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***Journal of Scientific and Engineering Research*, 2023, 10(5):44-51**

Research Article

ISSN: 2394-2630
CODEN(USA): JSERBR

Structural characteristics of transportation network in the central area of the Yangtze River Delta

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Abstract Taking 27 cities in the central urban agglomeration of the Yangtze River Delta as the research object, the Page Rank algorithm and the rank scale rule were comprehensively applied, based on railway train frequency and highway passenger transport frequency data, to deeply reveal the structural characteristics of the transportation network in the central area of the Yangtze River Delta. Research has found that: (1) the centrality of nodes in the central region of the Yangtze River Delta exhibits a power-law distribution. Moreover, both the railway and highway networks exhibit a spatial pattern of "dense in the east and sparse in the west", with Shanghai as the main core and cities such as Nanjing and Hangzhou as secondary cores, exhibiting a clear multi-core distribution pattern. (2) Overall, the connection strength of regional transportation networks shows a strong trend in the east and weak in the west, and there are differences in the importance of nodes between railway and highway networks. The node importance and connection strength of the railway network are distributed along the main railway line, while the overall node importance of the highway network shows a strong trend in the north and weak in the south.

Keywords transportation network, the central area of the Yangtze River Delta, complex networks, Page Rank, Rank Scale

1. Introduction

Transportation is a basic, leading and strategic industry in the national economy, an important service industry and an important part of the modern economic system, an important support for building a new development pattern, and a solid guarantee for serving the people's better life and promoting common prosperity [1]. The construction and development of transport infrastructure plays an important role in shortening the space and time distance between regions, reducing regional differences, strengthening contact and interaction, and promoting the development of regional economy [2]. In recent years, with the diversification of data acquisition methods, some scholars have studied and analyzed the structural characteristics of regional transportation networks from the perspective of "flow space". However, relevant research is mostly based on traffic flow data of a single transportation mode (such as air flow [3], road flow [4], railway flow [5]) to study the strength and structural characteristics of urban transportation connections. Mazzarisi considered the number of walks in the network and studied the centrality of the air traffic network [6]. Zheng Yibin found that the overall connectivity of the expressway network in Hubei Province is good, while some areas with low node degrees and clustering coefficients have poor connectivity [7]. Yuan Xiaofeng studied the structural characteristics of the Yunnan railway bulk cargo transportation network and found that it exhibits significant hub and spoke characteristics, with significant differences in the scale and transportation accessibility of each node [8]. Although some scholars have compared and analyzed the strength of transportation connections between cities under different transportation modes using multivariate traffic flow data [9,10], there are not many relevant research literature.

The transportation network is an important carrier for promoting the components of economic development, affecting the layout of regional economic development, factor supply patterns, and many other aspects. Compared to using traditional data such as railway mileage and highway mileage to measure transportation infrastructure, "flow space" data such as train frequency and car frequency can better reflect the connection strength of factor flow between cities under specific transportation network conditions. The central area of the Yangtze River Delta is a key urban cluster with rapid economic development and strong factor mobility in China, and has a typical representation in terms of transportation connectivity. In view of this, this paper takes 27 typical cities in the central area of the Yangtze River Delta as the research unit, and based on the perspective of "flow space" of railways and highways, uses Page Rank algorithm, rank scale rule, exploratory spatial analysis, geographical weighted regression and other research methods to compare and analyze the structural characteristics of railway and highway transportation networks in the central area of the Yangtze River Delta.

2. Overview of research area and data sources

2.1 Overview of research area

As a key urban agglomeration in China and even globally, the Yangtze River Delta Central Area urban agglomeration covers 27 cities including Shanghai, Nanjing, Wuxi, Changzhou, Suzhou, Nantong, Yancheng, Yangzhou, Zhenjiang, and Taizhou in Jiangsu Province, Hangzhou, Ningbo, Wenzhou, Jiaxing, Huzhou, Shaoxing, Jinhua, Zhoushan, and Taizhou in Zhejiang Province, and Hefei, Wuhu, Ma'anshan, Tongling, Anqing, Chuzhou, Chizhou, and Xuancheng in Anhui Province, It has obvious comparative advantages in terms of resources and transportation (Fig 1). As of 2021, the highway mileage in the central area of the Yangtze River Delta has reached 326100 kilometers, including 11626 kilometers of highways. In 2021, the GDP of the central region of the Yangtze River Delta was 23.8 trillion yuan, accounting for 20.8% of the total GDP of the country. The central area of the Yangtze River Delta is a representative area for the development of China's economy and transport infrastructure. Studying the characteristics of transportation structure and economic agglomeration in this area has important reference significance for leading the high-quality development of the country and building a modern economic system.

