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A study on reliability of high-speed passenger transport network based on complex network analysis[1]

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Abstract. On the basis of relative theories of complex network, a high-speed passenger transportation network using Pajek software is proposed and its topological characteristics as well as network structure are analyzed. Analyzed is also its reliability under two kinds of attacks, and suggestions on its construction recommended. The research in this paper helps to complete the overall network structure of high-speed passenger transportation, strengthens the node stability and enhances the connection, reliability and effectiveness of high-speed passenger transportation network.

Key words. Integrated transportation, reliability, global efficiency, high speed passenger transportation network, complex network.

1. Introduction

After years of efforts, China has gradually built the civil aviation network, which is centered by Beijing, Shanghai, Guangzhou and other hub airports with the airports in provincial capital and key cities as the backbone and under close relation among various main and feeder airports. In recent years, density of civil air routes has been increased and the connection among various civil airports has become increasingly close. The continuous improvement and advancement of civil aviation network enables the passengers to travel more conveniently and faster. Along with the rapid development of civil aviation industry, China's high-speed rail has entered a period of leapfrog development. Four Horizontal and Four Lengthwise high-speed rail networks are built, by which, the distance in time and space among different regions has been dramatically shortened and the tiring long journey of rushing about for Chinese passengers has been changed.

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Foreign scholars have first started their study of complex network in the end of the 20th century. A. L. Barabási and R. Albert revealed scale-free characteristic of a complex network through their study [1]. On this basis, research fellow from different scientific research fields have paid their attention to complex networks and conducted researches on topological characteristics, reliability, complexity and other parameters [2]. Other scholars in traffic and transportation filed have also applied the analytical methods for complex network in analysis of transportation network and made some researches on complexity of civil aviation and railway and other transportation networks [3]. Chinese scholars have also applied theories concerning complex network into researches in transportation field [4]. To be more specific, they analyzed topological property of civil aviation network, railway network and urban rail network, and they utilized two methods of random attack and attempted attack to study the reliability of transportation network [5], [6]. Because of a relatively shorter history of high-speed rail in China, scholars have only completed few researches on characteristics of complex network related to high-speed rail. Thus, there are only few complex analyses of the high-speed passenger transport network composed of high-speed rail and civil aviation. Based on the above mentioned works, this paper gives an analysis of the characteristics of the complex network of high-speed passenger transport, discusses its stability and provides corresponding suggestions on construction of the network.

2. Basic model structures of complex network

At present, complex network is mainly divided into two types, namely small-world network and scale-free network, of which, the construction algorithm is as follows.

2.1. Small-world network model

The construction algorithms for small-world network model starts from the rule network: it is assumed to be a nearest-neighbor coupled network containing N nodes forming a loop, among which, each node is connected with all adjacent $K/2$ nodes to the left and right (K being an even number). It must also satisfy randomization reconnection: to reconnect each edge in the network with the probability P randomly, that is to say, to remain one of the endpoint of the edge to be reconnected unchanged and the other endpoint is randomly selected in the network. Wherein, there can only be one edge between any two different nodes and no edge of any node can be connected to itself.

In order to guarantee the network sparsity, the requirement $N \ll K$ shall be met so that the network model to be built can be of a higher clustering coefficient. And the randomization reconnection process greatly declines the average path length of the network, thus the network model possesses the small-world characteristics. When P is relatively small, the randomization reconnection process exerts little influence on network clustering coefficient. When $P = 0$, the model degrades into a rule network. When $P = 1$, the model degrades into random network. That is to say, transition from a completely rule network into a completely random network of the model can be realized by adjusting the value of P.

2.2. Scale-free network model

A large number of empirical studies show that degree distribution function of many large-scale real networks (such as the Internet, metabolic networks, etc.) presents in the form of a power-law distribution $P(k) \sim k^{-\gamma}$. In such networks, degree of most nodes is relatively smaller, however, a small amount of nodes are of quite big degree with no characteristic scaling. Such kind of network is called scale-free network for there is no distinctive characteristic scaling of the connectivity degree of its nodes.

