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Research Article

Design of a High-Speed Railway Passenger Train Operation Scheme considering Survivability of the Network

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As an important part of modern comprehensive transportation system, high-speed railway (HSR), whether it is a transregional trunk line or an intercity line, always shapes the industrial layout and changes the living environment at different levels. Based on the analysis of the railway network topology and organization process of passenger train, this paper clarifies the connotation of passenger train operation scheme of HSR considering network survivability, and further explains the connotation of railway network system and its relationship with passenger train operation scheme. In this paper, a comprehensive quantitative index of the importance of key nodes and key edges is established, and an evaluation index of the survivability of railway service network based on the operating mileage of passenger trains is constructed, which is applied to the real local HSR network in China. With the aim of improving the survivability of HSR system, an alternative operation route of passenger trains between some OD stations is given according to the specific railway interruption situation.

1. Introduction

Railway plays an important role in economic and social development and plays a crucial role in the comprehensive transportation system. With its characteristics of high speed, comfort, and safety, high-speed electric multiple units (EMU) trains are widely operating in interregional, intraregional, and even urban areas, forming a fast rail transit service network with multiple areas and wide coverage and becoming an important part of China's national stereoscopic transportation network.

A complex physical network of high-speed railways should provide high-quality transport services. Only by relying on the line infrastructure and aiming at fitting the passenger flow, the passenger train operation plan can be formulated. Only by making full use of high-speed railway infrastructure and conforming to market demand, the traffic flow can meet the passenger flow to the greatest extent and high-quality transportation services can be guaranteed. Passengers care more about the safety, punctuality, and stability of high-speed railways than general-speed railways. This means that it is necessary to ensure that the passenger train operation plan has a certain fault tolerance rate in the face of emergencies.

A high-quality railway transport service network should be able to withstand damage to some extent. Many cases show that although emergency measures can be taken to alleviate the adverse consequences of emergencies on railway transport, once an emergency has a large-scale impact, it is bound to affect the normal travel of passengers within the network. Therefore, it is an important criterion for evaluating a high-speed railway transport service network to ensure that the functions of the high-speed railway transport service network are retained to the maximum extent, while the conditions of the high-speed railway line are affected [1].

Due to the special properties of travel service products, such as immateriality, unity of production, time consumability, and nonstorability, only if the high-speed railway lines and high-speed railway transport services are complete and coherent, passenger transport can be completed. In addition, due to China's vast territory and complex geographical and climatic patterns, it is inevitable that emergencies will affect the normal operation of railways.

However, under the planning system, the deviation between transport supply and passenger demand caused by emergencies can only be gradually alleviated through train operation adjustment. This paper will be based on the previous research results in the two aspects of survivability and the train running scheme. This paper will consider survivability as a set of passenger train plan reference factors as well as evaluate the quantitative indicators of the operation plan based on the network survivability of the high-speed railway, we put forward train operation plan adjustment and evaluation method, which will provide a scientific basis for the development of high-quality Chinese railway.

2. Existing Studies

2.1. Research Status of Railway Network and Its Survivability. Since Euler's Konigsberg Seven Bridge Problem started the study of the regular network model. With the deepening understanding of the characteristics of real network data, the academic community has gradually formed the modeling research method for random graphs. In recent years, with the enhancement of computing power and the establishment of some large-scale database paths, people have gradually realized that the real network is neither regular nor random. Watts and Strogatz proposed a small-world network to describe a network between the regular network and the random network with a large average aggregation coefficient and short path length [2, 3]. After that, Albert et al. pointed out that the degree distribution of the universal network has the characteristics of power-law distribution, showing linear correlation in the bilogarithm coordinate system and scale invariance, and called the network whose degree distribution obeys the power-law distribution scale-free network [4]. In the past 20 years, complex network research has spanned the fields of social science and natural science, started from the aviation network, and gradually penetrated into the research of the transportation network including the rail transportation network and the road transportation network.

In order to describe the complexity of the network, it is necessary to construct the topological features of the network. Before the research method of the complex network was deeply applied to the traffic network, the idea of constructing the physical network and the traffic network had already appeared. In the transportation network, especially in the railway network, there are not only the material foundation provided by the infrastructure such as stations and transportation lines but also the direct transportation services provided by the operation of transportation vehicles for passengers. Generally speaking, there are two measurement scales to describe the topological structure of the traffic network. One is to build the network with the infrastructure such as the station and traffic line, and the other is to build the network with the traffic service. Kurant and Thiran consider that it is obvious that railway stations can represent nodes, but which method to use to describe the edges of the railway physical network system depends on the purpose of using the railway network topology analysis and constructing transfer space, stopping space, and station space, respectively [5]. Wang Wei et al. followed Kurant and Thiran's method to construct a railway network. In this thesis, the railway physical network is composed of stations as nodes and tracks connecting each pair of stations as edges. The railway transportation service network is composed of all stations where the trains stop and handle passengers getting on and off as nodes, and the lines between adjacent stations on the same train path are taken as edges. The railway transfer network consists of all stations where the train passes as nodes and the lines between stations on the same train path as edges [6]. Zhao considers railway stations as nodes and lines as edges to construct the railway geographic network. At the same time, the train flow network is constructed with stations as nodes and trains running among stations and handling passengers as edges [7]. Among them, the traffic flow network and the transfer network proposed by Wang Wei are the same concept. Both of them have empirically analyzed the traffic flow network or the transfer network of Chinese railway, and all think that it is a scale-free small-world network. Wang et al. established China's civil air transport network by considering cities with navigable conditions as nodes and routes opened between cities as edges using the method of the complex network and explained that the network has the nature of a small world [8]. Ouyang et al., respectively, established a pure topological model with railway stations as nodes and lines as edges and also established a train flow network with lines between stations on the same train path as edges [9]. Fang et al. analyzed the topological structure of China's high-speed railway network, regarded many stations within the same city as a node, and simplified the model into a geographical network consisting of only part of important hubs and trunk lines [10]. Wen regards the top 40 cities in descending order based on passenger volume and the economic development level among railway stations in northwest China as nodes and regards the existing or under construction railway lines between cities as edges to build a railway physical network [11]. Xian built China's high-speed railway network and trained through all of the sites for nodes in order to train the adjacent site for the edge of the transport network. According to the results, the high speed railway geographic network has the characteristics of scale-free networks and the high-speed railway transport service network has the characteristics of small-world networks [12]. Ma distinguished the roles of each node in the physical network of customized bus and formed a multiobjective optimization problem with the minimum travel time and the minimum carbon emission as the goal and customized bus routes as the solution. The transportation service network of a customized bus was obtained by solving this problem [13]. From the perspective of a comprehensive three-dimensional traffic network, Wang divided the Chinese high-speed railway and civil aviation network into two layers. If there is an airport or the railway station in this city, it is a node. If there is airline or train operation between cities, it is the edge. Wang studied the survivability of this two layers network from the perspective of space time [14].

With the in-depth study of complex network, describing and evaluating the reliability of networks has gradually become a hot research topic. As one of the most important research issues in the complex network, the survivability of the complex network has a broad research prospect in many fields and a huge research space in the railway system. Homle et al. start with indicators such as the degree of node and betweenness centrality and analyze the nodes or edges in the network. According to the node degree and betweenness centrality indexes in the initial and recalculated network states, nodes or edges were deleted in turn, respectively, and the redefined distance index (average geodesic length) was used to evaluate the changes of network structural features [15]. Wu and Tan consider that invulnerability is not related to the reliability of network nodes and edges and is an indicator to measure the difficulty of destroying a system. The author defines the evaluation of network invulnerability as the maximum node or edge removal rate that the network can bear under the condition of ensuring certain connectivity. Therefore, starting from connectivity constraints, the concepts of fault-tolerance and attack resistance of edges and nodes are given, respectively, to evaluate network survivability [16]. According to Wang, although the definition of network survivability varies in different fields, survivability emphasizes the adaptability, recovery, and completion of key services of the system after the intrusion and the damage or destruction of key parts of the system comparing with other concepts. Wang summarized the previous evaluation methods of network survivability from two aspects: one is the survivability of the network topology structure and the other is the survivability of network business function, which has the same connotation as Wu's interpretation of complex network invulnerability from broad and narrow levels [17, 18]. At the same time, Wang considers that network topological structure survivability mainly studies the connectivity based on its unique topological structure after random failure or deliberate attack of nodes or edges in the network. Network service survivability mainly studies the performance and carrying capacity of the network in the event of an emergency. Based on the reality of railway transportation, Wang establishes network survivability evaluation indexes from the aspects of the railway physical network and the railway transportation network and gives the calculation method of indexes [17].

