

# Research on Urban Rail Transit Recovery Strategies Based on Resilience Theory

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**Abstract:** To improve the recovery ability of urban rail transit in response to emergencies, a resilience based network recovery model for rail transit is proposed, and recovery strategies under both unweighted and weighted networks are studied. Identify vulnerable stations in the rail transit network by sequentially attacking them and observing changes in network efficiency; Using network efficiency as a performance evaluation indicator, a recovery model with the goal of maximizing resilience is constructed using the "resilience triangle" method to solve the optimal recovery strategy for damaged sites. The identification of vulnerable sites based on the analysis results is related to their location in the network; The optimal recovery order is related to the location of the site in the network and the passenger flow of the site.

**Keywords:** Rail transit network; Resilience; Recovery strategy.

## 1. Introduction

In recent years, urban rail transit in China has developed rapidly and gradually become the main force of the public transportation system<sup>[1]</sup>. However, with the rapid improvement of urban rail transit, the road network structure is becoming increasingly complex, and it is highly susceptible to the impact of emergencies in daily operations<sup>[2]</sup>. It is crucial to develop a reasonable recovery strategy and quickly restore the traffic capacity of stations to ensure the normal operation of the transportation system after network damage.

For the research on the resilience of transportation systems, scholars mostly use network efficiency to measure network resilience and establish recovery models to solve the optimal recovery strategy<sup>[3-4]</sup>. On this basis, some scholars add other constraints to solve the optimal recovery strategy. As Zhang aimed to minimize network performance loss and lower recovery costs, they determined the optimal recovery sequence<sup>[5]</sup>. Zhang Wenjie et al constructed a fault recovery model with the goal of minimizing network resilience loss and total recovery time, and solved the repair plan. There are also studies that improve network efficiency calculation methods to establish recovery models<sup>[6]</sup>. Yin Yong used the overall network accessibility loss and the proportion of unaffected passengers as indicators to measure resilience loss and solved repair strategies<sup>[7]</sup>.

This article establishes a recovery model with the goal of maximizing resilience, and solves for the optimal recovery sequence after station failure, in order to provide reference for emergency management of Tianjin Rail Transit during operation..

## 2. Network Performance Evaluation

### 2.1 Resilience performance function

The rail transit network is commonly represented by an undirected unweighted graph  $G = (V, E)$ , where  $V$  is the set of stations and  $E$  is the set of edges. When analyzing a transportation network, it is often abstracted as a topological network structure composed of nodes and edges.

In the study of traffic resilience, the "resilience curve" is often used to represent the changes in system resilience, as shown in Figure 1.

In complex networks, network efficiency is generally used to evaluate the global connectivity performance of the network structure. Therefore, when measuring the performance changes of the network at different stages of the system, network efficiency is commonly used as a performance

metric on the vertical axis of the "resilience curve". Network efficiency is defined as the average of the sum of the reciprocal of all shortest paths in the network, as shown in equation (1).

$$E = \frac{1}{N(N-1)} \sum_{i,j \in V(i \neq j)} \frac{1}{d_{ij}} \quad (1)$$

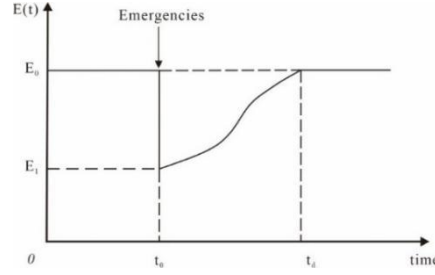


Fig.1 Performance change curve of transportation system network under unexpected events

However, the actual distance between urban rail transit network stations is not exactly the same. Therefore, when calculating efficiency, introducing the actual distance between stations to calculate network efficiency is more in line with reality, as shown in equation (2).

$$E = \frac{1}{N(N-1)} \sum_{i,j \in V(i \neq j)} \frac{\sqrt{\sigma_i \times \sigma_j}}{l_{ij}} \quad (2)$$