The construction algorithms for small-world network model includes is based on the following assumptions: at the initial moments, it is assumed that the network already contains m_0 nodes, and in each time step afterwards, a node with the connectivity degree of m ($m \leq m_0$) is added, and the newly added node is connected to the m existing nodes in the network without repeated connection. Then, during selection of connection point for new nodes, the probability Π_i of the connection between a new node and an existing node i is in direct proportion to the degree k_i of node i, which can be written in the form

$$\Pi_i = \frac{k_i}{\sum_j k_j}\,. \tag{1}$$

3. Construction of high-speed passenger transport network

High-speed passenger transport network refers to the high-speed passenger transport complex formed in the socialized transportation coverage and during united transportation process in accordance with the technical and economic characteristics of high-speed rail and civil aviation. Such complex is under coordination and distribution of responsibilities, organic combination, orderly organization and close connection. For the ease of study, the paper gives the following assumptions for Construction of the complex of high-speed rail and civil aviation network:

1. High-speed passenger transport network is a complex network built in p space. It is defined, according to flight or number of high-speed rail, that an air route or a train with the same number passing through every two cities, it is regarded that there is an edge between the two cities.

2. High-speed passenger transport network is a undirected weighted network. As long as every two cities are connected via airplanes or trains, no matter where they are going, an edge without vector pointing between the two cities shall be erected, that is to say, if one can get to city B from city A and vice versa, it is regarded that city A and city B are connected. No matter how far it is or how many airlines or trains connections are between the two connected cities, the weight is considered 1, namely, the departure frequency and number of the

high-speed trains and airlines in the high-speed passenger transport compound network is not taken into account.

3. In case there is high-speed rail station and airport in one city, or there are two and more airports or high-speed rail stations in one city, it is regarded that the city is a node.

4. Analysis of characteristics of high-speed passenger transport network

4.1. Construction of civil aviation sub-network

The data concerning civil aviation sub-network is obtained from the flight schedule in the summer of 2015 and covers 10,093 flights (except for flights from Hong Kong, Macao and Taiwan) from more than 20 airlines in China, and 196 airway destinations. With the use of Pajek, the topological graph of civil aviation network is obtained (as shown in Fig. 1).

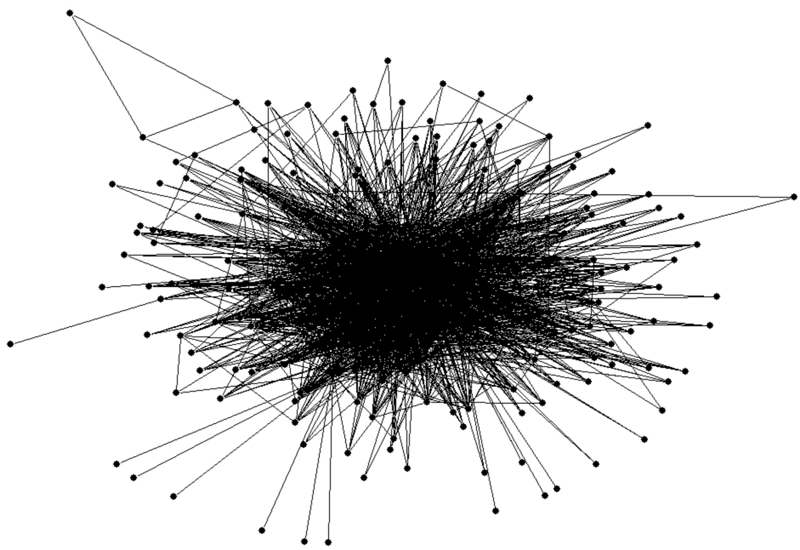

Fig. 1. Topological graph of civil aviation network

4.2. Construction of high-speed passenger transport network

The data of high-speed rail sub-network is obtained from statistics of the operation scheme of the high-speed rail, motor car and interurban rail. This network involves in about 4,000 high-speed trains and 425 high-speed rail stations. Refer to Fig. 2 for the network topological graph.

4.3. Construction of high-speed rail sub-network

The high-speed passenger transport network composed of 579 nodes and 14,312 edges is established according to the assumed conditions and in combination with relevant data of the civil aviation network and high-speed rail sub-network. The topological graph of high-speed passenger transport network is shown in Fig. 3.