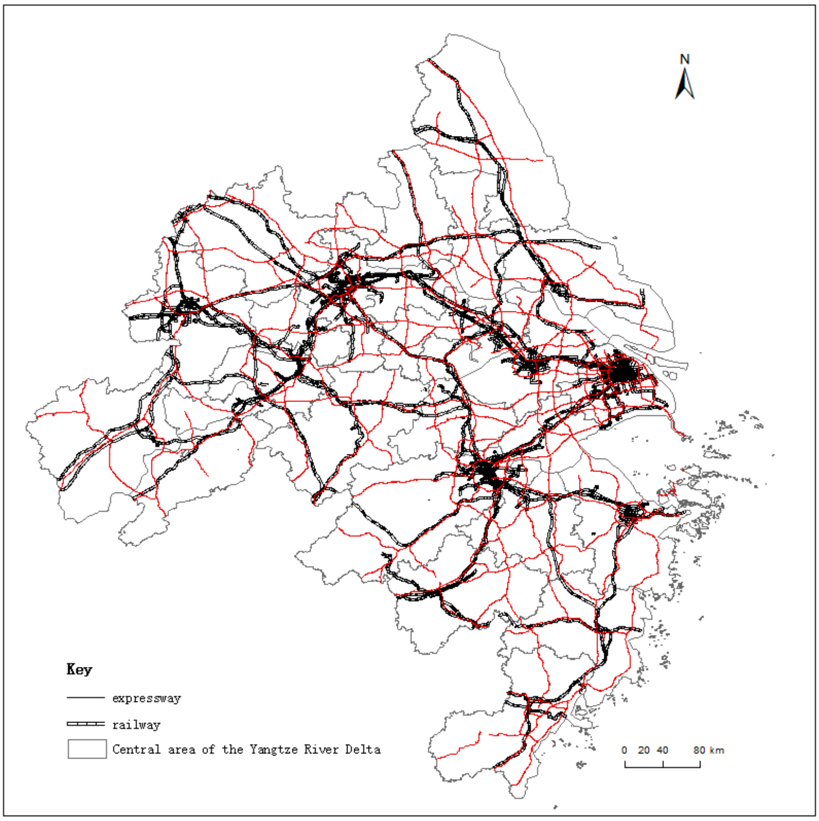


Figure 1: Traffic network distribution in the central area of the Yangtze River Delta

2.2. Data Sources

The intercity passenger transportation in the central area of the Yangtze River Delta mainly relies on highways and railways. Train frequency data and car frequency data between 27 cities in the central area of the Yangtze River Delta were obtained from China Railway 12306 and Ctrip, respectively, and constructed a 27× 27 matrix. Due to the relatively fixed number of train and bus trips per day, the data on March 16, 2021 was taken as research data. The kilometer mileage data and economic development data are sourced from the 2021 statistical yearbook and 2021 statistical bulletin of various cities in the central area of the Yangtze River Delta.

3. Models and Methods

3.1. Complex Network Analysis Method

The theory of complex networks originated from the "Seven Bridge Problem" proposed by Euler in the 18th century [11], and has been widely applied in various disciplines such as society, economy, life, and engineering. When analyzing the topological structure of complex networks, statistical indicators need to be selected for description and analysis. This article selects point centrality, proximity centrality, and intermediary centrality to analyze the transportation network structure of the Yangtze River Delta urban agglomeration.

(1) The degree of centrality is used to describe the degree of influence of a node in the entire network. The higher the centrality of a point, the higher its core position in the overall network, and the stronger its control over other cities [12]. The formula is as follows:

$$C_i^D = \frac{1}{n-1}\sum_{j=1}^{n} x_{ij} \tag{1}$$

C_i^D is the degree and centrality of the node; x_{ij} refers to the association between nodes. If there is an association, it is recorded $x_{ij} = 1$; otherwise, it is 0. N is the number of network nodes.

