level of transportation infrastructure in the Yangtze River Delta.

The coordination degree model of this study is as follows:

$$T = \alpha U_1 + \beta U_2, \tag{9}$$

$$D = \sqrt{C \times T}. \tag{10}$$

In **Eqs 9**, **10**, D is the degree of coupling coordination between urban resilience and the transportation infrastructure level, T is the comprehensive coordination index of urban resilience and the transportation infrastructure level, and α and β are undetermined coefficients, representing the importance of urban resilience and the transportation infrastructure level, respectively; it is stipulated that $\alpha+\beta = 1$. This study believes that urban resilience is as important as the level of transportation infrastructure, so α and β are, respectively, set to 0.5.

The calculation result of D reflects the relationship between urban resilience and the level of transportation infrastructure. The higher the degree of coupling coordination, the higher the level of coordinated development between the two. On the contrary, the lower the result, the lower the level of coordinated development between the two.

3.3.3 Spatial Autocorrelation Test

Spatial autocorrelation is defined as a spatial data analysis method that studies whether a series of data has spatial dependence on spatial units and reflects 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 spatial autocorrelation relationship. The spatial weight matrix can reflect spatial dependence and spatial interaction. The spatial weight matrix used in this study has four types: 0–1 queen weight matrix, geographic distance weight matrix, economic distance weight matrix, and economic geographic distance weight matrix.
(2) 0–1 queen weight matrix: It is a kind of spatial weight matrix based on whether there are adjacent points or boundaries between two units, which is set as follows:

$$W_{ij} = \begin{cases} 1\,(\text{when the units i and j have a common point or boundary}) \\ 0\,(\text{when the units i and j have no common points and boundaries}) \end{cases}. \tag{11}$$

(3) Geographic distance weight matrix: This matrix assumes that the spatial interaction is determined by the distance between the locations of the regional administrative centers between the