Pang summarized previous research results on the invulnerability of complex networks, and thought that in the traditional graph theory, the node connectivity and graph toughness could be used as invariant indicators to describe the invulnerability of graph topology [19]. Liu et al. (2019) used the total passenger delay of the railway transport system under the influence of emergencies as an evaluation index of vulnerability and proposed that the protection of the railway system belongs to the category of disaster management, involving three stages. First, we should take precautions before the occurrence of an emergency. Second, we should respond accurately to mitigate the impact of an emergency. Finally, we should carry out postdisaster maintenance or reconstruction work after the occurrence of an emergency. Vulnerability and robustness mainly involve the first two stages, while resilience covers the whole process and emphasizes the ability of the network structure to recover after damage, which is similar to Bešinović [20, 21]. According to the total passenger travel cost, such as lines that cannot reach the destination after adjusting the number of passengers and train service levels, Szymula and Bešinović described the vulnerability to evaluate the network system. The mathematical modeling method of the arc-based railway physical network and the passenger train transport service network, as well as the passenger flow modeling method based on path, are used to construct constraints. The main objective function is to maximize the impact on passenger flow interruption and passenger travel cost after an emergency [22]. Bešinović et al. constructed a four-layer integrated network consisting of the infrastructure network, the train service network, the passenger transfer network, and reconstruction activities after the interruption of the railway transport system in order to construct the resilience model of the railway network system and find the optimal recovery sequence after the failure of the railway network system [23].

2.2. Research Status of the High-Speed Railway Train Operation Scheme. With the gradual complexity of the railway network and the development of passenger flow demand in the direction of complex and diversified, passenger train operation scheme research is mainly aimed at network or multiple departure and destination points. The establishment of the model is also gradually from a single-planning objective to the development of multi-objective planning. Zhang et al. believe that high-speed railway should operate nonstop trains and trains with fewer stops to the maximum extent so as to ensure smaller deduction of passing capacity. In this paper, high-speed direct trains that can operate at each station are first developed based on the passenger flow forecast of each station, and then, the operation scheme of the stopping train to transport the remaining passenger flow is determined by using the multi-objective 0-1 programming mathematical model. In addition, considering the complexity of the problem, a multi-level 0-1 programming method was designed to solve it [24]. Chang et al., respectively, considered the requirements of operators and passengers on train operation, established a multi-objective planning model from the perspective of both supply and demand, and established two planning objectives of the minimum operating cost and minimum travel time [25]. He et al. proposed the convenience index of train operation and applied it to the modeling of the maximum passenger convenience goal. The maximum convenience goal and the maximum benefit goal constitute the upper programming of the multiobjective double-level programming model, and the minimum cost goal is lower programming. Finally, the chaos algorithm is used to solve the nonlinear mixed integer multi-objective bi-level programming problem [26]. Wang established a mathematical model of the train operation scheme based on the cycle operation chart and proposed a multi-objective and opportunity-constrained programming model with the optimization objectives of minimizing operating cost, minimizing the loss of seat vacancy, and minimizing passenger waiting time, on which the passenger train operation scheme of the Beijing-Tianjin intercity railway was determined [27]. Deng analysises of train plans on the passenger dedicated line benefits and costs associated with the two ideas: one is from the revenue and cost analysis of the railway transport enterprise, and the second is based on passenger revenue and expenses of research and establishes the underlying cost minimizing passenger plan for the bilevel programming model of enterprise benefit maximization. On this basis, the paper puts forward the construction of the transfer network and the method of railway passenger flow allocation according to the reality of passenger transfer. In addition, the paper also conducts cluster analysis on indicators in many passenger train operation schemes and provides a simplified evaluation index system for passenger train operation schemes [28].

In addition, with the continuous expansion of the railway network, the study of the train operation organization theory and the method under emergent conditions is increasingly rich. Bešinović et al. summarized previous studies on the relationship between emergencies and railway transport organizations and pointed out that transport organization problems in the case of railway network interruption can be dealt with from the perspective of transport organization management and infrastructure repair, respectively. Specifically, in terms of transportation organization and management, a better scheduling method can be developed in the case of interruption after the occurrence of emergencies, that is, train operation adjustment. Alternative train schedules can also be developed in advance for preset interruption. After the corresponding interruption occurs, the emergency plan can be immediately activated to speed up the recovery of network system capability [23]. Meng analyzed the random characteristics of interval capacity under emergencies and proposed a calculation method of interval passing capacity based on the probability and statistics principle, which provided capacity constraints for train path generation under emergencies and improved the path generation algorithm for emergency conditions. The k-shortest path algorithm based on mileage limits and the path generation algorithm based on sufficient capacity are constructed to search the train running path on the road network under the condition of emergency and form the path set [29]. Wang analyzed the uncertain factors involved in interval capacity calculation under the condition of emergencies and established a path search model based on capacity time density, which provided a basis for the selection of detour routes under the condition of emergencies [30]. Wang and Meng both constructed a bi-level planning model of train operation organization under emergent conditions, in which the distribution of train movement is lower level planning and the adjustment of train operation is upper level planning. Miao used the ant colony algorithm introducing the road resistance and considering the influence of run time, used the route capacity utilization value of variance as a measure of capacity proportionality, and considered optimal utilization of the railway line proportionality index as the target to build the optimization model. The above work provides the basis for selecting the k-shortest path for train operation scheduling in emergencies. Finally, a multi-objective optimization model is established to reduce the train delay time and the number of trains [30].

2.3. Research Status Analysis. To sum up, scholars have performed a lot of detailed research on the survivability analysis of the railway network and the formulation of the passenger train operation scheme.

(1) The modeling of the railway system is mainly divided into two parts, namely, the railway physical network and the railway transportation service network. At present, there are various understandings of the nodes and edges in the railway physical network and the railway transportation service network. For high-speed railways, cities or railway hubs are mainly regarded as nodes. This modeling method keeps the basic network structure while simplifying the network scale. However, unlike the aviation physical network, the construction of edges in the railway physical network is more complicated, and the nodes in the hub are more closely connected. In fact, there may be many passenger stations and connecting lines inside the city from the perspective of the interior of the hub. When all stations are connected to each other through contact lines, the interruption on one line will not have an absolute influence on other lines (edges), and the functions of different stations in the city are different. In addition, the main direction of passenger transport may be different in each station. The loss of some or all of the capacity of one station does not mean that other stations will be affected in the same way. Furthermore, transportation corridors serve urban agglomerations or metropolitan circles, and the interruption of a certain line does not mean that the supply serving a certain OD is completely lost in reality. Therefore, it can be seen that the establishment of the railway physical network and the railway transport service network with the city as the node does not conform to the realistic characteristics of high-speed railway and has limitations. Therefore, this paper establishes a high-speed railway physical network with stations as nodes and lines between stations as edges.

(2) At present, the relationship between railway network resistance and the passenger train operation scheme is unclear. In the process of railway operation planning, previous studies only discussed the importance of railway network management facing irresistible force from the follow-up point of view and the series of measures to restore the functions of nodes or edges in turn according to the related indexes of railway network. Previous studies have not made clear what role resilience plays in the formation of the passenger train operation plan, and the connection between railway network resilience and the strategic level of railway operation planning is rarely established. The concept of railway network resilience includes minimizing the loss of system function in the event of an emergency and maximizing recovery efficiency after an emergency. Therefore, there are few ways to think about the antidamage of the railway network from the perspective of preparing in fair weather prepare for foul, and the existing passenger train operation plan without establishing the node and edge of the railway physical network once fails has limitations. In this paper, the relationship between the railway physical network, the

railway transportation service network, and the operation plan is defined, the quantitative index of railway transportation service network survivability is established, and the relationship between railway physical network node, edge failure, and railway transportation service network survivability is expounded.

(3) The problem of the train operation scheme is mainly solved by establishing an objective programming model. Moreover, most of the current literatures are from the standpoint of passengers and railway operators. No matter what method is used to establish a planning model that comprehensively considers the two, no one has evaluated the passenger train operation scheme from the perspective of the railway physical network or railway transport service network survivability. It has never been considered whether the railway transport service network formed by this scheme is still efficient and has limitations even if the railway physical network is interrupted. According to the failure state of nodes and edges in the real railway physical network, this paper selects the actual operation scheme in the alternative transportation routes to meet the demand of passenger flow, which can ensure the normal operation of cross-regional passenger trains and meet the normal travel of most passengers in this OD.

