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Freeway Network Connective Reliability Analysis Based Complex Network Approach

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Abstract

The freeway plays an essential role in intercity transportation, due to its safety, convenience and efficiency. To ensure the gradually networked freeway system to operate smoothly and efficiently, the connective reliability evaluation become extremely important. Applying the complex network approach, the improved evaluation indicators of complex network, such as structural degree, betweenness and shortest path length are defined respectively to reflect the freeway network's structural properties firstly. Secondly, a measurement considering the effective paths number is proposed to evaluate freeway network's connective reliability. Finally, based on the freeway network in Shandong Province (SFN), which is the largest scale freeway network in eastern China, those evaluation indicators are calculated, and the freeway network's connective reliability are evaluated under different scenarios. The nodes with high structural betweenness must be given more protection so as to improve the reliability of the SFN under random attack The structural properties and reliability analysis of freeway networks are helpful for road planning and unexpected major events control.
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1. Introduction

The complex network theory has been given much attention over the last decade and has become an important tool to better understand social, technological, and biological real-world systems [1-6]. Transportation networks

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have motivated empirical analysis of various networks, such as airline networks [7-11], railway network [12-14], cargo ship networks [15-19], urban transportation network [20-26], and so on.

The freeway networks, as the terrestrial communication between cities, are becoming an essential part of transportation systems due to their safety, convenience and efficiency. It supports movement of city-to-city goods and people, and forms the backbone of economic development in a country. From 2000 to 2013, the freeway in China has grown from 163000 to 1044000 kilometres, and revealed the networking trend. Compared with other transportation networks, freeway network has some distinct features: firstly, given that freeway is fully controlled by the access and the adjacent access, the vehicles can't be dispersed in time due to the long distance between stations, when some unexpected events happen. Secondly, the vehicles drive in each direction on freeway, and ensure its closure by interchanges. In recent years, the convenience and efficiency of freeway are challenged by the ever-increasing travel demand, more frequent traffic accidents, and the increasing of the number of vehicle. Because the structure of a network often affects its function, deciphering the topology of the underlying freeway network is a prerequisite to a full understanding of interacting systems. It is noted, however, that not all freeway links of a network are equally critical to its functioning, that is, to say, some links have a greater impact on network flows than the rest. In this context, to ensure the gradually networked freeway system operating smoothly and efficiently exploring the structural characteristics and reliability of freeway system in China is of the utmost interest and importance for researchers and have great implications for road planning and unexpected major events control. Therefore, it is important to analyze the connective reliability of freeway network considering the importance of the roads within. Although some papers have investigated the topological property and risk of freeway from several aspects [27-32], there are little papers studying the structural characteristics and connective reliability by complex network theory. This paper is therefore to establish the improved structural and connective reliability model of freeway network. To accurately describe the properties and analysis the connective reliability of real freeway system, the remainder of this paper is organized as follows. Section 2 presents the freeway network representation model and proposes improved parameters for investigating structural characteristics. Section 3 discusses the connective reliability considering the number of effective paths between two nodes when it is subjected to different attack protocol with graph theory and complex network. In section 4, it depicts on a typical freeway network of Shandong in China and analysis the basic properties and connective reliability. And Section 5 states the conclusion and some discussion.

2. Statistical and structural properties

2.1. Network representation

Complex network analysis must start with the representation of a real system. The topology of freeway network is the basis of this research and all the assessments on characteristics are based on the physical topological structure of the network. The freeway network consists of toll stations or interchanges and links. In general, the bidirectional physical structure of freeway is not obvious and asymmetric. Hence, the freeway network can be generalized a abstracted as an undirected graph $\mathrm{G} = \{V, E, A, W\}$.

