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From capacity maximization to flagship train optimization: a novel framework for brand-oriented railway timetabling

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Abstract

Purpose – This study investigates the impact of flagship trains on high-speed railway capacity utilization and develops a brand value-oriented optimization framework that balances service quality enhancement with operational efficiency.
Design/methodology/approach – A mathematical optimization model based on integer programming is developed, incorporating flagship train constraints into capacity optimization. Case studies compare scenarios with and without flagship train considerations using the Beijing–Shanghai High-Speed Railway data across 20 experimental groups.
Findings – Operating flagship trains with hourly departure constraints results in an average decrease of 0.9 trains and an 8.4% reduction in capacity utilization rate. When scheduling 2 flagship trains within a 2-h timeframe, capacity utilization decreases from 86.43% to 83.73%, quantifying the trade-off between brand positioning and operational capacity.
Originality/value – This research provides the first quantitative framework for brand value-oriented railway capacity optimization, establishing clear definitions for flagship trains and mathematical foundations for evaluating service quality versus efficiency trade-offs. The findings offer practical decision support for railway operators balancing competitive positioning with capacity maximization.

Keywords High-speed railway, Flagship trains, Capacity optimization, Railway timetabling, Brand value, Service quality

Paper type Research article

1. Introduction

The rapid development of high-speed railway systems worldwide has fundamentally transformed intercity transportation, offering unprecedented travel speeds and service quality. As competition intensifies among different transportation modes and passenger expectations continue to rise, railway operators face the dual challenge of maximizing infrastructure capacity utilization while enhancing service quality and brand value. This challenge is particularly pronounced in densely operated high-speed railway corridors, where the strategic scheduling of premium services can significantly impact both operational efficiency and market competitiveness. The concept of brand value in railway operations has emerged as a critical factor, influencing not only passenger choice behavior but also the fundamental approaches to capacity planning and timetable design. This research addresses the intricate relationship between brand-oriented service design and railway capacity utilization, proposing a novel framework that balances operational efficiency with service quality enhancement in high-speed railway systems.

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1.1 Research background

Railway transportation optimization is a comprehensive optimization problem encompassing a series of optimization processes, including passenger flow demand, network planning, train operation scheme optimization, timetable optimization, rolling stock utilization optimization, and crew scheduling optimization. In railway operations, high-speed trains with high travel speeds, fewer stops, and serving intercity routes with large passenger volumes are commonly referred to as “flagship trains” by field practitioners. During the timetable compilation phase, China Railway Corporation currently adopts a phased approach, first scheduling same-line and cross-line flagship trains, followed by other trains. Flagship trains have gradually become premium services in high-speed railway transportation organization, possessing significant brand value. However, there is currently no clear definition for existing flagship trains.

To further quantify the impact of flagship trains on timetable compilation and capacity utilization, this study proposes the concept of “flagship trains” and investigates the issue of carrying capacity utilization from a brand value-oriented perspective. The operation of flagship trains is regarded as key to enhancing brand value. This study characterizes the number of train paths consumed by flagship trains under different transportation organization schemes, and further explores the impact of operating clock-face flagship trains—a service enhancement measure—on the actual capacity “deduction.” This research establishes non-value-oriented carrying capacity utilization as the foundation, and further develops a brand value-oriented high-speed railway carrying capacity utilization model. By comparing capacity optimization results under different train stopping pattern alternatives, case studies are conducted on the Beijing South-Jinan West section and the entire Beijing-Shanghai High-Speed Railway line. The results reveal the average changes in capacity indicators such as train numbers and capacity utilization rates under the brand value-oriented constraint of fixed clock-face departures for flagship trains.

1.2 Literature review

Due to their characteristics of fewer stops, higher average speed, superior service quality, operation on high-speed grade lines, and departure times at regular hourly intervals that are convenient for passengers to remember and recognize, flagship trains have become the preferred travel option for some passengers. With their higher occupancy rates, they should possess significant operational value. However, their scheduling requires sacrificing the number of operating train paths, which also has a notable impact on capacity utilization.

Lu (2019) analyzed the number of non-stop trains deducted (deduction coefficient) on high-speed railway parallel operation diagrams from the perspective of flagship train overtaking characteristics, and based on the analysis results, proposed relevant suggestions for the Beijing-Shanghai high-speed railway timetable planning. Zhang, Fan, Wang, and Guo (2022) considered the periodic train operation structure and utilized the close relationship between section passing capacity and train stops to optimize the number of flagship trains and their travel speeds. Xia, Li, Zhang, and Zhang (2024) constructed an integer linear programming model based on Event Activity Network (EAN) with the objectives of OD service balance and capacity utilization. The model considered basic timetabling constraints such as flagship train section running time and connection time, combined with special constraints including flagship train departure time constraints and grouping constraints, providing reference for high-speed railway flagship train timetable compilation and optimization.