3. Construction and Evaluation of the High-Speed Railway Physical Network

3.1. Construction of the High-Speed Railway Physical Network. At present, many urban agglomerations and metropolitan areas in China have formed transportation corridors, which means that the same OD demand can be shared by multiple routes. As shown in Figure 1, the passenger flow between Beijing and Tianjin can be shared not only by Beijing-Shanghai high-speed railway (Beijingnan to Tianjin) but also by Beijing-Tianjin intercity railway (Beijingnan to Tianjin or Tianjinxi). Homoplastically, the passenger flow between Shanghai and Nanjing can be shared not only to Shanghai-Nanjing intercity railway (via Kunshannan railway station, Wuxidong railway station, Suzhounan railway station, Changzhoubei railway station, etc.) but also to Beijing-Shanghai high-speed railway (Suzhou railway station, Wuxi railway station, Changzhou railway station, etc.).

The layout of stations and lines in the physical network of high-speed rail shows that the interruption of a line due to an emergency does not mean that the railway cannot provide alternative services for passengers. The disruption of one station in a city due to an emergency does not mean that different stations or lines in the same city will also be disrupted. Therefore, considering the city as a node cannot comprehensively summarize the railway physical network.

In this paper, the railway physical network can be established by taking railway stations as nodes and connecting railway lines between stations as edges. As the high-speed railways are all double-track railway both-way traffic, the physical railway network is undirected network, which is expressed as $G_p = (V^p, E^p)$, where V^p represents the collection of railway stations and E^p represents the collection of railway lines. The network modeling process of railway stations and railway lines is as follows:

Step 1. Storing Station Information. All stations and lines in the physical network of the high-speed railway in mainland China are, respectively, included in V^p and E^p.

Step 2. Simplifying Station Data. As the station with a 2 degree is an intermediate station, it does not affect the topological features of other stations in the railway transport service network, so it is deleted from V^p, and E^p is cleared at the same time.

Step 3. Redrawing Lines Data. If the remaining nodes are directly connected by lines, the lines between the node pairs are counted into E^p.

For example, in Figure 2, Zhengzhouxi and Zhengzhoudong as the starting and ending stations are all in V^p. The degree of Xinzheng Airport station is 0 in V^p. The degree of Xiangyang Dong station is 3 in V^p. For example, Gongyinan, Lankannan, and other stations are not in V^p because they are located in nonprefectural cities. Actually, deleting the nodes with partial degree value of 2 will make the whole network more compact, and will not affect the degree value of the remaining nodes. Specifically, in China's high-speed railway network, the stations deleted according to the standards in this article generally do not have the ability of train departure and final arrival, and only serve as intermediate stations for passenger trains to handle passenger boarding and landing business and train passing business. Therefore, this method will not affect the betweenness centrality of other nodes in the transportation service network. As for closeness centrality, although deleting some nodes will affect the value of closeness centrality of nodes, the deleted nodes are reflected in the network only as intercity railways rather than railway trunk lines, and the impact is limited. Therefore, it will not affect the characteristics of other nodes in the road network application level.

This paper selects the high-speed railway structure in mainland China in January 2022 as the data source. Considering that some lines currently adopt the mode of common high-speed railway lines or even passenger and freight lines, some intercity railways also provide cross-line operation conditions for high-speed train EMUs. The high-speed railway mentioned in this article includes the lines applicable to the Railway Technical Management Regulations (high-speed railway part), that is, 200 km/h and above lines and 200 km/h and below only EMU lines, and also includes the power of the dispersed EMU running lines, such as Lanzhou-Chongqing railway. At the same time, considering that some lines and stations are independent from the national high-speed railway network, such as Hainan Island high-speed railway, these lines and stations are deleted in this paper. According to statistics, there are 386 nodes and 966 edges in G_p.

3.2. Key Stations and Key Lines of the High-Speed Railway Physical Network. Emergencies have different effects on different stations and lines in the railway network. Therefore,

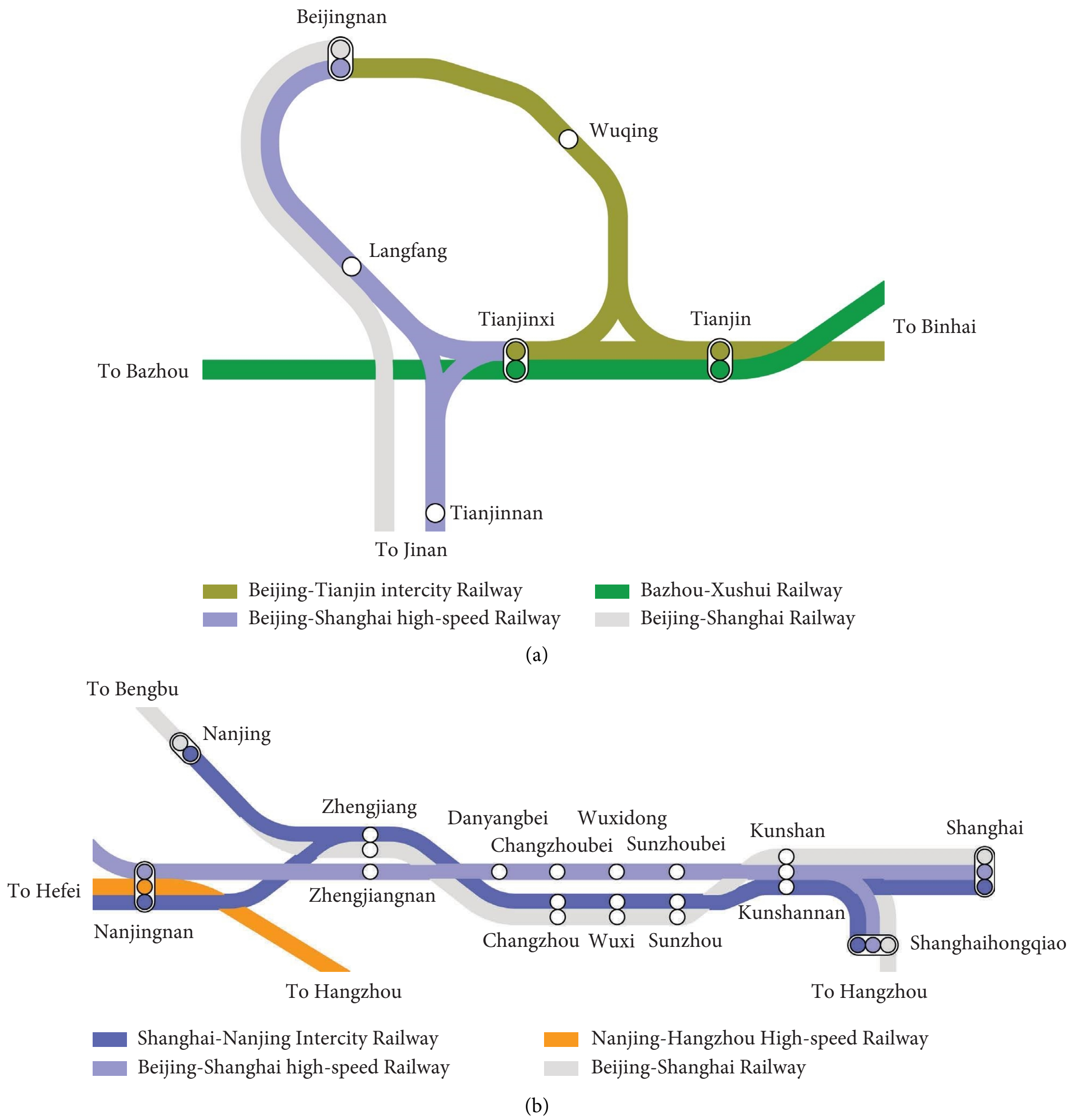

FIGURE 1: (a) Part of the Beijing-Tianjin-Hebei railway junction. (b) Part of the Yangtze River Delta junction.

it is necessary to classify and mark the nodes and edges in the railway network.

3.2.1. Measurement of Complex Characteristics of the Railway Network. Structure determines nature. In the railway system, whether it is the railway physical network or the railway transport service network, its nature must be judged by the network structure. The topology of the network can be described by the static geometry of the network; that is, the network structure can be represented by the microstatistical or macrostatistical average value of the network.

Centrality measures the relative importance of nodes in a network. Therefore, the centrality index can be used to measure the critical degree of nodes described in this paper. Because the importance of nodes described in this paper is related to the connectivity, aggregation, and media of nodes, there is no prior knowledge to show which representation method can better represent the importance of nodes. Hence, the eigenvector centrality which needs to utilize the importance of neighboring nodes is not used here. In this paper, three indexes of degree centrality, closeness centrality, and betweenness centrality are used to describe the degree to which a node is directly connected to other nodes, connected to surrounding nodes, and acts as an intermediary between other nodes.