Where $V = \{v_i \mid i = 1, 2, 3, \ldots, n\}$ is the set of nodes which can be represented by the toll stations or interchanges. And $E = \{< v_i, v_j > \mid v_i, v_j \in V, i \neq j\}$ is the set of edges, which can be replaced by the tracks directly connecting two stations. And $A = \{a_{ij} \mid \mathrm{v_i}, v_j \in V, i \neq j, < v_i, v_j > \in E\}$ is the associated adjacency matrix, if there is an edge between two nodes, then the entry element in the matrix is equal to 1, otherwise it is 0. Since the graph under the consideration is undirected, it means that the associated adjacency matrix A is symmetric and nonnegative. $\mathrm{W} = \{\mathrm{w}_{ij} \mid w_{ij} = \mathrm{d}_{ij} \cdot a_{ij}, v_i, v_j \in V, i \neq j, < v_i, v_j > \in E\}$ is the physical geographical distance weight set of edges, Where l_{ij} means the physical length of link between node i and j.

2.2. Structural properties analysis

In this section, the several improved topological parameters are given to investigate the structural characteristics.

(1) Node structural degree

Unlike traditional node degree [17], structural degree of a node i is defined as the total mileage of nodes which are directly connected to. Here, it reflects the coverage range of a node in the freeway network. The higher the structural degree of a node is, the greater impact of the node in the network is. The structural degree of a node i can be calculated using the formula:

$$sd_i = \sum_{j=1}^{M} \mathrm{w}_{ij} \tag{1}$$

In the equation, M represents the neighbours' set of node i, and w_{ij} is the weight value in the adjacent matrix, which is equal to the length of the link.

(2) Structural betweenness

The structural betweenness of a node i is calculated as the total length of the shortest paths between every pair of vertices that pass through the given node i towards the total length of all the shortest paths between OD pairs base on the betweenness or centrality measures [17]. The higher the value is, the more coverage range the station affects in freeway network. It measures the importance of a node with respect to the connective distance between other nodes of the network. Considering the node scale, hence, we have the betweenness:

$$sb_i = \frac{\sum_{j=1}^{N}\sum_{k=1}^{N-1} path_{jk}(i)}{\sum_{j=1}^{N}\sum_{k=1}^{N-1} path_{jk}} \tag{2}$$

Where $path_{jk}$ is the total distance of shortest path between j and k, and $path_{jk}(i)$ is the length of shortest paths between j and k that contain node i.

Moreover, the structural betweenness of the edge is defined as the total length of the shortest paths between OD pairs that pass through the given edge towards the total distance of all the shortest paths between OD pairs. The higher the value is, the more coverage range the link affects in FN. In this context, the edge with high betweenness will have the stronger effect in the whole network. It can be calculated using the formula:

$$sb_{\mathrm{ii}} = \frac{\sum_{j=1}^{N}\sum_{k=1}^{N-1} path_{jk}(\mathrm{e}_{ij})}{\sum_{j=1}^{N}\sum_{k=1}^{N-1} path_{jk}} \tag{3}$$

Where $path_{jk}(e_{ij})$ is the value of shortest paths between j and k that contain edge e_{ij}, $path_{jk}$ is the value of shortest path between j and k. Moreover, to be relatively comparable among data, we normalize the structural betweenness by maximum method.

(3) Average shortest path length

The average shortest path is a global property which is essential to the topology and communication efficiency of networks. It is defined as the length of a shortest path from node i to j in a given graph. It reflects the internal structure of a network because it contains the internal separations of all node pairs. In this context, it reveals the ease of travel among destinations.

$$ASP = \frac{1}{N(N-1)}\sum_{i \neq j} \mathrm{d}_{ij} \tag{4}$$

Where ASP is the average shortest path, d_{ij} is the structural shortest path between node i and j.

