Impact analysis of two kinds of failure strategies in Beijing road transportation network

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The Beijing road transportation network (BRTN), as a large-scale technological network, exhibits very complex and complicate features during daily periods. And it has been widely highlighted that how statistical characteristics (i.e. average path length and global network efficiency) change while the network evolves. In this paper, by using different modeling concepts, three kinds of network models of BRTN namely the abstract network model, the static network model with road mileage as weights and the dynamic network model with travel time as weights — are constructed, respectively, according to the topological data and the real detected flow data. The degree distribution of the three kinds of network models are analyzed, which proves that the urban road infrastructure network and the dynamic network behavior like scale-free networks. By analyzing and comparing the important statistical characteristics of three models under random attacks and intentional attacks, it shows that the urban road infrastructure network and the dynamic network of BRTN are both robust and vulnerable.

Keywords: BRTN; random attacks; intentional attacks; average path length; global network efficiency.

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1. Introduction

Complex networks play an important role in real life.¹ Urban road networks, as a kind of large-scale network, usually face two kinds of failures called the random failures and the intentional failures. The random failures mean that vertices (or

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edges) in a network are destroyed or defunctionalized, happening with a certain probability, which is caused by some unexpected phenomena, such as, transportation accidents, transportation congestions, transportation control, floods, fires, etc. The intentional failures are those vertices (or edges) defunctionalized by some determined strategy, which was caused by some proposal actives, such as criminal attacks, famous stars' concerts, vital sports games, other big festival and commercial activities, etc.² These two kinds of failures have different impact on urban road traffic networks. Therefore, it is necessary to reduce the impact of network failures on urban road networks. To understand the topological properties of the road network and to make a more detailed study of the statistical characteristics of the urban road network under failure conditions, the impact of network failures on urban road network is analyzed.

For the study of the network characteristics of complex networks under the condition of failure, Zeng *et al.* proposed a method to enhance the robustness of the network in the case of intentional attacks.³ Wang *et al.* used the complex network attack model in China's aviation network and simulation.⁴ Qiao *et al.* evaluated the structural characteristics and robustness of the coal transportation network.⁵ Qin analyzed the change of the vulnerability of the inter-city railway network under intentional attack.⁶ At present, the research on the statistical characteristics of complex networks under the condition of failure is mainly focused on line networks, such as aviation networks, public transportation networks, railway networks, etc. However, there is little work on the urban road traffic networks, especially on the urban road transportation network with weight.

Firstly, this paper compares three different forms of urban road transportation network models in Beijing by analyzing their main statistical characteristics. Furthermore, we compare the changes of the important statistical characteristics of BRTN under different network failure conditions, and the change of the important statistical characteristics of urban road transportation network in Beijing under different network failure conditions. Finally, the network models and the network characteristics of the network are verified. We provide the analysis results to the transportation management and planning departments, which can provide support for transportation guidance and road network transformation.

2. Statistical Analysis

In this paper, the Beijing transportation network is divided into three levels: the abstract network, the infrastructure network and the dynamic transportation network. The abstract network is the simplest topological description of BRTN, which contains only the vertices and edges. The characteristics of spatial distribution of urban road transportation systems are considered, on the basis of the abstract network, as well as the road mileage is added as the weights of the edges. The dynamic transportation network is a combination of traffic flow data and the network topology, so that the network model can truly reflect the daily dynamical characteristics of road transportation in Beijing.

2.1. Network modeling

Kuby *et al.* summarized the common methods of research on the topological characteristics of transportation network, such as mathematical programming, geographic information system, graph theory and complex networks, and so on.⁷ Using complex network methods to study transportation network is more advantageous, both in the macro theoretical and policy level in the system.⁸ The common method of the spatial geographical network is transformed into complex network, including the original method and the dual method, both of which are used to express the spatial network element relationship between vertices and edges. The original method, also known as the direct method or the main method, is with intersections as vertices, links between intersections as edges or arcs. This method is simple and intuitive, which retains the more complete geographic information. The dual method, can be thought of as the duality of the original method, and the section as the vertex, the intersection as the edge or arc.⁹

This paper takes Beijing road transportation network (BRTN) as an example. We selected 167 major intersections and sections of the connect between intersections including Dongyulincun, Beizhuangerqiao, and so on. Intersection numbers, using the method of original modeling, to structure network adjacency matrix $D(i, j)$, its meaning is: while $D(i, j)$ takes a positive, vertex i and vertex j are interconnected. $D(i, j)$ is equal to 0, then vertex i and vertex j are disconnected. By using the software to deal with the matrix data, the main road network of urban road transportation network in Beijing City is obtained, as shown in Fig. 1.