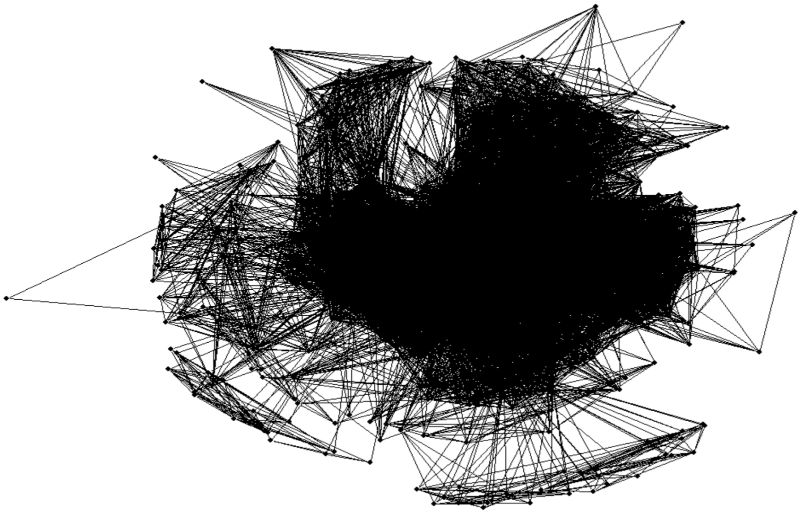

Fig. 2. Topological graph of high-speed rail sub-network

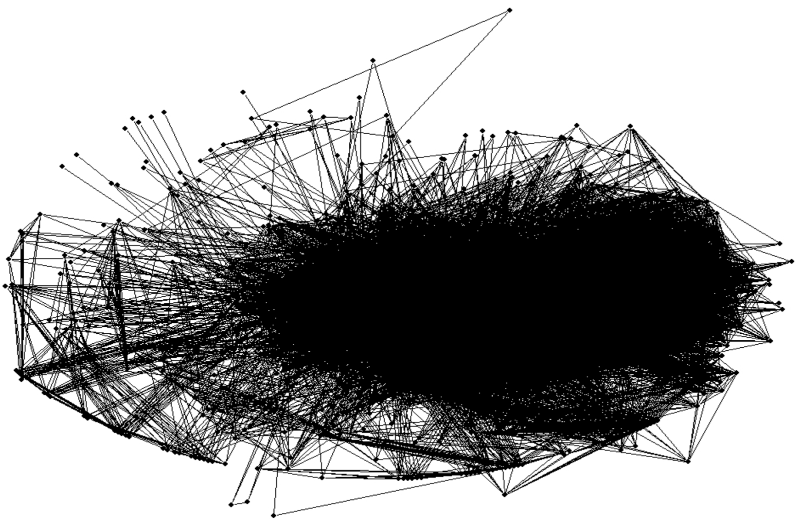

Fig. 3. Topological graph of high-speed passenger transport network

5. Numerical solution and discussion

The topological characteristic parameters of the high-speed passenger transport network and its sub-networks are obtained by statistical analysis, whose results are shown in Table 1.

Table 1. Comparison of network characteristics

Network	Number of nodes	Average degree	Average path length	Clustering coefficient
Civil aviation sub-network	196	19.67	2.058	0.8013
High-speed rail sub-network	425	56.18	2.195	0.7401
High-speed passenger transport network	579	47.43	2.248	0.7728

It is found (using Table 1) that the high-speed passenger transport network and its sub-network is of bigger clustering coefficient and shorter average path length and shows characteristics of small-world network.

Meanwhile, the degree distribution diagram and cumulative degree distribution diagram of high-speed passenger transport network and its sub-network is obtained by statistical analysis (as shown in Figs. 4–9).