3. The connective reliability of freeway network

3.1. Connective reliability

The connectivity reliability of freeway network is defined as the sum of the probability of freeway network in which there is an effective path at least between the origin and destination. It is affected comprehensively by some factors, such as the shortest path lengths, the number of effective paths, and network scale, and is given as follows:

$$CR = \frac{2}{N(N-1)}\sum_{i,j \in N}^{i \neq j} cr_{ij} \tag{5}$$

In which,

$$cr_{ij} = \frac{N_{ij}^{'} \cdot \mathrm{d}_{ij}}{N_{ij} \cdot d_{ij}^{'}} \tag{6}$$

Where CR is the connective reliability of the freeway network, and ranges from 0 and 1; cr_{ij} is the connective reliability between OD pair i and j, N is the number of the nodes in the network, $N_{ij}^{'}$ is the number of effective paths between i and j after different deletion attacks, N_{ij} is the number of effective paths between i and j at base case, the sum is over all $N(N-1)/2$ pairs of nodes. It's noted, the effective path is defined as that the length of path between OD pair is less than the double length of shortest path.

Based on the connective reliability index, the risk node or link of a freeway network can be defined as critical node/edge, the closure of which causes a significant change of network efficiency.

3.2. Attack scenarios

The nodes and edges are removed from the systems one by one until the networks collapse, the connective reliability changes of freeway network subjected to attacks can be assessed by these removal regulations. Remarkably, it is assumed that the attack node or edge is removed out of the freeway network and its connected nodes/edges are closed when the attack happens. That is to say, the paths passing through the failure node are not connected. The specific attack protocols include random attacks and malicious attacks, which are designed as follows.

(1) Random attacks. Tolerance to random attacks relates to those damages in infrastructure systems triggered by random contingencies, for example, natural disasters, equipment failures or human error. The attacked stations or edges are selected randomly and the topological properties can be recalculated after a deletion.

(2) Malicious attacks. Tolerance to malicious attacks relates to targets in the network that are chosen deterministically by the attacker, such as terrorist attacks. In this paper, it contains the highest structural betweenness edge-based attacks, and the highest structural betweenness node-based attacks.

3.3. Algorithm flowchart

Step1: Initialization. The initial state before attack is calculated and saved, including adjacency matrix and the length of shortest path between OD pair by Floyd's algorithm.

Step 2: Node /edge selection. The initial attacked node or edge is identified.

Step 3: Update the network topological structure. The attacked nodes or edges are removed out of the network. If no new failure nodes or edges are found, the attack process stops and the system remain to stable. And then the adjacency matrix and the incidence matrix are updated to calculate the shortest path length between OD pairs. Meantime, the number of effective paths between OD pairs is calculated by Dial algorithm.

Step 4: Compute the connective reliability of freeway network after attack by Eq. (5). Return the network to the initial state. This procedure is repeated until all the nodes or edges have been considered.

4. Numerical test

4.1. Data source

With the economic development, Shandong Province, including 140 counties, has become one of the most developed province in China and the resident population has exceeded 90 millions. As an eastern developed province in china, Shan Dong Province leads the nation in freeway development. The freeway network of Shandong (SFN) plays a crucial role in the cities’ communication of resident and freight, and the average number of daily traffic flow has exceeded 0.65 million. The study area spans across the whole freeway network in Shandong province in China, including 394 nodes and 410 edges.

4.2. Statistical and structural properties

(1) Structural degree

The result on the traditional degree feature is displayed in Fig.1. In Fig. 1. (a), it’s noted that the nodes whose degree equal to 4 or 5 are all interchanges, which can be explained that the interchanges play important roles in connecting freeway lines and dispersing the vehicles. Meantime, it indicates that the node degree distribution curve of the SFN has an identical peak and follows a Poisson distribution. According to the analysis of the fitting function, it shows that the degree distributions of SFN can be better fitted by the Gaussian function. The fitting functions are given by:

$$p(k) = a \cdot e^{(-(k-b)/c)^2} \tag{7}$$

Where the scaling factors a= 0.8177, b=1.938, c=0.6255.

