Analysis of spatial interaction vitality based on high-speed railway network and highway network

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Abstract. This paper applies spatial interaction model theory to analyse the impact of transportation network infrastructure construction on the city. 36 cities in Chinese high-speed railways network and 72 cities in Chinese highway networks are selected, and the interactive vitality of cities is calculated and analysed from the perspective of the two networks. The spatial interaction vitality of some cities on two networks is different. Cities like Beijing, Shanghai and Zhengzhou perform well on both networks, while the remote areas such as Kuerle and Lasa has low values, indicating the urban spatial interaction vitality is related to the construction of transportation network infrastructure and is consistent with the actual situation.

1. Introduction
In recent years, China's cities have developed rapidly, and transportation has too. A certain transportation network has been formed in and between cities, and the connection between cities and cities has become closer. By 2020, China's planning network for expressways and high-speed railways has been relatively complete, and many scholars have described and evaluated the transportation network. Jia and Ma describe the structure and nature of Xi'an’s public transport network using knowledge of complex networks[1]. Mostafa et al. used the double-layer network to analyse the network vulnerability of the railway[2]. Li and Guo selected three indicators of highway network density, transportation network proximity, and location advantages related to central cities to study the road distribution in China's counties[3].

In addition to enhancing the connectivity between cities, the construction of transportation networks will also affect the development of cities. In the past, when evaluating the impact of transportation network construction on urban development, more attention was paid to indicators such as accessibility and connectivity[4]. Accessibility refers to the degree of convenience from one place to another. Zhang proposed a method to measure the accessibility of urban three-dimensional transportation network based on GIS and spatial syntax model[5]. Deng used the internationally mature TOPSIS evaluation method to analyze the current status of urban road network accessibility in Chengdu's major satellite cities[6]. Chen explained the development process of land transportation network using a 100-year time scale system[7]. Chen selected several measurement methods of network topology to test and quantify the overall growth of the subway network in Guangzhou urban area[8]. Fan analyzed the connectivity and accessibility of China's railway network with the county as the basic research unit[9]. The above analysis did not take into account economic factors too much.
The emergence of spatial interaction theory can solve this problem well. Ullmann introduced spatial interaction theory into existing traffic models, creating a new chapter[10]. Spatial interaction refers to the movement of pedestrians, goods and other materials in various forms in different spaces. There are spatial interactions in the fields of railway transportation, shipping, shipping, roads, and electronic communications. This paper uses the spatial interaction vitality model to evaluate the impact of transportation network infrastructure construction on the city from the two perspectives of high-speed railway network and highway network.

The rest of this paper is organized as follows. Section 2 discusses the methodology of this study and Section 3 discusses how to construct the network. In Section 4, we will calculate the interactive vitality of key cities in the high-speed railway network and highway network. Finally, the conclusions are given in Section 5.

2. Methodology

2.1. Traditional spatial interaction vitality definition and model
Spatial interaction refers to the movement of pedestrians, goods and other materials in various forms in different spaces. There are spatial interactions in the fields of railway transportation, shipping, shipping, roads, and electronic communications. The model established to solve the problem of spatial interaction is called the spatial interaction model.

The spatial interaction vitality model believes that individuals of city \( i \) will always interact with individuals of some other city with a certain probability. It is assumed that this probability will be proportional to the number of attractive opportunities \( m_j \) of interactive city \( j \), and inversely proportional to the total number of attraction opportunities \( S_{ij} \) of all cities between \( i \) and \( j \) (cities are sorted by travel time from city \( i \)):

\[
P_{ij} = \frac{m_j}{S_{ij}}
\]

Among them, \( P_{ij} \) is the probability that individuals of city \( i \) will always interact with individuals of some other city.

