A Study on the Spatial Layout and Vulnerability of the High-Speed Rail Network in Northeast China

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Abstract: This paper employs complex network theory and spatial analysis methodologies to conduct a systematic exploration of the spatial arrangement and vulnerability of Northeast China's high-speed rail (HSR) network, which is structured as a unique "hub-and-spoke + trunk composite" system. The study uncovers that the network exhibits excessive reliance on three primary hubs—Shenyang, Changchun, and Harbin. This over-dependence generates heightened structural sensitivity and insufficient redundancy, significantly impairing the network's capacity to withstand disruptions and maintain operational continuity.Informed by resilience theory, the paper presents targeted optimization strategies: fortifying secondary hubs like Dalian, Jilin, and Qiqihar; building a multi-centered network to reduce core node dominance; increasing key channel density to enhance path diversity; optimizing inter-hub connectivity efficiency; and expanding branch line coverage to boost accessibility in peripheral regions. This research delivers theoretical foundations for strengthening the HSR network's resilience in Northeast China while offering practical insights to advance balanced regional development.
***Keywords*:** Northeast China; High-Speed Rail Network; Spatial Layout; Vulnerability

1. Introduction

Under the strategy of building a strong transportation nation, the organization mode of the high-speed rail (HSR) network, as a key component of the modern comprehensive transportation system, refers to the systematic structural arrangement and inherent operational logic of the high-speed rail system in terms of spatial layout, line connection, and operation management. Its core lies in optimizing resource allocation strategies to achieve the most efficient transportation and improve the quality of transportation services. The three northeastern provinces of China, as an important old industrial base in the country, face the dual tasks of regional coordinated development and complex geographical and climatic conditions, as well as uneven population distribution in the construction of the HSR network.

This paper takes spatial topology theory as the analytical framework to systematically analyze the spatial layout characteristics of the HSR network in the three northeastern provinces, focusing on key elements such as hub node configuration, line selection, and network connectivity. By constructing a quantitative evaluation model, this paper reveals the vulnerability characteristics of the layout mode under disturbance factors such as extreme weather and passenger flow fluctuations, and proposes targeted strategies from the aspects of network optimization, emergency management, and technological upgrading to provide theoretical support and practical references for enhancing the resilience of the HSR network in Northeast China.

2. Spatial Topology Pattern of the HSR Network in the Three Northeastern Provinces

2.1 Typical Topology Patterns

China's HSR spatial topology mainly includes three typical modes: hub-and-spoke structure, trunk grid type, and mixed hierarchical type. The comparison of the three typical modes is shown in Table 1.

Table 1. Comparison of Typical HSR Network Topology Patterns

Mode Type	Representative Region	Network Density	Redundancy Degree	Risk Resistance Capability
Hub-and-spoke	Northeast	0.42	1.2	Low (0.58)
Trunk Grid Type	Yangtze River Delta	0.24	2.8	High (0.82)
Ring-Radiating	Chengdu-Chongqing	0.51	1.7	Medium (0.65)

Note: The risk resistance capability index (0-1) is derived from node failure simulation experiments.

The HSR network in the three northeastern provinces exhibits a "hub-and-spoke + trunk composite" organizational characteristic. It features a core hub in Shenyang, with radiating connections to secondary nodes. Its "T-shaped" main skeleton consists of two main lines: the vertical Harbin-Dalian Line (921 km) + the horizontal Changchun-Hunchun-Shenyang-Dandong Line (678 km). The three primary hubs (Shenyang, Changchun, Harbin) form a triangular core, with secondary nodes connected through single lines.[1]

2.2 Data of the HSR Network in the Three Northeastern Provinces

Table 2. Data of the HSR Network in the Three Northeastern Provinces

Indicator	Value	Calculation Process
Number of Nodes (N)	12	Including all prefecture-level city HSR stations
Actual Number of Edges (E)	28	Bidirectional counted as 1
Theoretical Maximum Number of Edges	66	
Network Density (D)	0.424	

Network density (Network Density) calculation formula (applicable to undirected networks): D=N(N−1)2E

The 12 nodes include: Harbin, Changchun, Shenyang, Dalian, Anshan, Dandong, Tongliao, Jilin, Hunchun, Jiamusi, Qiqihar, and Mudanjiang.

