The accessibility analysis of Beijing-Tianjin-Hebei railway passenger transport network —— before and after the opening of Beijing-Zhangjiakou high-speed railway

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Abstract. This paper focuses on the changes in the accessibility of railway passenger transport network in the Beijing-Tianjin-Hebei region before and after the opening of the Beijing-Zhangjiakou high-speed railway. It mainly uses for models: a spatial model based on node location, cost model based on travel expenditure, model based on weighted average travel time, model based on economic potential index. These four models, combined with the required data, give the accessibility of the Beijing-Tianjin-Hebei railway passenger transport network before and after the opening of the Beijing-Zhangjiakou high-speed railway. The results of these calculations are visualized and analysed. The conclusions are as follows: (1) After the opening of the Beijing-Zhangjiakou high-speed railway, the accessibility of most cities in the Beijing-Tianjin-Hebei region is found to be enhanced. (2) Accessibility of some cities is found to be decreased in some models. (3) For different accessibility models, the degree of accessibility change of each city is different. (4) After the opening of the Beijing-Zhangjiakou high-speed railway, the accessibility distribution of Beijing-Tianjin-Hebei is still different.

Keywords: Accessibility, Railway network, Beijing-Tianjin-Hebei, Beijing-Zhangjiakou high-speed railway

1. Introduction
In November 2018, the state clearly pointed out the establishment of a new model with central cities leading the development of urban agglomerations and urban agglomerations driving regional development, promoting the integration and interaction between regional plates, and taking Beijing and Tianjin as the centers to lead the development of Beijing-Tianjin-Hebei Urban Agglomeration. The development and construction of Beijing, Tianjin and Hebei are one of the top priority of China's construction. Therefore, the state proposes the policy of coordinated development of Beijing, Tianjin and Hebei. To realize the development of regional integration of Beijing, Tianjin and Hebei, it is necessary to realize the traffic integration of Beijing, Tianjin and Hebei. To speed up the integration of Beijing, Tianjin and Hebei, in 2016, the national development and Reform Commission approved the planning of Beijing-Tianjin-Hebei intercity railway network (2014-2030), as shown in Figure 1. In recent years, China's high-speed rail facilities and technology have developed rapidly, and the speed of
infrastructure construction is very fast. But with the continuous improvement of people's living standards, people have become more sensitive to the comfortability and convenience of travel. Therefore, it is necessary to analyze and evaluate the service capacity of each station in the existing railway passenger transport network of Beijing, Tianjin and Hebei and degree of each station to meet the travel needs of passengers.

Figure 1. Beijing-Tianjin-Hebei intercity railway network planning (2014-2030)

To evaluate the accessibility of railway passenger transportation in Beijing-Tianjin-Hebei region, it is necessary to model the stations and lines of railway passenger transportation in Beijing-Tianjin-Hebei region into a network, combine the basic data of the station, such as the train operation time, operation schedule, etc., through a reasonable and reliable accessibility evaluation model, get the accessibility results of each station and organize the results into a chart form. After studying the existing accessibility level of the railway passenger transport network existing problems of the railway passenger transport network are analyzed from the perspective of accessibility and a reasonable and feasible plan is formulated to provide theoretical and data support for the management, operation and planning of the railway network in Beijing-Tianjin-Hebei region. Besides, it also provides a reference for passengers to travel, so it can also be combined with the travel needs of passengers to develop a more efficient, safe and comfortable travel plan.

By December 30, 2019, the Beijing-Zhangjiakou high-speed railway was officially put into operation, which is of great significance to further improve the passenger capacity of the Beijing-Tianjin-Hebei railway and promote the coordinated development of Beijing-Tianjin-Hebei railway. This paper will focus on the changes in the accessibility of the Beijing-Tianjin-Hebei railway passenger transport network before and after the opening of the Beijing-Zhangjiakou high-speed railway.