(2) Proximity centrality refers to the degree of proximity between a node in a network and other neighboring nodes. The larger the value is, the stronger the centrality of the node is, the better the relative reachability is [13], and the more important the node is. The calculation formula is:

$$C_i^C = \frac{1}{n-1}\sum_{j=1, j\neq i}^{n} d_{ij} \tag{2}$$

C_i^C represents the proximity centrality of node i ; d_{ij} represents the average path length between nodes i and j .

(3) The centrality of intermediaries represents the position of nodes in the network and reflects their ability to control system resources. If a city is on the shortest path of other node cities in the network, its resource control will be stronger, and the intermediary centrality will be higher [14,15]. The formula is:

$$C_i^B = \frac{1}{(\text{n-1})(n-2)}\sum_{j=1, k=1, j\neq k\neq i}^{n} \frac{b_{jk}(i)}{b_{jk}} \tag{3}$$

C_i^B represents the intermediate centrality of node i ; b_{jk} represents the number of shortest paths between nodes i and k ; $b_{jk}(i)$ represents the number of shortest paths passing through i in the shortest path between nodes j and k .

3.2. Importance of transportation network nodes

The importance of a city in a regional transportation network can be reflected by calculating the importance of its transportation network nodes. This article uses the Page Rank algorithm to measure it, and the relationship between the size of a city and its ranking is determined based on the ranking scale rule.

(1) The Page Rank algorithm. This algorithm was used in the early days to sort the importance of web pages, and this article applies it to urban importance sorting. Consider the 27 cities in the central area of the Yangtze River Delta as transportation network nodes, and the number of trains between the two cities is equivalent to a

link on a webpage. The more links there are, the higher the importance of the nodes [16]. The calculation formula is as follows:

$$PageRank_i = (1-\alpha)\frac{1}{N} + \alpha\sum_{i=1}^{N}\frac{PageRank_j}{K_j^{out}} \quad (4)$$

N is the total number of nodes in the city in the network; α is the damping coefficient, usually taken as 0.85; K_j^{out} is the number of vehicles flowing out of node j.

(2) Ranking Scale Rule. The order size rule was originally used to examine the distribution pattern of urban scale, revealing the relationship between the order and size of urban scale in descending order [17]. It generally adopts the Rotka model:

$$P_i = P_1 R_i^{-q}, (R_i = 1, 2, \cdots, n) \quad (5)$$

R_i is the ranking of city i in descending order; P_i is the city size corresponding to R_i in order; P_1 is the city size of the first city; q is a constant, commonly referred to as the Zipf dimension. Take the natural logarithm of the above formula to get the following formula:

$$\ln P_i = \ln P_1 - qR_i, (R_i = 1, 2, \cdots, n) \quad (6)$$

Taking $q=1$ as the benchmark, if $q>1$, it indicates that the distribution of urban size is relatively concentrated, that is, the high ranking cities are more prominent, and the development of small and medium-sized cities is insufficient. If $q<1$, it indicates that the distribution of city size is relatively scattered, with more cities in the middle ranking and more prominent cities in the high ranking, and the overall balance is relatively balanced [18].

4. Practical Analysis

4.1 Nodal analysis of Transportation Network

4.1.1 Analysis of network node importance

The centrality of each city in the central area of the Yangtze River Delta was calculated using the Page Rank algorithm, and the spatial distribution of centrality values of railway network nodes in the urban agglomeration of the central area of the Yangtze River Delta was analyzed using the inverse distance weighting method of Arc GIS (Fig 2 (a)) and the spatial distribution of centrality values of highway network nodes (Fig 2 (b)). From Fig 2 (a), it can be seen that in the ranking of railway transportation network node importance, the node importance of cities along the Shanghai Nanjing High Speed Railway, Shanghai Hangzhou High Speed Railway, and Nanjing Hangzhou High Speed Railway is higher, while the railway network node importance ranking of peripheral cities such as Yancheng, Chuzhou, and Chizhou is lower. Zhoushan City has not yet opened railways, so it ranks last in the railway transportation network and is in an isolated area of the network. Overall, the importance of railway transportation network nodes in the central area of the Yangtze River Delta shows a significant radial distribution along the railway main line, and the "Golden Triangle" distribution characteristics of Shanghai Nanjing Hangzhou are significant. The Shanghai Nanjing, Shanghai Hangzhou, and Nanjing Hangzhou high-speed railways play an important role in the formation of the tripartite distribution pattern of the urban agglomeration in the central area of the Yangtze River Delta.