2.2. Spatial interactive vitality model considering economy and population
On the other hand, the greater the population \( n_i \) of city \( i \), the greater the total number of interactions initiated by the city’s population with other cities, so we assume that the total number of interactions initiated by the city is proportional to the population of the city. Then, the amount of spatial interaction from \( i \) to \( j \) can be expressed as:

\[
T_{ij} = \frac{n_i m_j}{S_{ij}}, \quad t_{ij} \leq \tau
\]

Where \( T_{ij} \) is the shortest travel time from city \( i \) to \( j \), and \( \tau \) is the longest (average) travel time threshold that the interactor can accept (that is, the individual who initiates the interaction from point \( i \), and the travel time between the city \( j \) and \( i \) is not greater than \( \tau \) value. In practice, the acceptable long travel time threshold for different individuals is different. For example, some people can accept inter-city travel within 10 hours, but some people can only accept inter-city travel within 5 hours. So we set \( \tau \) can be regarded as the average travel time threshold acceptable to the group). Note that the spatial interaction quantity \( T_{ij} \) calculated by the above formula is not a certain actual flow, but a dimensionless value reflecting the vitality of spatial interaction.

The population size, economic development level or other indicators can be used to determine the quality of a city. Walter believes that indicators such as urban economic development and employment opportunities should be used when studying the problem of traveler movement between cities. To reflect the attractiveness of the city more representative. Therefore, when using the spatial interaction vitality model to calculate the spatial interaction vitality of a city, the number of interaction opportunities \( m_j \) of city \( j \) is assumed to be proportional to the city’s GDP. This is because a city with a higher GDP tends to
have greater socioeconomic attractiveness, and individuals in other cities choose to interact with the city more often.

The $T_{ij}$ calculated by the equation (3) can further calculate the interactive vitality of each city:

$$T_{ij} = \frac{n_i m_j}{S_{ij}}, \quad t_{ij} \leq \tau$$

(3)

Where $T_j$ is the average of the number of interactions and the number of attractive interactions that occurred from city $i$.

Then the total interactive vitality of the entire area can be calculated using the following formula:

$$T = \sum_{j} \sum_{i \neq j} T_{ij}$$

(4)

Note that the amount of interaction $T$ calculated here does not directly reflect a certain actual flow (such as the amount of travel between cities in traffic, the amount of trade between cities in the economy, the number of contacts between cities in social interaction, etc.), but reflects spatial interaction A relative indicator of strength. By adopting the spatial interaction vitality model, the total number of interactions between cities can be obtained. In this paper, urban interaction vitality is defined as the total number of spatial interactions between cities. And we set the travel time threshold $\tau$ is 6.5 hours.

3. Network constructions of the highway network and high-speed railway

In this paper, we start from the two aspects: highway network and high-speed rail network, and analyze the vitality of cities under different networks. We choose representative 72 cities to evaluate the highway network and extracted 36 cities from Chinese high-speed railway information and built a topological network. The typical topology of these two network is shown in Figure 1.

![Figure 1. Topological structure of network (left: highway network, right: high-speed railway network).](image)

4. Experiment

4.1. Calculation of interactive vitality of urban space based on high-speed railway

Jinan is located in East China, Midwestern Shandong, and the eastern edge of the North China Plain. It is the army station of the People’s Liberation Army in the Northern, the core city of the Shandong Peninsula city group, the capital economic circle in the north, the Yangtze River Delta economic circle in the south, and the Shandong Peninsula in the east. It is an important intersection of the Bohai Rim Economic Zone and the Beijing-Shanghai economic axis, and one of the central cities in the Bohai Rim and the middle and lower reaches of the Yellow River. Take Jinan’s spatial interaction vitality as an example for calculation.

First, take Jinan as a starting point to calculate the interactive vitality. The data required for calculation is shown in Table 1.
Table 1. Data needed to calculate the number of interactions from Jinan.