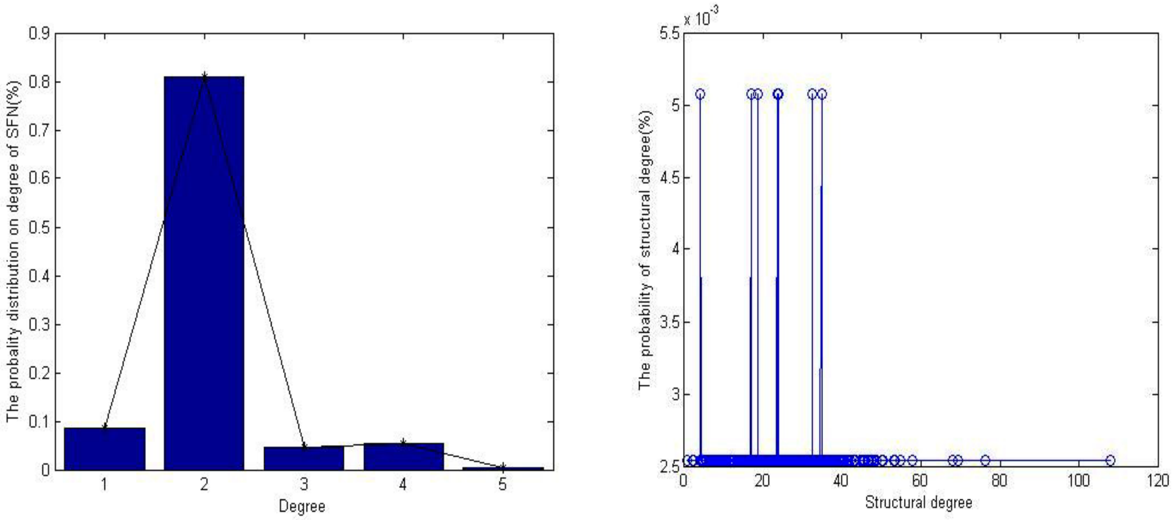

Fig. 1. (a) The node degree distribution of the freeway network in Shan Dong province; (b) The node structural degree distribution of the freeway network in Shan Dong province.

However, it's clearly noted that the structural degree shows large discrete extent in Fig. 1. (b), which differ from the distribution of degree and express the actual relationship with geographic distance.

(2) Structural betweenness

In Fig. 2.(a) and (b), it is observed that most of nodes and edge has the lower value structural betweenness. The nodes and edges in Jinan have the relatively higher structural value than others in the freeway network. Consequently, those can be explained that as the provincial capital of Shandong, Jinan plays a hub role in the freeway network of Shandong.

(3) Shortest path length

To compare with the actual distance, we also calculate the topological shortest distance which equals to 25.294. That is to say, the average number of the toll stations between pairs of nodes all over the networks can reach any destination in this network by passing through 25 nodes on average. Once some sudden events occur on some links of freeway network, in order to avoid the jam spread, the operating administrator of freeway can evacuate the vehicles in time according to ramp controlling. Fig. 3 shows that the cumulative probability distributions of the topological network and physical shortest path lengths can be better fitted by a Gauss distribution function and the curves have trends to move to the left with the decrease of the largest shortest path lengths of SFN. The Gauss fitting function is given by:

