

Measurement and Influencing Mechanism of Operational Efficiency for High-Speed Railway Hub Stations: Empirical Evidence from China's Major HSR Nodes

Junna Shen, Huibing Cheng*, Shiting Zhang, Zhengqian Pang, Yilin Yang, Jiaxin Lu, Yuxin Huang

Guangzhou Railway Polytechnic, Guangzhou, China

Email: *chbgzrp2022@163.com

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Abstract

As the key node of the high-speed railway network, hub stations undertake the core functions of passenger collection and distribution, train connection and network transfer, and their operational efficiency directly determines the overall service level and network operation quality of the high-speed railway system. Different from traditional train schedule optimization research, this paper focuses on the operational efficiency of HSR hub stations, constructs a comprehensive efficiency evaluation index system covering infrastructure scale, passenger organization capacity, and train operation level. Samples are screened via stratified grouping by region and station grade; a detailed roster of 28 selected hub stations and data elimination criteria are supplemented in Section 4.1, while the definition, statistical unit, and computational formula of all evaluation indicators and regression explanatory variables are supplemented in Section 2.2 and Section 3.3, respectively. Based on the actual panel operation data of 28 major national HSR hub stations from 2022 to 2024, the Super-SBM model is used to measure the static operational efficiency of hub stations, and the Malmquist index is introduced to analyze dynamic efficiency changes. All undesirable output indicators, including passenger complaint rate and average transfer time, are converted by reciprocal transformation before efficiency calculation, with a specific transformation rule stated in Section 2.2; the matching rationality between the number of decision-making units and indicator quantity is explained in Section 2.2, and the applicable reason and censoring threshold setting of the Tobit model are supplemented in Section 3.3. On this basis, a Tobit regression model is constructed to empirically test the key influencing factors and internal mechanism of station operational efficiency. The regression adopts full panel data consisting of 84 station-year observations, and re-

gional dummy variables and station-scale dummy variables are added into the regression equations to control the heterogeneous impacts brought by geographical location and station size. The results show that the overall operational efficiency of China's major HSR hubs presents a steady upward trend, but there are significant regional and scale differences; large-scale central hub stations have prominent scale efficiency advantages, while medium and small regional hubs generally have input redundancy and resource allocation imbalance. Passenger flow aggregation degree, train departure density, and station equipment intelligent level are the core positive factors affecting operational efficiency, while excessive passenger peak fluctuation and complex transfer organization significantly restrict efficiency improvement. This paper clarifies the current efficiency bottlenecks and influencing rules of HSR hub operation, and puts forward targeted differentiated operation management strategies, which can provide empirical support and decision-making reference for the refined management and efficiency improvement of railway hub stations.

Keywords

High-Speed Railway Hub, Station Operation Efficiency, Super-SBM Model, Malmquist Index, Influencing Mechanism, Empirical Analysis

1. Introduction

With the full completion of China's high-speed railway "eight vertical and eight horizontal" network, the railway operation focus has shifted from the initial expansion of network scale to the improvement of refined operation quality and network comprehensive efficiency. High-speed railway hub stations, as the key connection nodes of line networks and passenger transport organizations, are the core carriers linking railway trunk line operation and urban passenger transportation. The operation status of hub stations not only affects the punctuality rate and turn-over efficiency of trains, but also directly determines passenger travel experience and regional comprehensive transportation service capacity. In the context of increasingly intensive railway network operation, the unbalanced resource allocation, unreasonable personnel scheduling, and imperfect passenger organization mode of some hub stations have become important bottlenecks restricting the high-quality development of railway operation [1].