2. Related literature review

At present, there are plenty of theories and methods about the accessibility of railway network. Wang and Sun [1] established the accessibility cost model of Jiangsu high-speed railway network based on the door-to-door hierarchical cost distance method, analyzed and calculated the significant impact of the accessibility of Jiangsu high-speed railway network on the economy in 2020-2030, and studied the impact of passenger travel time on the accessibility. Chen [2] introduced three accessibility indicators by analyzing the location, economic market and other factors, analyzed the population, GDP and other indicators, and studied the impact of railway network density on China's economy. Montoya a, Coronado et al [3] studied the travel time, cost or distance of the Spanish high-speed railway system, evaluated the travel accessibility from two aspects: location-based and train schedule based, and found that some cities in Spain promoted the rapid economic development by HSR excellent accessibility services. Marin [4] measured the railway lib index of European Union countries through five indicators for passenger and freight performance index of European Union countries' railways, and divided the railways into three categories, clearly measuring and displaying the performance of each European railway system and allowing it to be used for comparison between different countries. Porter [5] studied the infrastructure of multimodal transport in Chicago, used the negative binomial distribution estimation and the
regression model of random effect to conduct in-depth research on the social and economic characteristics, land use mix, street network mode, etc. of Chicago, and found that the accessibility of infrastructure plays an important role in economic attraction. Ding et al [6] used two new methods of transit accessibility evaluation, two-step floating catchment area (2SFCA) and gravity method to evaluate the accessibility of public transport system in Xiamen, China. They found that in different periods, the fluctuation of travel demand and the passenger capacity of public transport stations make the bus capacity of the whole city significantly different. They also show that when the total demand is relatively lower than the total capacity of the bus station, the bus accessibility based on the extended 2SFCA model is equivalent to the bus system based on the extended gravity model. Nuzzolo A and Criselli [7] introduced the software for strategic planning of Intercity Railway developed by Italian company, and illustrated it in detail with the example of Torino Venezia railway. Kuby et al [8] proposed a spatial decision support system to solve the railway network design problem, which is suitable for different types of projects. Bussieck et al [9] proposed a route planning optimization model aiming at the minimum cost, and verified it with the data of the Dutch railway. Marin [10] studies the planning and design of railway network considering robustness.

3. Methodology

3.1. Spatial Model Based on Node Position

The location of each node in the traffic network is different, which leads to the difficulty of getting from any node to other nodes in the network. Different location in space is the essential factor of different accessibility of the traffic network. Without the influence of other factors, the spatial model can evaluate the accessibility of the traffic network well. The spatial model is a static index to evaluate the accessibility of the traffic network. As the accessibility value, the smaller the spatial distance is, the better is the accessibility. However, the transportation network is closely related to the transportation equipment, and the spatial distance cannot well reflect the accessibility of the transportation network. Therefore, this paper uses the pure operation time of the train. The pure operation time of the train refers to the total time spent when the train starts from one node and passes through the shortest path to the target node, only considering the movement time on the track. Dwell time and excess time are not considered in pure operation time of the train.

If the target node is i, the other node is j, the shortest path between i and j is (i, j), and the pure operation time of the train between (i, j) is, then the accessibility of i relative to j is as shown in formula 2-1.

\[ LB_{ij} = \exp(-\beta \cdot t_{ij}) \]  

\( LB_{ij} \) — reachability between target node i and node j;

\( t_{ij} \) — The pure running time of the shortest path between the target node i and another node j;

\( \beta \) — is the cost sensitivity parameter.

The reachability of the target point and all relevant nodes in the area are accumulated to obtain the reachability of the target point in the area as shown in Equation 2-2.

\[ LB_i = \sum \exp(-\beta \cdot t_{ij}) \]  

\( LB_i \) — reachability of target site i in the area;

\( t_{ij} \) — The pure running time of the shortest path between the target node i and another node j;

\( \beta \) — is the cost sensitivity parameter.
The spatial model reflects the spatial location information of the traffic network nodes and the network potential of the system, which is relatively simple. Moreover, the spatial model only considers the traffic network itself while neglects other important factors affecting accessibility. The result is biased which makes the spatial model a simple but preferential measurement and evaluation of the accessibility of the traffic network.