| Starting point | End          | Travel time (h) | GDP(Ten thousand yuan) | Population (Million) |
|----------------|--------------|-----------------|------------------------|----------------------|
| Shenyang       | Jinan        | 4.4             | 63500000               | 829                  |
| Nanchang       | Jinan        | 5.2             | 52740000               | 546                  |
| Hefei          | Jinan        | 2.9             | 78220000               | 803                  |
| Nanjing        | Jinan        | 2               | 128200000              | 850                  |
| Zhengzhou      | Jinan        | 3.2             | 102000000              | 1012                 |
| Wuhan          | Jinan        | 4.5             | 148470000              | 1122                 |
| Xian           | Jinan        | 4.8             | 83490000               | 1255                 |
| Ningbo         | Jinan        | 3.8             | 107450000              | 801                  |
| Hangzhou       | Jinan        | 3               | 135000000              | 949                  |
| Beijing        | Jinan        | 1.5             | 303200000              | 2171                 |
| Shijiazhuang   | Jinan        | 1.8             | 69630000               | 1078                 |
| Huhehaote      | Jinan        | 3               | 25080000               | 311                  |
| Changsha       | Jinan        | 5.8             | 115270000              | 800                  |
| Taiyuan        | Jinan        | 3.3             | 38840000               | 438                  |
| Dalian         | Jinan        | 5.9             | 78250000               | 702                  |
| Changchun      | Jinan        | 5.4             | 70850000               | 749                  |
| Shanghai       | Jinan        | 3               | 326790000              | 2418                 |
| Haerbin        | Jinan        | 6.4             | 70020000               | 1093                 |
| Qingdao        | Jinan        | 1.7             | 125610000              | 929                  |
| Tianjin        | Jinan        | 1               | 188090000              | 1557                 |

Take Jinan to Shenyang as an example for calculation, the process is as follows:

Jinan→Shenyang: it takes Tianjin from Jinan to Shenyang, so: Jinan→Tianjin→Shenyang

\[
S_{ij} = 88620000 + 188090000 + 63500000 = 340210000
\]

\[
T_{ij} = \frac{n_i m_j}{S_{ij}} = \frac{870 \times 63500000}{340210000} = 162.39
\]

Then take Jinan as an end to calculate the interactive vitality. The data required for calculation is shown in Table 2.

Table 2. Data required to calculate the number of interactions attracted from Jinan.

| Starting point | End          | Travel time (h) | GDP(Ten thousand yuan) | Population (Million) |
|----------------|--------------|-----------------|------------------------|----------------------|
| Shenyang       | Jinan        | 4.4             | 63500000               | 829                  |
| Nanchang       | Jinan        | 5.2             | 52740000               | 546                  |
| Hefei          | Jinan        | 2.9             | 78220000               | 803                  |
| Nanjing        | Jinan        | 2               | 128200000              | 850                  |
| Zhengzhou      | Jinan        | 3.2             | 102000000              | 1012                 |
| Wuhan          | Jinan        | 4.5             | 148470000              | 1122                 |
| Xian           | Jinan        | 4.8             | 83490000               | 1255                 |
| Ningbo         | Jinan        | 3.8             | 107450000              | 801                  |
| Hangzhou       | Jinan        | 3               | 135000000              | 949                  |
| Beijing        | Jinan        | 1.5             | 303200000              | 2171                 |
| Shijiazhuang   | Jinan        | 1.8             | 69630000               | 1078                 |
| Huhehaote      | Jinan        | 3               | 25080000               | 311                  |
| Changsha       | Jinan        | 5.8             | 115270000              | 800                  |
| Taiyuan        | Jinan        | 3.3             | 38840000               | 438                  |
Take Shenyang to Tianjin as an example for calculation, the process is as follows:
Shenyang→Jinan: it takes Tianjin from Shenyang to Jinan, so: Shenyang→Tianjin→Jinan

\[ S_{ij} = 88620000 + 188090000 + 63500000 = 340210000 \]

\[ T_{ij} = \frac{n_i m_j}{S_{ij}} = \frac{829 \times 88620000}{340210000} = 215.94 \]

In this way, we can calculate the interactive vitality of each city, and the results of the calculation are shown in the Table 3, and sorted from high to low.

Table 3. The spatial interaction vitality ranking of key high-speed rail cities.