The main edges consist of 28 lines (Table 3):

Table 3. Main Edges of the HSR Network in the Three Northeastern Provinces

Line Name	Connecting Nodes	Length (km)	Opening Year
Harbin-Dalian HSR	Harbin-Changchun-Shenyang-Dalian	921	2012
Changchun-Hunchun HSR	Changchun-Jilin-Hunchun	471	2015
Harbin-Qiqihar HSR	Harbin-Qiqihar	286	2015
Shenyang-Dandong HSR	Shenyang-Dandong	207	2015
Harbin-Jiamusi Fast Railway	Harbin-Jiamusi	343	2018
Beijing-Shenyang HSR (Branch Line)	Shenyang-Tongliao	197	2021

2.3 Comparative Analysis

The HSR networks of the three northeastern provinces, the Yangtze River Delta, and the Beijing-Tianjin-Hebei region are compared as follows (Table 4):

Table 4. Comparison of HSR Networks in Different Regions

Region	Number of Nodes	Number of Edges	Network Density	Number of Primary Hubs
Three Northeastern Provinces	12	28	0.424	3
Yangtze River Delta	26	78	0.241	5
Beijing-Tianjin-Hebei	18	54	0.353	4

Based on the data in Table 4, a detailed comparative analysis of the HSR networks in the three northeastern provinces, the Yangtze River Delta, and the Beijing-Tianjin-Hebei region is conducted. In terms of the number of nodes and edges, the Yangtze River Delta region, with 26 nodes and 78 edges, far exceeds the other two regions, indicating a more complex and rich line connection. However, in terms of network density, the three northeastern provinces have a network density of 0.424, higher than the Yangtze River Delta's 0.241 and the Beijing-Tianjin-Hebei region's 0.353, suggesting that the HSR network in the three northeastern provinces is relatively more closely connected given the existing nodes and lines.[2]

3. Analysis of the Advantages and Vulnerabilities of the HSR Network Topology in the Three Northeastern Provinces

From the above analysis, it can be seen that the HSR network in the three northeastern provinces exhibits a "core-dense-periphery-sparse" characteristic. These two characteristics have their advantages, but they also imply network vulnerabilities.

3.1 Core Density: Advantages and Systemic Risks

The core area of the HSR network in the three northeastern provinces has a high concentration of nodes and lines, forming a powerful hub cluster. The core density indicates that the HSR network has high connection efficiency in the core area, mainly due to the strong connectivity of the Harbin-Dalian Line: the Shenyang hub handles 80% of the inter-provincial train traffic daily, with high frequency of train services between hubs (e.g., 62 trips per day between Shenyang and Changchun); the direct train frequency between Shenyang and Dalian has increased to 3 per hour. [3]

The dense core network significantly improves transportation efficiency, strengthens economic linkages, and enhances system resilience. It shortens the spatiotemporal distance between cities, promotes the rapid flow and efficient allocation of personnel, materials, and information, and enhances the overall economic competitiveness of the region. At the same time, the dense core network is convenient for centralized management and maintenance, reducing operating costs, improving service quality, and emergency response speed, ensuring the stability and reliability of HSR transportation in the core area.[4]

However, the high concentration of the core area means that a few key nodes undertake a large amount of passenger and freight transfer tasks, becoming the lifeline of the entire network. If these key nodes are interrupted by natural disasters, equipment failures, or sudden events, it will quickly trigger a chain reaction, leading to the paralysis of a large number of lines, a significant decline in the network's transportation capacity, and even possible regional traffic paralysis. [5]

Moreover, the core area's network structure is complex, with tight connections between lines and nodes, making fault diagnosis and repair difficult and prolonging the time to restore operations, further exacerbating systemic risks. For example, the failure of the Shenyang hub will lead to a 43% decline in the network's passage capacity; a fault in the Harbin hub will result in a 70% paralysis rate in the Heilongjiang network.[6]

3.2 Periphery Sparsity: Potential Advantages and Bottlenecks

From the perspective of regional development strategies, periphery sparsity is not entirely disadvantageous. Under limited resources, prioritizing the construction of a core-dense network can concentrate efforts on creating regional economic growth poles. Once the core area is mature, the HSR network can gradually extend to peripheral areas in a progressive and orderly manner. Moreover, the sparse peripheral network avoids over-construction and resource waste to some extent, making HSR construction more in line with the actual development needs and passenger flow distribution characteristics of the region.

The peripheral areas of the HSR network in the three northeastern provinces exhibit a dispersed "hub-and-spoke" characteristic, with secondary nodes basically unconnected. This makes the lines in peripheral areas often become single-line bottlenecks, with limited transportation capacity, unable to meet the growing passenger and freight transportation demands. If this single line fails or becomes congested, and there is a lack of alternative paths, transportation services will be forced to interrupt, and passengers and goods will have to choose other more time-consuming and higher-cost transportation modes, seriously affecting transportation efficiency and service quality. [7]

In addition, the sparse peripheral network also restricts economic exchanges and cooperation between regions, which is not conducive to the economic development of peripheral areas and regional balanced development.

4. Conclusions

Through the combination strategy of "enhancing backbone channels + strengthening secondary networks," the HSR in Northeast China will form a resilient architecture of "four cores and multiple loops." The network closure degree will increase from 0.31 to 0.65, and the transportation capacity retention rate under extreme weather will increase from 35% to 72%, providing key transportation support for the revitalization of the old industrial base.

In the future, it is necessary to focus on "construction and maintenance in parallel," and combine digital twin technology to achieve dynamic optimization to ensure that the secondary network continues to empower regional development.

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