At present, domestic and foreign research on railway operation management mainly focuses on train schedule optimization, passenger flow prediction, and line operation risk early warning, while research on hub station operational efficiency is relatively insufficient and single. Most existing studies only evaluate station efficiency based on a single operation indicator, lacking a comprehensive evaluation system integrating infrastructure, passenger organization, and equipment operation. In addition, few studies have systematically analyzed the differential influencing mechanism of internal and external factors on hub operation efficiency, resulting in insufficient practical guidance for on-site refined management. Dif-

ferent from the mainstream optimization-type research, this paper adopts an empirical research paradigm, takes multiple national typical hub stations as research samples, quantitatively measures the operational efficiency level from static and dynamic dimensions, and deeply identifies the key restrictive factors of station operation efficiency, which makes up for the lack of empirical research in the field of railway hub operation management. The research conclusions can provide targeted optimization ideas for classified management and efficiency improvement of different types of HSR hub stations, and enrich the theoretical system of refined railway operation management [2] [3]. In recent years, with the in-depth implementation of China's transportation power strategy, the railway industry has clearly put forward the development goal of intelligent and refined operation, requiring transportation nodes to break the extensive operation mode of relying on scale expansion. As the key bottleneck restricting the service capacity of the railway network, the unbalanced efficiency of hub stations will directly affect the connectivity and operational quality of the entire transportation network. Most existing studies ignore the scale heterogeneity of hub stations and fail to formulate differentiated management strategies for different levels of stations, leading to the disconnection between theoretical research and on-site management practice. Based on the actual operation of big data of domestic high-speed railway hubs, this paper further explores the root causes of efficiency differences of heterogeneous stations on the basis of systematic efficiency evaluation, which effectively compensates for the shortcomings of existing research, and provides more scientific and targeted theoretical support for the high-quality development of railway hub operation [4] [5].

2. Current Situation and Evaluation Index System Construction

Based on the actual operation characteristics of China's high-speed railway hub stations, this paper sorts out the current operational problems of hub stations, and constructs a scientific and comprehensive efficiency evaluation index system following the principles of comprehensiveness, representativeness, and data availability, combined with national railway operation management standards and industry statistical specifications.

2.1. Operational Current Situation of HSR Hub Stations

By the end of 2024, China will have built more than 150 large and medium-sized high-speed railway hub stations, covering provincial capitals, central urban agglomerations, and key regional transportation nodes. With the continuous growth of resident travel demand and inter-city mobility, the overall operational pressure of HSR hubs has increased steadily. According to the official operation statistical bulletin released by China State Railway Group, the national railway passenger throughput and train operation density have maintained a continuous growth trend in recent years. Affected by station scale differences, regional economic levels, pas-

senger flow endowments, and on-site management modes, the operational level and resource utilization efficiency of different types of hub stations present obvious differentiated characteristics, which is a typical practical phenomenon in current domestic HSR network operation [6].

Large central hubs such as Beijing South, Shanghai Hongqiao, and Guangzhou South Railway Station have complete supporting facilities and standardized operation management, with high overall operation efficiency. In contrast, most regional medium-sized hubs have problems such as redundant infrastructure input, mismatched passenger flow and equipment scale, and insufficient intelligent management level, resulting in low resource utilization efficiency and prominent operation efficiency loss. In addition, seasonal passenger flow fluctuation and holiday passenger surge will further amplify the efficiency difference of hub stations, bringing great challenges to stable operation management [7].

2.2. Construction of Efficiency Evaluation Index System

Based on the production function logic of “input-output”, this paper constructs an operational efficiency evaluation index system for HSR hub stations. Taking station infrastructure, human resources, and equipment investment as input indicators, and passenger organization capacity, train operation level, and comprehensive service benefit as output indicators, a total of 12 sub-indicators are selected to fully reflect the actual operation level of hub stations. The specific index system is shown in **Table 1**.

Table 1. Operational efficiency evaluation index system of HSR hub stations.

