Journal of Highway and Transportation Research and Development
2024, 18(2): 76-81
ISSN 2095-6215
DOI: 10.26599/HTRD.2024.9480016

Resilience Analysis of Multi-Modal Transportation Networks: A Case Study of the Beijing-Tianjin-Hebei Region

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Abstract: The efficient, reliable, and sustainable nature of a transportation system is a prerequisite to support the development of urban agglomeration. This paper proposes network modeling and resilience assessment methods for public transportation in urban agglomerations. A multi-layer network is constructed. With the identification of the key nodes in a multi-modal transportation network (MMTN), a resilience assessment method is proposed that considers two phases: absorption and recovery after an attack. The Beijing-Tianjin-Hebei urban agglomeration network is taken as a case study. The results show that the attack on key nodes brings more influence to MMTN than random attacks. More attention is suggested to be paid to the larger hub-type stations in operation and management. The proposed method can be applied in different types of urban agglomerations and serve as technical support for reducing the disorder and imbalance of MMTN.

Key words: traffic engineering; resilience; urban agglomeration; multi-modal transportation network; key nodes identification

1 Introduction

With the improvement of urban form and function, urban agglomerations are gradually forming and developing. Transportation system is an important part of urban agglomeration. Its efficientcy, reliability, and sustainability are cesential to support the development of urban agglomeration. In some cities where the transportation networks of urban agglomerations are still in their infancy, the tolerance for uncertain risk events is low. Therefore, it is of great significance to study the resilience of transportation networks in urban agglomerations.

China, as a developing country, is making great efforts to develop urban agglomerations. Currently, China has planned 19 urban agglomerations, which carry 75% of the country's population with 25% of the land area, generating 88% of GDP[1], becoming the concentrated areas of population, enterprises, and economic activities. With the initial stage of urban agglomerations, the resilience of urban agglomeration comprehensive transportation systems is not high. Under the impact of uncertain risks, it is easy to cause the disorder and imbalance, and even the functional destruction of the entire urban agglomeration and the loss of life and property.

The word resilience was originally derived from Latin, and its original meaning is "to return to the original state"[2]. are time the concept of resilience has been applied to various scientific research fields, including ecology, physics, economics and other research. At the same time, cities are the most concentrated areas of human production and life, and transportation is the key to urban development. Therefore, the concept of resilience is naturally applied to the research of cities and urban transportation.

The research on traffic resilience mostly focuses on the single traffic system of a single city, and most of them are carried out based on the network topology model. For example, ZHANG et al.[3] used spatio-temporal clusters to define urban traffic resilience in real traffic. BEREZIN et al.[4], ZHAO et al.[5] and WANG et al.[6] studied the propagation characteristics of cascading failures after local attacks and analyzed the resilience. In addition to research on the resilience of road networks, more scholars have focused on public transport networks[7-11]. Liu et al. took the Beijing-Tianjin-Hebei regional railway network as an example, proposed a key

Received 27 March, 2023; Revised 6 September 2023; Accepted 15 September 2023

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node identification method considering the reliability of node connections, and evaluated the network vulnerability based on six attack methods[12]. Voltes-Dorta et al. simulated and analyzed the vulnerability of the European aviation network under the scenario of individual closure of the 25 busiest airports in Europe[13]. Zhang et al. took the average efficiency of the network as the resilience index, and used the exhaustive method to analyze the restoration strategy and sequence of transfer stations and ordinary stations[14]. In the evaluation of resilience, most scholars describe it through a single indicator, ignoring the process nature of network resilience.

Based on the above studies, it is not difficult to find that most of the current research focuses on single-layer networks, such as a single ground, bus network, or single subway network, railway network, etc. There are relatively few studies on multi-modal transportation networks (MMTN). In addition, although the concept and characteristics of resilience have been known for a long time, most of the research on resilience evaluation is concentrated on a static view, with a lack of process nature. MMTN of urban agglomeration is composed of different cities and different transportation subsystems. The dependence relationship and interaction mechanism between different cities and different transportation subsystems in the system need to be analyzed and determined.

Therefore, this paper aims to study the resilience of the urban agglomeration MMTN, considering the absorption and recovery process when facing an attack. A case study of the transportation network in the Beijing-Tianjin-Hebei region (BTH) was conducted to verify the suitability of the resilience evaluation method for the transportation network of urban agglomerations.

2 Methodology

2.1 Framework

The research method is divided into three parts, as shown in Figure 1. Firstly, a multi-modal transportation networks (MMTN) is constructed for the three transportation modes. Then a key node identification method considering the network topology and operational service capability is proposed. Finally, a network resilience metric is proposed, and by means of simulation, the attacks on the key nodes are implemented to observe the changes in network resilience.

