Multi-objective Optimization of Hub-and-Spoke Network for High-Speed Rail Logistics Considering Passenger Station Reconstruction

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Abstract: The rapid development of China's high-speed railway has brought a tremendous increase in transportation capacity, creating many opportunities for the optimization and upgrading of high-speed rail express logistics. However, the lack of freight-dedicated facilities such as luggage rooms and logistics channels at existing high-speed railway stations has severely restricted the large-scale operation of high-speed rail express. To address this bottleneck, this study proposes an adaptive retrofitting strategy to transform existing passenger stations into hubs. The study applies complex network theory, using indicators such as degree centrality and betweenness centrality to quantify node network characteristics. Combined with the CRITIC–variation coefficient combined weighting method, a comprehensive layout evaluation is conducted to screen out 14 candidate nodes for high-speed rail express retrofitting. On this basis, a hub-and-spoke network integrating highway connection services and high-speed railway trunk transportation is constructed. A bi-objective integer programming model is established with the objectives of minimizing total logistics cost and transportation time. The ε-constraint method based on the model is employed to obtain the Pareto frontier of the problem, and a genetic algorithm is designed for solution. The research results show that the optimal number of high-speed rail logistics hubs is 7–8. Among them, Shanghai, Guangzhou, Chengdu, and Zhengzhou are essential retrofitting nodes, while regional nodes can be dynamically configured according to actual needs. In addition, the operation of dedicated freight trains is restricted by idle resources of passenger lines, and the retrofitting of passenger stations must consider the compatibility of line resources.

1. Introduction

In 2024, China's express delivery volume reached 174.5 billion pieces, with a revenue of 1.4 trillion yuan, representing year-on-year increases of 21% and 13%, ranking first in the world for the 11th consecutive year. Traditional road transportation shows significant shortcomings in timeliness and carbon emissions. High-speed rail express, with advantages such as large capacity and low energy consumption, has become a key path to solving the transportation bottleneck of high value-added goods. However, its business volume in 2023 was only 0.02 billion pieces, accounting for less than 1% of the total, with the problem of uncoordinated specialized station facilities being prominent.

The large-scale development of high-speed rail express relies on professional operation stations. At present, passenger stations generally lack facilities such as luggage rooms and logistics channels, resulting in low efficiency in cargo distribution and collection. The construction of new freight stations is limited by cost and land constraints and cannot be deployed rapidly, while the adaptive reconstruction of existing stations shows significant advantages: retaining passenger functions while adding lightweight facilities such as loading and unloading platforms, making use of existing resources to improve transfer efficiency, and realizing rapid distribution of freight flows through highway connection and high-speed rail trunk linkage.

Existing studies mainly focus on hub location and freight organization. In terms of hub location, Li et al. designed a road–rail intermodal hub network [1]; Zhou et al. used a maximum coverage model

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to determine the number of hubs [2]; Li Q. et al. constructed a three-level network [3]. In terms of freight organization, Liang and Wang, Ertem and Keskin, Liang et al., Mathieu, and Bi et al. discussed the potential and operation modes of high-speed rail transportation [4–9]; Chen et al. predicted intercity demand [10]; Yu et al. studied train organization [11–13]. Most existing studies on stations focus on the location of logistics parks, such as Feng et al., who established a bi-level programming model to optimize reconstruction decisions and transport volumes [14].

Currently, few studies have focused on hub location for high-speed rail express, and construction modes have not been considered. Based on the needs of large-scale development, this paper takes the reconstruction of existing stations as the entry point, focusing on the coordinated optimization of cost and timeliness. A bi-objective integer programming location model is constructed with the goals of minimizing total cost and transportation time. Combined with capacity constraints, a genetic algorithm is used to solve the non-dominated solution set. The study aims to achieve the functional transition of passenger stations into freight transfer nodes through facility upgrading, providing a decision-making framework for networked layout and responding to the "14th Five-Year Plan for Modern Logistics Development", which calls for the upgrading of freight facilities at stations.

2. Model Construction

2.1 Problem Description

The layout of the high-speed rail express network is influenced by many factors. The following assumptions are made in this study:

(1) There are two transportation modes in the high-speed rail logistics network: the mixed-loading mode and the dedicated freight train mode.

