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RESEARCH PAPER

Performance Analysis of Urban Rail Transit Network

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Abstract: With the construction of new lines, urban rail transit network continues to expand. It is beneficial for the smooth operations of urban rail transit network to analyze the network characteristics of different development periods and summarize the law of development. Based on the theory of complex networks, the paper first compares the characteristic values of Beijing urban rail transit plan network and current operating network and the variation of values. The results indicate that some indicators of plan network such as average degree, clustering coefficient and average shortest distance has increased. However, due to expansion of service radius, the network efficiency decreased slightly. Then, aiming at important nodes failure and line failure, the paper compares the network flexibility after node failure and line failure, and calibrates the key nodes in the network. The results show that the node and line failure have smaller impacts on the planning network. The fundamentality of some nodes changes with the network improvement. For current operating network, it is necessary to guarantee the reliability of key nodes.

Key Words: urban traffic; network performance; complex networks; network flexibility

1 Introduction

The urban rail transit network is the foundation of the network operation, and the structural analysis of the static network is also one of the prerequisites for improving both the level of passenger flow analysis and the effect of transport organization. The static statistical characteristics of the network not only indicate the fundamentality of the nodes and lines but also provide a basis for line-level division and fundamentality evaluation of the nodes. Since some random factors (such as fluctuations of large passenger flow) always impact the performance of the network and even result in failures of the station functions, this study analyzes the influence of node failure and network reliability, and then provides a reference for emergency strategy making. Meanwhile, it presents the impacts of the network improvement on the rail transit network by comparing network characteristics and network efficiency after node failure during the different development periods. It provides a basis for rational planning of the rail transit network and the construction of new lines.

The urban rail transit network is a kind of complex transport network that contains stations, lines, and so on. Some academicians have already studied the urban rail transit network characteristics using a complex network theory. Angeloudis[1] analyzed the subway systems of most big cities in the world and found that the degree distribution of subway networks is subjected to an exponential distribution. Lee[2] analyzed the topology features of the Seoul subway network and used the passenger flow as path impedance. Li and Ma[3] analyzed the topological characteristics of the subway network in most big cities in the world, and found that they have the following in common: The clustering coefficient is very small, the diameter is larger, and the average degree is close to 2. Wang[4] performed an analysis of the subway network characteristics; conducted a comparison for the three cities of Beijing, Shanghai, and Guangzhou; and found that all of them are typical small-world networks. Liu[5] studied the network characteristics and network reliability of the Guangzhou Subway; Wang and Yang [6] performed a statistical analysis of the Shanghai rail transit network characteristics, and found that the network has small-world network characteristics; Ma[7] analyzed the Beijing urban rail transit network characteristics in Space P topological spaces, and derived statistical indicators such as node degree.

Most of the studies just cited only calculated the complex network statistical indicators of the rail transit and did not conduct an in-depth discussion on the variation rule of the

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network characteristics during the network evolution process. Based on the Space L method, this article built the topological structure of both the Beijing urban rail transit plan network (hereinafter referred to as the plan network) and the currently operating network (hereinafter referred to as the operating network). By analyzing the degree, clustering coefficient, average shortest distance, betweenness, and other indicators, we first compared the two networks and illuminated the characteristic parameters change law during the network development process. Then, we compared the influence of important node failure and line failure on the two networks.

2 Characteristic analysis of the Beijing urban rail transit network

2.1 Network topology of Beijing urban rail transit

With the construction and operation of new lines, the size of the urban rail transit network is increasing. At present, the Beijing operating network has 12 lines; we rejected the Fangshan Line, because it does not connect to the other lines. The Beijing 2015 plan network has 19 lines. Taking into account the ease of calculation, the lines in the same direction, such as the Line 4 and Daxing line, the line 1 and Batong line, were merged to build the network topology. However, this does not affect the overall results.

There are two major methods of building a rail transit complex network[4]. One is the Space *L* method, which regards the station as a node, if two nodes are adjacent in the same line, and they have an edge. The other is the Space P method, which regards the station as a node, if two nodes have direct access to each other, and they have an edge. This article built the network topology based on the Space *L* method. In the *L* space, the network edges do not consider the direction, and it is an undirected network, which can be shown as an undirected graph $G_p=(N_p, A_p)$, where N_p is the set of the nodes, and A_p is the set of edges. The length of the edge in the network is assumed to be 1, and this does not affect the results.

According to the topology structure and complex network theory, we extracted statistical indicators, calculated the network characteristic values of the plan network and the operating network, and analyzed the change law.

2.2 Selection of network characteristics

The *network statistical properties* mainly refer to the statistical distribution of microscopic quantities or the average values of macro statistics. The general statistical indicators [8] of the complex network include degree and average degree, average shortest distance, clustering coefficient, betweenness, network efficiency, and so on.

(1) Degree means the number of nodes that are directly connected to the node *k*. The network average degree is the average value of the degrees of all the nodes.

(2) The average shortest distance, which describes the distance between any two nodes from a global perspective, reflects the inter-site links. It can be derived by computing the mean of the minimum distances from each node to all other nodes in the network. The average shortest distance *l* can be calculated as follows:

$$l=\frac{2}{n(n-1)}\sum_{i\geq j}^{N} d_{ij} \tag{1}$$

where d_{ij} represents the shortest distance from node *i* to node *j*.

(3) Clustering coefficient, which is used to describe the aggregation of the nodes in the network, reflects the tightness of the network. It is calculated as follows: Assume the node *i* is adjacent to *m* nodes; among the *m* nodes, there are at most $m(m-1)/2$ edges; if only E_i edges actually exist, then the clustering coefficient of the node *i* is the ratio of E_i and $m(m-1)/2$.

(4) Betweenness, which is used to measure the number of all the shortest paths in the network that through some edge or node, can be divided into the edge betweenness and the node betweenness. The formula of betweenness B_i of the node *i* is:

$$B_i=\sum_{k,j\in N,k\neq j}\frac{n_{kj}(i)}{n_{kj}} \tag{2}$$

where n_{kj} means the number of the shortest paths between the node *k* and the node *j*; and $n_{kj}(i)$ means the number of the shortest paths through the node *i*. Betweenness reflects the role of the nodes or edges in the whole network; the greater the betweenness is, the greater influence the node has on the network.

(5) Network efficiency, which is used to measure network connectivity, can be calculated as follows:

$$E=\frac{2}{N(N-1)}\sum_{i\geq j}^{N}\frac{1}{d_{ij}} \tag{3}$$

where *N* is the number of the nodes in the network; and d_{ij} is the shortest distance between the node *i* and the node *j*. The higher the value of *E* is, the better the connectivity of the network is, and the higher the efficiency is.

2.3 Comparative analysis of the network characteristics

Based on the constructed topological network, the indicators just cited in relation to the operating network and plan network were, respectively, calculated. The statistical results are shown in Table 1. It can be observed in the table, compared with the operating network, that the plan network nodes are 1.85 times more than the operating network nodes, and the edges are 2.01 times more than the operating network edges. The average degree increases slightly, and the degrees of most nodes are still 2. The average shortest distance increases about one station distance. The network diameter increases seven station distances, indicating that the service radius of the plan network is expanding. The clustering coefficient of the operating network is 0, indicating that the operating network connectivity is poor. When the new line construction is completed, the local connectivity of the plan network will be improved.