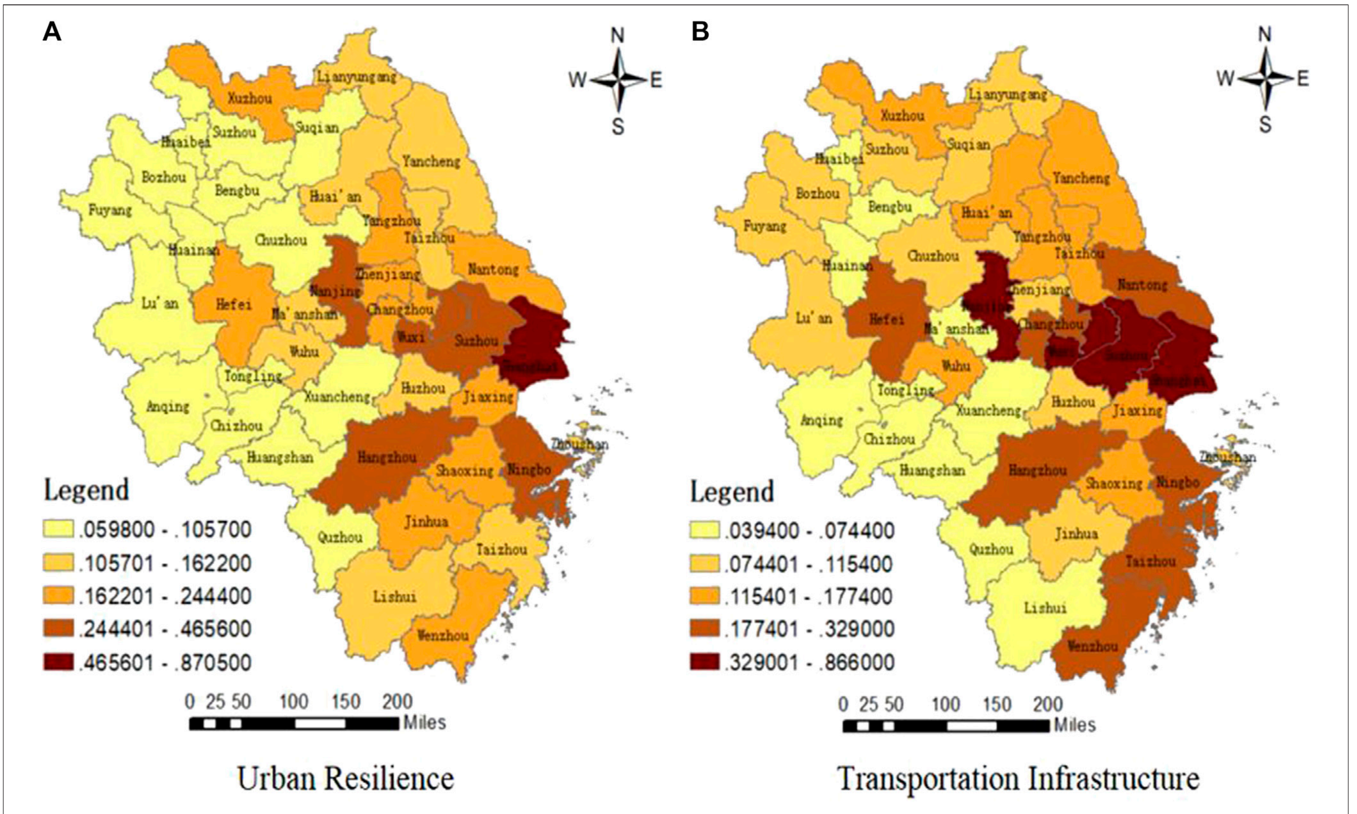

FIGURE 3 | Spatial distribution pattern of the overall average value of urban resilience and the transportation infrastructure level in the Yangtze River Delta from 2008 to 2018.

units. It is believed that the closer the distance between the units, the greater the weight assigned (Shoukun 2013). Using the inverse distance matrix method and set as follows:

$$W_{ij} = \begin{cases} \dfrac{1}{\mathrm{d_{ij}}} & (i \neq j) \\ 0 & (i = j) \end{cases}. \tag{12}$$

In **Eq. 12**, $\mathrm{d_{ij}}$ represents the distance between the two points of the regional administrative center of unit i and unit j.

(4) Economic distance weight matrix: This matrix contains regional economic factors. It is believed that the higher the similarity of regional economic development, the higher the degree of spatial agglomeration correlation. It is set as follows:

$$W_{ij} = \begin{cases} \dfrac{1}{\left|\overline{Y_i} - \overline{Y_j}\right|} & (i \neq j) \\ 0 & (i = j) \end{cases}. \tag{13}$$

In **Eq. 13**, $\overline{\mathrm{Y_i}}$ and $\overline{\mathrm{Y_j}}$ are the average values of the actual per capita GDP of units i and j over the years, respectively, and it is defined as:

$$\overline{Y_i} = \frac{1}{t_1 - t_0 + 1} \sum_{t_0}^{t_1} Y_{it}. \tag{14}$$

In **Eq. 14**, Y_{it} is the actual per capita GDP of unit i in year t.

(5) Economic geographic distance weight matrix: This matrix includes both geographic factors and economic factors and can take into account the actual impact environment of relevant indicators. It is set as follows:

$$W_{ij} = \begin{cases} \dfrac{1}{\mathrm{d_{ij}}} * \dfrac{1}{\left|\overline{Y_i} - \overline{Y_j}\right|} & (i \neq j) \\ 0 & (i = j) \end{cases}. \tag{15}$$

3.4 Calculation of global Moran's I statistics

This study uses the global Moran's I statistic to test the spatial autocorrelation degree of the coupling coordination degree of urban resilience and the level of transportation infrastructure in the Yangtze River Delta. The specific formula is as follows:

$$\text{Moran's } I = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} \left(X_i - \bar{X}\right)\left(X_j - \bar{X}\right)}{s^2 \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij}}. \tag{16}$$

TABLE 2 | Coupling coordination degree grade standard.

Coupling coordination	Coupling coordination level
$0.0 \le D < 0.2$	Severe imbalance
$0.2 \le D < 0.3$	Moderate imbalance
$0.3 \le D < 0.4$	Mild imbalance
$0.4 \le D < 0.6$	Primary coordination
$0.6 \le D < 0.8$	Intermediate coordination
$0.8 \le D \le 1.0$	Advanced coordination

In **Eq. 16**, n is the total number of units studied; w_{ij} is the value of the element in the *i*th row and *j*th column of the spatial weight matrix W; and X_i and X_j are the index values of the *i*th unit and the *j*th unit, respectively. Among them, $\bar{X}$ is the average value of the index, and s^2 is the variance of the index, which is:

$$\bar{X} = \frac{1}{n}\sum_{i=1}^{n} X_i, s^2 = \frac{1}{n}\sum_{i=1}^{n}\left(X_i - \bar{X}\right). \tag{17}$$

The value range of Moran's I index is [−1, 1]. If I ∈ [−1, 0], it indicates that the index has spatial negative correlation; if I ∈ [0, 1], it indicates that the index has spatial positive correlation; and if I = 0, it indicates that the index does not have spatial autocorrelation, that is, spatial random distribution.

4 ANALYSIS OF THE TEMPORAL AND SPATIAL DIFFERENCE BETWEEN URBAN RESILIENCE AND THE TRANSPORTATION INFRASTRUCTURE LEVEL IN THE YANGTZE RIVER DELTA

In this study, the comprehensive score evaluation of urban resilience and the transportation infrastructure level is carried out by the entropy method. The dimensionless processing of original data is carried out by **Eqs 1**, **2**, and then the entropy and information utility values of each index are calculated by **Eqs 3–5**. Finally, the comprehensive scores of urban resilience and the transportation infrastructure level of 41 prefecture-level and above cities in the Yangtze River Delta from 2008 to 2018 are obtained by **Eqs 6**, **7**.