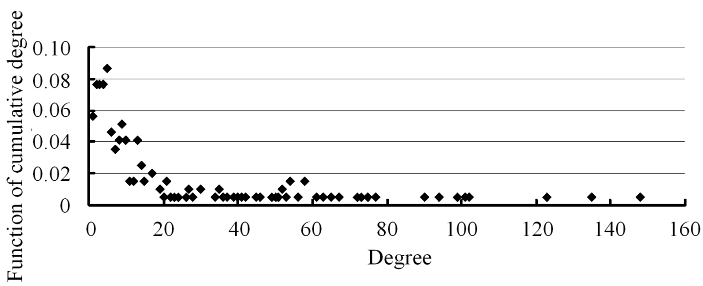

Fig. 4. Degree distribution diagram of civil aviation sub-network

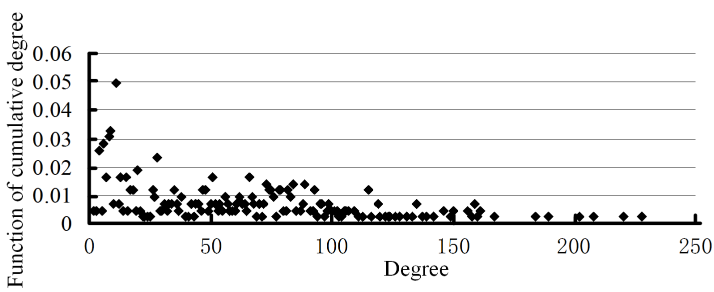

Fig. 5. Degree distribution diagram of high-speed rail sub-network

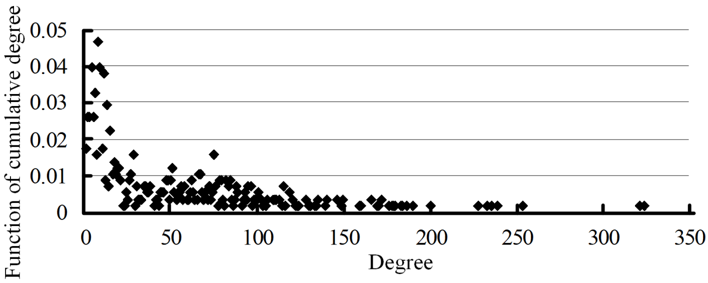

Fig. 6. Degree distribution diagram of high-speed passenger transport network

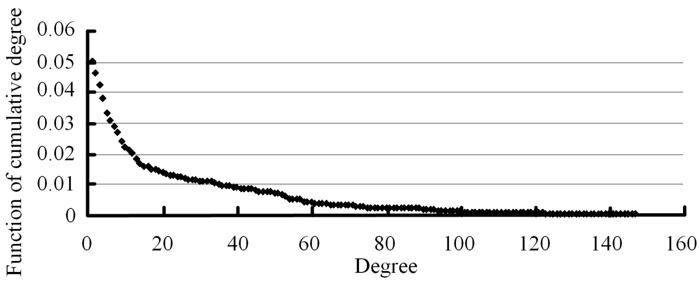

Fig. 7. Cumulative degree distribution of civil aviation sub-network

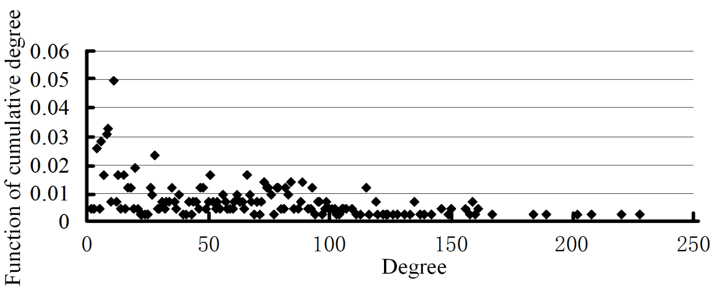

Fig. 8. Cumulative degree distribution of high-speed rail sub-network

From Figs. 4–9 we can see that the degree distribution of high-speed passenger transport network, high-speed rail network and civil aviation network conform to power-law distribution and cumulative degree distributions also follow exponential distribution with scale-free characteristics. Hence, the high-speed passenger transport network, high-speed rail network and civil aviation network are all scale-free small-world complex network.

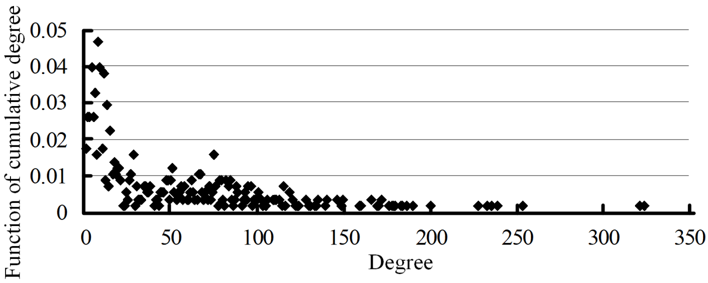

Fig. 9. Cumulative degree distribution of high-speed passenger transport network

6. Reliability analysis of high-speed passenger transport network

6.1. Measurement index for reliability of high-speed passenger transport network

The reliability of complex networks refers to the performance of the network to resist the impact brought by fault in case of attack or change in structure. Network attack comprises two modes, namely attempted attack and random attack. The former is also called targeted attack, refers to destruction of network nodes by certain strategies, among which, the strategy of deleting nodes generally starts from the biggest node of the network and the highest node is removed each time.