Where:  $l_{ij}$  is the actual distance between stations.  $\sigma_i$ ,  $\sigma_j$  is the weight of nodes  $i$  and  $j$ . Taking  $\sigma_i$  as an example, its value can be calculated using equation (3):

$$\sigma_i = \sigma_{i,D}^n \times \sigma_{i,f}^n \quad (3)$$

Where:  $\sigma_{i,D}^n$  and  $\sigma_{i,f}^n$  respectively represent the topological importance and passenger flow importance of station  $i$  after standardization, which are calculated using equations (4) and (5).

$$\sigma_{i,D} = \frac{D_i}{\frac{1}{N} \sum_{i \in V} D_i} \quad (4)$$

$$\sigma_{i,f} = \frac{f_i}{\frac{1}{N} \sum_{i \in V} f_i} \quad (5)$$

Where:  $D_i$  is the degree value of node  $i$ ,  $f_i$  is the passenger flow of node  $i$ .

## 2.2 Resilience indicators

As shown in Figure 1, the resilience curve is commonly characterized by network efficiency in terms of vertical network performance. The measurement formula for resilience  $R$  is shown in equation (6).

$$R = \frac{\int_{t_0}^{t_d} [E(t)] dt}{E_0 \times (t_d - t_0)} \quad (6)$$

## 3. Case Study

### 3.1 The Current Situation of Tianjin Urban Rail Transit System

As of December 2022, there are a total of 9 operating lines and 182 operating stations in Tianjin Rail Transit.

Construct the topology diagram of Tianjin rail transit network using the Space L method, as shown in Figure 2.

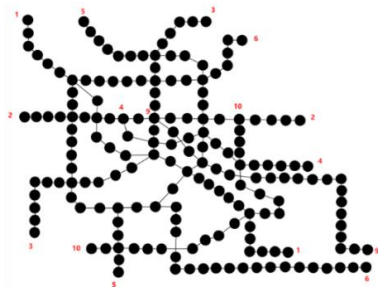


Fig.2 Tianjin rail transit network topology structure diagram

### 3.2 Research on Network Vulnerability

Simulate attacking each site sequentially, observe changes in network efficiency, and identify vulnerable sites. Figures 3 and 4 show the changes in network efficiency when a single site is attacked in both unweighted and weighted networks.

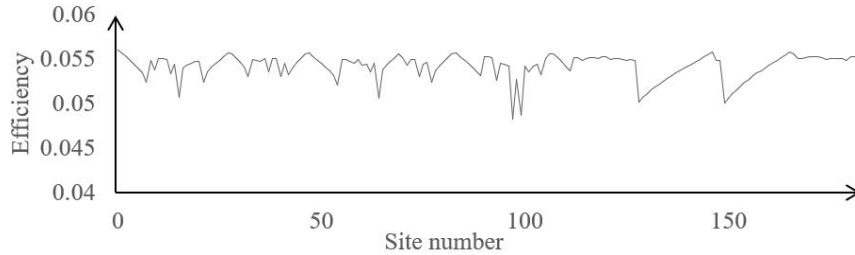


Fig.3 Changes in efficiency when a single site is attacked (unweighted network)

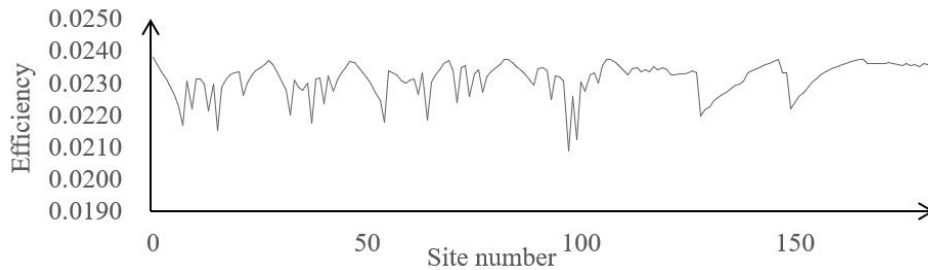


Fig.4 Changes in efficiency when a single site is attacked (weighted network)