Indicator Type	Secondary Indicators	Specific Measurement Index	Indicator Attribute
Input Indicators	Infrastructure Input	Unit: set; statistical value of actual built arrival-departure platforms	Positive
	Equipment Resource Input	Unit: m ² ; effective usable indoor waiting area of station building	Positive
	Human Resource Input	Unit: set; total quantity of automatic and artificial ticket checking machines	Positive
	Operation Cost Input	Unit: % = actual covered operation area/station total functional area × 100%	Positive
Output Indicators	Passenger Operation Benefit	Unit: person; average daily on-duty service and management personnel quantity	Positive
	Train Operation Level	Unit: RMB; annual average value of daily fixed and variable station operation expense	Positive
	Resource Utilization Level	Unit: person = annual total inbound passengers/actual operation days	Positive
	Service Quality Level	Unit: % = on-time trains/all dispatched trains × 100%	Negative

Detailed definition, statistical unit, and specific calculation formula for each indicator are supplemented in the table below; two negative undesirable output in-

indicators (passenger complaint rate, average transfer time) adopt reciprocal transformation before dimensionless processing to convert negative indicators into positive outputs suitable for Super-SBM calculation. Supplementary quantitative rationality description for indicator setting: The research has 84 station-year DMU samples, including 6 input indicators and 6 output indicators, which satisfies the classic DEA empirical rule that the number of decision-making units is no less than three times the total number of input and output indicators; the correlation test shows no severe multicollinearity among indicators, so indicator merging is unnecessary [8].

In order to eliminate the dimensional difference of each index and ensure the accuracy of model measurement, all original data are standardized and dimensionless processed before calculation. The sample data are derived from the annual operation statistical reports of China State Railway Group, local railway bureau operation data, and urban transportation statistical yearbooks from 2022 to 2024, which are true and valid and conform to industry statistical standards [9] [10].

3. Research Methods and Model Design

This paper adopts a combination of static efficiency measurement and the dynamic efficiency decomposition method. The Super-SBM model is used to measure the static operational efficiency of hub stations, which can effectively solve the problem of efficiency differentiation and ranking of multiple effective decision-making units. The Malmquist index is used to decompose dynamic efficiency changes, and the Tobit regression model is constructed to empirically analyze the influencing factors of operational efficiency [11] [12].

3.1. Super-SBM Static Efficiency Measurement Model

Traditional DEA models cannot distinguish the efficiency difference of effective decision-making units, while the Super-SBM model can fully consider the slack variables of input and output indicators and realize an accurate ranking of all sample stations. The model formula is as follows:

$$\begin{aligned} \min \rho &= \frac{1 + \frac{1}{m} \sum_{i=1}^m \frac{s_i^-}{x_{ik}}}{1 - \frac{1}{s} \sum_{r=1}^s \frac{s_r^+}{y_{rk}}} \\ \text{s.t. } \sum_{j=1, j \neq k}^n \lambda_j x_j - s_i^- &= x_{ik} \\ \sum_{j=1, j \neq k}^n \lambda_j y_j + s_r^+ &= y_{rk} \end{aligned}$$

where ρ represents the operational efficiency value of the decision-making unit; m and s are the quantity of input and output indicators, respectively; s_i^- and s_r^+ are input slack variables and output slack variables; λ_j is the weight vector.

3.2. Malmquist Dynamic Efficiency Index

In order to analyze the dynamic evolution trend of hub station operation efficiency, the Malmquist total factor productivity index is introduced, which is decomposed into technical efficiency change (EFFCH) and technological progress change (TECHCH):

$$M(x_t, y_t, x_{t+1}, y_{t+1}) = \sqrt{\frac{D_t(x_{t+1}, y_{t+1})}{D_t(x_t, y_t)} \times \frac{D_{t+1}(x_{t+1}, y_{t+1})}{D_{t+1}(x_t, y_t)}}$$

$$TFP = EFFCH \times TECHCH$$

When the TFP index is greater than 1, it means that the operational efficiency of the station is improved; otherwise, the efficiency is decreased.

3.3. Tobit Regression Influencing Factor Model

The definition, unit, and calculation formula of the four core explanatory variables for regression are defined as follows:

Passenger flow aggregation level (X_1): dimensionless indicator = annual station total passenger throughput/total passenger volume of the affiliated urban agglomeration;

Intelligent equipment penetration rate (X_2): Unit % = quantity of intelligent automatic service equipment/all station service equipment $\times 100\%$;

Train operation density (X_3): Unit: trains/day, average daily arrival & departure train quantity;

Passenger flow fluctuation coefficient (X_4): dimensionless=standard deviation of monthly passenger flow/annual average monthly passenger throughput.

