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Node Importance Evaluation of Urban Rail Transit Based on Signaling System Failure: A Case Study of the Nanjing Metro

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Abstract: Assessing the importance of nodes in urban rail transit systems helps enhance their ability to respond to emergencies and improve reliability in view of the fact that most of the existing methods for evaluating the importance of rail transit nodes ignore the disturbance effect of signaling system failures and are unable to objectively identify critical stations in specific disturbance scenarios. Therefore, this paper proposed a method for evaluating the importance of urban rail transit nodes in signaling system failure scenarios. The method was based on the research background of the signaling system failure that occurs most frequently and analyzed the network failure mechanism after the occurrence of a disturbance. The node importance evaluation indices were selected from the network topology and network operation performance in two aspects. The variation coefficient–VIKOR method was employed to comprehensively assess the significance of urban rail transit stations during signaling system failures. The Nanjing Metro network was also used as an example to evaluate the importance of network stations. The results showed that under the attack method of signaling system failure, most ECC and interlocking stations experienced significantly higher network performance losses compared to the original attack method, and a few interchange stations showed smaller performance losses. The critical stations identified based on the proposed method are mainly distributed in the passenger flow backbone of the Nanjing Metro and were constructed in the early stage; of these, 85% are ECC stations or interlocking stations, which are easily neglected in daily management, in contrast to interchange stations with heavy passenger flow. The results of this study can provide an important reference for the stable operation and sustainable construction of urban rail transit.

Keywords: urban rail transit; complex networks; signaling system failure; node importance; variation coefficient–VIKOR method

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1. Introduction

As an important infrastructure for urban transport, the urban rail network effectively relieves the pressure on ground transport and promotes environmental and economic sustainability due to its energy-saving, high-capacity, and non-polluting characteristics [1]. Currently, the scale of rail transport construction in China's major cities is expanding. According to the Ministry of Transportation and Communications, as of 31 December 2023, a total of 55 cities in mainland China had opened 306 urban rail transit operation lines, and the operation mileage exceeded 10,000 km, reaching 10,165.7 km [2]. Among them, 33 cities had three or more lines in operation, accounting for 60 percent of the total number of cities that had opened urban rail transit operations. This indicates that China's rail transport has entered the era of the interconnected and networked operation of stations and lines [3].

In the context of networked operation, urban rail transit is a complex system with complex lines, high equipment accuracy requirements, and a high frequency of train departures, which inevitably leads to frequent disturbances in daily operations [4]. In recent years, there has been a focus on urban rail disturbance incidents [5–7]. Disturbance event risk factors have been categorized as human factors [8], facility and equipment factors [9], and environmental factors [10], according to the cause of the incident. It can be seen that the failure of any subsystem or component of this complex system can lead to serious consequences in terms of train delays, stoppages, and even network paralysis [11].

Train failure, signaling failure, platform door failure, and power system failure are the four most common types of operational emergencies in daily operations, accounting for 95% of all operational emergencies [12]. Among these, signaling system failures had the highest frequency of occurrence among all disturbance events in urban rail transit, accounting for 37% of the total number of disturbances, and they are the main cause of such events [13]. In addition to the high frequency of the signaling system's own failures, human causes, mechanical failures, and environmental factors can also lead to the occurrence of signaling failures, resulting in a high frequency of signaling failures. According to New York Metro data, out of 125 morning rush hours in the first half of 2021, 104 (or 80%) of the New York Metro experienced train delays due to signaling problems [14]. According to Beijing Metro data, in the five years from 2014 to 2018, the Beijing Metro accumulated 405 primary failures of various types. All of these failures caused delays ranging from a few minutes to a few hours or even led to more serious consequences. Among these, 198 signaling failures occurred, which accounted for nearly half of them [15]. It can be seen that the frequent occurrence of signaling system failures seriously affects the safe and stable operation of urban rail transit, greatly impacting urban residents' travel. Therefore, if the critical nodes in the urban rail transit network can be found and protected in advance under the disturbance scenarios of signal system failure, it not only enhances the technical safety of the rail transit network but also helps to guarantee the network operation safety and improve the service quality. This paper intends to propose a node importance assessment method under the signaling system failure scenario and apply it to the actual case of the Nanjing Metro to identify the critical stations. Furthermore, the proposed method provides a framework for assessing the significance of nodes in practical applications across various metro networks, including those in New York, London, Beijing, Shanghai, and other extensive rail systems.

The rest of this paper proceeds as follows: Section 2 gives an overview of the research on node importance evaluation and network failure mechanisms; Section 3 provides an overview of the construction of an urban rail transit network model and defines the network failure mechanisms in signaling system failure scenario; in Section 4, an evaluation method of node importance is constructed, and the selection of evaluation indices and the comprehensive evaluation method of node importance is described in detail; Section 5 applies the critical station identification method proposed in this paper to the Nanjing Metro network and analyzes the results; and finally, conclusions and future work are provided in Section 6.

2. Literature Review

Node importance evaluation has been a hot research topic in the field of urban rail transport. In recent years, scholars have conducted some case studies on the evaluation of the importance of nodes in real rail networks. Amideo et al. [16] evaluated the importance of urban rail nodes using the London Underground network as a practical example. Kilic et al. [17] conducted a comprehensive evaluation of the rail lines of the Republic of Turkey State Railways (TCDD). Peng et al. [18] used the metro network in Suzhou, China, to evaluate the node importance of the metro network.

In terms of evaluation indices, scholars initially selected node degree [19], facility service level [20], and other factors to evaluate rail transit stations from a local perspective. Subsequently, some scholars adopted the complex network theory from a global perspective, using node degree centrality, betweenness centrality, closeness centrality [21,22], and other indicators to evaluate the importance of nodes in static urban rail transit networks [23,24]. The evaluation method can only reflect the performance of the network when it is in a stationary state (that is, under normal operation), and cannot reflect the change in the network state of urban rail transit in actual operation. For example, the degree can only reflect the distance between nodes, and the degree of centrality can only reflect the existence of connecting edges between nodes.

