Comprehensive Analysis of High-Speed Railway Network Based on Complex Network Theory

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Abstract. With the development of the high-speed railway, the topology of the railway network is becoming more and more complicated. The railway network characteristic analysis is the base of optimization of the railway network topology and the operation plan of service. So it is essential to study the characteristic of the high-speed railway network to support the construction planning of the railway and the operation decision making. This paper first lists the key indexes of a high-speed railway network – node degree, clustering coefficient, degree centrality, betweenness, closeness centrality, coreness and network efficiency. And we analyze the significance of the indexes for the network. Then we select two representative high-speed railway networks of China and calculate the indexes of the selected railway work. Analysis is carried out to find the characteristics of the networks, pointing out the key stations and the weak spots of the two railway networks respectively. Then we compared the two high-speed railway network, analyzing the merits and the shortage of them. The conclusion of this work can serve as an important useful resource for the railway constructor and the operator.

Keywords: High-speed railway · Comprehensive analysis · Complex network theory

1 Introduction

Railway network analysis has drawn great attention in recent years. It is necessary to analyze the transport system from the network level before developing specific train departure plans and operation plans. Based on the analysis results of the railway network, its service ability can be obtained to guide the preparation of the line plans.

Actually, many characteristics should be studied when we focus the research work on the high-speed railway network. Average path length, clustering coefficient, degree distribution, reachability, and reliability are all the typical characteristics of a network. Average path length, clustering coefficient and degree distribution has the explicit definition while the other two characteristics do not. In this paper, we choose two representative regional high-speed railway networks of China to analyze the characteristics of them, trying to draw some conclusions to establish the foundation for the future study.

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2 Related Works

Railway transportation network design and analysis is a hot topic in recent years. Xu et al. (2020) calculated and analyzed the connectivity characteristics of railway networks in China [1]. Wang et al. (2020) built a complex model to do analysis work in Chinese rail network and found it is a small- world network [2]. Szymula and Bešinović (2020) designed a mathematical model to evaluate the vulnerability of a railway network for passenger traffic [3]. Calzada-Infante et al. (2020) analyzed the direct connection and passenger transfers characteristic of European rail network [4]. Armstrong and Preston (2020) proposed a new method to harmonize the rail availability and passageway [5]. Gu (2019) design the method to calculate the reliability of the rail network and proved its effectiveness [6]. Li et al. (2017) constructed an innovate network model to analyze how the failures in the network spread [7]. Shan et al. (2021) designed a framework to offer a method to build the rail transportation network [8]. Alvioli (2021) analyzed the rockfall susceptibility in view of the rail transit network and tested the model with Italian railway network [9]. These publications have done much research work on the railway network from different aspects, which give us a lot of inspiration. In this paper, we define several evaluation indicators to do a comprehensive analysis of high – speed railway network.

3 Characteristics of a High-Speed Railway Network

There are many characteristics of a network. Here we present seven of them that are essentially important for analyzing the high-speed railway network. In this paper, we choose note degree, clustering coefficient, degree centrality, betweenness, closeness centrality, coreness and network efficiency to evaluate the characteristics of the railway network. The definition and calculation method are introduced in Refence [10].

4 Characteristics Analysis of High-Speed Railway Network

4.1 Basic Data of Two High-Speed Railway Subnetworks

To analyze the characteristics of the high-speed railway network of different regions of China, we choose two representative subnetworks of the whole network to carry out the study, which are Northwest China, Southwest China. Figure 1 shows the topology structures of the two high-speed railway subnetworks of China, Northwest China and Southwest China railway network.