Qu, Shi, and Xu (2022) explored the increase in the number of high-speed railway flagship trains, adopting an hourly balance-centralized scheduling approach to explore improvements in flagship train service quality. When analyzing the factors affecting the passing capacity of corridor-type high-speed railways in existing train timetables, they identified the pattern that flagship trains generally depart at regular hourly intervals to improve service quality. Fan, Shen, Liu, Li, and Liang (2024) analyzed from a systematic perspective, simplifying train path efficiency as the ratio of technical indicators to invested transportation resources to objectively and effectively evaluate the efficiency of various types of train paths. Through DEA projection analysis, they provided targeted suggestions for improving train path efficiency. The results showed that the comprehensive efficiency of trains adopting high-speed grade operating standards was higher than other categories of trains in the entire timetable.

Mei, Lai, Zhang, Pan, and Cui (2024) examined flagship trains' operational characteristics through comprehensive evaluation metrics. Their analysis using the improved TOPSIS method revealed that flagship trains such as G4, G3, and G8 ranked among the top performers on the Beijing-Shanghai HSR, characterized by high speed, high grade, high mileage rates, and fewer stops. Sun, Jing, Li, Tian, and Tian (2024) proposed a method for predicting passenger flow distribution in high-speed railway train riding sections based on an interpretable machine learning framework to explain the impact of passenger service product characteristics on passenger flow distribution prediction. They focused on analyzing the relationships between features such as benchmark trains, ticket prices, travel time, date, day of the week, train number, departure time, and passenger flow. The results showed that date and benchmark trains exhibited a nonlinear positive correlation with passenger flow distribution prediction, while travel time showed a nonlinear negative correlation. Benchmark trains with low travel time, high ticket prices, and departure times at regular hourly intervals had a positive impact on passenger flow distribution prediction, with benchmark trains having a significant influence on both passenger flow and revenue. Wu, Shan, and Zhao (2025) identified that flagship trains exhibit relatively low stop ratios in their optimization model for the Beijing-Shanghai high-speed railway, as these trains primarily serve longer travel distances and high-level stations. Their analysis showed that a small number of flagship trains maintain stop ratios below 0.6, distinguishing them from other train types that make more frequent stops at county-level stations to serve local passenger demand.

In other studies regarding timetables, capacity, and service elements, Jensen, Schmidt, and Nielsen (2020) addressed railway infrastructure capacity determination for strategic long-term planning without requiring fixed timetables. They formulated capacity determination as an optimization problem to find the maximal train set that minimizes average waiting time between trains of the same type, testing feasibility through train sequence sampling rather than fixed timetable generation. Zhong, Zang, Yang, Sheng, and Xu (2024) investigated the impact of timetable elements on railway line capacity, establishing the relationship between consumed capacity and timetable elements as the signed sum along a "critical path." They demonstrated that changing timetable elements impacts capacity with neighboring trains in a combinatorial manner, analyzing stop plans and extending findings to capacity factors including average speed and heterogeneity. Pouryousef and Lautala (2015) investigated applying European timetable management methodologies to the less structured U.S. rail system through a hybrid simulation approach combining RTC and RailSys tools. They demonstrated that optimizing dwell time constraints can significantly improve level of service parameters while managing the trade-off with capacity utilization, showing the potential benefits of structured timetable management in traditionally unstructured rail networks. Gu, Wei, and Xia (2025) transformed the train timetable scheduling problem into a node routing problem where nodes represent train paths and directed arcs depict sequential connections between paths. They constructed an optimization model maximizing the number of trains under the constraint that total arc weight does not exceed available time-space resources, revealing how train path sequences impact section carrying capacity and proposing optimization strategies for improving capacity utilization of high-speed railways. Xu *et al.* (2023) addressed railway capacity optimization through quantum computing by developing a space-time network-based binary integer programming model for train timetabling. They demonstrated that quantum simulators, particularly the coherent Ising machine (CIM), can effectively solve capacity-constrained timetabling problems, offering a novel computational approach for maximizing line capacity utilization in complex high-speed rail networks where traditional methods face computational limitations. Gao, Chen, Xu, Liu, and Chen (2025) developed a bi-objective optimization model for high-speed train rescheduling under disruptions that enhances capacity recovery and service quality by minimizing both timetable deviation and impacts on transferring passengers. Their computational intelligence framework achieved significant service improvements by preserving line capacity and service levels during disruptions. D'Ariano, Pacciarelli, and Pranzo (2008) introduced flexible timetables as an alternative to traditional time reserves for improving railway punctuality without reducing line capacity. Their approach plans less rigidity in baseline schedules while empowering real-time management to resolve inter-train conflicts dynamically. Jensen, Landex, Nielsen, Kroon, and Schmidt (2017) developed a strategic planning framework for calculating railway infrastructure occupation and capacity consumption independent of specific timetables. Their model generates and assesses different train sequences to achieve timetable independence, employing stochastic delay simulation to determine capacity consumption.