However, the urban rail transit network is dynamically changing in actual operation, and considering the actual operation of rail transit, some studies have introduced the network interdiction model [25], which simulates the network failure by removing nodes and edges in the network. The network interdiction model was first introduced for military purposes, intending to identify and determine the most critical set of arcs in a network [26,27], and has subsequently been extended to the domain of complex networks, such as electric power networks [28], wireless sensor networks [29], and rail transit networks [25]. Combined with the actual operation of rail transit, the existing research constructed a node importance evaluation system based on the dynamic perspective, selecting indicators such as average network efficiency [30], maximum connectivity subgraph change [31], network efficiency accessibility [32,33], and unsatisfied passenger demand [34,35] from the aspects of network topology and network operation performance. Then, the network interdiction model was used to carry out station failure simulations in urban rail transit networks to carry out network node importance evaluations and key station identification.

In terms of network failure mechanisms, most of the studies only remove the failed station itself and its connected lines from the network when simulating station failure [25,36], while a few studies improve the failure mechanism by taking into account the actual characteristics of the rail network and disruption scenarios. Chen et al. [37] considered that urban rail transit operates on specific routes, used spatial syntax to analyze the line accessibility of rail transit to improve the topological network, and proposed the node importance evaluation method. Hu et al. [38] incorporated the adjustment of train operation interchanges after station failure to evaluate the importance of rail transit stations in the scenario of bidirectional operation disruption. Zhang et al. [39] proposed a weighted multi-layer network node importance evaluation method that considers node connectivity, diverse transportation modes, and service capabilities. Zheng et al. [40], combined with the unexpected situations encountered in the actual operation of public transport, considered two types of attacks against the bus–subway composite network nodes for node importance evaluation research.

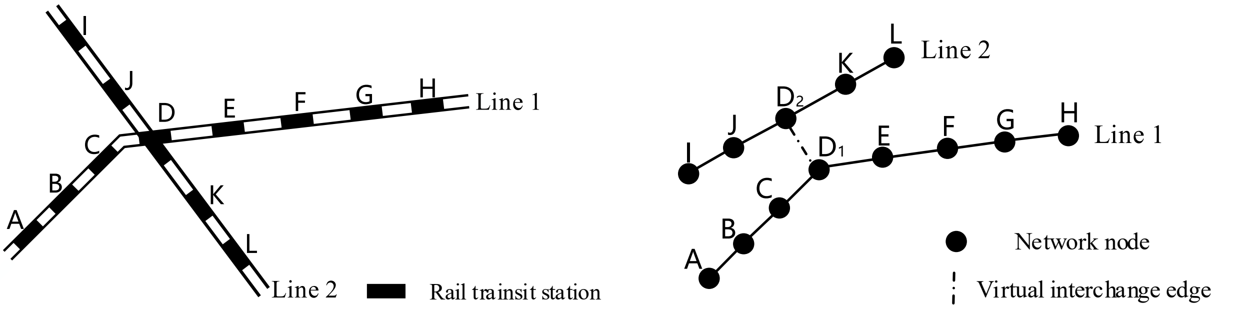
However, the urban rail transit system is a complex system containing many subsystems, in which normal operation is built on the basis of mutual cooperation and the stable operation of facilities and equipment among the subsystems. In particular, the signaling system, as the key to the signal transmission of the rail transport network and the component that ensures that the trains run according to the plan, is an important guarantee for the safety of rail transport [41]. If the critical stations where the facilities and equipment are located are not identified and maintained in advance, it will lead to a series of chain reactions once it fails. From the summary of the above literature, there are few studies that consider the failure mechanism of signaling system failures in the evaluation of the importance of urban rail transit stations.

To address the aforementioned issues, this paper fully considers the structural characteristics of urban rail transit networks and proposes a method to evaluate the importance of urban rail transit nodes under the signaling system failure disturbance scenario. Firstly, based on complex network theory, the improved Space L method is used to construct the urban rail transit network. Then, the signaling system failure scenario is taken as the research background to analyze the failure mechanism of the urban rail transit network after the occurrence of the perturbation. Finally, according to the characteristics of urban rail transit, the indicators are selected from two aspects of network topology and network operation performance, and the evaluation method of the importance of urban rail transit network nodes based on the coefficient of variation–VIKOR method iss proposed. The greatest innovation of this approach is that it considers the structural characteristics of the rail network, as well as the network failure mechanisms during disturbance events. In this study, the Nanjing Metro network was selected as a study case.

3. Network Failure Mechanism in Signaling System Failure Scenario

3.1. Urban Rail Transit Network Model

Based on the complex network theory [42], the Space L method, which can better reproduce the actual topology of the network, is used to construct the urban rail transit network model. With the Space L method, the rail transit stations are abstracted as nodes, and the lines between adjacent stations are abstracted as connecting edges for modeling [43]. However, in actual operation, different rail transit lines are relatively independent, so this paper assumed that the failure of one line in the same interchange station does not affect the operation of another line and proposed the virtual interchange edge method [44] to construct the rail transit network model, which splits the interchange stations into multiple virtual nodes connected with each other by virtual edges. The specific network model construction method is shown in Figure 1.



(**a**) Wiring diagram of the actual urban rail transit network (**b**) Space L method with introduction of virtual interchange edge

Figure 1. Urban rail transit network modeling method.

3.2. Network Failure Mechanism

Established studies mostly focused on low-frequency and high-loss types of man-made disturbances and natural disturbances, while less consideration was given to high-frequency low-loss types of technical disturbances. According to China's urban rail transit data statistics, signaling system failure accounts for 42.53% of technical disturbance events in urban rail transit [13]. On 27 September 2011, after a signal failure at Xintiandi Station on Line 10 of the Shanghai Metro, the telephone occlusion method was used, resulting in a rear-end collision of the train and injuring 271 passengers [45]. All these data indicate that although the disturbance impact and damage level of signaling system failures can be easily predicted, they occur with high frequency, and when they occur, they must also be technically overhauled before resuming operation. Therefore, the problem of signaling systems affecting the stable operation of rail transit needs to be solved urgently. In this paper, the technical disturbance scenario of signaling system failure was used as the background to analyze the network failure mechanism of urban rail transit after the failure, and the evaluation of station importance is carried out on this basis.