(2) The dedicated freight train mode has certain requirements for station capacity; therefore, the candidate passenger stations must be adaptively reconstructed to become transfer hubs.

(3) The express parcels of one city can only be transferred through one transfer hub.

(4) The mainline transportation process under the dedicated freight train mode has economies of scale, resulting in transportation discounts.

(5) The reconstruction cost of each candidate hub is constant.

(6) The number and locations of candidate hubs and demand points are known.

(7) Different organization modes of high-speed rail express have different capacity constraints (See Figure 1).

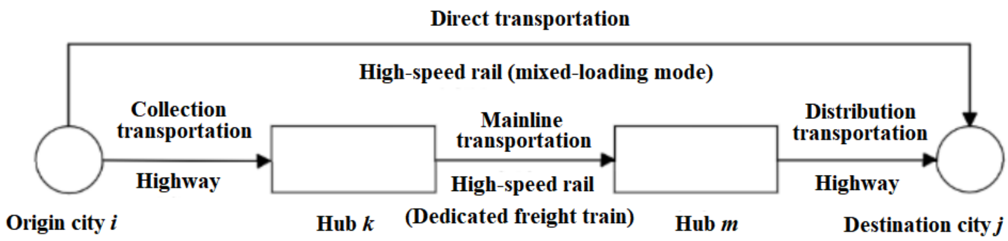

Figure 1 High-speed rail express network transportation flow chart

2.2 Symbol Description

The sets, parameters, and decision variables involved in this paper and their descriptions are as follows (See Table 1):

Table 1 Sets, parameters, variables, and their descriptions

Symbol	Description	Symbol	Description
N	Set of cities	t_{mj}	Time required for highway distribution transportation
P	Set of candidate hubs $P \subseteq N$	t_{km}	Time required for high-speed rail dedicated freight mainline transportation
i	Origin city of express delivery, $i \in N$	t_{ij}	Time required for high-speed rail mixed-loading direct transportation

j	Destination city of express delivery, $j \in N$	Q^s	Capacity limitation of transportation mode s
k,m	Candidate hub, $k \in P$	λ	Average weight of express delivery
p	Number of transfer hubs	t_1	Transfer time at hub
S	Set of transportation modes, $s \in S$. $s = 0$ represents highway transportation, $s = 1$ represents high-speed rail dedicated freight, and $s = 2$ represents high-speed rail mixed-loading transportation.	c_z	Cost of converting a candidate point into a transfer hub
d^0_{ik}, d^0_{mj}	Highway transportation distance between nodes	T	Planning period for station reconstruction
d^2_{ij}, d^1_{km}	High-speed rail transportation distance between nodes	c_r	Transfer cost at hub
f_{ij}	Express delivery volume between origin city i and destination city j	y_k	Whether the candidate point is converted into a hub
c^s	Unit variable cost of transportation mode s	U_{km}	Maximum number of passenger trains allowed in parallel operation with freight trains between hub k and hub m
c_0	Fixed cost for operating dedicated freight trains	V_{km}	Number of passenger trains between hub k and hub m
α	Transportation discount for mainline transportation	X_{ij}	Whether the origin city i directly transports express deliveries to destination city j via high-speed rail mixed-loading
v^s	Transportation speed of mode s	X_{ikmj}	Whether express deliveries from origin city i are transported through hubs k, m to destination city j
t_{ik}	Time required for highway collection transportation		

2.3 Model Construction

2.3.1 Objective Functions

This study focuses on the coordinated optimization of cost and timeliness and constructs a multi-objective location model for high-speed rail express logistics based on the adaptive reconstruction of existing passenger stations.

Minimization of Logistics System Cost min F_1

The operating cost of the high-speed rail express logistics network includes transportation cost, hub transfer cost, and reconstruction cost of transforming passenger stations into transfer hubs.