3.2. Expense model based on travel expenses

The travel cost of passengers has a great impact on the choice and evaluation of travel mode. At present, with economic growth, people pay greater attention to travel time, convenience and comfort. Therefore, more attention is given to the convenience of getting from the starting node to the target node. The accessibility of transportation network can be used to measure the "convenience degree". From the travel expenditure of passengers, the time value of passengers can be considered and the cost model can be established. Generally speaking, the travel cost of passengers includes two aspects, one is the total travel time including waiting time, transit waiting time and pure travel time, and the other is the travel cost of passenger tickets. The total travel time of the passenger from the target node i to node j is multiplied by the hourly time value \( v \) for all kinds of people to get the time cost. Then the total travel cost of the passenger is shown in formula 2-5.

\[
Z_{ij} = t_{ij} \times v + c_{ij}
\]  

\( z_{ij} \) — Reachability of target node i relative to node j;

\( t_{ij} \) — The total travel time from target node i to node j;

\( v \) — Hourly time value of various groups of people;

\( c_{ij} \) — Fare expenses for passenger travel.

The travel cost between the target node i and each node is accumulated to obtain the total travel cost of the target node i in the entire network, as the reachability of the target node in the entire network is shown in Equation 2-6.

\[
Z_i = \sum (t_{ij} \times v + c_{ij})
\]  

\( z_{ij} \) — Reachability of target node i in the transportation network;

\( t_{ij} \) — The total travel time from target node i to node j;

\( v \) — Hourly time value of various groups of people;

\( c_{ij} \) — Fare expenses for passenger travel.

3.3. Accessibility model based on weighted average travel time

Weighted average travel time represents the average level of the shortest travel time from one city to other cities, reflects the degree of mutual connection and interaction between cities, and focuses on the measurement of regional accessibility level from the perspective of time cost. This index is not only affected by the level of traffic arrangement, but also related to the size of the city, reflecting the impact of economic aggregate, population size and other urban attributes on the city connection. The lower the weighted average travel time index score is, the higher is the accessibility level, and the closer the is relationship with other cities. The formula is as follows:

\[
A_i = \frac{\sum_{j=1}^{n-1} (T_{ij} \times M_j)}{\sum_{j=1}^{n-1} M_j}
\]

\[
M_j = \sqrt{GDP_j \times POPU_j}
\]
In the formula: $A_i$ refers to the accessibility of the starting city $i$ in the urban agglomeration; $T_{ij}$ refers to the shortest travel time from the starting city $i$ to the destination city $j$ by using the rail transit network; $M_j$ refers to the flow of social and economic factors of the destination city $J$, and describes the influence of the city on the surrounding cities. It is represented by the total population $POP_U_j$ and the Gross Regional Product $GDP_j$; $n$ is the total number of research cities in the urban agglomeration.

3.4. Model based on economic potential index

The economic potential index indicates the number of economic activities that a city can reach to overcome the time cost. It reflects the spatial "resultant force" or economic radiation ability of each region to accept the central city. It focuses on measuring the accessibility level of the city from the perspective of the potential of the location advantage obtained by the city through the transportation network in the whole region. The calculation formula is as follows:

$$PA_i = \sum_{j=1}^{n-1} \left( M_j / T_{ij}^\beta \right)$$

(7)

In the formula, $PA_i$ represents the economic potential index of city $i$, the larger the value is, the stronger the city $i$ is exposed to the economic radiation of other cities; $M_j$ represents the social and economic scale of city $j$; $\beta$ is the distance friction coefficient, taking 1.