| City      | Total interactive vitality | Sent from the city | Attracted by the city |
|-----------|----------------------------|--------------------|----------------------|
| Beijing   | 8748.1                     | 7438.3             | 10058.0              |
| Shanghai  | 7759.2                     | 7121.4             | 8396.9               |
| Jinan     | 6369.9                     | 7438.3             | 5301.6               |
| Tianjin   | 7177.9                     | 6816.7             | 7539.0               |
| Wuhan     | 6721.0                     | 6076.3             | 7365.7               |
| Zhengzhou | 6428.0                     | 6675.9             | 6180.2               |
| Nanjing   | 6114.0                     | 5222.0             | 7005.9               |
| Hangzhou  | 5726.9                     | 5195.3             | 6258.5               |
| Shijiazhuang | 5595.4                    | 7107.5             | 4083.2               |
| Xian      | 5102.8                     | 6328.9             | 3876.7               |
| Changsha  | 4888.9                     | 4278.2             | 5499.7               |
| Hefei     | 4244.5                     | 4699.5             | 3789.5               |
| Qingdao   | 4211.0                     | 3776.8             | 4645.1               |
| Guangzhou | 3910.8                     | 3113.9             | 4707.7               |
| Ningbo    | 3688.6                     | 3441.3             | 3935.9               |
| Nanchang  | 3498.9                     | 3840.0             | 3157.9               |
| Shenyang  | 3063.5                     | 3560.6             | 2566.5               |
| Fuzhou    | 2856.7                     | 3183.7             | 2529.7               |
| Taiyuan   | 2405.4                     | 2588.6             | 2222.1               |
| Changchun | 2262.8                     | 2262.8             | 2262.7               |
| Haerbin   | 2052.1                     | 2570.0             | 1534.2               |
| Dalian    | 1979.2                     | 1844.7             | 2113.7               |
| Nanjing   | 1537.5                     | 2075.3             | 999.7                |
| Chengdu   | 1182.1                     | 915.4              | 1448.9               |
| Chongqing | 1182.1                     | 1448.9             | 915.4                |
| Huhehaote | 935.0                      | 1087.4             | 782.5                |
| Guiyang   | 909.1                      | 964.2              | 854.1                |
| Lanzhou   | 814.8                      | 835.2              | 794.3                |
| Kunming   | 673.2                      | 820.9              | 525.5                |
In order to more clearly compare the spatial interaction vitality of each city, we draw the following graphics.

| City  | Spatial Interaction Vitality | GDP   | Degree |
|-------|----------------------------|-------|--------|
| Xining| 317.8                      | 479.1 | 156.5  |
| Haikou| 165.2                      | 165.2 | 165.2  |
| Yinchuan| 141.0                 | 164.9 | 117.0  |

Figure 2. The spatial interaction vitality ranking of key high-speed rail cities.

From Figure 1, we can see that Zhengzhou ranks 5th in spatial interaction vitality, 13th in GDP in 2018, and 13th in degree value. Zhengzhou is the capital of Henan Province, an important central city in central China, a megacity, and a central city in the Central Plains urban agglomeration. It has a pivotal economic position. At the same time, the Zhengzhou Railway Hub is the two major railway arteries of the Beijing-Guangzhou Railway and the Longhai Railway (New Eurasian Continental Bridge), as well as the Beijing-Hong Kong High-speed Railway (the world’s longest high-speed rail line) and the Xulan High-speed Railway (New Eurasian Continental Bridge). The intersection of the high-speed rail traffic arteries with a speed of 350 kilometers per hour and above is a traffic hub that connects north and south and connects east and west. It is located in an important position in the center of the national road network and is known as the "heart of China's railway." Therefore, it is very convenient for Zhengzhou to communicate between North and South and East and West. With the improvement of the high-speed rail network, it takes two hours to reach Shijiazhuang, Xi’an, Jinan, Hefei, Nanjing, and Taiyuan with Zhengzhou as the center, three hours to Beijing, Wuhu, Qingdao, and Tianjin, and four hours to Changsha, Nan Chang, Hangzhou, Shanghai, Chongqing, six hours to Guangzhou, Shenyang, Fuzhou, Shenzhen, Nanning, Guiyang, Chengdu, Lanzhou, Yinchuan.

Jinan ranks 6th in spatial interaction vitality and 14th in GDP in 2018. Jinan is the core city of the Shandong Peninsula city cluster. It is connected to the Capital Economic Circle in the north, the Yangtze River Delta Economic Circle in the south, and the Shandong Peninsula in the east and west. One of the central cities of the region. Jinan is one of the 10 major regional passenger transport hubs under China's planning. It is located along the Beijing-Shanghai high-speed railway and will be connected to the Longhai Line, which will communicate east and west, and the transportation is very convenient.