The operating cost of the high-speed rail express logistics network is expressed as:

$$F_1 = \sum_{i,j\in N} f_{ij}\lambda c^2 d^2_{ij} X_{ij} + \sum_{i,j\in N}\sum_{k,m\in P} f_{ij}\lambda\left(c^0 d^0_{ik} + c^0 d^0_{mj}\right) X_{ikmj} + \sum_{i,j\in N}\sum_{k,m\in P} \alpha f_{ij}\lambda\, c^1 d^1_{km} X_{ikmj} + \sum_{i,j\in N}\sum_{k,m\in P} c_0 X_{ikmj} + \sum_{i,j\in N}\sum_{k,m\in P} c_q f_{ij} X_{ikmj} + \frac{\sum_k c_1 y_k}{T} \tag{1}$$

In Equation (1), the first term represents the direct transportation cost under the high-speed rail mixed-loading mode, the second and third terms represent the variable costs of highway collection/distribution transportation and high-speed rail trunk (dedicated train) transportation, the fourth term represents the fixed cost of operating dedicated freight trains, the fifth term represents the hub transfer cost, and the sixth term represents the adaptive reconstruction cost of passenger stations (amortized over the planning period).

Minimization of Transportation Time min F_2

$$F_2 = \sum_{k,m\in P}\sum_{i,j\in N}(t_{ik} + t_{mj} + t_{km} + t_1) X_{ikmj} + \sum_{i,j\in N} t_{ij} X_{ij} \tag{2}$$

In Equation (2), the first term represents the time required for highway–rail intermodal transportation, and the second term represents the time required for high-speed rail direct transportation.

2.3.2 Constraints

In the optimization of the high-speed rail express logistics network, constraints such as the number of hubs and flow balance must be satisfied. The specific constraint conditions are as follows:

$$\sum_{k} y_k = p \tag{3}$$

$$X_{ikmj} \le y_k, \forall \mathrm{i,j} \in \mathrm{N}, \forall k,m \in \mathrm{P} \tag{4}$$

$$X_{ikmj} \le y_m, \forall i,j \in N, \forall k,m \in P \tag{5}$$

$$\sum_{k,m \in P} X_{ikmj} + X_{ij} = 1, \forall i,j \in N \in N \tag{6}$$

$$\sum_{k,m \in P} \sum_{i,j \in N} f_{ij} X_{ikmj} + \sum_{i,j \in N} f_{ij} X_{ij} = \sum_{i,j \in N} f_{ij} \tag{7}$$

$$t_{ik} = \frac{d_{ik}^{0}}{v^{0}} \quad t_{mj} = \frac{d_{mj}^{0}}{v^{0}} \quad t_{km} = \frac{d_{km}^{1}}{v^{1}} \quad \forall \mathrm{i,j} \in \mathrm{N}, \forall k,m \in P \tag{8}$$

$$t_{ij} = \frac{d_{ij}^{2}}{v^{2}} \quad \forall \mathrm{i,j} \in \mathrm{N} \tag{9}$$

$$\sum_{i,j \in N} f_{ij} X_{ikmj} \le Q^{1} \quad \forall k,m \in P \tag{10}$$

$$f_{ij} X_{\mathrm{ij}} \le Q^{2} \; \forall i,j \in N \; \forall k,m \in P \tag{11}$$

$$\mathrm{V}_{km} \le \mathrm{U}_{km} \; \forall k,m \in P \tag{12}$$

$$S \in 0,1,2, \forall s \in S \tag{13}$$

$$y_k \in 0,1, \forall k \in K \tag{14}$$

$$X_{ikmj} \in 0,1, \forall i,j,k,m \in N \tag{15}$$

$$X_{ij} \in 0,1, \forall i,j \in N \tag{16}$$

Equation (3) defines the number of transfer hubs in the high-speed rail express network.

Equations (4) and (5) stipulate that express transfer can only occur in cities selected as transfer hubs.

Equation (6) stipulates that express delivery must select one of the two modes: direct transportation or intermodal transportation.

Equation (7) ensures the freight flow conservation within the high-speed rail express network.

Equations (8) and (9) are the formulas for calculating transportation time.

Equations (10) and (11) define the capacity limitations for different organization modes of transportation.

Equation (12) specifies the constraint for operating dedicated freight trains.

Equations (13)–(16) define the value range constraints for the variables.

3. Case Analysis

3.1 Screening of High-Speed Rail Hub Candidate Set

Cities with high-speed rail service are selected as the research objects. A multidimensional preliminary screening is conducted: on the economic dimension, the provincial capital or the city with the highest GDP in the province is selected; on the transportation dimension, the city must have a high-speed rail station; and on the policy dimension, cities included in the national logistics hub planning and receiving policy preference are considered. Cities meeting at least two of these conditions are retained. Based on this, the high-speed rail network connectivity is optimized. Cities with at least three direct trains per day are regarded as effectively connected, while cities connected to only three or fewer other cities are excluded as low-connectivity nodes, forming a core candidate set.