Reliability of high-speed passenger transport network can be measured by the global efficiency of the network under attack, which is calculated through the shortest distance E^{global} between the nodes via the following formula

$$E^{\text{global}} = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} \frac{1}{d_{ij}}}{N\,(N-1)} \tag{2}$$

Here, N represents the total amount of nodes in the network, V denotes the set of points of the network nodes, d_{ij} is the distance between the nodes i and j $(i, j \in V,\ i \neq j)$. The global efficiency is the average efficiency of the local subgraph, plays a similar role as that of the clustering coefficient C, and represents the efficiency of the compound network with some nodes deleted. Thus, $E^{\text{local}} \approx C$.

6.2. Reliability analysis of high-speed passenger transport network

With the use of Pajek and R-software, the variation diagram of the global efficiency of civil aviation sub-network under two attack modes was calculated and shown in Fig. 10.

It is found using Fig. 10 that the resistance of civil aviation sub-network to attempted attack is dramatically stronger than that to random attack as its global efficiency declines to 0 under attempted attack to about 60 nodes and about 180

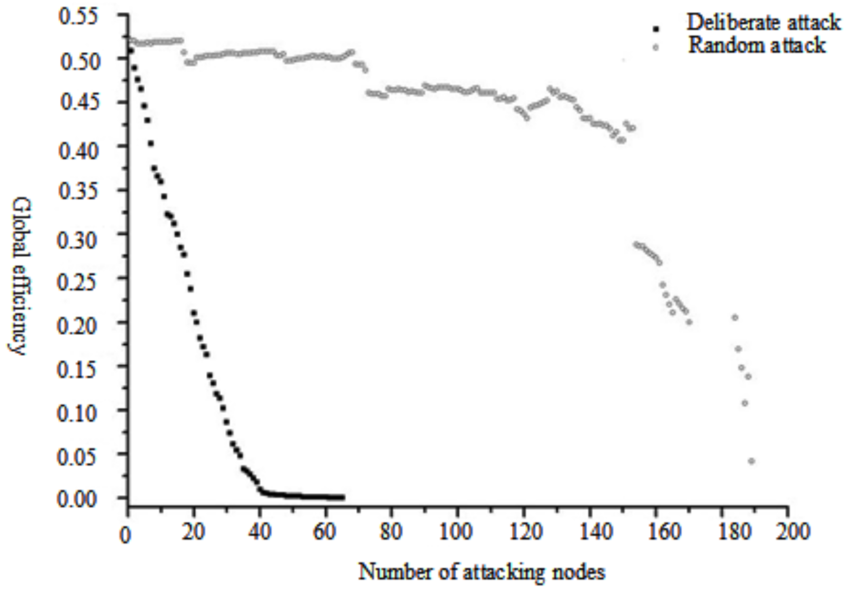

Fig. 10. Variation diagram of global efficiency of civil aviation sub-network under two attack modes

nodes under random attack. Using the same method, we can analyze the variation diagram of global efficiency of high-speed rail sub-network and high-speed passenger transport network under two modes of attack (as shown in Figs. 11 and 12).

The high-speed rail sub-network presents similar characteristics to those of the civil aviation sub-network under two modes of attack. Its global efficiency declines to 0 under attempted attack to about 360 nodes and about 420 nodes under random attack. Thus, it can be seen that, the high-speed rail sub-network is more reliable than civil aviation sub-network.

Global efficiency of high-speed passenger transport network declines to 0 under attempted attack to 410 nodes, and 550 nodes under random attack. Thus, it can be seen that, the high-speed passenger transport network is more reliable under random attack.

From comparison of Figs. 10, 11, 12, the initial values of efficiency of the three kinds of networks are about 0.5. The number of nodes under random attack civil aviation sub-network high-speed rail sub-network is 420 and 180 respectively, at which point, the efficiency declines to 0, whereas, the efficiency of high-speed passenger transport declines to 0 under such attack to 550 nodes; in the face of attempted attack, the global efficiency of civil aviation sub-network high-speed rail sub-network declines to 0 under attack to 60 and 360 nodes respectively, but that of high-speed passenger transport declines to 0 under attack to 410 nodes. It is shown that, under two modes of attack, the high-speed passenger transport network is more reliable than civil aviation and high-speed rail network.