(1) Degree Centrality. Degree centrality $C_D(i)$ refers to the number of edges connected to nodes, representing the importance of a node in the network, as shown in the following formula:

$$C_D(i) = \sum_{j=1}^{n} a_{ij}, \tag{1}$$

where when the node i is directly connected to the node j, a_{ij} is equal to 1; otherwise, a_{ij} is equal to 0. In directed graphs, in-degree and out-degree are usually used to represent the

Figure 2: Description of selection of station sets (only underlined stations are counted).

number of edges pointing to nodes and edges pointing to other nodes, respectively. Because the railway line has the condition of double-track traffic, it is a symmetric network, so this paper regards the railway network as an undirected graph.

(2) Closeness Centrality. Closeness centrality $C_c(i)$ describes how close a node is to other nodes along the shortest distance. When the distance between a node and other nodes is very short, the average shortest distance of nodes is very small, and these nodes are easier to establish connections with other nodes; the influence on other nodes is more direct [6]. The greater the closeness centrality, the closer the node is to other nodes. It is expressed by the following formula:

$$C_c(i) = \frac{n-1}{\sum_{v_i \in V, i \neq j} d_{ij}}, \quad (2)$$

where d_{ij} represents the number of nodes from the node i to the node j and n represents the number of nodes in the figure.

(3) Betweenness Centrality. Betweenness centrality $C_B(i)$ describes the degree to which a node is distributed along the path between other nodes. If a node is on the shortest path between other nodes, it means that the node is at the core and is often more powerful. Nodes with high betweenness centrality have a strong influence on the network because they control the message passing between other nodes [6]. Normalized $C_{BN}(i)$ between (0, 1) is required to make the obtained betweenness centrality $C_B(i)$ distribution more concentrated and even and is expressed as

$$C_B(i) = \sum_{k \neq i \neq j \in N} \frac{\sigma_{kj}(i)}{\sigma_{kj}}, \quad (3)$$

$$C_{BN}(i) = \frac{C_B(i)}{(N-1)(N-2)/2}, \quad (4)$$

where σ_{kj} is the sum of the number of shortest paths between the node v_k and the node v_j and $\sigma_{kj}(i)$ is the number of shortest paths passing through the node v_i.

3.2.2. Concept of Key Stations and Key Lines. In the formulation of the passenger train operation planning, the corresponding treatment can be made according to the importance of various stations or sections, which can reduce or even avoid the adverse impact of emergencies on railway transport services. Wang considers that the key nodes and key edges of the railway network refer to those nodes and edges that play an important role in maintaining or restoring the normal functions of the railway network [17]. In the railway physical network and the railway transport service network, there are different definitions of key nodes and key edges, as shown in Table 1.

Wang summarized the basic idea of the quantification of key nodes and key edges. On one hand, the critical degree of nodes and edges can be explained according to the degree of damage to network functions after nodes or edges are removed. On the other hand, the critical degree of nodes and edges can be judged by the attribute information of nodes and edges in the network, such as degree, betweenness centrality, and closeness centrality [17, 19]. This paper argues that the attribute information of nodes and edges should be used to describe the critical degree of the node and edge in the railway physical network. The description of the damage level of network function should be based on the critical degree of nodes and edges after the flow is formed by the physical structure.

3.2.3. Quantitative Methods of Key Stations and Key Lines. The key nodes and key edges in the railway physical network can be simplified through the location characteristics of nodes in the network; that is, the importance of nodes can be described from different angles by integrating the indicators in the network structure, node centrality, and correlation. Due to the correlation among the calculation processes of these indexes, the complexity of problem analysis is increased, and the analysis is inconvenient. If we analyze each index independently, we can only get isolated conclusions from different perspectives. Therefore, it is necessary to find a reasonable method to reduce the number of network topology indicators that need to be analyzed and ensure that the information contained in the original indicators is not lost so as to achieve the purpose of comprehensive analysis of the collected data.

As shown in Figure 3, in order to obtain the importance of comprehensive indicators to quantify nodes, principal component analysis (PCA) was used to solve the problem by SPSS, and three indicators describing nodes, such as degree, closeness centrality, and betweenness centrality, were mapped to one-dimensional coordinates. A comprehensive index describing the importance degree of nodes can be obtained on the basis of retaining the topological characteristics of the original nodes, namely, the comprehensive quantitative index of the critical degree of node v_i via the application of PCA.

According to the calculation of PCA, the Kaiser-Meyer-Olkin value is 0.622, and the Bartlett sphericity test $P < 0.05$ shows that the three indexes of degree centrality, closeness centrality, and betweenness centrality meet the requirements of principal component analysis. The analysis results are shown in Table 2.

According to the results of principal component analysis, degree centrality plays a decisive role in the key node index, accounting for nearly 60%, followed by closeness centrality and betweenness centrality. The proportion of each component in the comprehensive quantitative index of key nodes is shown in Figure 4. Therefore, in the railway physical network, the comprehensive quantitative index I_i of node v_i criticality is expressed as follows:

$$I_i = 0.5988\, C_D(i) + 0.2390\, C_C(i) + 0.1623\, C_{\mathrm{BN}}(i), \tag{5}$$

where, $C_D(i)$ is the degree of the node v_i, $C_C(i)$ is the closeness centrality of the node v_i, and $C_{\mathrm{BN}}(i)$ is the normalization betweenness centrality of node v_i.

According to Holme et al., the edge degree can be expressed by the degree product of nodes connected by edges [15]. Since edges are interconnected through nodes, this paper refers to Holme's conclusion when quantifying the criticality of edges; that is, the comprehensive quantitative index I_e of edge $e_{v,w}$ criticality in the railway physical network is expressed as follows:

$$I_e \equiv I_v \times I_w, \tag{6}$$

where v and w are the two nodes with the edge e and I_v and I_w are the quantitative indicators of the critical degree of the nodes v and w, respectively.

After calculation, the 10 most critical nodes and edges in China's high-speed railway physical network are shown in Table 3.

4. Design of the Passenger Train Operation Scheme considering Network Survivability

Due to the occurrence of emergencies, the train paths between OD can be adjusted according to the position of damaged nodes or edges in the network. According to this method, a temporary operation scheme of passenger trains is proposed for the damage of nodes or edges in the regional network so as to improve the resistance of the railway transport service network under the damage of the railway physical network.

4.1. Construction of the High-Speed Railway Transport Service Network. In this paper, it is considered that if a station or section fails, the impact on other stations can be reduced by adjusting the trains passing through the station or line to another path. The steps are as follows:

(i) *Step 1. Storing Train Path.* According to the existing passenger train operation data after the January 2022 timetable adjustment and the local network structure, routes with similar mileage were selected into the optional path set and trains with the same OD and the same path was classified.

(ii) *Step 2. Comparing Different Paths.* According to the failure of different nodes or sides on the track, an alternative track set different from the original track but with similar mileage is provided for a specific pair of trains.

(iii) *Step 3. Evaluating the Survivability of Alternative Path.* The importance of different roads is different, and a road with lower operating mileage is finally

Table 1: Definition differences of key nodes and key edges in the railway physical network and the railway transport service network.

	Railway physical network	Railway transportation service network
The key nodes	Describe the importance of a station in a railway infrastructure, independent of train pick-up, passenger landing, and other transport services	Describe the importance of the station in railway transportation, focusing on the description of the station train reception and departure, passenger travel, and other service indicators
The key edges	Describe the importance of interstation or interstation lines in the railway infrastructure, independent of traffic density, cross section passenger flow, etc	Describe the importance of railway lines between stations or between stations in railway transportation, focusing on the description of traffic density, section passenger flow, and other transport service indicators

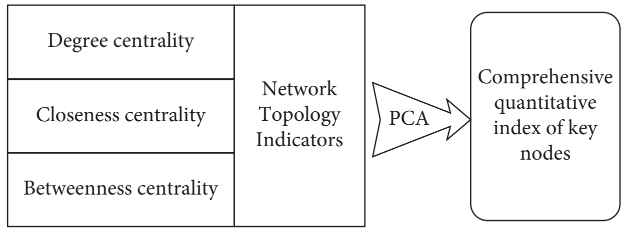

Figure 3: Acquisition of comprehensive quantitative indexes of key nodes.

Table 2: Calculation results of principal component analysis.