$$P(l) = a \cdot e^{(-(l-b)/c)^2} \tag{8}$$

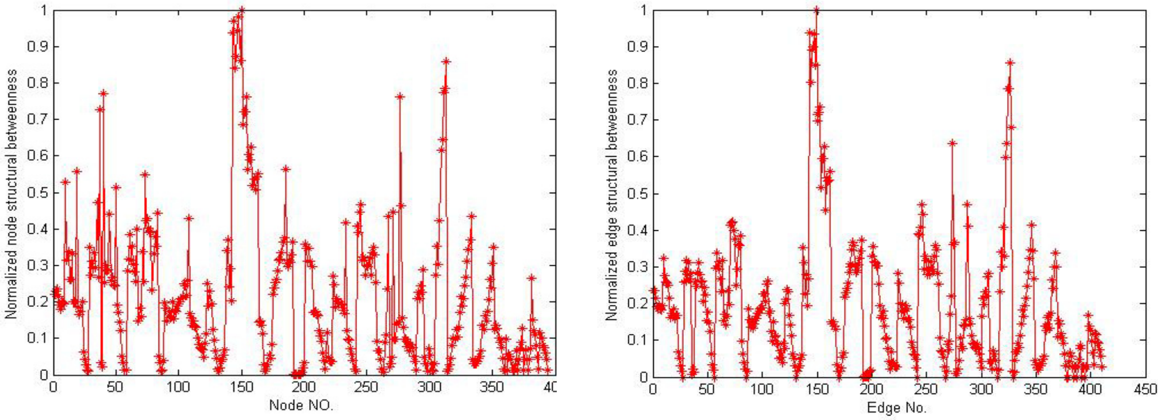

Fig. 2. (a) Normalized node structural betweenness of freeway network in Shandong province; (b) Normalized edge structural betweenness of freeway network in Shandong province.

Where the scaling factors are chosen as the corresponding values as shown in Table 1.

Table 1. Scaling factors of shortest paths.

	a	b	c
Topological shortest path	0.9835	2.528	28.01
Physical shortest path	0.9579	37.94	349.2

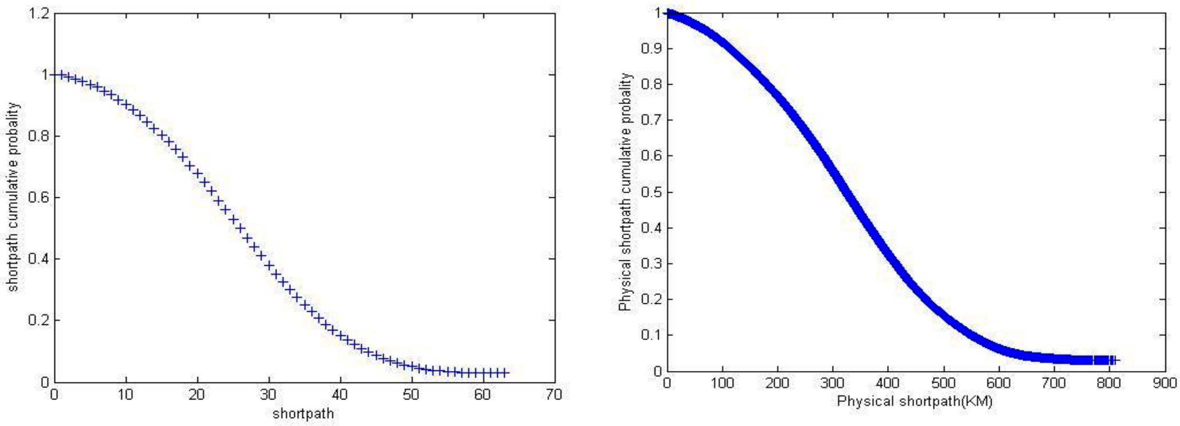

Fig. 3. (a) Cumulative probability distribution of the network shortest path length in terms of network distance; (b) Probability distribution of the shortest path length in terms of the physical distance between nodes.

4.3. The connective reliability

In this section, we analyze the connective reliability to assess the changes for subjection under different attack protocols. Fig. 4. (a) and (b) show the changes of the network connective reliability for a freeway network subjected to random and malicious attack protocols. The horizontal axis represents the proportion of removed nodes or edges, and the ordinate value represents the change of connective reliability. Fig. 4. (a) and (b) show similar results for the freeway network in Shandong province, and the improved connective reliability of freeway network decrease with increase of the fraction of removed nodes and edges. However, there are some special things to deserve attentions as follows: (1) when the fraction of node and edge exceeds 30% under random attack, the connective reliability is down to 20%. However, when the fraction of node or edge exceeds 20% under malicious attack, the connective reliability is down to 20%. (2) When the fraction of node is equal to the fraction of edge, the connective reliability under node attack has a faster rate than that of edge attack. All of phenomena those show that the connective reliability of the freeway network becomes very much worse when subjected to highest betweenness node-based and edge-based attacks than when subjected to random attacks, which means that the freeway network is very fragile when subjected to malicious attacks, and it is robust against random attacks rules, and shows that the freeway network is robust against random attacks and vulnerable to malicious attacks. Therefore, we can declare that the highest betweenness node and edge-based attack protocol is the most effective mode for destroying Shandong freeway network, especially the nodes with high betweennesses must be given more protection, so as to improve the reliability of the SFN under random attack.