2.2. Statistical characteristics

A degree of a vertex is defined as the number of neighbors of the vertex, usually expressed in k . If the edge weight is considered, the strength of a vertex is defined

Fig. 1. (Color online) The main road network of BRTN.

as¹⁰: $s_i = \sum_j \omega_{ij}$, where ω_{ij} is the weight of the edge between two vertices (i, j) . The degree distribution of vertices is usually represented by $P(k)$, which is defined as the probability of any vertices with the degree that is exactly equal to k .¹¹

The d_{ij} is defined as the number of the shortest edges that are connected to two vertices, where d_{ij} is distance between two vertices in the network. L is defined as the average value of the distance between any two vertices, where L is the average path length of the network. The formula is as follows:

$$L = \frac{2}{n(n-1)} \sum_{i>j} d_{ij}. \tag{1}$$

The average path length is known as the network characteristic path length.¹² The smaller the L , the smaller the distance between the vertices in the network. The average path length ignores the local characteristics of the network structure, instead of considering the global characteristics of the network structure.

We use the original method in Beijing urban road network to build up a topological model. Through MATLAB and the Pajek software, the basic topological structure indexes of the abstract road network are obtained, as shown in Table 1.

In Table 1, the number of network edges is 580. The average value of the vertex degree is 3.4731, which shows that intersections are mostly connected with 3 or 4 sections in the road network. The average path length is 6.4016, which indicates that from one intersection to another, it needs to go through 6–7 sections on average. The mileage is taken as the weight, the greater the weight, the stronger the road transportation capacity will be. In this way, the abstract network is transformed to a kind of weighted network, named the infrastructure network.

Modeling and analysing using the same methods, we get some statistical characteristics indexes of network topology of infrastructure network in Beijing, as shown in Table 2.

As shown in Table 2, the average path length of the infrastructure network in Beijing is 20.4271. The minimum average distance from one intersection to another is 20.4271 miles. The weighted path length reflects the geographical length of different roads in the actual road network, which has a close relationship with the urban road

Table 1. Topological statistical characteristics of the abstract network of BRTN.

Characteristic index	The number of network vertices	The number of edges	The average value of the vertex degrees	Average path length	Network efficiency
Numerical	167	580	3.4731	6.4016	0.1999

Table 2. Topological statistical characteristics of the infrastructure network.

Characteristic index	The number of network vertices	The number of edges	The average value of the vertex degrees	Average path length	Network efficiency
Numerical	167	580	14.7675	20.4271	0.0977

Table 3. Topological statistical characteristics of the dynamic network.

Characteristic index	The number of network vertices	The number of edges	The average value of the vertex degrees	Average path length	Network efficiency
Numerical	167	580	0.2092	0.3362	2.5162

network construction plan, the city layout planning, the road network spacing, etc. Its value often depends on the size of the road network density. It also influences the accessibility of roads. The proper path length is conducive to the distribution of transportation flow. Now, the travel time as the weight is a direct response to the road transportation state. These weights reflect the strength of the actual road capacity. The travel time can be obtained by direct calculation of detected velocity data. Because the travel time is changing with time, we choose one time period as an example. Travel time is as the weight of edges. Through modeling and analyzing, topological statistical characteristics of the dynamic transportation network in Beijing are obtained, as shown in Table 3.

In Table 3, the average path length of the dynamic transportation network in Beijing is 0.3362. It shows that, in this time period, from one intersection to the other, the vehicle takes an average of 0.3363 h. The travel time has global characteristics. In the process of calculating the dynamic transportation network, the path length calculation depends not only on the length of the path in the infrastructure network, but also on the transportation state of all the paths. That is to say, in the actual transportation, the path of the shortest travel time is not necessarily the path of the minimum mileage. Therefore, it is more reasonable to use travel time as the network weights to evaluate statistical characteristics of the network. We deal with the vertex degree of the abstract network in Beijing, and obtain the distribution of vertex degree, as shown in Fig. 2.

Fig. 2. (Color online) Degree distribution of the abstract network.

Fig. 3. (Color online) The strength and the strength distribution in the infrastructure network.

As shown in Fig. 2, the vertex degree distribution of the abstract network of BRTN has a certain characteristic about Poisson distribution. Its peak value is 4. It has smaller average path length and smaller clustering characteristics. So, it exhibits the characteristics of random networks.

Because the vertex strength of the infrastructure network is noninteger, we deal with the noninteger into the integer. The vertex strength of the dynamic transportation network is reserved for a decimal number. The strength and strength distribution of the infrastructure network and the dynamic transportation network are treated by double logarithm. The double logarithmic relation between the strength and the strength distribution of the two kinds of networks and their fitting results are obtained, as shown in Figs. 3 and 4.

Fig. 4. (Color online) The strength and the strength distribution in the dynamic transportation network.

In Figs. 3 and 4, we know that the strength and the strength distribution of the infrastructure network and the dynamic transportation network are approximately linear. The power law degree distribution function is obtained by the least square method. There are $P(k) = 16.7015k^{-1.7091}$, $P(k) = 0.0095k^{-1.5801}$. So we know that the intensity distribution of the infrastructure and the dynamic transportation network in Beijing can be fitted by power law function. The value of the index is 1.7091 and 1.5801, respectively, which shows that the infrastructure network and dynamic transportation network of Beijing are the scale-free network.