Under attempted attack, the global efficiency decreases by more than 0.01 after

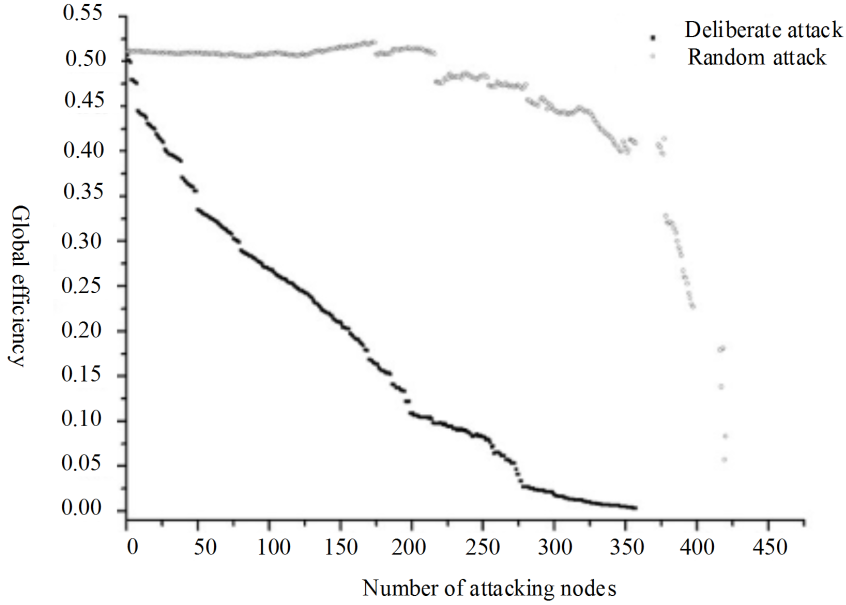

Fig. 11. Variation diagram of global efficiency of high-speed rail network under two attack modes

removal of the10 of the deleted 410 nodes, which are Chengdu, Xi'an, Xianning, Dalian, Kunming, Urumqi, Haikou, Sanya, Luoyang. Those are key nodes in high-speed passenger transport network and in case of abnormal operation of those nodes, certain influence will be exerted on the network.

Take the above mentioned nodes as the dividing points, the nodes with similar global efficiency in the high-speed passenger transport network can be classified into a group. Thus, all the nodes can be divided into 11 groups, among which, the first group includes Beijing, Shanghai, Guangzhou, Hangzhou, Nanjing, Shenzhen, Wuhan and Changsha. Those nodes are all of big degree and connect main cities throughout the country and play as central hubs in the whole network. The second group includes Chengdu, Nanchang, Kunshan, Xiamen, Hefei, Jinan, Zhengzhou, Chongqing, Fuzhou, Wuxi, Xuzhou, Changzhou, Ningbo and Suzhou, which are backbone node cities of the high-speed passenger transport network and combine well the high-speed rail network and civil aviation network. Therefore, they play the role of diversion and stabilization for the central hubs.

7. Corresponding suggestions on construction of high-speed passenger transport network

By comparison of the calculation results in this paper and those concluded by relevant scholars according to data in 2012, it is found that the number of nodes