4. Calculations and analysis

4.1. Calculation and analysis of spatial models based on node locations

4.1.1. Data sources and calculations. The Beijing-Tianjin-Hebei area has a large number of rail transit network lines, many stations, and a wider reach. The location of each station in the transportation network has a great significant impact on its accessibility, and the results obtained are closer to the actual network. It is necessary to evaluate the accessibility of each station in the transportation network from the location. The spatial barrier model is based on the station location, and the main parameter is the pure running time of the train.

Using data from 12306.cn and Dijkstra's shortest path, pure running time between railway stations in major cities in the Beijing-Tianjin-Hebei region before and after the Beijing-Zhangjiakou high-speed railway was calculated. The shortest path is calculated first and shortest running time for the shortest path is determined for different stations, which is summarized to obtain the pure running timetable of the Beijing-Tianjin-Hebei regional rail transit. The accessibility results of the stations in the Beijing-Tianjin regional rail transit network based on the location of the target stations in the entire Beijing-Tianjin-Hebei regional rail transit network are collated, as shown in Figure 2.

![Figure 2. Accessibility of spatial model based on node location](image)
4.1.2. Results analysis. The spatial barrier model is based on the location of each station in the rail transit network to measure the accessibility, and the main parameter is the pure operation time. The duration of pure operation time represents the degree to which passengers are hindered by various factors in the rail transit network. Therefore, in the spatial barrier model, the smaller the pure operation time is, greater is the accessibility result, and the better is the accessibility.

As shown in Figure 2, after the opening of the Beijing-Zhangjiakou high-speed railway, the accessibility of the spatial model based on the node location of each city in Beijing-Tianjin-Hebei region has increased to varying degrees. The increase of accessibility in Zhangjiakou is the most obvious, which is expected because the opening of Beijing-Zhangjiakou high-speed railway greatly reduces the pure operation time between Beijing and Zhangjiakou, shortens the distance between Beijing and Zhangjiakou, and indirectly shortens the distance between Zhangjiakou and other cities through Beijing transfer. For other cities, although the accessibility has increased, the growth rate is not the same. For cities with high accessibility, such as Beijing and Tianjin, the increase of accessibility is more obvious; for cities with low accessibility, such as Chengde and Qinhuangdao, the increase of accessibility is not significant. The accessibility of each city is reflected on the map of Beijing-Tianjin-Hebei region, as shown in Figure 3 and Figure 4. It can be seen that before and after the opening of Beijing-Zhangjiakou, only the accessibility value of Zhangjiakou City has changed significantly, while other cities have little change, and the distribution is almost the same. The accessibility of central cities, such as Beijing, Tianjin and Baoding, is the highest. The accessibility of southern cities, such as Shijiazhuang and Xingtai, is moderate. The accessibility of northern cities, such as Zhangjiakou, Chengde and Qinhuangdao, is low.

![Figure 3. Accessibility of spatial model based on node location before and after the opening](image)

4.2. Calculation and analysis of cost model based on travel expenditure

4.2.1. Data source and calculation. From the aspect of travel cost, we need to consider the waiting time of passengers, the waiting time of transit passengers and the time value of passengers.

The average waiting time in Beijing, Tianjin and Hebei is 37 minutes. The hourly time value of the passenger population is 31.2 yuan by querying the monthly wages of Beijing, Tianjin and Hebei in 2019, working four weeks a month, five days a week and eight hours a day. The accessibility calculation results obtained by the above processing are shown in Figure 4.
4.2.2. Result Analysis. The cost model comprehensively considers the time value of passengers, the total travel time and the fare expenditure. From the perspective of the total cost incurred by passengers when traveling, it makes a comprehensive evaluation of the accessibility of each station in the Beijing-Tianjin-Hebei high-speed railway network. The lower the total travel cost incurred by the station, the better the accessibility.