Interlocking system for urban rail transport refers to the mutual constraints established by technical means between signaling machines, turnouts, and approaches to ensure the safety of running and shunting operations in railway stations [46]. The equipment that realizes this relationship is called interlocking equipment, and according to the interlocking equipment, rail transit stations can be divided into interlocking stations, element control computer (ECC) stations, and non-centralized stations. Among these, the ECC uses the component control computer to extend the operation capability and control range of its signaling system. Its basic function is to send and issue control commands to external execution devices, receive dynamic information from these devices, and feed it back into the interlocking computer to complete the feedback process of information [47]. That is, it outputs commands and collects information to all non-centralized stations within the ECC boundary and sends the dynamic information received back to the interlocking station. The role of the interlocking station is to transmit and receive information from all ECC stations within the interlocking boundary. The schematic diagram of an urban rail transit signaling interlocking system is shown in Figure 2.

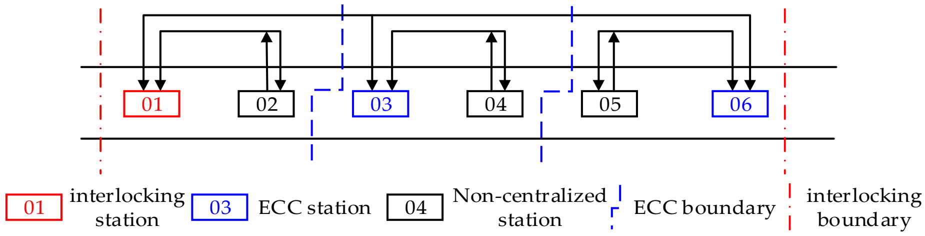


Figure 2. Schematic diagram of urban rail transit signaling interlocking system.

Based on the interlocking relationship of urban rail transit signaling systems, the network failure mechanism is defined. When signaling system failure occurs in urban rail transit, there are three scenarios. If the ECC station fails, it will cause the station and line within the control range of the ECC station (within the ECC boundary) to lose control of the outdoor executive equipment and stop receiving dynamic information, making the station and line within the ECC boundary fail. If the interlocking station fails, the station and line within the control range of the interlocking station (within the interlocking boundary) will not be able to receive and feed back the information, which means that the stations and lines within the entire interlocking boundary fail. If the non-centralized station fails, the station will not be able to communicate with the ECC station, which means that the station and its connected line fail. Based on the above analyses, we know that the signaling failure incident at Xintiandi Station of Shanghai Metro Line 10 in 2011 had a huge impact on network operation and passenger travel.

Figure 3 provides an example of the network model before and after station attacks. Figure 3a,b depict the actual wiring diagram and the abstract network model, respectively. Figure 3c,d simulate two types of attacks resulting from signaling system failures. It can be seen that the original attack method only considers the failure station itself, ignoring the structural characteristics of the rail transit itself and the failure mechanism after a disturbance, so the rail transit network model after the attack is not compatible with reality.

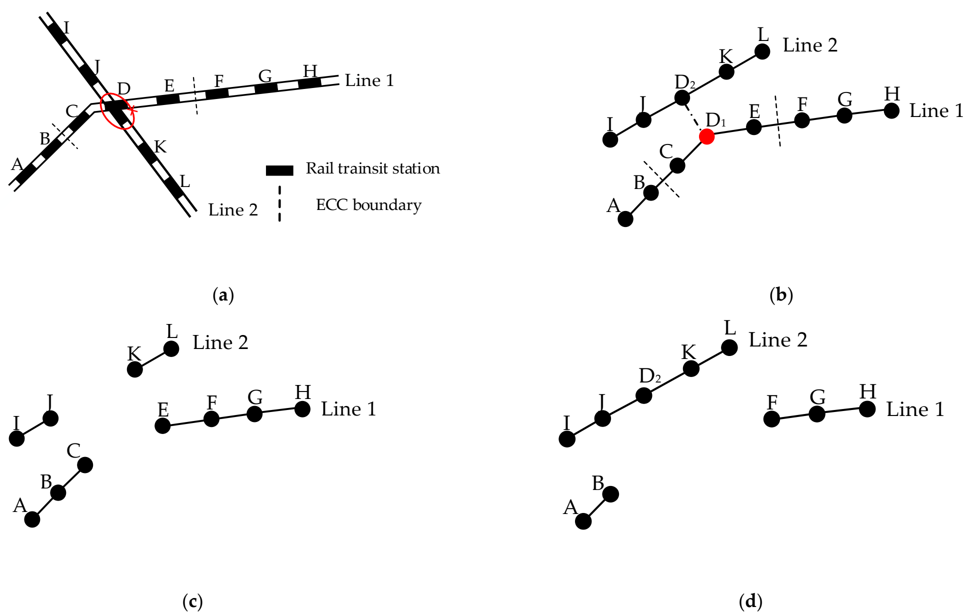


Figure 3. Network model before and after the attack on the stations. (**a**) Actual wiring diagram (assuming the signaling system failure at ECC station D on line 1); (**b**) Modeling of the rail transit network before the attack; (**c**) Modeling the rail transit network under the original attack approach; (**d**) Modeling rail transit networks under the attack approach of this paper.

4. Node Importance Evaluation Model

4.1. Indices for Evaluating the Importance of Urban Rail Transport Nodes

Compared to static evaluation, dynamic metrics are able to capture the change in network performance after site removal, thus providing a more accurate measure of the impact of site failure on the network and evaluating site importance. Therefore, in this paper, we mainly select two dynamic indicators to measure the impact of site failure: network topology and network operational performance.

4.1.1. Subsubsection

The network efficiency loss and maximum connected sub-network loss after the failure of urban rail transit stations are selected as dynamic evaluation indices to reflect the impact of station failure on network topology performance.

(1) Network efficiency loss

The network efficiency of urban rail transit, as a convenient and efficient mode of public transport, quantifies the efficiency of the network on a global scale. After the failure of an urban rail station, the shortest paths between certain starting and finishing points in the network changed, resulting in efficiency losses for the network. The loss of network efficiency is shown in Formulas (1) and (2).

$$E = \frac{1}{N(N-1)} \sum_{i \neq j} \frac{1}{d_{ij}} \tag{1}$$

$$\Delta E_a = E_0 - E_a \tag{2}$$

E is the network efficiency, N is the total number of stations in the network, d_{ij} is the shortest path length between stations i and j. Then, E_0 is the initial network efficiency, E_a is the efficiency of the network after the failure of station a, and ΔE_a is the loss of network efficiency before and after the failure of station a.