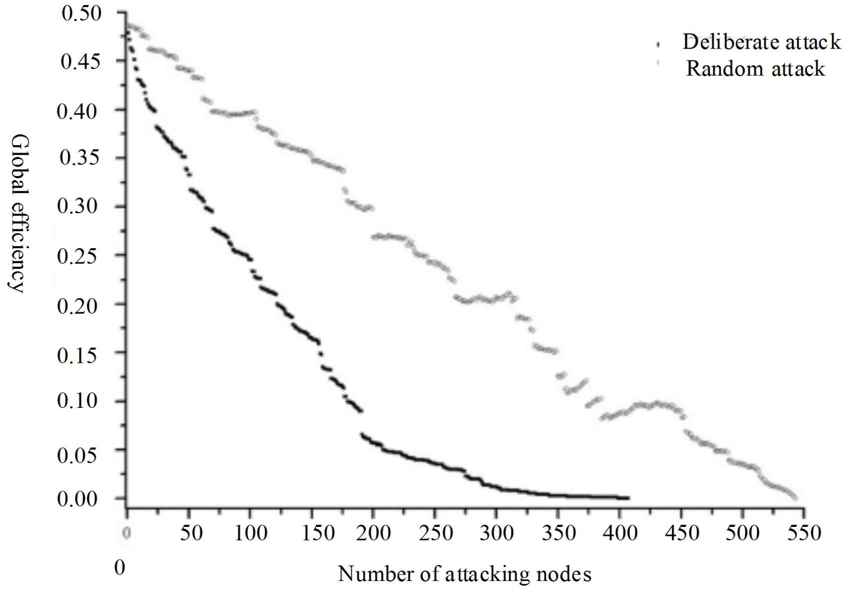

Fig. 12. Variation diagram of global efficiency of high-speed passenger network under two attack modes

of some existing high-speed passenger transport network has increased to two times that of the former high-speed passenger transport network and the number of edges has increased to three times, in addition, the average degree and other indexes have increased substantively. The former high-speed passenger transport network is disrupted under attempted attack to 40 nodes and 215 nodes under random attack, however, the existing high-speed passenger transport network is disrupted under the two modes of attack to 410 and about 550 nodes, respectively. Comparatively speaking, the resistance to destruction of the existing network is greatly enhanced. Yet, the existing high-speed passenger transport network only yields a global efficiency of 0.4861, which is slightly higher than that of the former network 0.4753, which means the reliability of the network is slightly increased. The existing network is still dependent on several key hub cities in transfer of passenger flow with poor coverage in remote areas and the increase in network nodes and edges fails to bring dramatic enhancement in network efficiency. Based on the above mentioned, this paper gives following suggestions on construction of China high-speed passenger transport network:

1. To add more hub nodes: the hub nodes in high-speed passenger transport network play an important role of transfer and can lighten the burden of central hub nodes, enhance resistance to destruction of the network and improve network stability. In reality, if the central hub nodes fail to operate smoothly under certain trouble including bad weather, it is quite helpful to add more hub nodes playing the role of transfer to slow down increase in the average

path length of the network.

2. To improve the network structure: at present, central and western regions in China, the high-speed passenger transport network still relies on civil aviation nodes in transfer and the high-speed rail network is yet to be closely connected with the intensive network lines in the eastern region. Such network structure is liable to hamper the operation efficiency of the entire region in the case of attack of certain node in the central and western regions in China. For this reason, it is necessary to accelerate extension into the sub-line regions of the civil aviation to cover more cities, and at the same time, to quicken construction and improvement of the high-speed rail sub-network so as to realize coverage of the central and western regions with some remote areas to enable the hub urban nodes in central and western regions to play a more important role.

3. To add more cross-regional trains: it is helpful to realize more close connection among nodes in the network, reduce transfer, enhance reliability and present more options for the passengers by adding more cross-regional and overline trains. Currently, the high-speed rails lines in normal operation cannot fully meet the need of passengers, thus, more cross-regional high-speed rail lines shall be opened to meet the travel demand of passengers.

4. To diversify arrangement of flights in airports at the end-point of civil aviation network: some small airports in China (for example: Jiuhuang Airport) basically connect the provincial cities where they are located with few flights to airports in the neighboring areas. In case of attack of the provincial attack, connectivity among those small airports drops to zero, thus passengers are forced to travel by high-speed rail that is rarely seen in those cities oftentimes. Therefore, it is of certain necessity to diversify arrangement of flights in airports at the end-point of civil aviation network so as to enhance network stability.

8. Conclusion

Through calculation of relevant indexes of high-speed passenger transport network, this paper proves the high-speed passenger transport network is a typical complex network, and on this basis, it combines the two kinds of networks in construction of the high-speed passenger transport network. At first, the paper proves high-speed passenger transport network is a typical scale-free small-world network with its characteristics of better connectivity, fewer times of transfer and higher clustering coefficient. And then, trough reliability analysis of the network under attempted and random attack respectively, it is found by simulation, that it is more reliable under random attack and less reliable under attempted attack and it is more reliable than high-speed rail and civil aviation network. Finally, the paper gives corresponding suggestions on construction of the high-speed passenger transport network from four perspectives of hub node, network construction, overline trains and flights according to the current condition and deficiencies revealed by simulated attack to the network.

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