Total variance interpretation			
Composition	Characteristics of the root	Percentage of variance (%)	Cumulative
Degree centrality	1.796	59.88	59.88%
Closeness centrality	0.717	23.90	83.77%
Betweenness centrality	0.487	16.23	1

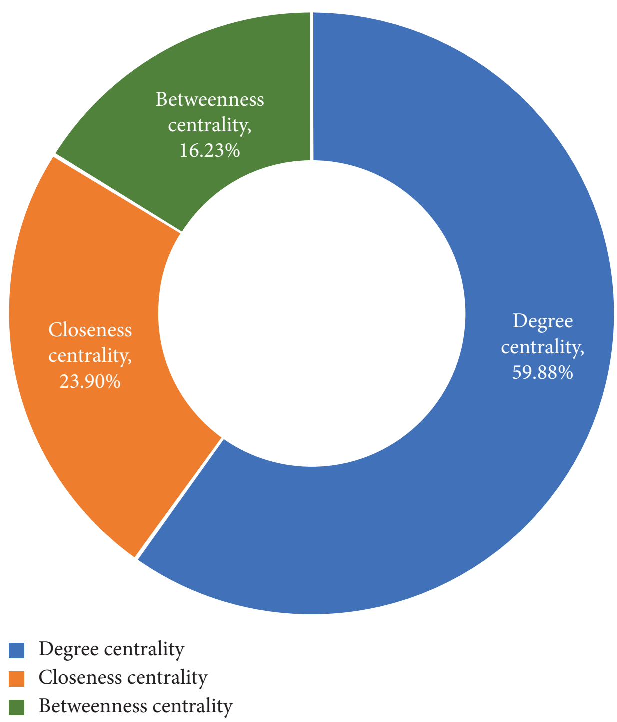

Figure 4: Proportion of each component in the comprehensive quantitative index of key nodes.

Table 3: Top ten key nodes and key edges.

Key node quantization			Key edge quantization			
Stations	Rank	Comprehensive evaluation index	Edges (a pair of stations)		Rank	Key edge quantification index
Zhengzhoudong	1	4.8310	Zhengzhou	Zhengzhoudong	1	23.5050
Wuhan	2	4.2503	Wuhan	Hankou	2	17.2041
Chongqingbei	3	4.2497	Guiyangbei	Guiyangdong	3	14.7036
Nanjingnan	4	3.6255	Chongqingbei	Bishan	4	13.7583
Zhengzhou	5	3.6251	Xu Changdong	Zhengzhoudong	5	11.8231
Guiyangdong	6	3.6236	Xinxiangdong	Zhengzhoudong	6	11.8213
Hangzhoudong	7	3.6225	Zhengzhoudong	Zhengzhoudong	7	11.8170
Xuzhoudong	8	3.0433	Wuhan	Hong'anxi	8	10.3794
Xi'anbei	9	3.0407	Chongqingbei	Guangannan	9	10.3674
Hankou	10	3.0407	Chongqingbei	Chongqingxi	10	10.3625

chosen to avoid the extra cost of detour transportation. At the same time, the alternative path used to meet capacity constraints is ensured.

(iv) *Step 4. Evaluating Alternative Paths Survivability.* The survivability of the alternative path is compared with that of the original path, and the network survivability under the alternative path is evaluated.

4.2. The Connotation of Survivability of the Railway Transport Service Network. Most complex networks have loads, which can be material, information, or energy, and can be concrete or abstract. In the railway physical network, the load of the network actually runs on fixed lines and passenger trains in fixed intervals. When the network structure changes, if new nodes or edges are added to the network (new stations and lines) or existing nodes or sides are removed (existing stations and lines are interrupted due to emergencies), the trains running on fixed lines will be reassigned. This means that nodes in the network are not isolated, but rather that the coupling between other nodes can be affected by sudden failures, leading to cascading effects that can lead to the collapse of a significant number of nodes or even the entire network.

The node failure referred to in this paper refers to the failure of the node due to the impact of an emergency, and the direct connection between the node and its neighbors cannot be established. In the railway physical network, node failure means the complete loss of station function. Due to the large number of businesses handled by railway stations, the business related to passenger trains includes passenger train passing and other traffic operations in addition to passenger boarding and landing. Therefore, as shown in Figure 5, the failure of nodes in the railway physical network not only means that passengers cannot take and land at the station but also means that they cannot cross the station even if they pass through the train without stopping. The failure of the edge means that no train can pass through the damaged area for a certain period of time.

At the same time, this paper borrowed the viewpoint of Bešinović and thinks that survivability refers to the ability of a system to control losses within an acceptable range after emergencies occur, and survivability, vulnerability, and reliability are all the subconcepts of resistance [23]. The survivability of the railway network is related to the degree to which the function of the railway network system declines after the station or line breaks down in an emergency.

As an organization plan to transform passenger flow into train flow, the train operation plan should be formulated according to the requirements of passenger flow characteristics and transportation organization conditions. First of all, the passenger flow condition reflects the travel demand of passengers, the nature of passenger flow determines the type and section of train operation, and the passenger flow determines the number of trains. Secondly, the transportation organization conditions refer to the hardware equipment conditions including the line conditions, train conditions, and traffic organization. Therefore, this paper thinks that the passenger train line planning problem (LPP) can be regarded as two parts: the process of making a plan and the result.

The railway transportation service network for passengers is also built on the railway physical network composed of the railway infrastructure, which represents the train flow on the railway physical network, and has the same connotation as the solution of the LPP problem. At this time, the railway transportation service network for passengers can be regarded as the solution result of the LPP problem. Therefore, the survivability evaluation of the railway transportation service network can be regarded as the survivability evaluation of the passenger train operation scheme.

In the railway transport service network, node failure means that the function of the station for the passengers to enter and exit the station or transfer in station is completely lost. The node failure of the railway transport service network focuses on a specific train. For example, during the lockdown of Wuhan due to the epidemic in early 2020, passenger boarding and landing services of most trains were suspended at stations in Wuhan hub, but trains could still cross stations and complete technical stops and other related operations. In addition, edge failures in the railway transport service network mean that a particular train cannot operate in a particular section.

Since the railway transport service network is built on the basis of the railway physical network, the system function of the railway physical network is mainly reflected in the transport service it can provide, and the impact of the railway physical network caused by emergencies is directly reflected in the change of the railway transport service network. According to the general consensus, the failure of edges in the passenger transport service network only affects a specific passenger train; that is, the relationship between edges and nodes in the railway transport service network is more independent, and the failure of edges and nodes in the transport service network will not affect the infrastructure, that is, the railway physical network. Specifically, if there are multiple pairs of passenger trains running in the same OD, when a pair of trains is out of service, it is easy to make the supply and demand balance again by running reconnection trains and so on. But on the other hand, the state of the railway physical network directly determines the state of the transportation service network, and the suspension of a line or station directly affects all the trains passing through them. Therefore, this paper takes the railway physical network as the target of attack and observes the impact of the failure of nodes or edges in the railway physical network on the railway transport service network so as to judge the survivability of the railway transport service network.

If the influence of nodes removed by a single index on the network is independently analyzed, only an isolated analysis conclusion can be obtained, and the network resistance cannot be completely quantified. As the quantitative indexes of node criticality I_i and edge criticality I_e in this paper have been used to reduce the dimension of topological feature values of multiple nodes by principal component analysis, this paper deleted them in descending order according to the index values of I_i and I_e.

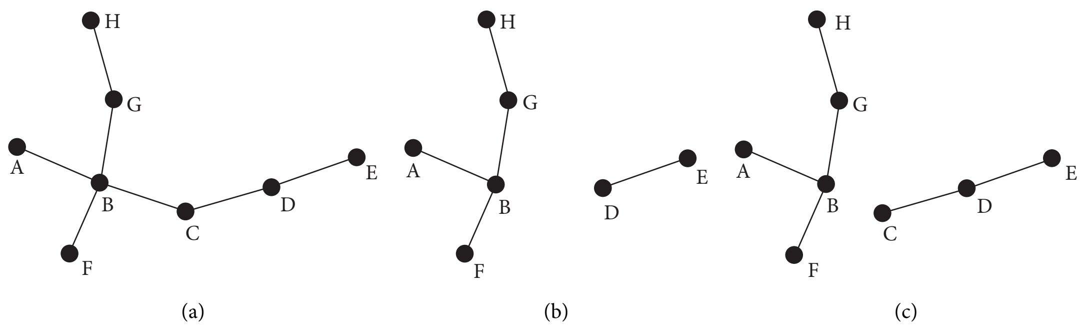

Figure 5: Schematic diagram of railway physical network attack: (a) railway physical network, (b) node C failure, and (c) edge B-C failure.

4.3. Railway Transport Service Network Survivability Assessment. Survivability emphasizes the ability of a system to maintain or recover to an acceptable range of functions after transitioning from a normal or planned state to an interrupted state due to an emergency. Different survivability requirements correspond to different survivability evaluation methods which reveal different aspects of network survivability. To describe the survivability of the railway transport service network, it is necessary to consider that the service function of the station or line is affected by emergency. Therefore, the average shortest path, aggregation coefficient, network efficiency, and other indicators describing the railway physical network cannot be used to directly describe the change of transport supply.