(2) Maximum connected sub-network loss

After the failure of urban rail transit network stations, the network becomes divided into different connected sub-networks. The sub-network with the highest number of connections is referred to as the maximum connectivity sub-network. The calculation of the maximum connected sub-network loss can measure the impact of the station failure on network connectivity. The loss of the maximum connected sub-network is represented by Formula (3).

$$\Delta S_a = 1 - \frac{N_a}{N} = \frac{N - N_a}{N} \tag{3}$$

N_a is the number of stations in the maximum connectivity sub-map of urban rail transit after the failure of station a, and ΔS_a is the maximum connected sub-network loss before and after the failure of station a.

4.1.2. Based on Network Operational Performance

Considering the importance of passenger traveling services in the operation of rail transit networks, network efficiency accessibility loss and unsatisfied passenger demand are selected as dynamic evaluation indices to reflect the impact of station failure on network operational performance.

(1) Network efficiency accessibility loss

Network efficiency accessibility is based on the network efficiency indicators, adding the consideration of the passenger flow between the stations in the network, which can reflect the difficulty of different passengers in the urban rail transit network to reach the destination station from the initial station [33], and network efficiency accessibility loss is shown in Formulas (4) and (5).

$$A = \frac{1}{f}\sum_{i}^{n}\sum_{j}^{n-1}\frac{f_{ij}}{t_{ij}} \quad (4)$$

$$\Delta A_a = A_0 - A_a \quad (5)$$

A is the network efficiency accessibility, f_{ij} is the flow of passengers from station i to j, f is the total number of passengers in the network, t_{ij} is the time it takes a passenger to travel from station i to j, A_0 is the initial efficiency accessibility of the network, A_a is the network efficiency accessibility after the failure of station a, and ΔA_a is the loss of network efficiency accessibility before and after the failure of station a.

(2) Unsatisfied passenger demand

The disruption of some stations in the rail transit network splits the network into several disconnected sub-networks, resulting in the absence of connected paths between the origin and destination points of some passengers' trips, and the passengers are unable to complete their trips by the rail transit, which is the unsatisfied passenger demand, and the expression is shown in Formula (6).

$$U = \frac{f_a}{f} \quad (6)$$

f_a indicates passengers who are unable to complete their journeys using urban rail transit after the failure of station a, and U indicates unmet passenger demand after the failure of station a.

4.2. Comprehensive Evaluation Based on the Variation Coefficient–VIKOR Method

Multiple criteria decision-making (MCDM) is an important technique that presents a systematic approach to helping decision-makers in this field [48]. The MCDM method includes AHP, TOPSIS, VIKOR, and PROMETHEE, among others. Among these, the basic idea of the VIKOR method is to normalize the original data, construct the initial matrix, select the optimal and the worst solution in the whole solution set, and determine the comprehensive ranking results according to the distance between the optimal and the worst solution between different values, that is, the criterion that the optimal solution is the closest, and the worst solution is the furthest [49]. The method is often a compromise between the attributes so that the feasible solution can ensure the maximum benefit of the group but also take into account the individual loss, which can effectively deal with the problem of urban rail transit station importance based on the evaluation of a number of indicators and make full use of the original data in the calculation process. Therefore, the VIKOR method is selected in this paper for the comprehensive evaluation of station importance.

However, the VIKOR method defaults to equal weighting of all evaluation indicators, which is not consistent with the actual situation. This paper adopted the coefficient of variation method, which is an objective weighting method, to enhance the VIKOR comprehensive evaluation method. The improved method evaluates the degree of the data dispersion of indicators as an assignment criterion, assigning higher weights to indicators with greater variation dispersion [38]. The specific evaluation process is as follows.

4.2.1. Determination of Indicator Weights

Assuming that there are evaluation objects and evaluation indicators, the coefficient of variation method is used to determine the weights of the indicators, which are calculated as shown in Formulas (7) and (8).

$$v_k = \frac{\sigma_k}{\overline{x_k}} = \frac{1}{\overline{x_k}}\sqrt{\frac{1}{m}\sum_{i=1}^{m}(x_{ik} - \overline{x_k})^2} \quad (7)$$

$$w_k = \frac{v_k}{\sum\limits_{k=1}^{n} v_k} \tag{8}$$

x_{ik} is the value of the ith evaluation object for the kth indicator (i = 1,2,$\cdots$,m; k = 1,2,$\cdots$,n) , $\overline{x_k}$, σ_k is the mean and mean square of the jth indicator for all stations, and v_k is the coefficient of variation of the kth indicator.

4.2.2. Comprehensive Evaluation of the VIKOR Method

(1) Normalizing the raw data

Normalizing the raw data yields matrix X, as shown in Formula (9).

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \tag{9}$$

(2) Determining positive and negative ideal solutions for each indicator

Positive ideal solutions x_k^+ and negative ideal solutions x_k^- are shown in Formulas (10) and (11).

$$x_k^+ = \{\max x_{1k}, \max x_{2k}, \cdots, \max x_{nk}\} \tag{10}$$

$$x_k^- = \{\min x_{1k}, \min x_{2k}, \cdots, \min x_{nk}\} \tag{11}$$

(3) Determining group utility values S_i and individual regret values for each evaluator R_i

When the positive ideal solution is used as a reference, the group utility value S_i^+ and individual regret value R_i^+ of each evaluation object are calculated, as shown in Formulas (12) and (13).

$$S_i^+ = \sum_{i=1}^{m} \left(w_k \frac{x_k^+ - x_{ik}}{x_k^+ - x_k^-} \right) \tag{12}$$

$$R_i^+ = \max \left(w_k \frac{x_k^+ - x_{ik}}{x_k^+ - x_k^-} \right) \tag{13}$$

When the negative ideal solution is used as a reference, the group utility value S_i^- and individual regret value R_i^- of each evaluation object are calculated, as shown in Formulas (14) and (15).

$$S_i^- = \sum_{i=1}^{m} \left(w_k \frac{x_{ik} - x_k^-}{x_k^+ - x_k^-} \right) \tag{14}$$

$$R_i^- = \min \left(w_k \frac{x_{ik} - x_k^-}{x_k^+ - x_k^-} \right) \tag{15}$$

In summary, the group utility value S_i and individual regret value R_i of each evaluation object are calculated as shown in Formulas (16) and (17).