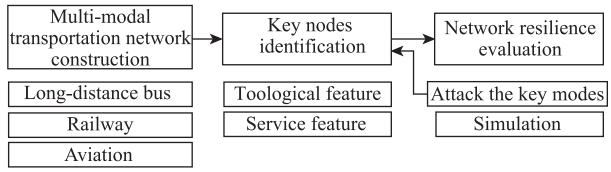


Fig. 1 Research flow chat

2.2 Network construction

The method to build MMTN is introduced. Given a network $G=(G_x \mid x=l,r,f)=(V,E)$, where $x=l,r,f$ represents the mode of long-distance bus, railway and aviation. $V=(V_l,V_r,V_f)$ is the set of the nodes, $E=(E_l, E_r, E_f, E_{\text{connect}})$ is the set of the edges. The rules of network construction are as follows:

(1) Nodes

Bus stop, railway station and airport are considered as nodes.

(2) Edges in each mode

For the bus mode, if the shortest path between two nodes does not exist at a third node, an edge is considered to exist between the two nodes. The edge set is represented by E_l. For railway mode, there is an edge between two railway nodes if there is an access. The edge set is represented by E_r. For aviation mode, there is an edge between two airports if a service exists. The nodes set is represented by E_f.

(3) Edges between the modes

An edge with railway node and long-distance bus node is formed if there is transport services as airport bus between nodes. Moreover, edges for bus stops within a radius of d near the railway station are constructed. These edges form the set E_{connect}.

(4) Adjacency matrix

According to the rules of nodes and edges, the adjacency matrix is shown in Equation. In MMTN, passengers can transfer to each of the three mode for their trip.

$$A=\begin{cases} a_{ij}=1,\ i \text{ is connected to } j \\ a_{ij}=0,\ i \text{ is not connected to } j \end{cases}. \qquad (1)$$

2.3 Key node identification

The key differences between each mode of MMTN is that they have the different network features and service capability. Long-distance bus mode has the shortest service distance of the three, with small capacity and a denser network. Railway mode covering more distant areas with a moderately dense network. Aviation mode is the fastest among the three, but the network is sparse. According to these characteristics, the key nodes identification considers two topological features and one operational service features, which are described in detail below.

(1) Node degree

Node degree can measure the network connectivity. It is defined as the number of the adjacent edges to the node, as shown in Equation. The larger the degree value, the more critical the node is in the network, such as a hub node, which can be used by different transportation modes for interchange. If it is failed, more passengers will be affected.

$$k_i = \sum_j e_{ij}, \tag{2}$$

where, e_{ij} is the edge in E, j is the node adjacent to node i.

(2) Closeness centrality

Closeness Centrality measures the average distance of a node to other nodes. A higher value indicates a shorter distance from other nodes. It can be used to measure the time it takes for passengers to travel from the node to other nodes, as shown in Equation (3).

$$c_i = \frac{n-1}{\sum_j d_{ij}}, \tag{3}$$

where, d_{ij} is the topological distance of the shortest path from node i to node j; n is the number of the nodes in V.

(3) Service Capability

Nodes of different modes have different service capacities to serve passengers. If a node with high service capacity fails, more passengers will be affected. The node service capacity is related to the frequency and the capacity of the carrier, which is obtained by the Equation (4).

$$s_i = p_i \times f_i, \tag{4}$$

where, p_i is the capacity of a carrier in node i; and f_i is the number of departure frequencies of the carriers in node i during the study period.

(4) Key nodes identification indicator

Considering the above three features, a key node indicator H_i is proposed, as shown in Equation (5). The higher the value, the more important the node is, and the greater the impact brought to passengers after an attack.

$$H_i = k_i c_i s_i \tag{5}$$

2.4 Network resilience evaluation

The resilience of the network is a process evaluation that contains an absorption phase and a recovery phase, as shown in Figure 2. The corresponding description indicators are proposed for each stage, and the overall resilience assessment metrics are proposed.

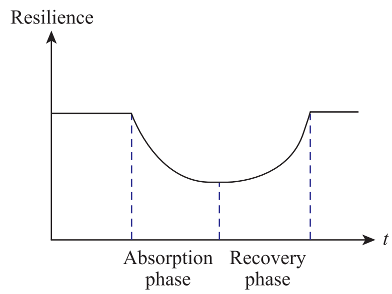


Fig. 2 The process of resilience

(1) Absorption phase

Absorptive capacity of the network is defined as the resistance in the face of attacks. When a node is failed by an attack, passengers traveling on the shortest path containing this node are affected and switch to other paths. The absorption characteristics of the network are thus expressed by the change in the number of redundant paths in the network, as shown in Equation (6). The larger the R_A achieve, the better the absorption capacity of the network is.

$$R_A = \frac{\sum_{i,j \in V_1} n_{ij}}{\sum_{i,j \in V} n_{ij}}, \tag{6}$$

where, n_{ij} represents the redundant paths in the network; V_1 is the node set after some nodes failed.