According to the network efficiency changes during single node attacks on the unweighted and weighted networks of Tianjin Rail Transit, it can be seen that the degree of efficiency changes for the two networks is roughly the same under this attack mode. Among the vulnerable sites without access to the network, most of them are directly connected to the central line network and branch line network, such as 149, 128, etc. This is because these vulnerable sites are mostly located in the only connection position between the suburbs and the city center. This is because once these sites are destroyed, The connection between the city center and the suburbs is interrupted, and there are still a large number of stations outside the connection between the suburbs and the city center, which has a significant impact on the efficiency of the entire transportation network. If the stations connected to these stations, such as 150 and 129, fail, it will cause other stations in the branch network to be unable to reach the transfer stations, affecting the connectivity of the entire network and also being fragile stations. Therefore, the vulnerability of stations is closely related to their position in the rail transit network. In daily operation, in addition to paying attention to stations that intersect the central and branch line networks, it is also necessary to strengthen the management of stations connected to transfer stations in the branch line network. In a weighted network, most vulnerable stations are located at the transfer points between two lines, such as Xiawafang Station, Tianjinxi Station, Yingkoudao Station, etc. This is because these stations have relatively high daily passenger flow, so it is necessary to weight stations based on passenger flow to determine their importance.

### 3.3 Research on Network Recovery

This section assumes that the top four sites in terms of vulnerability will simultaneously solve the recovery order for failures.

The weighted network selects Zhigu Station (node 97), Cultural Center Station (node 99), Xiawafang Station (node 15), and Tianjinxi Station (node 7) for attacks, with node degrees of 4, 3, 4, and 4, respectively, to determine the recovery order after the four stations are damaged. According to Matlab, the network efficiency after four sites were damaged is 0.0158, and the recovery order that maximizes resilience is 97-7-99-15. The recovery curve is shown in Figure 5. The weight of a site is determined by its passenger flow and node degree, but the recovery sequence is not fixed according to the site weight. Therefore, when determining the recovery order, although

the weights of the sites have a certain impact, not all are sorted according to their weight sizes. Station 99 is a transfer station between Line 5 and Line 6. As a suburban station connected to the central area of Line 6, restoring this station has a greater impact on the overall efficiency of the network. The passenger flow of this station ranks third among the four stations. Therefore, it can be seen that the impact of passenger flow as a weight on the order of station recovery is not as significant as the position of the station in the network.

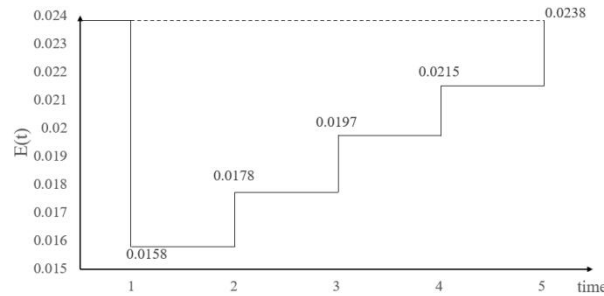


Fig.5 Network recovery curve under optimal recovery sequence (weighted network)

In summary, in the actual operation of urban rail transit, when multiple stations fail, it is necessary to prioritize the restoration of irreplaceable transfer stations to ensure the connectivity of the entire network. The location of a site in the network has a greater impact on determining its recovery order than the passenger flow of the site.

## 4. Summary

(1) The connecting stations between the center and the suburbs are fragile stations in the subway network, and management needs to be strengthened in daily operations to prevent station damage and transportation network collapse.

(2) In reality, when multiple sites fail, priority should be given to restoring irreplaceable sites, and the order of recovery is determined by the location of the sites in the network and the performance of the nodes.

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