Using network analysis tools, the structural characteristics of the high-speed rail network of candidate cities are quantitatively analyzed. Key indicators such as degree centrality, betweenness centrality, and closeness centrality are calculated to measure the direct connection scale, transfer control ability, and transportation accessibility efficiency of each node, respectively. To evaluate node importance, a combined weighting model is constructed using the CRITIC weighting method and the coefficient of variation method. The former accounts for indicator correlation and information content, while the latter highlights data dispersion characteristics. After determining comprehensive indicator weights, the overall node scores are calculated. The ranking results yield the comprehensive layout evaluation of high-speed rail express logistics, as shown in Table 2.

Table 2 Comprehensive layout evaluation of high-speed rail express

Rank	**City**	**High-Speed Rail Network Evaluation**	**Rank**	**City**	**High-Speed Rail Network Evaluation**	**Rank**	**City**	**Comprehensive High-Speed Rail Network Evaluation**
1	Shanghai	0.9306	11	Jinan	0.5055	21	Guiyang	0.4223
2	Beijing	0.8653	12	Xiamen	0.5012	22	Nanchang	0.4183
3	Guangzhou	0.6749	13	Shijiazhuang	0.4999	23	Hefei	0.4034
4	Shenzhen	0.6479	14	Kunming	0.4719	24	Changchun	0.3912
5	Chengdu	0.6462	15	Xi'an	0.4674	25	Ningbo	0.3797
6	Zhengzhou	0.6197	16	Changsha	0.4623	26	Harbin	0.3742
7	Wuhan	0.6136	17	Qingdao	0.4488	27	Dalian	0.3370
8	Chongqing	0.5469	18	Nanning	0.4394	28	Fuzhou	0.3326
9	Nanjing	0.5455	19	Shenyang	0.4324	29	Tianjin	0.3297
10	Hangzhou	0.5143	20	Taiyuan	0.4241			

According to the comprehensive ranking of high-speed rail network scores, the top twelve cities are selected as candidate hubs for high-speed rail express. Considering that the high-speed rail network coverage in the northeast and northwest regions is relatively sparse, resulting in lower overall scores for nodes, Xi'an and Shenyang are added as candidate hubs based on node centrality evaluation results, in order to enhance the regional logistics network's accessibility.

3.2 Estimation of High-Speed Rail Freight OD Volume Between Cities

This study constructs a freight volume prediction model based on traffic flow theory and the logistics demand analysis paradigm.

A model of high-speed rail freight attraction intensity between cities is established. Referring to the mechanism of the relationship between logistics connection intensity and economic and distance factors, the attraction intensity of high-speed rail freight between cities *i* and *j* is defined as:

$$\beta_{ij} = \frac{k_i k_j \sqrt{G_i \cdot R_j}}{l_{ij}}$$

In the formula, k_i represents the ratio of the GDP of city *i* to the total GDP of all cities within the study area, reflecting the relative weight of the city's economic strength; G_i represents the GDP of city *i*, measuring the freight supply potential on the production side; R_j represents the total retail sales of consumer goods of city *j*, reflecting the freight demand scale on the consumption side; and l_{ij} represents the high-speed rail transportation distance between cities *i* and *j*.

Based on the statistical data of city-level express delivery volumes, the "attraction intensity–express volume–share rate" model is applied to estimate and obtain the forecast results of express freight OD volumes among major cities nationwide.

3.3 Parameter Setting

Based on comprehensive considerations of line capacity constraints, coordination between passenger and freight operations, and dispatching safety, the critical threshold of mixed passenger-freight operation on high-speed rail lines between hubs is set as 32 passenger trains per direction per day.

The transportation cost parameters are set as follows: Unit cost of highway transportation: 0.6 yuan/(km·t). Unit cost of high-speed rail dedicated freight mainline transportation: 2.5 yuan/(km·t). Unit cost of high-speed rail mixed-loading direct transportation: 2 yuan/(km·t). The fixed cost of operating a high-speed rail dedicated freight train is 20,000 yuan per trip, calculated on an annual average basis. The reconstruction cost of each hub is 25 million yuan, with a planning period of 5 years. The hub transfer cost is charged by weight at a rate of 0.1 yuan/kg, covering expenses such as loading and unloading, warehousing, and information processing.