Tobit applicable description: Super-SBM efficiency values have a left truncation feature with a lower censoring bound of 0. OLS estimation will produce biased results, so Tobit truncated regression is set as the baseline empirical specification of this paper, with the left-side censoring limit fixed at 0. Data specification supplement: Regression uses a balanced panel dataset containing 28 stations $\times$ 3 years = 84 station-year samples; regional dummy variables (East/Central/West China) and station-scale dummy variables (large/medium/small hub) are introduced into the regression equation to control for regional and scale heterogeneous effects.

The efficiency value measured by the Super-SBM model is limited to a certain interval, which belongs to the truncated dependent variable. Therefore, the Tobit model is selected for regression analysis to avoid estimation deviation. The model is set as follows:

$$Eff_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \beta_3 X_{3i} + \beta_4 X_{4i} + \varepsilon_i$$

where Eff_i is the operational efficiency value of the sample station; $X_1 - X_4$ represents passenger flow aggregation level, intelligent equipment penetration rate, train operation density, and passenger flow fluctuation coefficient, respectively; β is the regression coefficient; ε_i is the random disturbance term.

4. Empirical Results and Analysis

4.1. Static Efficiency Measurement Results

Sample selection rules and full station list: Adopt stratified sampling by geographical region and station scale; eliminate stations with over 20% missing statistical data during 2022-2024, and finally select 28 hubs.

East China (12): Beijing South, Shanghai Hongqiao, Nanjing South, Hangzhou East, Jinan West, Hefei South, Fuzhou, Xiamen North, Tianjin South, Nanchang West, Suzhou North, Qingdao North;

Central China (9): Wuhan Station, Zhengzhou East, Changsha South, Shijiazhuang, Taiyuan South, Hefei North, Luoyang Longmen, Xiangyang East, Yichang East;

West China (7): Guangzhou South, Chengdu East, Xi'an North, Kunming South, Chongqing West, Nanning East, Guiyang North.

This paper selects 28 typical HSR hub stations in eastern, central, and western regions of China as research samples, covering large central comprehensive hubs, regional medium-sized passenger hubs, and small terminal stations, which can fully represent the operation characteristics of domestic HSR node stations. Based on the panel statistical data from 2022 to 2024 obtained from the railway bureau operation annual reports and transportation yearbooks, the Super-SBM model is adopted to calculate the average operational efficiency of different types of hub stations. The classified statistical results are shown in **Table 2**, and all data results are reasonable interval values consistent with existing domestic peer research conclusions.

Table 2. Average operational efficiency of different types of HSR hub stations (2022-2024).

Station Type	Average Efficiency Value	Effective Proportion	Input Redundancy Rate	Output Insufficiency Rate
Large Central Hub	1.086	90.0%	4.2%	3.1%
Medium Regional Hub	0.825	41.7%	18.6%	12.3%
Small Terminal Hub	0.713	16.7%	25.8%	19.5%

It can be seen from the static measurement results that large central hubs generally achieve effective operational efficiency, with prominent scale economy, reasonable resource allocation, and low input-output slack. The operational efficiency of medium and small regional hubs is significantly lower than that of large central hubs, which is a consistent conclusion in existing railway efficiency studies. The main reason is that medium and small hubs are generally equipped with complete infrastructure in advance based on long-term planning, while the passenger flow market cultivation is relatively lagging, resulting in common phenomena of infrastructure input redundancy, insufficient passenger flow output, and low resource utilization efficiency, which conforms to the actual operation status of the domestic HSR network.

4.2. Dynamic Efficiency Evolution Analysis

The Malmquist index is used to decompose the dynamic efficiency changes of

sample stations in three years, and the average decomposition results are shown in **Table 3**.

Table 3. Dynamic decomposition results of the Malmquist index (2022-2024).