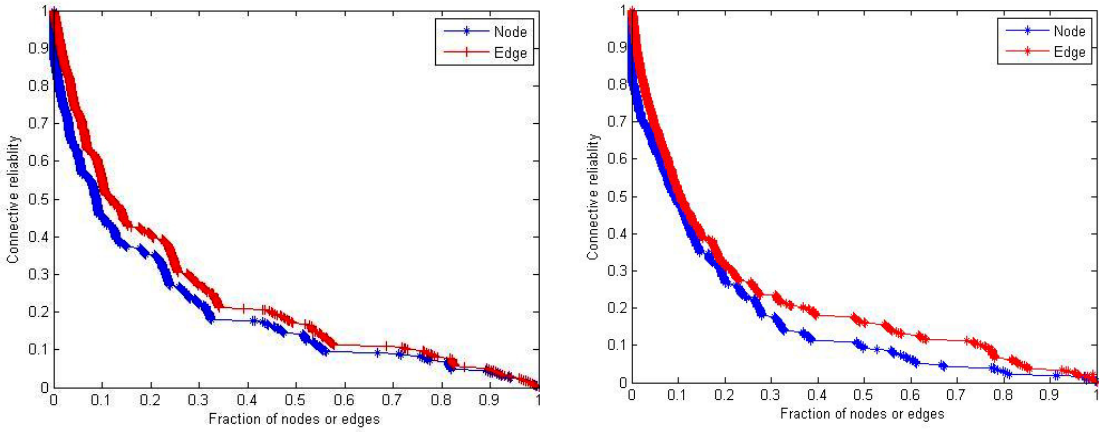

Fig. 4. (a) The changes of the network connective reliability with random attack protocols; (b) The changes of the network connective reliability with malicious attack protocols.

Based on the metrics elaborated above, we investigate the structural properties of the SFN in this section. By analyzing the data from the Shandong freeway network, we have shown that SFN exhibits Poisson distribution of degree, and the cumulative structural shortest path length in SFN can be fitted by the Gauss distribution. We analysis the connective reliability changes under different attacks. When the nodes or edges of the network are removed from the network one by one, we find that the connectivity of the freeway network becomes very much worse when subjected to highest betweenness node-based and edge-based attacks than when subjected to random attacks. And the nodes with high betweenness must be given more protection, so as to improve the connective reliability of the SFN under random attack.

5. Conclusion and discussion

Freeway has been experiencing a rapid development due to unique advantages, such as convenience and safety. It supports movement of city-to-city goods and people, and forms the backbone of economic development in a country. In recent years, the convenience and efficiency of freeway are challenged by the ever-increasing travel demand, more frequent traffic accidents, and the increasing of the number of vehicle.

Applying the complex network approach, this paper proposes the evaluation indicators of freeway network's structural properties, and evaluates freeway network's connective reliability. First, the improved evaluation indicators of complex network, such as structural degree, betweenness and shortest path length are defined respectively to reflect the freeway network's structural properties. Second, a measurement considering the effective paths number is proposed to evaluate freeway network's connective reliability. Finally, based on the SFN, which is the largest scale freeway network in eastern China, the freeway network's structural properties and reliability are evaluated. The results show, that the freeway network in Shandong exhibits the mixed topological network with random network according to Poisson distribution of degree; the nodes and edges in Jinan have the relatively higher structural betweenness value than others in the freeway network; the cumulative structural shortest path length in SFN can be fitted by the Gauss distribution. Moreover, through analyzing the connective reliability, the nodes with high structural betweenness must be given more protection so as to improve the reliability of the SFN under random attack. It should be said that this research can provide several proposals for planners and engineers to investigate the network optimization of freeway network in China.

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