The time trend is shown in **Figure 2**, which shows that during the study period, the overall urban resilience in the Yangtze River Delta shows a wave of the upward trend, and the transportation infrastructure level in the Yangtze River Delta has a fluctuating development trend after a stable rise. It shows that from 2008 to 2018, on the one hand, the construction of relevant functions to resist risks in the urban system in the Yangtze River Delta tends to be complete, and the emergency handling capabilities of man-made risks further consolidate the urban safety system. On the other hand, the Yangtze River Delta has gradually improved the construction of the urban transportation system, and the urban transportation infrastructure has been continuously adjusted and optimized to build the integrated development of the Yangtze River Delta transportation network. According to specific time-phased analysis, from the perspective of urban resilience development, from 2008 to 2014, due to the outbreak of the international financial subprime mortgage crisis, the construction of urban resilience within the city was affected, the progress of urban resilience construction in the Yangtze River Delta region was slow, and the rate of improvement was not high. However, due to the government's strong macro-control, the adverse effects of the economic crisis can be mitigated to the greatest extent, the overall trend of resilience has been steadily rising, and the fundamentals of urban resilience construction have not changed. From 2015 to 2018, due to the "stock market crash" and a new round of state-owned enterprise reforms in China's stock market, it indirectly affected economic resilience and social resilience, resulting in varying degrees of decline in the resilience system of most cities in the Yangtze River Delta in 2015, and different cities suffered varying degrees of blows. Among them, cities with high resilience, such as Shanghai, Nanjing, Suzhou, Hangzhou, and Hefei, saw the largest decline. However, in the following 3 years, the resilience level of cities with high resilience quickly rebounded to the level before 2015. The resilience level of the city and even the resilience level of some prefecture-level cities have been further developed, indicating that reasonable and sufficient urban resilience construction through precise layout and steady adjustment can effectively respond to conflicts of interest brought about by economic and social risks and strengthen the tolerance of the urban system itself. From the perspective of transportation infrastructure development, the average comprehensive score increased from 0.14 to 0.18 year by year from 2008 to 2012, indicating that the transportation infrastructure construction of cities in the Yangtze River Delta region was in full swing at this stage. The vigorous development of transportation infrastructure has improved the operation of the city's transportation system, which drove the orderly development of the city. From 2013 to 2018, due to the rapid development of urbanization, the scale of the city and the scope of the spatial layout continued to expand, the number of private cars has increased sharply, and a large number of people and vehicles have poured into the city. However, the construction of transportation infrastructure lagged behind the development speed of urbanization, resulting in the declination of road acceptance and vehicle traffic efficiency and the congestion of the traffic system. The average comprehensive score fluctuated between 0.16 and 0.18 and even had a slight downward trend, indicating that the increasing urban scale in the process of urbanization conflicted with the lagging inherent traffic system. The improvement and development of transportation infrastructure are becoming more and more difficult.

Using ArcGIS 10.7 software to plot the spatial pattern of the overall average value of urban resilience and the transportation infrastructure level, as shown in **Figure 3**, it can be seen that there are significant regional differences in the urban resilience and traffic infrastructure level of 41 prefecture-level and above cities in the Yangtze River Delta. The urban resilience presents a spatial distribution pattern of "higher in the east and the south, gradually decreasing to the northwest," and the traffic infrastructure level presents a spatial distribution pattern of "higher in the east and the north, decreasing to the southwest edge." From the distribution pattern of urban resilience, during the study

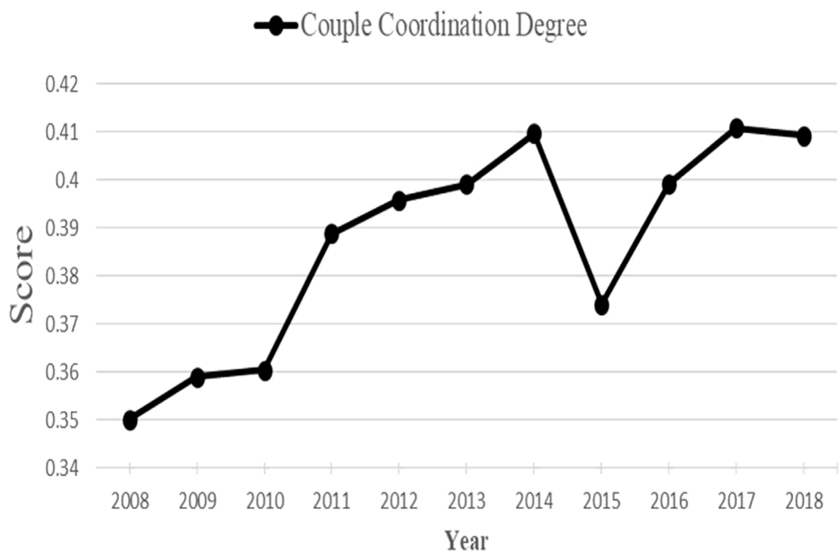

FIGURE 4 | Time trend of the average coupling coordination degree of cities in the Yangtze River Delta from 2008 to 2018.