From Fig 2 (b), it can be seen that the importance of highway transportation network nodes in the central area of the Yangtze River Delta shows a clear characteristic of "strong in the east and weak in the west". Shanghai ranks first in terms of the importance of highway transportation network nodes, followed by Hangzhou and Nanjing. However, some cities in the western part of the Yangtze River Delta central area, such as Anqing, Chuzhou, Tongling, and other eastern cities, have relatively low levels of highway transportation network connectivity. The western urban road network in the central area of the Yangtze River Delta is relatively complete, but due to the limited connection with the eastern urban road schedules, the importance of the western urban road network nodes is relatively low. In future development, it is necessary to further enhance the radiation breadth and depth of the eastern cities in the central area of the Yangtze River Delta, and promote the better integration of western cities into the central area of the Yangtze River Delta.

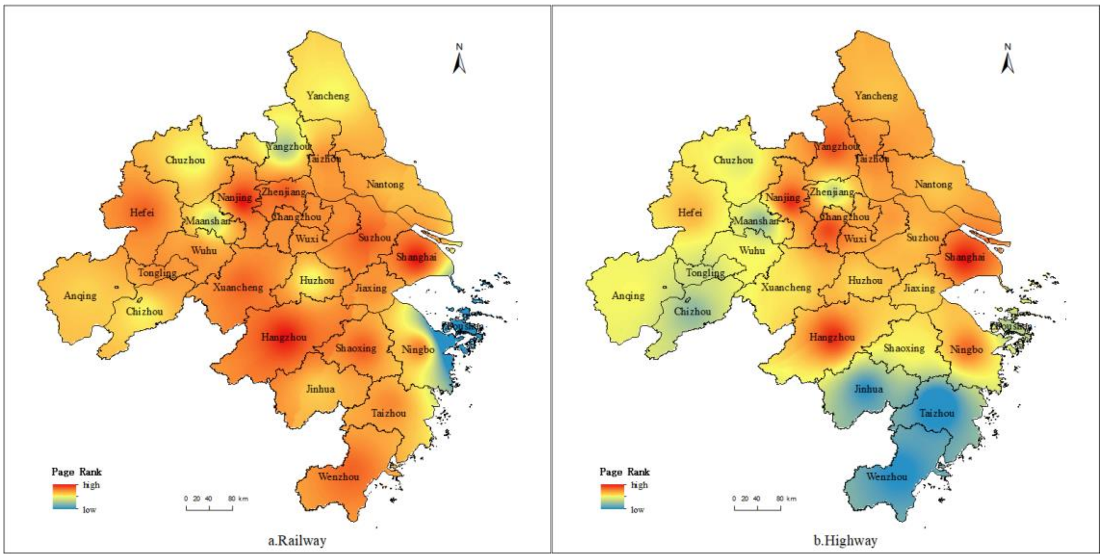
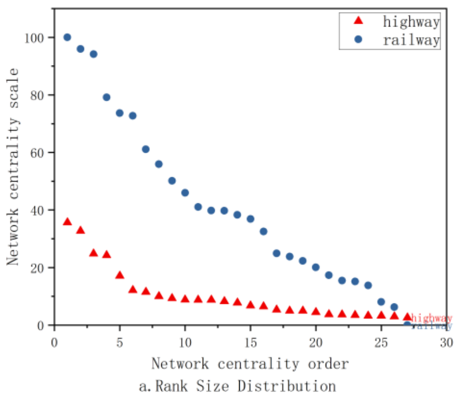


Figure 2: The distribution of node importance of the multi traffic flow network in the central area of the Yangtze River Delta