Fang et al. considered that the loss of functions of a single node due to an emergency will have an impact on the operating mileage of trains [10]. Considering that in the railway network system, if the failure of lines or nodes is only judged by the number of trains, the impact on the network cannot be represented in the whole network, nor can it be represented on the impact of passenger travel across the country. Therefore, Fang's opinion is cited and promoted in this paper, which believes that the residual mileage of total train operation after node or edge failure can be used as the evaluation index of the resistance of the railway transport service network.

Since the operating mileage of the train directly determines the service scope of the train, the impact of different operating mileage of the train can be used to represent the survivability of the node v_i after the interruption of an emergency, denoted as CTM_i, as follows:

$$\mathrm{CTM}_i = \sum_{t\epsilon T} \mathrm{TM}_i^t + \sum_{t'\epsilon T} \mathrm{ATM}_i^{t'}, \tag{7}$$

where CTM_i denotes the cumulative travel mileages of the affected trains after a node v_i emergency and TTM is the operating kilometers of all trains in the network.

It should be noted that if the interruption node is located at the departure and arrival stations of the train route, the affected operating mileage is the whole operation of the train because the train cannot complete its departure, return, or return section reconditioning, which is represented by the train t. However, if the interruption node is located along the train path, the impact of the emergency on the whole train journey needs to be analyzed in a case-by-case manner, which is represented by the train t'. For example, if a train takes a detour after an emergency occurs, the actual route will change compared to the planned route. If the train chooses to return midway, it can only serve a portion of the route planned. For example, during the 2021 summer travel season, Z130 from Lanzhou to Beijingxi and T114 from Lanzhou to Hangzhou turned back at Sanmenxiaxi railway station due to heavy rain within the jurisdiction of Zhengzhou Railway Bureau, a railway transport enterprises located in Central China. This means that if the train cannot run safely within the range, passenger boarding and landing services cannot be handled at the corresponding station, thus affecting the actual operating mileage of the train. In this paper, it is considered that after the node failure, the affected train operating mileage is the mileage from the interrupted node v_i to the train terminal station along the train running direction. At the same time, it is assumed that if two or more nodes or edges fail on a train path, the train stops running, and the train mileage affected should be the total mileage of the whole route up and down. Therefore, the impact of the station or line emergencies on the railway transport service network can be divided into the following two types: First, when the nodes located at the departure and arrival stations v_i of trains are interrupted, the impact should include the total mileage of these trains, which is recorded as TM_i^t. Second, when the interrupt node v_i is located on the train path, the impact is the operating mileage between the node and the adjacent starting point on the train path, denoted as $\mathrm{ATM}_i^{t'}$.

When the line is interrupted by an emergency, all trains passing through the line will be affected. Thus, the survivability of the edge l_{ij} is shown in the following equation:

$$V_{ij}^F = \frac{\mathrm{CTM}_{ij}}{\mathrm{TTM}}. \tag{8}$$

Similar to node failure, when the edge l_{ij} is located in the interval immediately adjacent to the starting and ending points of the train, the impact should include the total operating mileage of these trains, denoted as TM_{ij}^t. When the edge l_{ij} is located in the path of the train, the impact is the edge node of the first failure interval along the direction of the train.

4.4. Basic Assumptions

4.4.1. Failure Level Hypothesis. The extent to which a line or station is affected by an emergency depends not only on the emergency itself but also on the characteristics of the damaged parts, such as the life span, materials, and

Table 4: Train tracks between Zhengzhoudong-Nanjingnan and Zhengzhoudong-Hefei/Hefeinan.

Paths	Mileage	Train pairs
Zhengzhoudong-Nanjingnan		
Zhengzhoudong-Shangqiu-Xuzhoudong-Bengbunan-Nanjingnan	691/711	17
Zhengzhoudong-Shangqiu-Fuyangxi-Hefei/Hefeinan-Nanjingnan	744/764	0
Zhengzhoudong-Zhoukoudong-Fuyangxi-Hefei/Hefeinan-Nanjingnan	690/710	16
Zhengzhoudong-Hefei/Hefeinan		
Zhengzhoudong-Zhoukoudong-Fuyangxi-Hefei/Hefeinan	536/556	9
East Zhengzhou-Shangqiu-Fuyangxi-Hefei/Hefeinan	590/610	18
Zhengzhoudong-Shangqiu-Xuzhoudong-Bengbunan-Hefei/Hefeinan	648/668	0

Note. The mileage data "A/B," A refers to the mileage of the route or the final destination to the Hefei station; B refers to the mileage of the route or the final destination to the Hefeinan station. *Note.* Mileage unit is km.

Table 5: Original route of Zhengzhoudong-Nanjingnan trains.

Train codes	Station of the origin terminal	Departure station	Arrival station	The original path	
				Mileage	Path
G1973/ G1976	Chongqingxi-Shanghai Hongqiao	Zhengzhoudong	Nanjingnan	2469	Xuzhoudong through the Beijing-Shanghai high-speed railway to Nanjing
G1825/ G1828	Zhengzhoudong-Shanghai Hongqiao			986	
G1821/ G1824	Zhengzhoudong-Shanghai Hongqiao			986	
G1805/ G1808	Zhengzhoudong-Shanghai Hongqiao			986	
G1865/ G1868	Zhengzhoudong -Ningbo			1300	
G1817/ G1820	Yinchuan-Shanghai Hongqiao			2126	
G362/ G359	Xi'anbei-Shanghai Hongqiao			1509	
G1935/ G1938	Xi'anbei-Shanghai Hongqiao			1509	
G1923/ G1926	Xi'anbei-Shanghai Hongqiao			1509	
G1919/ G1922	Xi'anbei-Shanghai Hongqiao			1509	
G1915/ G1918	Xi'anbei-Shanghai Hongqiao			1509	
G1911/ G1914	Xi'anbei-Shanghai Hongqiao			1509	
G1809/ G1812	Luoyang Longmen-Shanghai Hongqiao			1129	
G1969/ G1972	Lanzhouxi-Shanghai Hongqiao			2077	
G1813/ G1816	Anyangdong-Shanghai Hongqiao			1163	
G367/ G370	Zhengzhou-Shanghai Hongqiao			1000	
G1947/ G1950	Jiaozuo-Shanghai Hongqiao			1078	

Note. Mileage unit is km.

construction standards. This paper assumes that the impact of an emergency on the station or line is absolute and that the functions of the station can only be completely lost or completely retained; that is, the functions of the station or line are only 0% or 100%, and there is no intermediate state between 0% and 100%. This means that it is impossible for trains to pass directly or for passengers to take or drop passengers after the station fails. After the edge failed, all trains that should have passed the edge could not pass.

4.4.2. Spatial Timeliness Hypothesis. This paper assumes that all trains are affected by station or line emergencies, regardless of their relative position on the line. That is to say,

Table 6: Alternative path set.

Train codes	OD	The original path		Xuzhoudong, etc		Shangqiu and other failures	
		Route 2	The mileage	Path 3	The mileage	Route 1	The mileage
G1973/G1976	Chongqingxi-Shanghai Hongqiao		2469		2522		2468
G1825/G1828	Zhengzhoudong-Shanghai Hongqiao		986		1039		985
G1821/G1824	Zhengzhoudong-Shanghai Hongqiao		986		1039		985
G1805/G1808	Zhengzhoudong-Shanghai Hongqiao		986		1039		985
G1865/G1868	Zhengzhoudong to Ningbo		1300		1353		1299
G1817/G1820	Yinchuan-Shanghai Hongqiao		2126		2179		2125
G1935/G1938	Xi'anbei-Shanghai Hongqiao		1509		1562		1508
G1923/G1926	Xi'anbei-Shanghai Hongqiao	Transfer from Xuzhou to Beijing and Shanghai to Nanjing	1509	To Shangqiu through Shangqiu-Hefei-Hangzhou high-speed railway	1562	Through Zhengzhou-Fuyang high-speed railway to Fuyang to Hefei to Nanjing	1508
G1919/G1922	Xi'anbei-Shanghai Hongqiao		1509		1562		1508
G1915/G191r8	Xi'anbei-Shanghai Hongqiao		1509		1562		1508
G1911/G1914	Xi'anbei-Shanghai Hongqiao		1509		1562		1508
G1809/G1812	Luoyang Longmen-Hongqiao of Shanghai		1129		1182		1128
G1969/G1972	Lanzhouxi-Shanghai Hongqiao		2077		2130		2076
G1813/G1816	Anyangdong-Shanghai Hongqiao		1163		1216		1162
G367/G370	Zhengzhou-Shanghai Hongqiao		1000		1053		999
G1947/G1950	Jiaozuo-Shanghai Hongqiao		1078		1131		1077

Note. Mileage unit is km.