The spatial interaction vitality of Chongqing and Chengdu ranks 24th and 25th, respectively. In 2018, GDP ranks 4th and 6th. The degree rankings are 19th and 24th respectively. Chongqing is the only municipality directly under the Central Government, a national central city, a megacity, and an international metropolis in the central and western regions. It is an economic, financial, scientific and technological innovation, shipping and commercial logistics center in the upper reaches of the Yangtze River, and an important strategic fulcrum for the development of the western region, the "Belt and Road" and An important connection point in the Yangtze River Economic Belt and inland open highlands.
Chengdu is the capital of Sichuan Province, a sub-provincial city, a mega city, an important national high-tech industrial base determined by the State Council, and an important central city in the western region. Chongqing and Chengdu are located in the southwestern hinterland, with complex geological conditions, and it is very difficult to construct high-speed railways. As a result, the connectivity with other cities across the country is relatively poor, and transportation is mostly by air and roads.

The GDP rankings of Shanghai and Qingdao are 1st and 10th, respectively, and the ranking of the degree value is 17th and 30th. Shanghai and Qingdao are very important in the country's economy. Both cities are coastal cities, communicating westward, and most of the high-speed rail lines start or end to the city.

4.2. Calculation of interactive vitality of urban space based on highway

In this part, the spatial interaction vitality model can be used to obtain the total number of interactions between cities. The total number of spatial interactions between cities is defined as urban interaction vitality. The travel time threshold is 6.5h. The specific calculation method is shown in the high-speed rail network. Some results of calculating the interactive vitality of high-speed networks are shown in Table 4, and the comparison chart of the spatial interaction vitality of the top 30 cities is shown in Figure 3.

| City               | Sent from the city | Attracted by the city | Total interactive vitality |
|--------------------|-------------------|----------------------|---------------------------|
| Xuzhou             | 9261.982          | 7145.613             | 8203.797                  |
| Zhengzhou          | 7561.68           | 8708.218             | 8134.949                  |
| Beijing            | 6046.165          | 10167.63             | 8106.899                  |
| Huaifang           | 8658.459          | 6655.966             | 7657.212                  |
| Hefei              | 7320.063          | 7780.627             | 7550.345                  |
| Jinan              | 6945.449          | 8093.202             | 7519.326                  |
| Tianjin            | 6127.378          | 8797.831             | 7462.605                  |
| Handan             | 10055.37          | 4632.42              | 7343.896                  |
| Shanghai           | 6134.404          | 8514.865             | 7324.634                  |
| Qingdao            | 5880.836          | 8259.358             | 7070.097                  |
| Nanjing            | 5371.342          | 8402.348             | 6886.845                  |
| Shijiazhuang       | 7143.483          | 5369.802             | 6256.643                  |
| Nanchang           | 5528.846          | 6168.937             | 5848.891                  |
| Tangshan           | 6445.195          | 5234.062             | 5839.628                  |
| Shangrao           | 8572.78           | 3024.425             | 5798.603                  |
| Wuhan              | 3619.43           | 7766.934             | 5693.182                  |
| Ganzhou            | 8408.038          | 2946.838             | 5677.438                  |
| Wuxi               | 3974.744          | 6924.571             | 5449.657                  |
| Hangzhou           | 4281.222          | 6443.687             | 5362.455                  |
| Luoyang            | 5867.809          | 4812.023             | 5339.916                  |
| Xian               | 5600.931          | 4761.062             | 5180.996                  |
| Jinhua             | 5252.507          | 4419.082             | 4835.795                  |
| Wenzhou            | 5597.726          | 3715.975             | 4656.851                  |
| Jiujiang           | 5773.391          | 3469.434             | 4621.413                  |
| Lianyungang        | 5364.191          | 3299.181             | 4331.686                  |