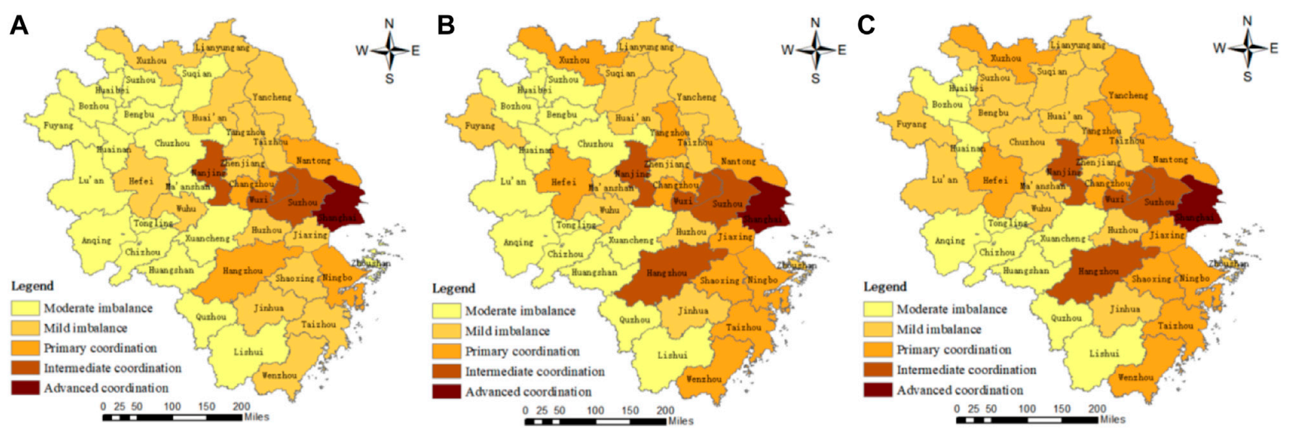

FIGURE 5 | Spatial distribution of coupling coordination degree in the Yangtze River Delta in 2008, 2013, and 2018.

period, Shanghai's urban resilience was significantly higher than other cities in the Yangtze River Delta region and the overall average level, indicating that the urban spatial structure and development planning of Shanghai as China's economic center and the core city of the Yangtze River Delta's integration are adapted to high-level urban system construction requirements with strong linkage and high synergy, radiating to the Yangtze River Delta region. However, from the absolute value, except for Suzhou and Hangzhou in some years, the urban resilience of other cities is still lower than 0.5, indicating that the cities far away from the core area of the Yangtze River Delta have insufficient self-recovery capacity and are currently in a relatively low resilience stage. It shows that the construction of urban resilience has a long way to go. Resilience city planning is an important direction in the future integration process of the Yangtze River Delta. Not only do the core cities need to take the lead, but the central cities of the other three provinces also need to build a high-level urban system as a strategic goal of urban planning to drive the development of surrounding cities and narrow the overall gap. From the distribution pattern of the traffic infrastructure level, during the study period, Shanghai's overall score was still at the highest position, much higher than other cities in the region. This shows that Shanghai, a transportation hub in the Yangtze River Delta, has developed a high-density and high-connected transportation network. The integration process of the comprehensive transportation system in the Yangtze River Delta has played a demonstrative role. From the results, except for Nanjing and Wuxi in some years, the level of transportation infrastructure is still lower than 0.5, and the traffic development of each city is fluctuating and stable, indicating that due to the

TABLE 3 | Moran's I index of the degree of coupling coordination between urban resilience and transportation infrastructure in the Yangtze River Delta from 2008 to 2018.