$$S_i = \frac{S_i^+}{S_i^-} \tag{16}$$

$$R_i = \frac{R_i^+}{R_i^-} \tag{17}$$

(4) Calculating the discounted assessed value of the subject of the evaluation Q_i

$$Q_i = v\frac{S_i - S_{i\min}}{S_{i\max} - S_{i\min}} + (1 - v)\frac{R_i - R_{i\min}}{R_{i\max} - R_{i\min}} \tag{18}$$

where v is the coefficient of the decision-making mechanism, $0.5 < v \leq 1$ indicates that the evaluator prefers group utility to individual regret, and $0 \leq v < 0.5$ indicates that the evaluator prefers individual regret. In order to maximize group utility and minimize individual regret at the same time, this paper chooses $v = 0.5$ [49]. The value of the compromise evaluation is used as the evaluation value of the importance of the stations of the urban rail transit network in this paper, and the smaller the value of the compromise evaluation is, the higher the importance of that station is indicated.

5. Case Study

5.1. Nanjing Metro Network

In this paper, we select the Nanjing Metro network as an example and apply the method proposed in this paper to evaluate the station's importance in a signaling system failure scenario.

As of September 2023, Nanjing has opened 12 metro lines for operation, with a total length of about 449 km and containing a total of 208 stations (with double counting of interchange stations) and 217 line intervals, and has entered the stage of networked operation. The Nanjing Metro network is shown in Figure 4.

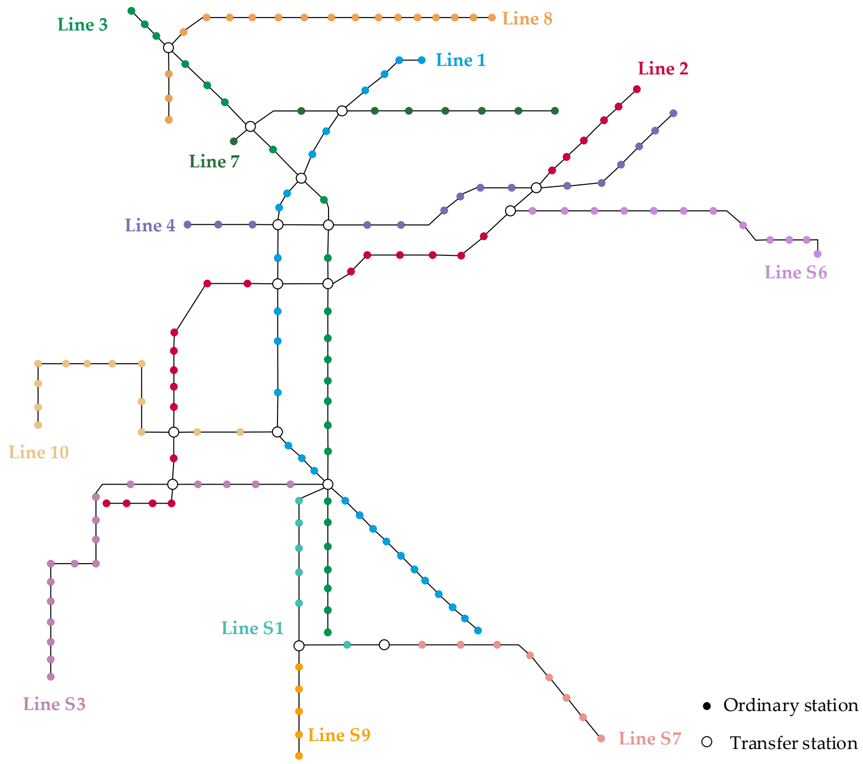


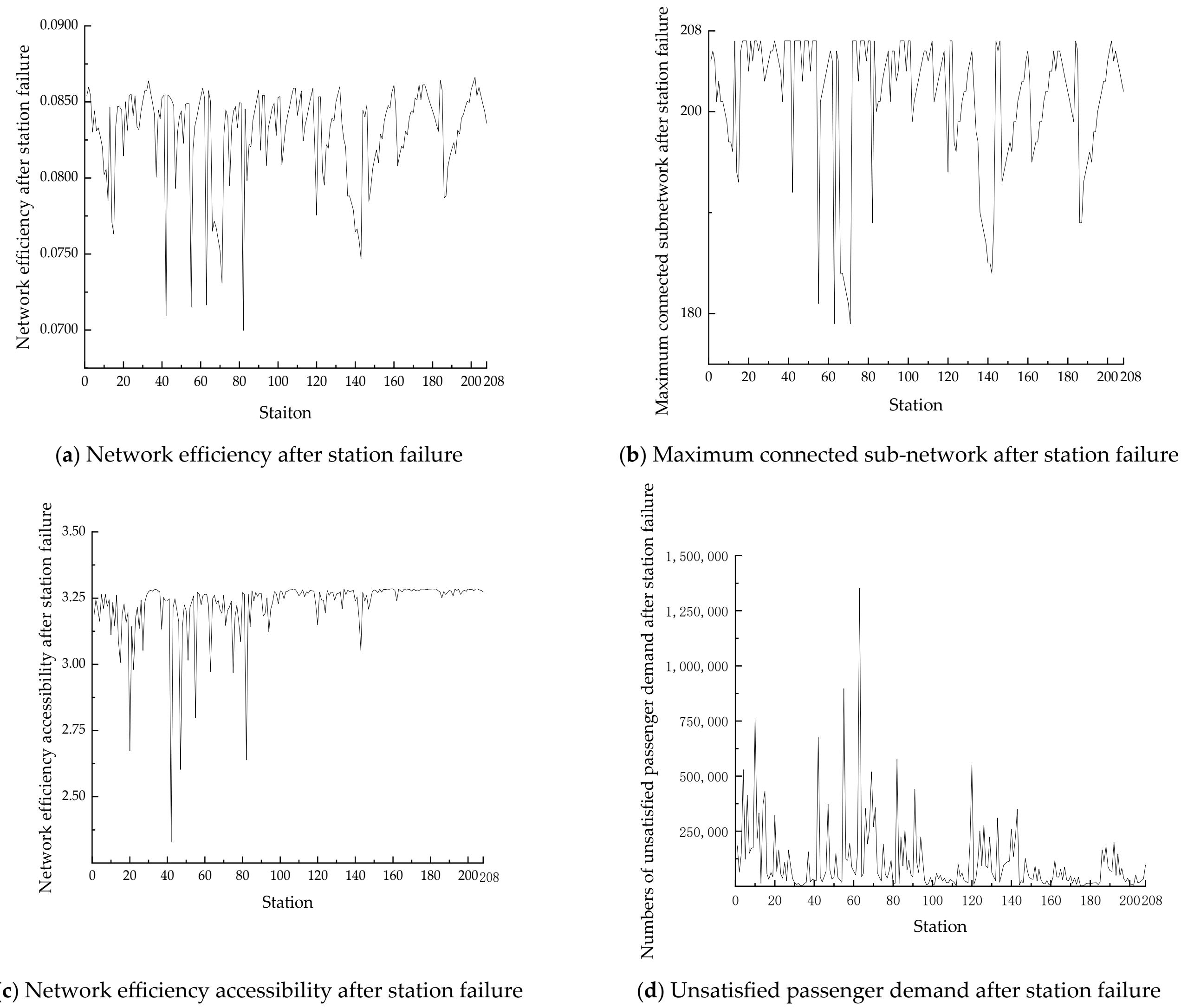
Figure 4. Nanjing Metro network (September 2023).