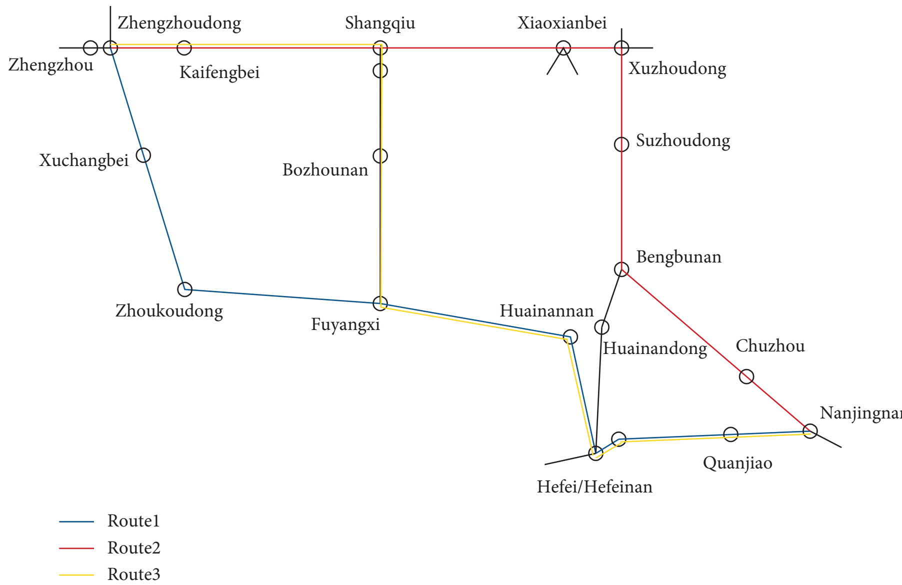

Figure 6: Optional road between Zhengzhoudong and Nanjingnan.

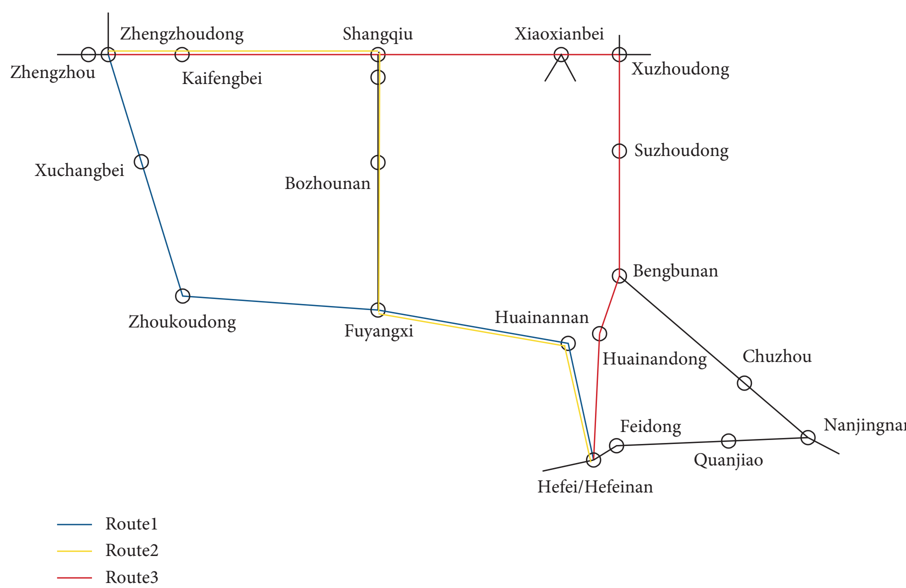

Figure 7: Optional path between Zhengzhoudong and Hefei/Hefeinan.

there is no train through the station or section, the station or line again failure, so that the train does not affect the situation. If the station or line is in the path of the train, the failure of the station or line will inevitably affect the train. As the railway transport service network discussed in this paper (i.e., the passenger train operation scheme) repeats in a cycle of 24 hours, it is assumed that only trains within 24 hours will be affected after a line or station failure.

4.4.3. Train Operation Hypothesis. This paper assumes that all trains run in pairs every day and have identical train paths. This means that a station or line failure due to an emergency can affect both trains at the same time. It is not possible to affect only one direction and retain capacity in the other direction, nor is it possible for one train to be affected without affecting the other train. In addition, if two or more nodes or edges of the train path fail, the train is considered to be out of service. In this case, the reduced train path is the entire operation of a pair of trains.

4.5. Survivability Analysis of the Railway Transportation Service Network. This paper analyzes two pairs of OD passenger trains between Zhengzhoudong-Nanjingnan and Zhengzhoudong-Hefei or Hefeinan. Between the two pairs of OD, there are 3 train paths, respectively, after the map adjustment in January 2022, as shown in Table 4.

Table 7: Influence of path adjustment on the system after east Xuzhou failure.

	Route 2	Route 1 or route 3
Zhengzhoudong	28612	4258
Zhengzhou	0	0
Nanjingnan	150022	125668
Xuzhoudong	196890	172536
Hefeinan	2065	2065
Hefei	0	0
Feidong	4058	4058
Xiaoxianbei	25445	1091
Bengbunan	184652	160298
Huainan east	35653	35653
Fuyangxi	0	0
Quanjiao	0	0
Shangqiu	25445	1091
Suzhoudong	184652	160298
Huainannan	0	0
Zhoukoudong	0	0
Xuchangbei	0	0
Chuzhou	148999	124645
Kaifengbei	24354	0
Bozhounan	0	0
Shangqiudong	0	0

Table 5 lists all the trains from Zhengzhoudong to Nanjingnan OD that transfer to Beijing-Shanghai high-speed railway through Xuzhou-Lanzhou high-speed railway to Xuzhoudong railway station. When Xuzhoudong railway station fails, the transport services of these trains will not run through the OD but run in sections. Therefore, if an emergency occurs at stations or lines along the route, it will directly reduce the passenger supply between Zhengzhoudong and Nanjingnan railway station and also affect the travel of passengers between stations in Zhengzhoudong upward direction and Nanjingnan direction. In order to avoid the influence of station or line failure on long-distance cross-line trains in local scope, it is necessary to adjust the transport routes of some trains whose OD is not in this area. This paper provides alternative routes for these trains as shown in Table 6.

Figures 6 and 7, respectively, show all existing paths in the Zhengzhou-Nanjingnan section and Zhengzhou-Hefei/Hefeinan section, which are ranked in order by length of path, as well as the nodes and sides of these paths that can serve passenger trains between OD. In this paper, if the nodes or edges of one path fail, other paths can be selected. If there are multiple other paths, the choice should be based on the minimum sum of the quantitative indexes of the critical degree of the edges along the path.

4.6. Comparison of Survivability of Adjusting Passenger Train Operation Schemes. Table 7 takes Xuzhoudong as an example to show that when Xuzhoudong fails, adjusting the traffic flow that originally passes through Xuzhoudong between Zhengzhoudong and Nanjingnan, OD can reduce the impact on all stations in the region, and the transport mileage loss of marked stations is reduced. In this way, if there is a certain path that can serve a certain OD room in the region, the operation line of the alternative path can be drawn under the condition that the route and the station passing capacity permit. When the drawing and sizing of the train are interrupted due to an emergency, the alternative path can be immediately used to serve the OD demand.

5. Conclusions

The physical network topology of China's high-speed railway is constructed. On the basis of establishing the comprehensive quantitative index of key nodes and edge importance, the survivability evaluation index of the railway transportation service network based on the operating range of passenger trains is constructed and applied to the local railway network. With the goal of improving the speed survivability of railway systems, the alternative operation schemes of some passenger trains between OD are given.

The main research work of this paper is as follows:

(1) This paper establishes the evaluation indexes of key stations and key lines of the high-speed railway physical network. In this paper, principal component analysis (PCA) is used to reduce the dimension of the three indexes describing the complexity of nodes into a comprehensive evaluation index, which not only preserves the physical characteristics of nodes but also simplifies the description process of key nodes. Using this method, this paper finally forms a quantitative index of key nodes of physical network with degree as the main body, supplemented by closeness centrality and betweenness centrality. After that, the critical degree quantitative index of edges is defined according to the critical degree evaluation index of nodes.

(2) This paper constructs the high-speed railway transport service network with the train stopping as the node and the two adjacent stations where the train stops as the side and analyzes their survivability. In this paper, it is considered that the railway transport service network survivability can be expressed by attacking the nodes and edges of the railway physical network and observing the impact of the actual train operation. Furthermore, considering the cascade effect of node and edge failure, the survivability of the local road network is analyzed by using the existing mapped train data in the local road network. It is considered that the cascade effect obtained by using the survivability index based on operating mileage is unbalanced, and the reasons are analyzed.