(2) Recovery phase

When the node contains more information, it is more difficult to recover. Since the complexity in the node is brought by people, the entropy value R_R of the service capacity is chosen to reflect the recoverability of the node. The larger the R_R achieve, the better the recoverability is.

$$R_R = -\sum_i \frac{s_i}{n} \log_2 \frac{s_i}{n}, \tag{7}$$

where n is the number of the nodes in V_1.

(3) Resilience assessment metrics

The network resilience is characterized by a linear combination of two-stage indicators, as shown in Equation (9). The larger the R achieve, the more resilient the network is. To observe the change in resilience, resilience reduction ΔR is used for the analysis, as shown in Equation (9). The larger the ΔR achieve, the greater the impact on the network when this node fails, $-1 \leqslant \Delta R \leqslant 1$.

$$R = \alpha R_{\mathrm{A}} + (1 - \alpha) R_{\mathrm{R}}, \quad (8)$$

$$\Delta R = \frac{R_{\mathrm{origin}} - R_1}{R_{\mathrm{origin}}}, \quad (9)$$

where, α is a parameter, $0<\alpha<1$; R_1 is the resilience metric after some nodes removed; R_{origin} is the resilience of the origin network.

(4) Simulation design

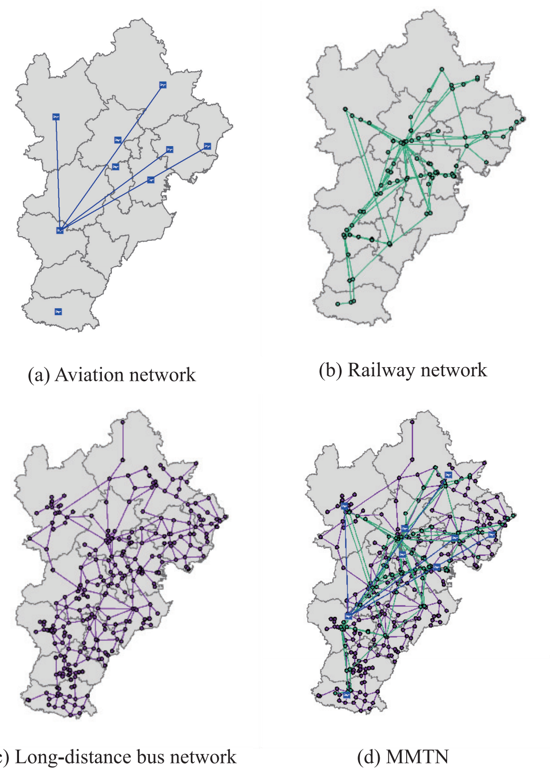
In network resilience calculation, the change in resilience of the network is observed by removing the nodes. When a node is removed, the edges connected to it are also removed accordingly. Two simulation experiments are designed, one is to remove the top ten key nodes separately, and the other is to remove cumulatively by critical node ranking.

3 Case study

Beijing-Tianjin-Hebei area (BTH) is a world-class urban agglomeration with the capital as the core. It contains 9 airports, 79 railway stations and 269 passenger depots. The experiments were conducted via python 3.8 language in PyCharm 2020.2.3 version.

3.1 Results of network construction

According to the rules of network construction, MMTN in BTH is constructed, as shown in Figure 3. Beijing and its southeast area are well connected and can reach more parts of the city through MMTN, while public transportation in areas such as Zhangjiakou in the northwest of the map is concentrated in the center of the region and requires reaching the center of the city before reaching other parts.



(a) Aviation network (b) Railway network

(c) Long-distance bus network (d) MMTN

Fig. 3 Transportation network in BTH [GS(2019)1822 号]

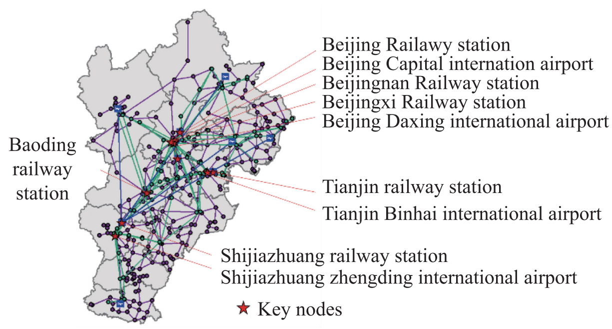


Fig. 4 Distribution of key nodes

3.2 Results of key nodes identification

Based on the key node identification indicator proposed above, the top 10 most critical nodes are shown in Figure 4.