The transportation speeds are set as follows: Highway transportation: 60 km/h. High-speed rail dedicated freight: 300 km/h. High-speed rail mixed-loading mode: 200 km/h, considering station stops. The transfer time at hubs is set to 1 hour. The daily capacity limit of high-speed rail dedicated freight trains is 200 tons, while the average daily capacity limit per route for the mixed-loading mode is 50 tons.

3.4 Case Solution

3.4.1 Solution Results

This study employs a genetic algorithm for problem solving. As an adaptive global optimization search algorithm that simulates the biological evolution process, the genetic algorithm has strong robustness and global search capability, making it suitable for handling multi-objective combinatorial optimization problems. By simulating natural selection and genetic mechanisms, the algorithm can efficiently search within a vast solution space, gradually approaching the optimal solution and providing an effective method for hub optimization.

In this study, the number of reconstructed stations is set as p = 7, and the discount coefficient α = 0.7. The population size is set to 40, the number of iterations to 100, the crossover probability to 0.8, and the mutation probability to 0.2. The program is executed in MATLAB, and two location schemes and their objective values are obtained, as shown in Table 3.

Table 3 Location schemes and objective values

Scheme	Passenger station reconstruction cities	F_1	F_2
1	Shanghai, Guangzhou, Shenzhen, Chengdu, Zhengzhou, Chongqing, Xi’an	128.73 million yuan/year	17,443 hours
2	Shanghai, Guangzhou, Xi’an, Wuhan, Chongqing, Zhengzhou, Chengdu	129.84 million yuan/year	16,848 hours

Table 3 shows that Scheme 1 has a total cost of 128.73 million yuan and a total time of 17,443 hours; Scheme 2 has a total cost of 129.84 million yuan per year and a total time of 16,848 hours. Compared with Scheme 1, the cost of Scheme 2 increases by 1.1%, while the time decreases by 3.4%. Both cannot be optimized simultaneously, forming a Pareto optimal solution set. This indicates that with a fixed number of hubs, reducing logistics costs comes at the expense of increased time.

Scheme 1 includes seven cities such as Shanghai and Guangzhou, while Scheme 2 replaces Jinan and Xiamen with Chongqing and Xi'an, increasing the cost by 1.11 million yuan per year and reducing the time by 595 hours. The results show that western hubs such as Chongqing and Xi'an can improve timeliness, whereas eastern hubs such as Jinan and Xiamen can reduce costs. This indicates that hub layout should balance business volume with regional demand in remote areas. Beijing and Nanjing are not selected and will be further discussed. Overall, 7–8 hubs constitute the optimal solution.

3.4.2 Influence of the Number of Reconstructed Stations

By setting the number of reconstructed stations between 7 and 10, the location schemes for different numbers of transfer hubs are obtained.

Table 4 shows that when the number of hubs increases from 7 to 8, the total time decreases by 3.7%, while the total cost increases by 0.3%, representing the optimal marginal benefit. When increased to 10 hubs, time decreases by only 1.3%, but cost increases by 3.7%, indicating the existence of an optimization threshold. Between 7 and 10 hubs, the reconstruction cost rises from 35 million yuan to 50 million yuan, an increase of 42.9%, while transportation and transfer costs drop from 93.73 million yuan to 89.52 million yuan, a decrease of 4.6%, showing that reconstruction of hubs can optimize costs through economies of scale in dedicated freight train transportation.

Table 4 Pareto optimal solutions and objective function values for different numbers of hubs

Number of Hubs	**Station Reconstruction Scheme**	**Hub Reconstruction Cost**	**Transportation and Transfer Cost**	F_1	F_2
7	Scheme 1: Shanghai, Guangzhou, Jinan, Chengdu, Zhengzhou, Shenzhen, Xiamen	3500	9373	12873	17443
	Scheme 2: Shanghai, Guangzhou, Xi'an, Chongqing, Zhengzhou, Shenzhen, Chengdu	3500	9484	12984	16848
8	Shanghai, Guangzhou, Jinan, Wuhan, Zhengzhou, Xiamen, Chengdu, Xi'an	4000	9030	13029	16024
9	Shanghai, Guangzhou, Jinan, Wuhan, Shenzhen, Xiamen, Chengdu, Xi'an, Zhengzhou	4500	8952	13452	15800
10	Shanghai, Guangzhou, Jinan, Wuhan, Shenzhen, Xiamen, Chengdu, Xi'an, Zhengzhou, Nanjing	5000	8952	13952	15800

However, when the number of hubs increases from 9 to 10, the addition of the Nanjing hub raises the reconstruction cost by 5 million yuan, while transportation and transfer costs remain unchanged, indicating that it is not included in the freight train network.