(3) This paper establishes the formulation method of the alternative passenger train operation scheme in the local network. This paper takes all trains from Zhengzhoudong to Nanjingnan and Zhengzhoudong to Hefei/Hefeinan as examples and adjusts them to other lines according to the critical degree evaluation index of the path edge and the specific node and side failure and observes the influence on system function.

The deficiency of this article is as follows:

(1) The quantitative index of the critical degree of nodes and edges has limitations. The quantitative index of the critical degree of nodes and edges obtained by principal component analysis can avoid the isolated conclusion and avoid the disadvantage of subjective factors such as artificial determination to the conclusion. However, this paper has shown that the node distribution states of the railway physical network and the railway transport service network are different, and their topological features do not completely coincide. This paper describes the key nodes and key edges only through the characteristics of the railway physical network, without reference to the node characteristics of the railway transport service network, which has limitations. In the future, a more comprehensive evaluation index of key nodes and key edges can be established by combining the characteristics of the railway physical network and the railway transportation service network.

(2) The survivability evaluation index has limitations. In this paper, the influence caused by node and edge failure is represented by the operating mileage of affected trains, that is, the resistance of the railway transport service network to damage. This method can reflect the service range of the affected train in the data, and it also takes into account that the loss of network function varies with the relative position of the failed node and edge in the train path. However, this method cannot represent the passenger flow between OD which is affected. In the future, based on the passenger flow data between OD and the affected trains, the affected passenger flow data and operating mileage can be comprehensively considered to obtain the comprehensive evaluation index of the railway transport service network's resistance to damage.

(3) The alternative train operation scheme has limitations. The alternative passenger train operation scheme proposed in this paper is based on the existing passenger train operation scheme and is only adjusted on the basis of the minimum quantitative index of the critical degree of path side. Although this method guarantees the passenger flow between the starting and ending points of the train or a small part of the complete path, it does not consider the passenger flow within the adjustment range of the path, and this paper does not involve the problem of the flow distribution in this section. In addition, this method is also established on the basis that the existing passenger train operation scheme can highly fit the passenger flow, but this paper assumes that the existing passenger train operation scheme is reasonable, but it is not verified. In the future, on the basis of path adjustment, passenger flow can be loaded between stations to meet the goal of passenger flow between OD, and then, the passenger flow path affected by station or edge damage can be adjusted to meet the requirements of passenger flow between OD on the basis of antidamage requirements.

(4) In the future, the integrated network model of the high-speed and universal high-speed railway can be established based on the survivability evaluation of the railway transport service network. By integrating the topological features of national high-speed and universal speed railway networks and fitting the passenger flow demands between OD, the online and offline operation strategies of universal high-speed railway trains after node or edge failure are designed for the purpose of improving the survivability of the transportation service network in the integrated high-speed and universal speed railway network.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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References

[1] M. Newman, *Networks*, Oxford University Press, Oxford, UK, 2018.

[2] D. J. Watts and S. H. Strogatz, "Collective dynamics of 'small-world' networks," *Nature*, vol. 393, pp. 440–442, 1998.

[3] S. H. Strogatz, "Exploring complex networks," *Nature*, vol. 410, pp. 268–276, 2001.

[4] R. Albert, H. Jeong, and A. L. Barabási, "Diameter of the world-wide web," *Nature*, vol. 401, pp. 130-131, 1999.

[5] M. Kurant and P. Thiran, "Extraction and analysis of traffic and topologies of transportation networks," *Physical Review*, vol. 74, no. 3, Article ID 036114, 2006.

[6] W. Wang, J. Liu, X. Jiang, and Y. Wang, "Topology properties on Chinese railway network," *Journal of Beijing Jiaotong University*, vol. 34, no. 3, pp. 148–152, 2010.

[7] H. Zhao, "Study on network nature of Railway passenger transport network in China," *Acta Physica Sinica*, vol. 55, no. 8, pp. 3906–3911, 2006.

[8] J. Wang, H. Mo, F. Wang, and F. Jin, "Exploring the network structure and nodal centrality of China's air transport network: a complex network approach," *Journal of Transport Geography*, vol. 19, pp. 712–721, 2011.

[9] M. Ouyang, H. Tian, Z. Wang, L. Hong, and Z. Mao, "Critical infrastructure vulnerability to spatially localized failures with applications to Chinese railway system," *Risk Analysis*, vol. 39, no. 1, pp. 180–194, 2019.

[10] C. Fang, P. Dong, Y. P. Fang, and E. Zio, "Vulnerability analysis of critical infrastructure under disruptions: an application to China Railway High-speed," *Proceedings of the*

Institution of Mechanical Engineers Part O:Journal of Risk and Reliability, vol. 234, no. 2, pp. 235–245, 2020.
[11] L. Wen, "Study on railway Network reliability in northwest China," *Railway Transport And Economy*, vol. 5, pp. 1–6, 2020.
[12] W. Xian, "Topological characteristics analysis of High-speed railway network in China," *Journal of Lanzhou Jiaotong University*, vol. 40, no. 4, p. 6, 2021.
[13] C. Ma, C. Wang, and X. Xu, "A multi-objective robust optimization model for customized bus routes," *IEEE Transactions on Intelligent Transportation Systems*, vol. 22, no. 4, pp. 2359–2370, 2021.
[14] Y. Wang, X. Cao, F. Qin, and L. C. Tong, "Vulnerability analysis of the Chinese coupled aviation and high-speed railway network," *Chinese Journal of Aeronautics*, vol. 35, no. 12, pp. 189–199, 2022.
[15] P. Holme, B. J. Kim, C. N. Yoon, and S. K. Han, "Attack vulnerability of complex networks," *Physical Review*, vol. 65, no. 5, Article ID 056109, 2002.
[16] T. Wu, "Research on vulnerability measure of complex networks," *Journal of Systems Engineering*, vol. 20, no. 2, p. 4, 2005.
[17] Wang, *Analysis and Study on the Survivability of Railway Network*, Diss. Beijing Jiaotong University, Beijing, China, 2011.
[18] Wu, *Research on the Invulnerability of Complex Network Topology*, Diss. National University of Defense Technology, Changsha, China, 2008.
[19] Pang, *Network Model and Research on Invulnerability for Transportation System*, Diss. East China Jiaotong University, Jiaotong, China, 2012.
[20] L. Hong, B. Ye, H. Yan, H. Zhang, M. Ouyang, and X. Sean He, "Spatiotemporal vulnerability analysis of railway systems with heterogeneous train flows," *Transportation Research Part A: Policy and Practice*, vol. 130, pp. 725–744, 2019.
[21] N. Bešinović, "Resilience in railway transport systems: a literature review and research agenda," *Transport Reviews*, vol. 40, no. 4, pp. 457–478, 2020.
[22] C. Szymula and N. Bešinović, "Passenger-centered vulnerability assessment of railway networks," *Transportation Research Part B: Methodological*, vol. 136, pp. 30–61, 2020.
[23] N. Bešinović, R. Ferrari Nassar, and C. Szymula, "Resilience assessment of railway networks: combining infrastructure restoration and transport management," *Reliability Engineering & System Safety*, vol. 224, Article ID 108538, 2022.
[24] F. Q. Zhang, C. Y. Yang, and M. Xue, "Study on high-speed train operation scheme," *Journal of Southwest Jiaotong University*, vol. 7, no. 1, pp. 5-6, 1998.
[25] Y. H. Chang, C. H. Yeh, and C. C. Shen, "A multiobjective model for passenger train services planning: application to Taiwan's high-speed rail line," *Transportation Research Part B: Methodological*, vol. 34, no. 2, pp. 91–106, 2000.
[26] Y. He, Y. Zang, T. Jiang, G. Gong, S. Xie, and J. Xiao, "Handedness-related functional connectivity using low-frequency blood oxygenation level-dependent fluctuations," *NeuroReport*, vol. 17, no. 1, pp. 5–8, 2006.
[27] Y. Wang, "The research on the train operation plan of the beijing-tianjin intercity railway based on periodic train diagrams," *Journal of the China Railway Society*, vol. 29, no. 2, p. 6, 2007.
[28] Deng, *Study on the Optimal Problems of Passenger Train Plan for Dedicated Passenger Traffic Line*, Diss. Central South University, Changsha, China, 2007.
[29] Meng, *Theories and Methods on Train Operating in Emergency*, Diss. Beijing Jiaotong University, Beijing, China, 2011.
[30] Wang, *Fuzzy Random Optimization for Train Operation in Emergency*, Diss. Beijing Jiaotong University, Beijing, China, 2012.
[31] Miao, *Research on Train Operation Scheduling Model and Algorithm in Emergency Conditions*, China Academy of Railway Sciences, Beijing, China, 2015.