4.1.2 Ranking scale distribution characteristics

Based on the order scale rule, the distribution map of urban order scale in the central area of the Yangtze River Delta was calculated (Fig 3 (a)). The overall distribution of urban order and scale in the central area of the Yangtze River Delta follows a power exponential function, and as the network centrality order decreases, the network centrality gradually decreases. The decay rate of urban order scale based on railway network is significantly higher than that of highway network. The double logarithmic linear fitting results based on the centrality order scale of railway and highway transportation networks are shown in Fig 3 (b) and 3 (c), respectively. The judgment coefficients R^2 are 0.967 and 0.990, both of which passed the significance test. At the same time, the slope k of the fitting curve is greater than 1, indicating that the distribution of network centrality scale in the central area of the Yangtze River Delta is relatively concentrated, with core cities such as Shanghai, Nanjing, and Hangzhou playing a prominent role in the first place, and the scale effect is prominent. However, cities such as Chizhou, Anqing, Wenzhou, and Taizhou are developing slowly.



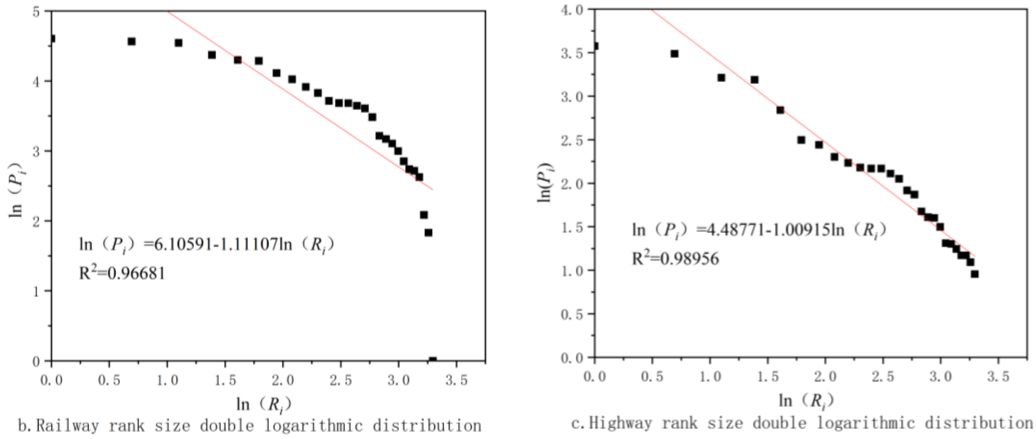


Figure 3: Urban location size distribution characterized by traffic flow network centrality in the central area of the Yangtze River Delta

4.2 Analysis of Network Connection Strength

Using the train and bus schedules between two cities as the strength of the connection between cities, a connection matrix between cities is drawn. Using the natural breakpoint method of Arc GIS, the node flow and connection strength of the railway and highway networks are divided into five levels, and a comparative analysis is conducted (Fig 4). From the overall connection strength, the railway network between cities in the central area of the Yangtze River Delta is close, while the highway network is relatively weak; From the perspective of spatial form of connections, the central area of the Yangtze River Delta presents a clear multi center feature, with Shanghai as the main core and Hangzhou and Nanjing as secondary cores.