This paper was based on the Nanjing Metro line wiring diagram, and the Nanjing Metro passenger flow data extracted from the AFC system was analyzed. We obtained information on the signaling system facilities and equipment of each line from the metro line wiring diagram and found that there are 60 interlocking stations, 37 ECC stations, and 111 non-centralized stations in the Nanjing Metro. The AFC data used are the data from the set counting method, including the average daily OD between stations and the passenger flow in and out of the stations based on the direct counting of the swipe card data from the entrance and exit gates of the stations and the passenger flow of the interchanging passengers calculated using the clearing model of the metro company.

5.2. Evaluation of the Importance of Urban Rail Network Nodes

5.2.1. Calculation of Evaluation Indicator Values

Based on the Space L method, with the introduction of a virtual interchange edge, the urban rail transit network model has been constructed. Figure 5 presents the impact on the network after the station failure using the attack method in this paper in terms of the network efficiency, maximum connected sub-network, network efficiency accessibility, and level of unsatisfied passenger demand after the station failure. We found that there is a big difference in the impact of the different station failures on the network topology and operation performance. This is also in line with the actual operation of urban rail networks. For example, the 47th station, Xinjiekou, is located in the core business area of Nanjing and is a large interchange station serving 192,218 passengers each day. When the Xinjiekou station (ECC station) of Line 2 fails, there will be a loss of network efficiency in terms of network topology of 0.0078 and a loss of maximum connectivity subgraph of 0.0240. In terms of passenger traveling service, 373,385 passengers will not be able to satisfy their traveling needs via urban rail, with a loss of network efficiency accessibility of 0.6823 and a loss of unmet passenger demand of 0.1667.



(**a**) Network efficiency after station failure

(**b**) Maximum connected sub-network after station failure

(**c**) Network efficiency accessibility after station failure

(**d**) Unsatisfied passenger demand after station failure

Figure 5. Impact of station failure on the network.

Table 1 lists 10 representative station indicators, with values calculated according to Formulas (1)–(6). These values represent the indicators of each station in the urban rail transit network.

Table 1. Example of values for evaluation indicators.

Station Type	Station Name	Network Efficiency Loss		Maximum Connected Sub-Network Loss		Network Efficiency Accessibility Loss		Unsatisfied Passenger Demand	
		The Original Way	This Paper	The Original Way	This Paper	The Original Way	This Paper	The Original Way	This Paper
Interlocking station	China Pharmaceutical University Station (Line 1)	0.0005	0.0017	0.0005	0.0144	0.0372	0.1017	0.0151	0.0825
Interlocking station	Tianlongsi Station (Line 1)	0.0022	0.0108	0.0048	0.0721	0.0901	0.2786	0.0269	0.1927
Interlocking station	Gulou Station (Line 1)	0.0053	0.0139	0.0240	0.0144	0.2145	0.3057	0.0851	0.0733
Interlocking station	Nanjing South Station (Line S3)	0.0232	0.0124	0.2163	0.0913	0.4986	0.2333	0.3931	0.1566
ECC station	Xinjiekou Station (Line 2)	0.0069	0.0078	0.0096	0.0240	0.6643	0.6823	0.1414	0.1667
ECC station	Xiaoshi Station (Line 3)	0.0034	0.0139	0.0048	0.1394	0.0365	0.1387	0.0108	0.0595
ECC station	Ruanjiandadao Station (Line 1)	0.0022	0.0100	0.0048	0.0673	0.0376	0.1981	0.0111	0.1658
Non-centralized stations	Zhujianglu Station (Line 1)	0.0021	0.0021	0.0048	0.0048	0.1426	0.1426	0.0303	0.0303
Non-centralized stations	Xuanwumen Station (Line 1)	0.0016	0.0016	0.0048	0.0048	0.1133	0.1133	0.0245	0.0245
Non-centralized stations	Yuantong Station (Line2)	0.0085	0.0032	0.0577	0.0048	0.0896	0.0464	0.0670	0.0139

In Table 1, it can be seen that in the attack method based on a signaling system failure scenario, the values of the indicators for most of the non-centralized stations did not change. Most of the ECC and interlocking stations, such as China Pharmaceutical University Station and Xinjiekou Station, have values that are significantly larger than those of the original attack method, which indicates that the original attack method ignores the network failure mechanism during signaling system failure and weakens the negative impact of some station failures on network performance. However, there are also a few interchange stations, such as Gulou Station, Nanjing South Station, and Yuantong Station, where the values of the metrics are smaller than those of the original attack method. This is because under the original attack method, the characteristics of the urban rail network in which each line operates independently of each other are ignored, and when the interchange station fails, the station and its connected lines are all removed from the network, which overestimates the impact of its failure on the network.

5.2.2. Calculation of Evaluation Indicator Weights

Combined with the value of each evaluation index, according to Formulas (7) and (8), the coefficient of variation method is used to calculate the weight of each index, as shown in Table 2.