As shown in Figure 4, after the opening of the Beijing-Zhangjiakou high-speed railway, the travel cost in Beijing has slightly decreased. This is because the opening of the Beijing-Zhangjiakou high-speed railway has greatly reduced the pure travel time of the train from Beijing to Zhangjiakou, and Beijing as the departure station has no additional time for transfer. The travel cost of Zhangjiakou has increased significantly, because although the opening of Beijing-Zhangjiakou high-speed railway has reduced the pure travel time from Beijing to Zhangjiakou, the departure density of the line is not high at the initial stage of the operation of Beijing-Zhangjiakou high-speed railway, while the total travel time from Zhangjiakou to other areas will be changed through Beijing, which makes the total travel time less than before, but the degree of reduction is not large. In addition, the ticket price of Beijing-Zhangjiakou high-speed railway is much higher than that of the previous ordinary speed railway, which eventually leads to the increase in travel costs in Zhangjiakou. In other cities, if there is a direct train to Zhangjiakou before the opening of Beijing-Zhangjiakou high-speed railway, such as Tianjin, Langfang, Tangshan, etc., after the opening of Beijing-Zhangjiakou high-speed railway, the travel cost will increase; if there is no direct train to Zhangjiakou before the opening of Beijing-Zhangjiakou high-speed railway, such as Xingtai, Handan, etc., the travel cost will remain almost the same. As shown in Figure 5, in Beijing-Tianjin-Hebei region, before the opening of Beijing-Zhangjiakou high-speed railway, the travel costs of Beijing, Tianjin, Baoding and other central cities are relatively low, the travel costs of southern and northern cities are relatively high, and the North-South accessibility is basically balanced; after the opening of Beijing-Zhangjiakou high-speed railway, the travel costs of northern cities are relatively high. As a whole, the accessibility is significantly lower than that of the south, and the accessibility from high to low is in the order of the central city, southern city and northern city.
4.3. Calculation and analysis based on weighted average travel time model

4.3.1. Data source and calculation. The shortest travel time between railway stations in main cities in Beijing-Tianjin-Hebei region before and after the opening of Beijing-Zhangjiakou high-speed railway is obtained from GDP and resident population of Beijing, Tianjin and Hebei in 2019 were obtained from National Bureau of statistics. The weighted average travel time of Beijing-Tianjin-Hebei region before and after the opening of Beijing-Zhangjiakou high-speed railway can be calculated by bringing the shortest travel time between cities, GDP and urban population data into the formula (Figure 6).

4.3.2. Result analysis. The weighted average travel time considers the spatial location of the starting city and the comprehensive social and economic strength of the ending city. The shorter the weighted average travel time is, the higher is the accessibility of the city; the longer is the weighted average travel time, the lower is the accessibility of the city.

As shown in Figure 6, after the opening of the Beijing-Zhangjiakou high-speed railway, the weighted average travel time of all cities in Beijing-Tianjin-Hebei region will be reduced. This is because, after the opening of Beijing-Zhangjiakou high-speed railway, the shortest travel time of Zhangjiakou and other cities will be reduced. Among them, Zhangjiakou's weighted average travel time is the most obvious reduction, because the opening of Beijing-Zhangjiakou high-speed railway has reduced the travel time of the direct train between Zhangjiakou and Beijing and the transit train between Zhangjiakou and other cities. For other cities, the opening of Beijing-Zhangjiakou high-speed railway only affects the travel time between the city and Zhangjiakou, and the increase of medium transfer travel time in most cities only slightly reduces the weighted average travel time of other cities. The accessibility of
weighted average travel time of each city is reflected on the map of the Beijing-Tianjin-Hebei region. It can be seen that before and after the opening of the Beijing-Zhangjiakou high-speed railway, the weighted average travel time of Zhangjiakou City has decreased, and the accessibility of other cities has not changed much. Generally speaking, Zhangjiakou is still the best city in the middle, followed by the south, and the worst in the north.