4.2 Analysis on Computing Results

The indexes calculation result of Northwest China high-speed railway network is showed in Table 1. We can see that the Xi'an city has the largest connection degree in Northwest China high-speed railway network, which indicates that the number of the connected stations of Xi'an is the largest in the network. And it is somewhat surprising that the

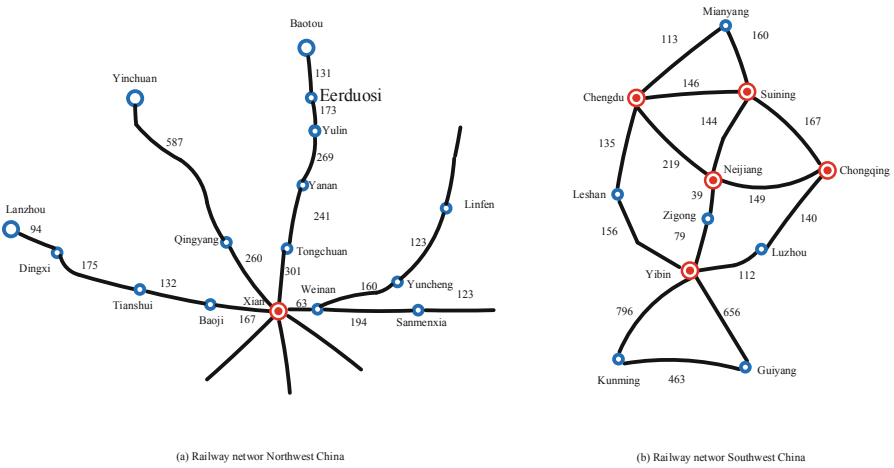

Fig. 1. Topology structure of high-speed railway network

clustering coefficients are all zero. Why? We found that the neighbor nodes of a station have no other connecting lines. So we can see that the connecting degree of the stations is not so deep. A station node is connected with several nodes by the railway lines, but these neighbor nodes of the node have no connection.

Xi'an has the largest coreness, which is 7. Core degree implies the fact that how deep a node is in the network. And it is obvious that Xi'an is at the most center of the high-speed railway network of Northwest China. Xi'an has the largest degree centrality, which is 0.2188. Degree centrality shows that the degree that a node is at the center of the network that is formed with the neighbor nodes. Xi'an also has the largest node betweenness, which is 342.1667. Accordingly, Xi'an has the largest betweenness centrality, which is 0.6899. Xi'an also has the largest Closeness centrality, which is 0.0018779.

It can be concluded that Xi'an has the most important position in Northwest China railway network. To assure the availability of Xi'an high-speed railway is essential to keep the function of Northwest China high-speed railway network.

The indexes calculation result of Southwest China high-speed railway network is showed in Table 2. We can see that Yibin has the largest node degree in Southwest China high-speed railway network, which is connected with 5 stations. And the stations which have the largest clustering are Mianyang, Kunming and Guiyang. Mianyang is connected with Chengdu and Suining, and there is a line connecting Chengsu and Suining. Mianyang, Chengdu and Suining form a ring and Mianyang has the clustering coefficient of 1. It is the same for Kunming and Guiyang. Yibin has the largest coreness, which connects five stations. As a result, Yibin also has the largest degree centrality in the network. The betweenness of Yibin is 19.6667, which is the largest in the network, implying it is most important in the network. Accordingly, Yibin has the largest betweenness centrality, which is 0.4370. Yibin also has the largest Closeness centrality, which is 0.003199.

The indexes calculation result of the presented representative high-speed railway network is showed in Table 3. Southwest China high-speed railway network has the larger clustering coefficient among the two networks. As a result, it also has the larger network density, which is 0.2909. Northwest China high-speed railway network has the larger network coreness, which is 7, meaning that there is a station node whose coreness is also 7. It implies that this mode has the highest depth in the network and it is most important and powerful for the railway network.

The density of the railway networks varies from 0.0726 to 0.2909. We can see that Southwest China has the higher network density, which means that it has better infrastructure to offer high quality transportation service for the passengers. And more railway lines should be constructed in Northwest China to increase the network density.

The degree centrality of the four networks vary from 0.071 to 0.2556. Southwest China railway network has higher centrality, which means that the railway network of Southwest China has the higher concentration degree. The railway lines connect closely in Southwest China.

The Northwest China railway network has the higher betweenness centrality. The fact proves that there are some central station nodes that have very high betweenness in the network. The closeness centrality of railway network varies from 0.001689 to 0.001725. Southwest China has the higher closeness centrality, which means that there are some station nodes which are close to the network center. The centers of the network are distributed more evenly in this network than that in other networks.