Year	0–1 Queen matrix		Geographic distance matrix		Economic distance matrix		Economic geographic distance matrix	
	Moran's I	Z-variance	Moran's I	Z-variance	Moran's I	Z-variance	Moran's I	Z-variance
2008	0.264	3.088***	0.105	5.317***	0.468	6.499***	0.535	6.619***
2009	0.248	2.935***	0.107	5.443***	0.486	6.767***	0.543	6.752***
2010	0.246	2.939***	0.104	5.355***	0.477	6.702***	0.53	6.659***
2011	0.263	3.06***	0.108	5.395***	0.495	6.815***	0.547	6.721***
2012	0.249	2.888***	0.103	5.199***	0.494	6.757***	0.544	6.651***
2013	0.262	3.029***	0.105	5.247***	0.496	6.77***	0.543	6.629***
2014	0.256	2.959***	0.101	5.099***	0.494	6.733***	0.537	6.549***
2015	0.252	2.938***	0.100	5.084***	0.48	6.604***	0.522	6.414***
2016	0.246	2.869***	0.096	4.902***	0.478	6.584***	0.521	6.407***
2017	0.253	2.924***	0.098	4.948***	0.468	6.407***	0.515	6.296***
2018	0.252	2.924***	0.100	5.053***	0.464	6.365***	0.509	6.249***

*Note: ***, **, * mean passing the 1, 5, and 10% significance level tests, respectively.*

difference between the urban economic environment and the geographical environment, the construction of urban internal transportation infrastructure is in the "bottleneck period". To form the grid of the transportation system in the Yangtze River Delta region, it is necessary to combine advanced urban deployment and coordinated planning and cooperate with the surrounding cities in the construction of transportation infrastructure through the developed cities to drive the traffic construction of the surrounding cities and strive for efficient connections between urban transportation.

5 ANALYSIS OF TEMPORAL AND SPATIAL DIFFERENCES IN THE DEGREE OF COUPLING COORDINATION BETWEEN URBAN RESILIENCE AND THE TRANSPORTATION INFRASTRUCTURE LEVEL IN THE YANGTZE RIVER DELTA

According to the comprehensive evaluation scores of urban resilience and the transportation infrastructure level in the Yangtze River Delta from 2008 to 2018, the coupling coordination degree model is used to calculate the coupling coordination degree D of 41 cities at the prefecture level and above in the Yangtze River Delta. To directly reflect the coordination relationship between urban resilience and the level of transportation infrastructure, this study refers to existing research [10], and it classifies the coupling coordination values of the two systems and divides them into levels, as shown in **Table 2**. It analyzes the degree of coupling coordination of cities in the Yangtze River Delta from two aspects: temporal trend characteristics and spatial pattern characteristics.

5.1 Time Trend Characteristics

Figure 4 shows the time trend of the average coupling coordination degree of cities in the Yangtze River Delta from 2008 to 2018. From the perspective of the overall score, it rose from 0.3501 in 2008 to 0.4093 in 2018, showing a fluctuating upward trend; from the perspective of the coordination level, it showed a transition from a mild imbalanced state to a primary coordination state. From the aforementioned two perspectives, it can be seen that, on the one hand, the overall performance of urban resilience and transportation infrastructure levels during the study period has shown an upward trend over the same period, and the coordination and linkage between the two have gradually become apparent, indicating that the government has designed a scientific, reasonable, and innovative urban planning layout from all aspects, multi-level and wide fields, actively strengthened the governance of urban, natural, and man-made risks, and at the same time, continuously increased the construction of transportation infrastructure, which has improved the development quality of the urban hardware transportation network system, thereby promoting the continuous and coordinated progress of urban resilience and the transportation infrastructure level. On the other hand, the overall coordination degree of the Yangtze River Delta region is still at a low level, the coordination level is low, and it is in the transition stage from a mild disorder to primary coordination. It shows that the coordinated development of urban resilience and the transportation infrastructure level in the Yangtze River Delta has great plasticity. In the future, for the transformation and construction of urban transportation infrastructure, it should pay more attention to the integration with urban hardware safety and environmental governance and continuously improve the city's livability and gridding level to achieve the synergistic effect of urban resilience and transportation development.

5.2 Spatial Pattern Characteristics

To further explore the spatial changes of the coupling coordination degree of urban resilience and the level of transportation infrastructure in the Yangtze River Delta from 2008 to 2018, ArcGIS 10.7 software was used to draw the spatial distribution map of the coupling coordination degree of the Yangtze River Delta in 2008, 2013, and 2018 (**Figure 5**). It can be seen from **Figure 3** that there are significant spatial and inter-city differences in the coordination between urban resilience and the level of transportation infrastructure in the Yangtze River Delta

TABLE 4 | Types of the spatial distribution of coupling coordination in the Yangtze River Delta in 2008, 2013, and 2018.