It can be seen that the Beijing area contains more key nodes. Most of the top ten key nodes are dominated by railway stations and airports, and there are no passenger depots. Mutual peers in urban agglomerations mostly involve longer distances, thus railway and aviation are more likely chosen by passengers. When the service capacity of these nodes decreases, it will affect the travel plans of many passengers.

3.3 Results of resilience evaluation

To evaluate the resilience performance of the network, identified key nodes are removed separately, and the network resilience reduction ΔR are observed, as shown in Figure 5. When the key nodes indicator H proposed in this paper are adopted, the trend of the changes in resilience is more consistent with the order of node importance. As the importance of a node decreases, its failure has less impact on the network. Resilience lost the most when the third important node "Beijing Capital International Airport" was removed. The loss is smaller than the other first 9 nodes after the removal of Baoding Railway station. While the impact on network resilience after failure of each node shows a fluctuating increase and decrease when removing nodes by node degree value and closeness centrality. This phenomenon also proves the effectiveness of the key node index proposed in this paper.

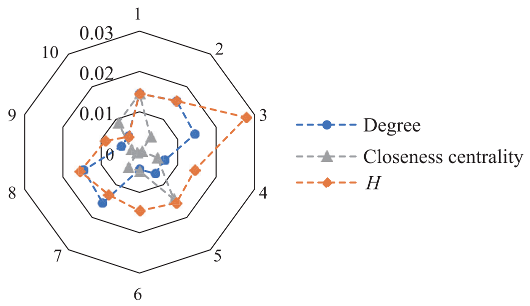


Fig. 5 Resilience reduction of MMTN by key nodes removed

Based on the cumulative removal of nodes in the order of importance obtained from the indicator proposed in this paper, the results are shown in Figure 6. It can be seen that as the number of removed nodes increases, the greater the decrease in network resilience. The curve is convex, which means that the more important nodes are, the more damaging to the network resilience is. The absorption capacity of the network decreases very quickly, with only 20% absorption performance after removing 50 nodes (14% of the nodes). And the recovery performance of the network degrades much more slowly than the absorption performance.

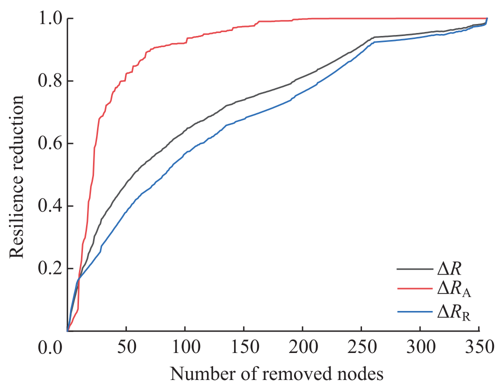


Fig. 6 Resilience reduction of MMTN with the increasing of removed nodes

To further explore network resilience, a comparison experiment of random attacks is added as a baseline method and the results are shown in Figure 7. It can be seen that attacking key nodes causes faster loss of network resilience than random attacks. Therefore, it is important to more strictly monitor key nodes for abnormalities and give quick control measures to prevent further network collapse.

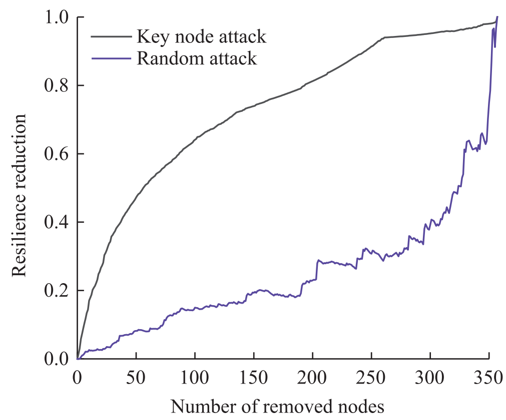


Fig. 7 Change in resilience reduction under different attacks

Based on the results of the above resilience assessment, it can be found that hub-type nodes need to be given priority attention in the deployment of public transportation networks in urban agglomerations, their failure will affect more passengers' trips. Thus, when allocating operational resources, greater efforts can be invested in key nodes, such as airports and railway stations, which will reap greater benefits than investing resources in passenger depots.

4 Conclusions

This paper proposed the network modeling and resilience assessment methods for public transportation in urban agglomerations, with the following main contributions.

(1) A multi-layer network construction method is proposed that can be transferred to the modeling of public transportation networks in different urban agglomerations.

(2) The key nodes in a multi-modal transportation network are identified considering the network topology and service capacity. A resilience assessment method considering two phases of absorption and recovery after the attack is proposed.

(3) The method was verified through the Beijing-Tianjin-Hebei urban agglomeration network. More atten-

tion is suggested paid to the larger hub-type stations in operation and management.

Due to the limitation of data, the consideration of actual travel passenger flow does not include here, which is a direction that should be further considered in the future.

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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