3. Characteristics Analysis

In many statistical characteristics of the network, the average path length and the global network efficiency are very representative, and are both used to characterize the global characteristics of the network. The global network efficiency is expressed as the average degree of traffic of the network. In this paper, we take the average path length and the global network efficiency as an example to analyze the statistical characteristics of the network under the condition of failure.

In Tables 1–3, the average path length of the abstract road network, infrastructure network and dynamic transportation network in Beijing are 6.4016, 20.4271 and 0.3362 in the initial state, respectively. The global network efficiency index formula is as follows:

$$E_{\text{glob}}(G) = \frac{1}{n(n-1)} \sum_{i \neq j \in \Omega} \frac{1}{d_{ij}}, \quad (2)$$

where d_{ij} is the shortest path length between i vertex and j vertex. $\frac{1}{d_{ij}}$ is the efficiency between vertex i and vertex j . The global network efficiency reflects the level of difficulty of transportation in the network. In Tables 1–3, the global network efficiency of the abstract road network, infrastructure network in Beijing are 0.1999, 0.0977 and 2.5162 in the initial state, respectively.

The thinking of the failure of intentional attack on urban road network in Beijing is as follows: (1) Computing edge betweenness of road networks, and to fracture the edge of the best of betweenness. (2) Using Floyd algorithm to calculate the shortest path length between any two vertices, and then to calculate the average path length and the global network efficiency. (3) Again, to fracture the edge of the best of betweenness, repeat step 2, until all the edges of the network are broken. The idea of the random attack is similar to the intentional attack, but the attack strategy is no longer based on edge betweenness, instead of random fracture of the edge. According to the above workflow, the simulation based on MATLAB, the abstract network, the infrastructure network and the dynamic transportation network are analyzed. As the average path length changes as shown in Figs. 5–7, the horizontal axis is the ratio of the edge of the fracture, the longitudinal axis is the average path length value.

As shown in Figs. 5–7, compared to random attack strategy, the average path length values of the three networks are increasing faster under the intentional

Fig. 5. (Color online) The changes of average path length of the abstract network under attacks.

Fig. 6. (Color online) The changes of average path length of the infrastructure network under attacks.

attacks, when the ratio of the fracture is less than 25%. That is to say, the transportation efficiency, capacity and reliability of BRTN are falling faster. Under random attacks or intentional attacks, the scale of the edges and/or the vertices is decreased. The whole road network is broken into pieces finally, which causes no

Fig. 7. (Color online) The changes of average path length of the dynamic network under attacks.

Fig. 8. (Color online) The changes of global network efficiency of the abstract network under attacks.

effective communication paths to exist, as well as the average path length value is changed to zero.

Under two different failure conditions, the global network efficiency changes the abstract network, the infrastructure network and the dynamic transportation network in Beijing as shown in Figs. 8–10. In the figure, the horizontal axis is the ratio of the edge of the fracture, the longitudinal axis is the global network efficiency value.

For urban road transportation networks, the failure of the edge means that the road is invalid. From the above three diagrams, the global network efficiency of the three networks are falling faster under the intentional attacks. The trends in the infrastructure network and dynamic transportation network are more obvious. For the infrastructure network and the dynamic transportation network, the global network efficiency varies greatly in the two failure conditions.

Under intentional attacks, the values of global network efficiency of the infrastructure network and the dynamic transportation network are very low, when the

Fig. 9. (Color online) The changes of global network efficiency of the infrastructure network under attacks.

Fig. 10. (Color online) The changes of global network efficiency of the dynamic network under attacks.

ratio of the edge of the fault is 60%. The abstract network is in the state of collapse. Under random attacks, the value of global network efficiency of the infrastructure network is reduced to about half. The value of global network efficiency of the dynamic transportation network is reduced to $1/3$ of the original. It shows that the infrastructure network and the dynamic transportation network are robust against random failures of nodes, as well as being vulnerable to intentional attacks. The vulnerability and the robustness are close to the typical characteristics of scale-free networks, which are not obvious on the abstract network.

4. Conclusion

In this paper, the multiple topological models of BRTN are constructed and analyzed according to the methodologies from complex network research domain. By analyzing degree distributions of the network models, it is known that the degree distribution of the abstract network model is subject to Poisson distribution which characterizes random networks. The degree distribution of the infrastructure network model and the dynamic transportation network model are both close to power-law distribution. The statistical characteristics of three kinds of network models under different attack modes are simulated, the analytic results show that the urban road infrastructure network model and the dynamic transportation network model in Beijing are both robust and vulnerable to some extent. The statistical characteristics of urban road transportation network of Beijing under the condition of network failures are analyzed in a more comprehensive way, which is not in the form of a simple abstract network model, but with three different forms of networks. Based on the work in the paper, the network cascading failure can be considered for analyzing dynamical properties of urban transportation networks in future research.

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