City Type	2008	2013	2018
High–high	Shanghai, Wuxi, Changzhou, Suzhou, Nantong, Yangzhou, Zhenjiang, Jiaxing, Taizhou	Shanghai, Wuxi, Changzhou, Suzhou, Nantong, Yangzhou, Ningbo, Jiaxing, Shaoxing, Taizhou	Shanghai, Wuxi, Changzhou, Suzhou, Nantong, Ningbo, Jiaxing, Shaoxing, Taizhou
High–low	Nanjing, Xuzhou, Hangzhou, Ningbo, Wenzhou, Hefei	Nanjing, Xuzhou, Hangzhou, Wenzhou, Hefei	Nanjing, Xuzhou, Hangzhou, Wenzhou, Hefei
Low–high	Yancheng, Taizhou, Huzhou, Shaoxing, Jinhua, Zhoushan, Ma'anshan, Xuancheng	Zhenjiang, Taizhou, Huzhou, Jinhua, Zhoushan, Ma'anshan, Xuancheng	Yancheng, Yangzhou, Zhenjiang, Taizhou, Huzhou, Jinhua, Zhoushan, Ma'anshan, Xuancheng
Low–low	Lianyungang, Huai'an, Suqian, Quzhou, Lishui, Wuhu, Bengbu, Huainan, Huaibei, Tongling, Anqing, Huangshan, Chuzhou, Fuyang, Suzhou, Lu'an, Bozhou, Chizhou	Lianyungang, Huai'an, Yancheng, Suqian, Quzhou, Lishui, Wuhu, Bengbu, Huainan, Huaibei, Tongling, Anqing, Huangshan, Chuzhou, Fuyang, Suzhou, Lu'an, Bozhou, Chizhou	Lianyungang, Huai'an, Suqian, Quzhou, Lishui, Wuhu, Bengbu, Huainan, Huaibei, Tongling, Anqing, Huangshan, Chuzhou, Fuyang, Suzhou, Lu'an, Bozhou, Chizhou

region, which forms a spatial distribution pattern of "strong east coast and gradually decreasing to the west edge" in particular.

As can be seen from **Figure 5A**, in 2008, most cities in the Yangtze River Delta were in a state of moderate and mild imbalance, and only eight cities were in a state of coordination. Specifically, Shanghai is an advanced coordination city, Nanjing, Wuxi, and Suzhou are intermediate coordination cities, Changzhou, Nantong, Hangzhou, and Ningbo are primary coordination cities, and the other 33 cities are in a state of imbalance. At this research time point, there are few coordination cities, most of which are located in economically developed cities in the province. The base number of maladjusted cities is too large, resulting in a low level of overall coupling coordination in the Yangtze River Delta. The main reason is that the spatial distribution of the development process of urbanization in the Yangtze River Delta in 2008 is different. On the one hand, the proposal and construction of urban resilience were in the enlightenment stage. Facing the macro- and micro-environmental changes and social development changes brought by the international financial crisis had a great impact on the operation of the urban system. On the other hand, there were great differences in the construction of transportation infrastructure. The traffic system of maladjusted cities was far less than the corresponding supporting requirements put forward by the development of urban resilience, resulting in poor coupling coordination between the two levels.

It can be seen from **Figure 5B** that the distribution of coupling coordination degrees in the Yangtze River Delta region expanded in 2013. Specifically, Xuzhou and Yangzhou in Jiangsu and Hefei, the capital of Anhui, have begun to change from a state of imbalance to a state of coordination. The coastal area of Zhejiang has the largest number of cities that have been transformed into a state of coordination. The coupling coordination differences between the two began to shrink. The main reason is that these cities have taken advantage of the economic foundation developed by urbanization and began to pay attention to the social atmosphere, ecological environment, and infrastructure construction. Among them, the social benefits brought by the construction of transportation infrastructure were particularly important for the development of new urbanization and strengthening urban resilience. The linkage construction of the city promoted the simultaneous coordination and improvement of urban resilience and the level of transportation infrastructure.

It can be seen from **Figure 5C** that the biggest feature of the distribution of coupling coordination degrees in the Yangtze River Delta in 2018 is the increase in coordination levels of most maladjusted cities, but they are still in a state of imbalance, and the basic coordination distribution pattern remains unchanged. Specifically, the areas where the level of coordination has increased are mainly distributed in the west and northeast of Anhui, and only Yancheng in Jiangsu has increased from imbalance to coordination. The main reason is that the development of transportation infrastructure has encountered obstacles. The traffic congestion caused by urbanization has become a temporary problem that is difficult to solve. It is difficult to break through the bottleneck in the short term. The construction of urban safety systems has gradually formed a fixed mode, which is important for strengthening urban resilience and stable linkage. Increasing the degree of coordinated development of the two brings new challenges.