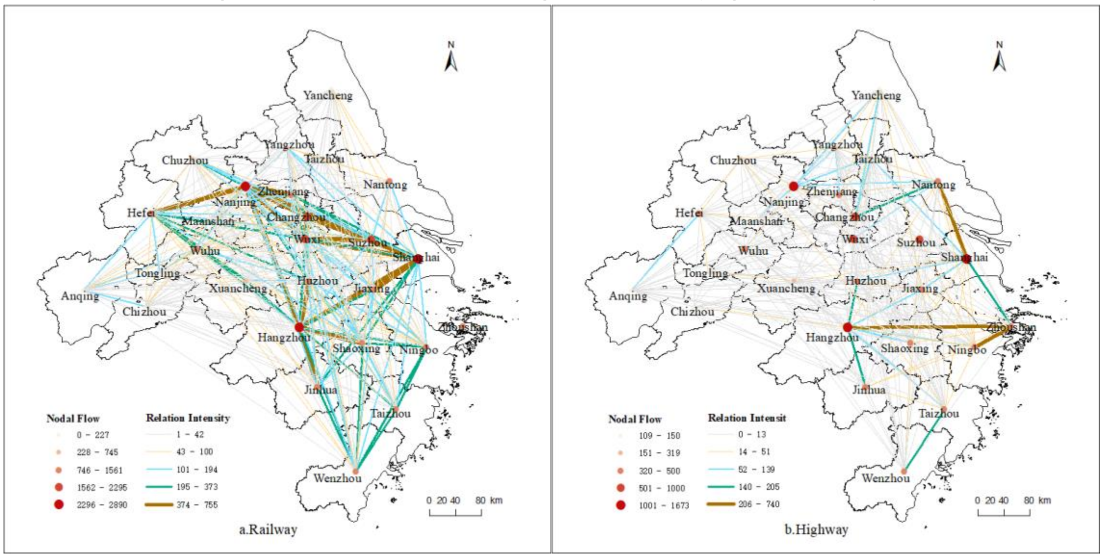


Figure 4: Spatial pattern of traffic flow network in the central area of the Yangtze River Delta

In the railway transportation network, the central area of the Yangtze River Delta forms a high-intensity railway flow along multiple railway trunk lines such as the Shanghai Hangzhou Line, the Shanghai Nanjing He Line, and the Nanjing Hangzhou Line. Among them, Shanghai, Nanjing, and Hangzhou have the highest node traffic and have the closest connection with other cities in the Yangtze River Delta, with node traffic reaching over 2700 times; Most cities in Anhui and peripheral cities in Jiangsu have low node traffic, with less than 500 times. From the perspective of railway transportation connections, Shanghai Suzhou Wuxi Changzhou Nanjing, Shanghai Hangzhou Jiaxing, Hangzhou Shaoxing, Hangzhou Zhoushan, Hangzhou Huzhou, and Hangzhou Jinhua are at the first level of connection, with frequent urban exchanges and significant clustering effects. However, the overall connection strength between central Jiangsu, northern Jiangsu, and Anhui Province is relatively low, and there is relatively little communication with core cities. Hefei and Nanjing should fully play their radiating and driving role to promote economic and cultural exchanges between central Jiangsu, northern Jiangsu, and Anhui Province with other cities.

Compared with the railway transportation network, the highway transportation network is relatively sparse, with fewer node flows and fewer daily average train trips. The strength of external connections between the highway networks of different cities varies greatly, and they are in an unbalanced state. Comparing the node flow of the Yangtze River Delta and the strength of the connection between the two cities, it was found that Shanghai, Hangzhou, and Zhoushan occupy the first level of the highway network, and are closely connected to surrounding cities such as Suzhou, Wuxi, Nanjing, Changzhou, Jiaxing, and Shaoxing. Zhoushan is an island city with abundant tourism resources. There are scenic spots such as Putuo Mountain and Shengsi Islands in the city, and residents of surrounding cities come to visit. Therefore, the node flow in the highway transportation network is high and the connection strength is high.

5. Results and Discussion

In the context of the integrated development strategy of the Yangtze River Delta urban agglomeration, this article comprehensively applies complex network analysis, Page Rank algorithm, and order scale rule to analyze the network structure characteristics of the central area of the Yangtze River Delta urban agglomeration from the perspectives of railway network and highway network. The following conclusion is drawn:

(1) In the nodal analysis, it is found that the spatial distribution of highway and railway transportation networks has certain similarity, with Shanghai as the main core and Nanjing, Hangzhou and other cities as the secondary core, showing an obvious multi-core network pattern. Moreover, the node centrality of cities in the central area of the Yangtze River Delta follows a power law distribution, and the scale distribution of node centrality is relatively concentrated. The role of core cities such as Shanghai, Nanjing, and Hangzhou is prominent.

(2) In the overall connection, the railway network in the central area of the Yangtze River Delta presents a three-dimensional structure, while the highway network presents a spatial pattern of "dense in the east and sparse in the west". The Shanghai Nanjing Hangzhou Ningbo development belt has frequent exchanges and close ties, which is highly consistent with the comprehensive transportation network layout of the Yangtze River Delta urban agglomeration, reflecting that transport infrastructure plays a good role in promoting the close ties between cities and the coordinated development of regions.

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