Figure 7. Accessibility based on weighted average travel time model before and after the opening

4.4. Calculation and analysis of the model based on economic potential index

4.4.1. Data source and calculation. The shortest travel time between railway stations in main cities in the Beijing-Tianjin-Hebei region before and after the opening of Beijing-Zhangjiakou high-speed railway is obtained from website 12306.cn website. By querying the website of the National Bureau of statistics, the GDP and resident population of Beijing, Tianjin and Hebei in 2019 were obtained. The economic potential index of the Beijing-Tianjin-Hebei region before and after the opening of Beijing-Zhangjiakou high-speed railway can be calculated by bringing the data of the shortest travel time between cities, GDP and urban population into the formula, as shown in Figure 8.

Figure 8. Accessibility based on economic potential index model

4.4.2. Result Analysis. The economic potential index is determined by the economic location node of a city. It refers to the opportunity of a city to participate in economic activities by overcoming the time distance cost, and reflects the economic radiation of other cities in the region that the city receives. The larger the economic potential index, the better the accessibility; the smaller the economic potential index, the worse the accessibility.
As shown in Figure 8, after the opening of Beijing-Zhangjiakou high-speed railway, Zhangjiakou's economic potential index has increased significantly. This is because after the opening of the Beijing-Zhangjiakou high-speed railway, the time from Zhangjiakou to other cities has been greatly shortened, the cost of overcoming time distance has also been greatly reduced, and Zhangjiakou can effectively participate in economic activities with other cities. While the economic potential index of other cities has increased, but the increase is not obvious. On the one hand, due to the opening of Beijing-Zhangjiakou high-speed railway, the travel time between Zhangjiakou and other cities is reduced, but the degree of reduction is not obvious in most cities; on the other hand, due to the small socio-economic scale of Zhangjiakou, the economic effect on other cities is small, so for other cities, the increase of economic potential index is not obvious. The accessibility of each city based on the economic potential index is reflected on the map of Beijing-Tianjin-Hebei region, as shown in Figure 9. It can be found that after the opening of Beijing-Zhangjiakou high-speed railway, the economic potential index of Zhangjiakou City has increased significantly, which makes the gap between the economic potential index of the cities in the north and the south of Beijing-Tianjin-Hebei region decrease and develop towards the balanced accessibility.

**Figure 9.** Accessibility based on economic potential index model before and after the opening

5. Conclusion

Based on the accessibility theory, this paper establishes the model and calculates the accessibility results of Beijing-Tianjin-Hebei railway passenger transportation before and after the opening of the Beijing-Zhangjiakou high-speed railway, draws the accessibility results into histogram and distribution map, and analyses the accessibility with the characteristics of Beijing-Tianjin-Hebei railway passenger transportation network. From the results of accessibility analysis, the following conclusions can be drawn:

1. After the opening of the Beijing-Zhangjiakou high-speed railway, the accessibility of most cities in the Beijing-Tianjin-Hebei region has increased. Among them, the degree of change in different cities is different, especially in Beijing and Zhangjiakou.

2. Under different accessibility models, the accessibility of some cities decreases. For example, under the expense model based on travel expenses, due to the increase of travel time and ticket price after the opening of Beijing-Zhangjiakou high-speed railway, the accessibility of other cities except Beijing has been reduced.

3. For different accessibility models, the degree of accessibility change is different. The accessibility of the spatial model based on the node location of each city changes greatly, while the accessibility of the model based on the economic potential index changes little.

4. After the opening of the Beijing-Zhangjiakou high-speed railway, the accessibility of the Beijing-Tianjin-Hebei region is still comparatively better in the central city, the average in the South and the worse in the north. However, the gap between the northern cities and the southern cities is decreasing and gradually tends to be in balance.
In the research of this paper, the factors of each accessibility model selected in this paper are different, which results in different trends and sizes of accessibility. Different influencing factors can be considered comprehensively, and a comprehensive model can be established for further analysis.

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