On the whole, Shanghai has always been in a state of high-level coordination from 2008 to 2018, and Nanjing, Wuxi, and Suzhou have always been in a state of intermediate coordination. Hefei and Hangzhou have also been upgraded to primary and intermediate coordination cities in the later stages, and the coordinated development of the Jiangsu and Zhejiang regions has been steadily developed. In progress, most of Anhui is still in a state of imbalance. The coupled coordinated distribution shows that Shanghai is the core and the provincial capital city is the sub-center. The overall layout decreases from east to west, and the provincial layout diverges from central cities to peripheral cities. It shows that Shanghai, the core city of the Yangtze River Delta integration strategy, has not only reached a high level of development in its urban resilience safety construction and transportation infrastructure construction and has become a strong city in the country's resilience construction and transportation system but also the city's development planning focuses on allocating social high-quality resources rationally, providing incentive policies and financial support for resilient development and infrastructure construction, and initially establishing a dynamic mechanism for urban sustainable development, which has a strong demonstrative effect on surrounding cities and drives surrounding cities to jointly promote the steady and coordinated improvement of urban resilience and the level of transportation infrastructure. On the other hand, compared with the Jiangsu, Zhejiang, and Shanghai regions, most cities in Anhui have a low proportion of secondary and tertiary industries and scarce characteristic industries. The investment intensity of infrastructure and the importance of urban security risk management are all at a low level, and it is difficult to get rid of the low level. The dilemma of the horizontal urban system and the low-level transportation network makes the relationship between urban resilience and the level of transportation infrastructure fall into a serious situation of linkage difficulties and difficulty in coordination.

6 SPATIAL AUTOCORRELATION ANALYSIS

To further explore the spatial agglomeration characteristics of the coordinated development of urban resilience and the level of transportation infrastructure in the Yangtze River Delta, an exploratory spatial autocorrelation analysis method is used to conduct a spatial correlation analysis on the degree of coupling coordination between urban resilience and the level of transportation infrastructure in the Yangtze River Delta. The annual change values of the global Moran's I index under the four different spatial weight matrices during the study period are shown in **Table 3**.

It can be seen from **Table 3** that the global Moran's I index under the four different weight matrices from 2008 to 2018 are all positive, and the p values all pass the 1% significance test. It shows that the level of coupling coordination of cities in the Yangtze River Delta has a positive spatial correlation. The agglomeration of high-value cities promotes a further increase in coupling coordination, and the mutual gathering of low-value cities leads to limited development of coupling coordination. From the perspective of time trends, the global Moran's I index under the four matrices shows a steady development trend, indicating that the degree of mutual agglomeration of coupling coordination in the Yangtze River Delta region is developing steadily. Although the problem of the expansion of intra-regional differences still exists, the significant spatial correlation in the overall scope is conducive to intensifying the positive radiation effect brought by the resource mobilization of developed cities in the Yangtze River Delta and promoting the process of integrated and coordinated development.

However, the global Moran index can only reflect the average agglomeration degree of the coupling coordination level of the entire region and cannot reflect the specific agglomeration type of the local area. Therefore, the local autocorrelation model is introduced to further explore the spatial distribution type of the coupling coordination degree between cities in the region. The local Moran scatter plots in 2008, 2013, and 2018 divided 41 cities in the Yangtze River Delta into four spatially related city types, namely, high–high type cities, high–low type cities, low–high type cities, and low–low type cities, as shown in **Table 4**. The specific types of analysis are as follows:

(1) High–high type city, that is, this city and its surrounding cities have a high degree of coupling coordination, forming a spatial agglomeration, mainly distributed around the eastern coastal cities with Shanghai as the center. During the study period, this type mainly includes seven cities: Shanghai, Wuxi, Changzhou, Suzhou, Nantong, Jiaxing, and Taizhou. In the later period, Ningbo and Shaoxing were newly added. During the study period, Yangzhou and Zhenjiang withdrew from the high–high type to the low–high type. Such cities often have a relatively high urban resilience and transportation infrastructure level in the region, and the coupling coordination of the two develops well, which can promote the orderly and coordinated development of the relationship between the two in the surrounding areas.
(2) High–low type cities, that is, this city has a high degree of coupling coordination, and its surrounding cities have a low degree of coupling coordination and are mainly located in provincial capitals and economically strong cities within the province. During the study period, this type mainly included five cities, Nanjing, Xuzhou, Hangzhou, Wenzhou, and Hefei. During the study period, Ningbo dropped out of the high–low type and joined the high–high type. Such cities have a high degree of urban resilience construction, but the gridding degree of the transportation infrastructure system is not yet fully mature, and cities with weaker construction of surrounding urban systems have not yet linked development, which hinders the coordinated development of the two.
(3) Low–high type city, that is, the city has a low degree of coupling coordination, and its surrounding cities have a high degree of coupling coordination, mainly centered on the provincial capital cities and economically strong cities in the province. During the study period, this category mainly included Taizhou, Huzhou, Jinhua, Zhoushan, Ma'anshan, and Xuancheng. Yancheng once withdrew from this category in the mid-term but returned and added two cities, Yangzhou and Zhenjiang, in the later stage of the study. Shaoxing withdrew from the low–high type and joined the high–high type. Such cities have a relatively large bottleneck in their development due to their urban resilience construction and transportation system development not being as good as those of the surrounding cities. The surrounding highly coordinated cities do not have a strong radiation effect, and it is difficult to fully drive the coordinated operation of the two development levels.
(4) Low–low type cities, that is, this city and its surrounding cities have a low degree of coupling coordination to form a spatial agglomeration, which is mostly distributed in northern Jiangsu, western Zhejiang, southern Zhejiang, and most of Anhui. During the study period, this type mainly includes 18 cities: Lianyungang, Huai'an, Suqian, Quzhou, Lishui, Wuhu, Bengbu, Huainan, Huaibei, Tongling, Anqing, Huangshan, Chuzhou, Fuyang, Suzhou, Lu'an, Bozhou, Chizhou. Yancheng was once merged into this type in the middle of the study, but it rose to a low–high type in the later stage of the study. The