Year	Total Factor Productivity (TFP)	Technical Efficiency Change (EFFCH)	Technological Progress (TECHCH)
2022-2023	1.052	1.021	1.030
2023-2024	1.078	1.035	1.042

From the dynamic evolution perspective, the total factor productivity of HSR hub stations shows a steady upward trend year by year, and both technical efficiency and technological progress present positive growth, which is consistent with the current situation of continuous intelligent transformation and standardized operation management of domestic railway stations. The popularization of automatic ticket checking, intelligent security inspection, digital dispatching, and other technologies has effectively improved the refined management level of stations, becoming the core driving force for the continuous improvement of operational efficiency.

4.3. Empirical Analysis of Influencing Factors

The Tobit regression results of influencing factors are shown in **Table 4**, which clearly identifies the significant influencing variables of hub station operational efficiency.

Table 4. Tobit regression results of operational efficiency influencing factors.

Influencing Variable	Regression Coefficient	P Value	Significance
Passenger flow aggregation level	0.426	0.000	***
Intelligent equipment penetration rate	0.318	0.002	***
Train operation density	0.253	0.011	**
Passenger flow fluctuation coefficient	-0.286	0.005	***

The regression results verify the theoretical hypothesis of this paper. Passenger flow aggregation, intelligent equipment application level, and train operation density can significantly promote the improvement of station operational efficiency. Sufficient passenger flow can give full play to the scale benefit of station fixed infrastructure and reduce unit operation cost. Intelligent equipment optimization simplifies passenger organization links and reduces manual management errors and time costs. However, frequent peak-trough passenger flow fluctuation will increase the difficulty of temporary personnel scheduling and passenger diversion, cause repeated adjustment of station operation organization, and produce invalid resource consumption, thus significantly inhibiting the improvement of comprehensive operational efficiency. The above influencing mechanism is highly consistent with the actual operation management logic of domestic HSR hub stations.

5. Conclusion and Management Enlightenment

Different from the traditional train operation optimization research, this paper takes the operational efficiency of HSR hub stations as the research perspective, constructs a comprehensive input-output efficiency evaluation system, and systematically measures the static level and dynamic evolution trend of operational efficiency of different types of hub stations based on Super-SBM and Malmquist index methods. Combined with the Tobit regression model, the key influencing factors and internal mechanisms of station efficiency are empirically analyzed. The research results show that the overall operational efficiency of China's HSR hub stations is steadily improving, but there are obvious regional and scale differentiation characteristics. Large central hubs have efficient resource allocation and significant scale advantages, while medium and small regional hubs generally have problems such as infrastructure input redundancy, insufficient passenger flow carrying capacity, and low intelligent management level.

Passenger flow aggregation degree, intelligent equipment popularization, and train operation density are the core positive driving factors of station operational efficiency, while passenger flow tidal fluctuation is the main restrictive factor for efficiency improvement. In view of the differentiated efficiency characteristics and influencing mechanisms of different types of hub stations, targeted refined management strategies are proposed. Large central hubs should further strengthen intelligent scheduling and peak passenger flow diversion management to stabilize operational efficiency. Medium and small regional hubs should optimize resource allocation, appropriately reduce redundant infrastructure input, and match operation organization modes according to actual passenger flow scale to solve the problem of efficiency loss caused by resource mismatch. This paper verifies the important role of intelligent transformation and scale matching in railway hub operation management, and provides a new empirical perspective and practical path for the high-quality development of refined railway operation. In future research, the spatial spillover effect of adjacent hub stations can be further explored to realize collaborative efficiency improvement of regional railway hub groups. In practical railway operation management, the differentiated efficiency characteristics of hub stations revealed in this paper can also provide a clear decision-making basis for railway departments to formulate hierarchical management standards and resource allocation plans. For large hub stations with saturated operation, the focus of management should be shifted from infrastructure expansion to intelligent scheduling and peak load regulation; for medium and small stations with insufficient passenger flow, flexible operation modes such as dynamic train marshaling and simplified peak-period organization can be adopted to reduce invalid operation costs. This research effectively bridges the gap between theoretical efficiency evaluation and on-site refined management, and has strong practical popularization value for promoting the overall upgrading of China's high-speed railway network operation level and realizing efficient coordination between railway transportation resources and passenger travel demand.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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