Table 2. Weights of evaluation indicators.

Indicator type	Indicators	Weights
Network topology	Network efficiency loss	0.1499
	Maximum connected sub-network loss	0.1897
Network operational performance	Network efficiency accessibility loss	0.3727
	Unsatisfied passenger demand	0.2877

5.2.3. Results and Analysis of Node Importance Evaluation

Based on the actual fault failure mechanism of the urban rail transit signaling system, the group utility value and individual regret value of each rail transit station are obtained according to Formulas (9)–(17), and the compromise evaluation value of each station is calculated by combining Formula (18). The compromise evaluation value is ranked from low to high to obtain the results of the ranking of the importance of each station of the Nanjing Metro network. The top 20 stations in terms of node importance are listed as critical stations, as shown in Table 3.

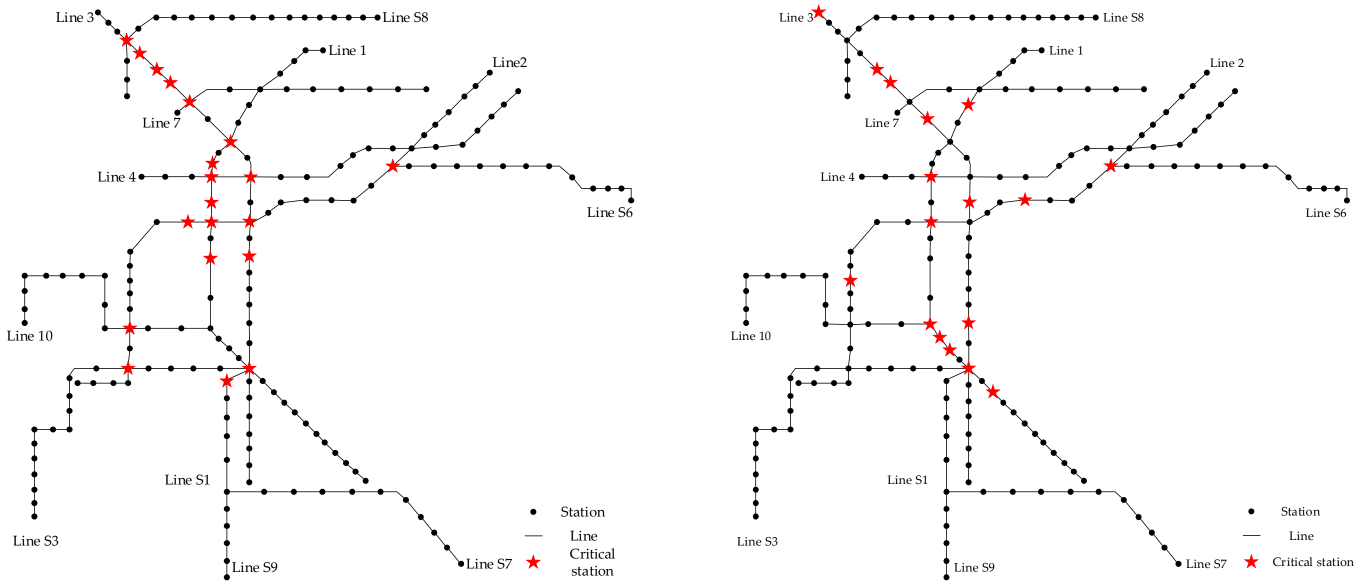
Table 3. Critical stations identified based on signaling system fault failure mechanism.

Station Type	Station Name (Line)	Compromise Evaluation Value	Station Ranking (The Original Attack Method)	Station Type	Station Name (Line)	Compromise Evaluation Value	Station Ranking (The Original Attack Method)
Interlocking station	Jiqingmendajie Station (Line 2)	0.0000	1(32)	Interlocking station	Gulou Station (Line 1)	0.6097	11(4)
Interlocking station	Daminglu Station (Line 3)	0.1196	2(117)	ECC station	Ruanjiandadao Station (Line 1)	0.6147	12(81)
Interlocking station	Maqun Station (Line 2)	0.1284	3(9)	Interlocking station	Hedingqiao Station (Line 1)	0.6178	13(26)
Interlocking station	Linchang Station (Line 3)	0.2505	4(154)	ECC station	Muxuyuan Station (Line 2)	0.6417	14(41)
ECC station	Xinjiekou Station (Line 2)	0.3531	5(2)	ECC station	Shangyuanmen Station (Line 3)	0.6505	15(16)
Interlocking station	Xinjiekou Station (Line 1)	0.4197	6(2)	Interlocking station	Andemen Station (Line 10)	0.6605	16(49)
Interlocking station	Tianlongsi Station (Line 1)	0.5080	7(24)	Non-centralized stations	Nanjing South Station (Line S1)	0.6820	17(1)
Interlocking station	Nanjing South Station (Line S3)	0.5421	8(1)	Interlocking station	Maigaoqiao Station (Line 1)	0.6915	18(27)
ECC station	Fuqiao Station (Line 3)	0.5632	9(56)	Non-centralized stations	Nanjing South Station (Line 1)	0.7009	19(1)
ECC station	Xiaoshi Station (Line 3)	0.5919	10(73)	Non-centralized stations	Liuzhoudonglu Station (Line 3)	0.7116	20(7)

As shown in Table 3, there are 11 interlocking stations and 6 ECC stations in the top 20 stations in terms of node importance, with 85% of the total number of critical stations. Each interlocking sub-district manages multiple stations, which will indirectly lead to the disability of the stations in the whole interlocking sub-district to operate normally once its signaling system fails. For example, the Jiqingmen Street interlocking zone manages 16 stations in the Yuzui–Daxinggong zone, and the failure of this interlocking station will prevent 675,576 passengers across the region from completing their journeys on the metro, so its importance is very high. In reality, this conclusion has also been verified; for example, on 6 November 2023 at 6:54 A.M. during the morning high peak, the Nanjing Metro interlocking station, Andemen Station, suffered a sudden signaling equipment failure, which resulted in a temporary stop of the train, affecting a large number of passengers' commuting trips [50]. Some non-interlocked stations, such as the Nanjing South Station of Lines 1, S1, and S3, have a greater impact on the Nanjing Metro network, and even the transport network, which is due to their transport hub properties, making their importance relatively high.