Regarding mode selection, hub cities with large freight volumes are suitable for dedicated freight train transportation, while other cities with smaller volumes and no need for transfer are more suitable for the mixed-loading mode. All schemes include Shanghai, Guangzhou, Chengdu, and Zhengzhou as mandatory planned hubs, with optional high-speed rail stations for reconstruction in cities such as Chongqing and Shenzhen. Beijing and Nanjing are not selected and will be discussed further. Overall, 7–8 hubs remain the optimal configuration.

3.4.3 Influence of Dedicated Freight Train Operation Constraints

Beijing, despite being one of China's four top-tier cities, was not selected as a hub city. To quantify the impact of operational constraints, the restrictions are lifted, and the location model is recalculated with p = 7. The results are shown in Table 5. Under these conditions, Beijing is included in both optimized hub configurations, with total logistics costs significantly reduced by 10.9%–15.3% and total time shortened by 12.3%–18.1%.

Table 5 Location results after removing dedicated freight train operation constraints

Plan	Cities for Passenger Transport Station Renovation	F_1	F_2
1	Beijing, Shanghai, Guangzhou, Shenzhen, Chengdu, Zhengzhou, Chongqing	114.72 million yuan/year	14,293 hours
2	Beijing, Shanghai, Guangzhou, Xiamen, Chongqing, Zhengzhou, Chengdu	108.93 million yuan/year	15,627 hours

Compared with the results under the operation constraint, the main reason why Beijing was not selected as a hub is the limitation of freight line resources due to the "passenger priority" principle. Under heavy passenger scheduling constraints, only three freight train directions (Beijing–Guangzhou, Beijing–Shenzhen, and Beijing–Chengdu) can be opened, thus restricting mainline transportation coverage capacity.

Cities such as Shanghai, Guangzhou, and Zhengzhou, with better high-speed rail network connectivity and more balanced passenger scheduling, can provide 6–8 freight train routes and thus become priority options. The results show that hub location decisions depend not only on freight volume and spatial factors but are also strongly constrained by line resource compatibility under passenger scheduling priority.

4. Conclusion

This study constructs a multi-objective optimization model for a high-speed rail logistics hub-and-spoke network based on the reconstruction of existing passenger stations and solves it using a genetic algorithm. The main conclusions are as follows:

(1) When the number of hubs is fixed, there exists a significant trade-off between total logistics cost and transportation time, and both cannot be optimized simultaneously. Improving timeliness requires higher cost, with transportation and transfer costs being the dominant components. During planning, hub functions and transportation modes should be reasonably configured according to optimization objectives.

(2) Under the current parameters, the optimal number of high-speed rail logistics hubs is 7–8, with Shanghai, Guangzhou, Chengdu, and Zhengzhou as mandatory hubs. Cities such as Xiamen, Chongqing, and Jinan can be selected for expansion or reconstruction based on demand. Mandatory hubs should possess advantages in high-speed rail connectivity and economic scale, while regional nodes should be dynamically configured. Cities with low connectivity or heavy passenger flow pressure are unsuitable for reconstruction. Increasing the number of hubs leads to marginally rising reconstruction costs and diminishing transportation efficiency. Beyond a certain threshold, efficiency improvement ceases, so resource and benefit balance should be maintained during planning.

(3) The operation of dedicated freight trains depends on the release of resources from non-saturated passenger lines, as mainline freight transportation is constrained by passenger route utilization. This study introduces passenger–freight coordination constraints, clarifying that hub location decisions must center on line resource compatibility.

In practical application, existing high-speed rail stations generally lack express logistics facilities such as luggage rooms, and design standards have not reserved functional space for express services. Only a few newly built stations meet freight operation requirements. This study does not consider the freight adaptability of high-speed rail stations, which should be systematically evaluated in future research to support practical implementation.

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