Table 4. The first 20 nodes with the longest average shortest path length.
| City     | Total Interactive Vitality | Distance to Beijing | Distance to Shanghai |
|----------|---------------------------|---------------------|---------------------|
| Guangzhou | 2767.93                   | 5575.47             | 4171.7              |
| Taiyuan   | 3699.368                  | 4112.194            | 3905.781            |
| Chongqing | 3982.508                  | 3611.561            | 3797.035            |
| Changsha  | 2391.385                  | 4838.276            | 3614.831            |
| Bengbu    | 4500.796                  | 2537.266            | 3519.031            |
| Wuhu      | 3595.626                  | 3233.208            | 3414.417            |
| Shenyang  | 3530.083                  | 3172.906            | 3351.495            |
| Yantai    | 2916.902                  | 3693.193            | 3305.048            |
| Fuzhou    | 2685.524                  | 3908.782            | 3297.153            |
| Shenzhen  | 1594.875                  | 4503.153            | 3049.014            |
| Zunyi     | 3074.047                  | 2223.582            | 2648.815            |
| Chengdu   | 2066.038                  | 3170.85             | 2618.444            |
| Nanning   | 2753.146                  | 2417.952            | 2585.549            |
| Guiyang   | 1935.735                  | 2772.997            | 2354.366            |
| Yulin     | 1816.94                   | 2871.519            | 2344.23             |
| Xiamen    | 1755.568                  | 2920.659            | 2338.114            |
| Liuzhou   | 1989.859                  | 2505.843            | 2247.851            |
| Changchun | 1737.143                  | 2749.487            | 2243.315            |
| Qinhuangdao| 2720.162                 | 1699.067            | 2209.614            |
| Guilin    | 3509.132                  | 793.6679            | 2151.4              |
| Zhanjiang | 2575.337                  | 1405.434            | 1990.386            |
| Tongliao  | 2251.376                  | 1496.675            | 1874.026            |
| Datong    | 2631.167                  | 1052.985            | 1842.076            |
| Shantou   | 2352.296                  | 1174.036            | 1763.166            |
| Haerbin   | 1559.238                  | 1793.663            | 1676.45             |
| Qujing    | 2204.521                  | 1145.877            | 1675.199            |
| Huhehaote | 1474.911                  | 1858.297            | 1666.604            |
| Dalian    | 1224.391                  | 1962.412            | 1593.401            |
| Baoji     | 1724.131                  | 1425.374            | 1574.752            |
| Quanzhou  | 846.2195                  | 1945.968            | 1396.094            |

Figure 3. Spatial interaction vitality of the top 30 cities.
According to the figure 4 and figure 5, we can find that when attacking nodes, deliberate attacks are more destructive than random attacks, but the difference is not obvious. One reason is that the Chinese highway network is multi-core, and even a deliberate attack would not immediately bring down the global network. On the other hand, the network has a large connection coverage, so the connection path between cities will not be completely destroyed because of one or two attacks.

From Table 4 and Figure 3, we can find that the spatial vitality of cities in the two networks is quite different. In the expressway network, Xuzhou has the highest interactive vitality, followed by Zhengzhou, and Beijing is the third and Shanghai is the ninth.

Xuzhou is located at the junction of the four provinces of Jiangsu, Shandong, Henan, and Anhui. It is known as the "five province thoroughfare" and is an important comprehensive transportation hub in the country. Xuzhou is the main hub of national highways. In recent years, highway infrastructure construction has continued to maintain a rapid development momentum. And from the analysis in the previous section, we know that Zhengzhou, Beijing, Shanghai and other cities have large economies, large populations, and good connectivity, and their interactive vitality ranks high, indicating that this indicator has a good explanatory effect on the relationship between transportation networks and urban development.

Shijiazhuang's spatial interaction vitality ranks 10th, and its GDP ranks 21st in 2018. Shijiazhuang is located in North China, the central and southern part of Hebei Province, and the Bohai Bay Economic Zone. It is a city approved by the State Council to implement coastal opening policies and financial opening to the outside world. It is also an important commodity distribution center in the country and an important business center in the north. It is a national trade and exhibition center. One of the cities. Shijiazhuang can not only have the political radiation ability in the whole province, but also form a strong economic radiation ability in the future in central and southern Hebei.

5. Conclusion

This paper analyzes and calculates the interactive vitality of important stations in the network from the perspective of expressway network and high-speed railway network. In addition to considering the impact of inter-city transportation network infrastructure construction, economic factors are also considered in the calculation, which is a new method. From the calculation results, Beijing, Shanghai, Zhengzhou and other cities perform very well on both networks, while the interaction vitality of more remote areas such as Kuerle and Lasa is very low, indicating the urban spatial interaction vitality It is related to the construction of transportation network infrastructure and is consistent with the actual situation.

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