Combined with Table 2, it can be seen that there are large differences in the identification results of critical stations based on the two attack methods. On the one hand, it is because the original attack method ignores the relatively independent characteristics of rail transit line operation, which overestimates the importance of some interchange stations in the network. On the other hand, it is because the original attack method does not consider the network failure mechanism after the disturbance occurs, that is, the failure of the interlocking stations will lead to the disruption of the operation of other stations in their interlocking interval, so the importance of some interlocking stations is underestimated.

Figure 6 shows the distribution of the top 20 critical stations in the network of the Nanjing Metro before and after the improvement of the attack method. From Figure 6a, it can be seen that the critical stations identified based on the original attack method are mainly distributed in the transfer stations in the central area of the network and some non-transfer stations with heavy passenger traffic. This is because the original attack method only considers a single station, and the interchange stations in the central area of the network have high traffic volume and contribute more to the network performance; thus, the assessed stations have a high degree of importance. Figure 6b shows the critical stations identified based on the failure mechanism of the signaling system; most of the critical stations are the interlocking stations of the signaling system, such as Jiqingmendajie Station and Linchang Station. The failure of such stations in the original attack method does not have a great impact on the network directly, but because the interlocking zone under their management contains other important stations, the failure of such stations has a wider impact. Most of the critical stations are located on Lines 1, 2, and 3, which are the backbone of the Nanjing Metro passenger flow, carrying most of the interchange traffic and relying on the interchange function of the metro network in the city center. Once the critical stations fail, they will form an isolated line, which will have a serious impact on the traveling of the residents along the line.



(**a**) (**b**)

Figure 6. Distribution of critical stations. (**a**) Distribution of critical stations identified based on the original attack approach; (**b**) Distribution of critical stations identified based on the attack approach in this paper.

It can be seen that the method can not only more realistically describe the network's state after signaling a system failure but also effectively identify the critical stations that are easily ignored in other studies, as well as daily management to provide a reference for the identification and protection of critical stations in urban rail transit networks. Considering the actual structural characteristics of urban rail transit, it is necessary to determine the failure mechanism according to the signaling system in the urban rail transit network and to evaluate the critical stations of the rail transit network under the failure of the signaling system further.

6. Conclusions

This paper uses the disturbance scenario of signaling system failure as the research background and analyzes the impact on the rail transit network after the disturbance. Firstly, the Space L method with the introduction of a virtual interchange edge is used to construct the urban rail transit network. Then, indices of two aspects, network topology and network operation performance, are selected, and the comprehensive evaluation method of the variation coefficient–VIKOR method is adopted to propose the evaluation method of the importance of urban rail transit nodes in the signaling system failure scenario. The main conclusions from the case study are as follows.

(1) This paper considered the structural characteristics and actual operation characteristics of urban rail transit, including the mutual independence of different line operations in the construction of rail transit networks and the failure mechanism of signaling system failure in the evaluation of node importance. This method can more comprehensively and objectively determine the value of the evaluation indices of each metro station and correct the impact of station failure on the network in technical disturbance scenarios.
(2) The variation coefficient–VIKOR method is used to propose a comprehensive evaluation method of site importance, incorporating passenger flow as an important factor into the dynamic index of network operation performance and combining it with the dynamic index of network topology. This made the node importance evaluation results more objective and practical.
(3) The method in this paper identified that 85% of the top 20 critical stations in terms of node importance are interlocking stations, and most of them are distributed in Nanjing Metro passenger flow backbone Lines 1, 2, and 3. Compared with the original attack method of identifying critical stations, the method in this paper can identify critical stations that are easily ignored by daily management, which are not necessarily the stations with the heaviest passenger flows or interchange stations in the metro network. The focused maintenance of these stations can minimize the loss of the network caused by the failure of the signaling system and guarantee the stable operation of the urban rail transit network.
(4) On the basis of identifying critical stations using the method proposed in this paper, for the management and maintenance of the critical stations of urban rail transport, the management department should formulate a perfect emergency response plan to deal with emergencies occurring at the identified critical stations. For example, interlocking stations and ECC stations, such as Jiqingmen Street Station, Xinjiekou Station, Nanjing South Station, etc., should strengthen the emergency training of the staff and the management of the equipment to comprehensively improve the emergency response capability of the critical stations of the rail transport and even the rail transport network. Only in this way can the occurrence of disturbance events, such as signaling failures caused by various factors, be solved.

In summary, it is recommended that the study on the evaluation of the importance of urban rail transit nodes be carried out in a specific disturbance event scenario. Considering the structural characteristics and operational characteristics of the rail transit itself, using the coefficient of variation–VIKOR method to evaluate the results is more objective and practical.

The research in this paper can help the metro operation and management departments find the critical stations in a signaling system failure and protect them in advance, which can effectively reduce the frequency of failure and its negative impacts and further ensure the stable operation of the rail transit and the safe travel of passengers. In addition, the method proposed in this paper has wide applicability and transferability. It can be widely applied to other types of large rail transit networks such as those in New York and London by evaluating node importance during signaling system failures, according to their network topology and network operation performance characteristics. It is also possible to adapt the comprehensive evaluation method proposed in this paper to evaluate node importance under other disturbance event scenarios. Failure mechanisms are identified based on fault types, and thus, critical stations are identified to provide special protection for urban rail transit networks against various types of disturbance events. This helps to improve the operational management and service level of the metro.

This paper has some implications and limitations for future studies. In terms of disturbance event context, this paper only considered the signaling system failure scenario with the highest frequency of failures and analyzed the network failure mechanism for this type of failure, while other disturbance scenarios were not considered. In future studies, the identification results can be compared with the results of node importance evaluation under other scenarios when possible. In terms of the evaluation method, we considered both network topology and network operational performance indicators to measure the network performance but did not conduct a sensitivity analysis for the change in network indicator weights to further illustrate the robustness of the research results. In terms of the research object, this paper only considered the passenger flow within the urban rail transit network, whereas urban rail transit, as part of the urban public transport network, can be combined with the surface bus network in the future to consider the passenger flow in the dynamic integrated network. These aspects can be further studied in the future to better promote the development of urban rail transit networks in the direction of safety, stability, and reliability.

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