urban resilience and transportation infrastructure level of such cities is at a lower level. The two are in a state of struggling development and are support areas that urgently need to be developed. In the future, it is necessary to vigorously develop infrastructure construction from the perspective of resilience, deepen the concept of the urban safety system, and promote the same improvement of urban resilience and transportation infrastructure level.

7 CONCLUSION AND SUGGESTIONS

7.1 Conclusion

Based on the theory of urban regional development, this study constructed an analytical framework of coupling coordination evolution between urban resilience and transportation infrastructure. On this basis, we conducted an empirical study on the coupling coordination evolution characteristics between urban resilience and transportation infrastructure of the Yangtze River Delta from 2008 to 2018. The results show the following: First, the overall urban resilience level of the Yangtze River Delta shows a wave rising trend, and the region presents a spatial distribution pattern of "higher in the east and the south, and gradually decreasing to the northwest." The overall level of transportation infrastructure in the Yangtze River Delta has a fluctuating development trend after a stable rise, while the construction of most urban internal transportation infrastructure is in a "bottleneck period." Second, the degree of coupling coordination between urban resilience and the transportation infrastructure level in the Yangtze River Delta region is generally fluctuating and rising, but the coordination level is low, and it is in the transition stage from mild imbalance to primary coordination, and there is a significant spatial differentiation phenomenon, gradually forming a spatial pattern of "strong in the east coast and gradually decreasing toward the west edge." Finally, the level of coupling coordination in the Yangtze River Delta region has a positive spatial autocorrelation as a whole, and the degree of mutual agglomeration is developing steadily. However, the degree of differences in coordination and agglomeration between cities in the region has been expanding, with most low coupling coordination agglomeration cities and few high coupling coordination agglomeration cities.

7.2 Suggestions

Based on the research conclusions, this article proposes the following three suggestions: establish the concept of resilient urban development, make up for shortcomings, and improve risk response capabilities. Most of the uncoupled cities in the Yangtze River Delta are underdeveloped cities with urban resilience construction. Accelerating the transformation of underdeveloped cities to resilient cities has become the focus of boosting the construction of various branches of the city in the future. Therefore, in future urban development planning, the concept of urban resilience construction and the characteristics of connotative development should be learned and deepened, multidimensional and multi-level resilience of top-level design should be carried out, scientific and reasonable system improvement plans should be formulated, and the urban internal resilience systems, such as economy, society, ecology, and infrastructure, should be started. Making the development degree of the urban system can match the response and recovery capabilities in the face of major safety risk accidents and maximize the city's self-adjustment and self-adaptive capabilities. Second, promote the integration of urban agglomeration transportation infrastructure, break bottlenecks, and narrow the gap in urban development. The operation status of the transportation infrastructure in developed urban resilience areas is too saturated, and there are a series of negative problems such as urban traffic congestion and increased traffic pressure. However, the transportation capacity of transportation infrastructure in areas with underdeveloped urban resilience is insufficient, and there is a large gap in the construction of urban safety systems, which affects the operating efficiency of the overall transportation network in the Yangtze River Delta. Therefore, for cities with a low degree of transportation network development, government functions to strengthen cooperation with social capital must be flexibly used, innovative financing mechanisms must be used to increase the proportion of infrastructure construction expenditures, and the development of urban integrated systems must be promoted. For cities with more mature transportation networks, the strength of the transportation network connection and the resilience of the network structure must be improved or guaranteed, the interconnection of transportation infrastructure between cities must be strengthened, and the high-quality development of transportation network integration in the Yangtze River Delta must be led and supported. Finally, mutual assistance and cooperation within urban agglomerations should be actively carried out to promote the coordinated development of urban safety systems and infrastructure. While ensuring that cities with relatively high levels of resilience development in the Yangtze River Delta region continues to deepen their urban security systems, these cities can carry out policy support and financial assistance to the underdeveloped regions in the Yangtze River Delta, drive the resilience development level of multiple entities in the urban system to enhance the ability of cities to withstand disasters, further enhance the positive effect of spatial agglomeration on enhancing the city's security risk prevention, effectively reduce the development level differences between cities, and promote the overall balanced and coordinated development of the Yangtze River Delta.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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