Table 1. Indexes of Northwest China high-speed railway network

City	Node degree ki	Actual edge number Mi	Clustering coefficient Ci	Coreness	Degree centrality	Node betweenness	Betweenness centrality	Closeness centrality
Lanzhou	1	0	0	1	0.0313	0.0000	0.0000	0.0009766
Dingxi	2	0	0	2	0.0625	31.0000	0.0625	0.0010719
Tianshui	2	0	0	2	0.0625	60.0000	0.1210	0.0012914
Baoji	2	0	0	2	0.0625	87.0000	0.1754	0.0015084
Xi'an	7	0	0	7	0.2188	342.1667	0.6899	0.0018779
Yinchuan	1	0	0	1	0.0313	0.0000	0.0000	0.0007481
Qingyang	2	0	0	2	0.0625	31.0000	0.0625	0.0013019
e'erduosi	2	0	0	2	0.0625	31.0000	0.0625	0.0007571
Yulin	2	0	0	2	0.0625	60.0000	0.1210	0.000859
Yan'an	2	0	0	2	0.0625	87.0000	0.1754	0.0010671
Tongchuan	2	0	0	2	0.0625	112.0000	0.2258	0.0013354
Weinan	3	0	0	3	0.0938	134.6667	0.2715	0.0017793
Sanmenxia	3	0	0	3	0.0938	52.3333	0.1055	0.0014635
Yuncheng	3	1	0	3	0.0938	56.0000	0.1129	0.001519
Linfen	2	0	0	2	0.0625	36.0000	0.0726	0.0013255

From the analysis above, we can see that the main characteristics of the railway network in the representative regions are weak. The railway network of Northwest China should be paid more attention because it has the weaker characteristicsbetween the two regions except for the betweenness centrality. More railway lines should be added in Northwest China to strengthen the structure of the railway network.

Table 2. Indexes of Southwest China high-speed railway network

City	Node degree k_i	Actual edge number M_i	Clustering coefficient C_i	Coreness	Degree centrality	Node betweenness	Betweenness centrality	Closeness centrality
Chengdu	4	2	0.3333333	4	0.4	8.6667	0.1926	0.0025562
Leshan	2	0	0	2	0.2	7.3333	0.1630	0.0026532
Yibin	5	1	0.1	5	0.5	19.6667	0.4370	0.003199
Zigong	2	0	0	2	0.2	4.0000	0.0889	0.003199
Neijiang	4	2	0.3333333	4	0.4	6.1667	0.1370	0.0031596
Suining	4	3	0.5	4	0.4	4.1667	0.0926	0.0027579
Mianyang	2	1	1	2	0.2	0.0000	0.0000	0.0021617
Chongqing	3	1	0.3333333	3	0.3	4.6667	0.1037	0.0025641
Luzhou	2	0	0	2	0.2	4.3333	0.0963	0.0026357
Kunming	2	1	1	2	0.2	0.0000	0.0000	0.0010752
Guiyang	2	1	1	2	0.2	0.0000	0.0000	0.0012436

Table 3. Indexes of two high-speed railway networks

Region	Northwest China	Southwest China
Average distance of railway network (km)	872.7167	416.4132
Clustering coefficient of railway network	0.0104	0.4182
Coreness of railway network	7	5
Density of railway network	0.0726	0.2909
Degree centrality of railway network	0.071	0.2556
Betweenness centrality of railway network	0.6173	0.3496
Closeness centrality of railway network	0.001725	0.001689
Network efficiency	0.0016	0.00409

5 Conclusion

This paper has discussed the railway network analysis problem, using the typical characteristics calculation method. Seven characteristics are listed and introduced to be used to

analyze the four representative high-speed railway network of China. We found that the two railway network had different characteristics: Southwest China high-speed railway network has the larger clustering coefficient and highest degree centrality andNorthwest China railway network has the higher betweenness centrality. In general, The Northwest China railway network is weak and more railway lines should be added in Northwest China.

For future research, we are interested in defining the reliability of the railway line network and optimizing the network, especially in the case of emergencies occur. It will help the railway managers to plan the railway line network more reasonably, making the network stronger and more efficient. Another promising research topic is to study the construction and optimization of the train service network, which is built on the railway line network.

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