Existing research has not clearly defined the quantitative relationships between service levels for different types of trains, including flagship trains, cross-line trains, and other mainline trains. Research on flagship train timetable compilation methods is relatively limited overall. Existing studies indicate that operating flagship trains is an effective way to improve service levels, with their establishment being driven by both the necessity and public welfare nature of macro policies on one hand, and the convenience and comfort of passenger travel on the other. However, in existing research, there is limited analysis of the impact of flagship trains on capacity, making it difficult to provide effective analysis for capacity utilization.

2. Definition and classification of flagship trains

2.1 Definition and characteristics of flagship trains

Before discussing flagship train classification, this study first explores the characteristics and connotations of flagship trains. In railway operations, high-speed trains with high travel speeds, fewer stops, and serving high-traffic intercity routes are commonly referred to as flagship trains. Train timetabling involving flagship trains represents a special category with distinct objectives and constraints compared to conventional timetabling methods.

Flagship trains feature fast travel speeds, fewer stops, operation at maximum speed standards, stops mainly at key provincial capitals, and typically whole-hour departures. Taking the Beijing-Shanghai high-speed line in Q4 2022 as an example, five of the 28 trains (G1-G28) depart at non-whole-hour times. Through analyzing current flagship train data, existing research has found it difficult to identify common characteristics. This paper identifies the following key issues:

(1) Consideration of whole-hour departures

While most whole-hour trains on the Beijing-Shanghai line are flagship trains, it remains unclear whether non-whole-hour departure trains can be flagship trains and whether whole-hour departure necessarily defines a flagship train.

(2) Consideration of stops

Flagship trains on the Beijing-Shanghai line stop at 2–5 stations, but the specific threshold for "few stops" among 23 stations remains undefined. Whether trains stopping at 6–7 stations qualify as flagship trains is debatable. While flagship trains primarily serve provincial capitals, some also stop at high-traffic stations like Xuzhou East, making stopping standards difficult to define.

(3) Consideration of travel speed

Whether "flagship trains" should exist among lower-grade trains operating below maximum speed, and whether lower-grade trains with whole-hour departures and few stops qualify as flagship trains requires further discussion.

Given these conceptual uncertainties, this study proposes the concept of flagship trains and examines their impact on capacity utilization.

This study defines flagship trains as a special category of flagship trains that: depart at whole hours, operate at maximum speed grade, stop at no more than one-quarter of total line stations, and serve major prefecture-level cities with high passenger flow. Key characteristics include short travel times and balanced whole-hour departures, which are crucial for optimizing capacity utilization in high-speed railway systems.

(1) Short travel time

All flagship trains operate at 350 km/h with limited stops (≤25% of line stations), enabling higher speeds and reduced stopping time, thereby improving passenger travel efficiency and satisfaction.

(2) Balanced whole-hour departures

Whole-hour departure times provide regularity and predictability, facilitating passenger planning while enhancing reliability and optimizing transportation organization efficiency.

Flagship trains are primarily characterized as flagship trains—high-quality trains with strict timetabling requirements that serve as reference standards for timetable optimization.

2.2 Classification and value types of flagship trains

Based on operating characteristics, flagship trains can be classified as:

(1) Different stopping patterns

Flagship trains can be divided into direct and limited-stop services. Different stopping patterns help evaluate operational performance by comparing travel time, station spacing, and passenger demand satisfaction to select optimal stopping schemes.

(2) Different time periods

Peak and off-peak flagship trains may have different timetables and stopping schemes to accommodate varying passenger demand and traffic flow.

This classification helps planners evaluate different train schemes to improve railway efficiency and service quality.

As reference standards in high-speed railway systems, flagship trains possess significant value:

(1) Brand value

Flagship trains provide high-quality transportation services that meet rapid travel demands, promote economic exchange, and drive regional integration. They attract passenger flow from other modes and serve as the flagship brand of high-speed rail products.

(2) Economic value

Short travel times reduce time costs and promote business/tourism development. Whole-hour departures improve reliability and capacity utilization while attracting more passengers, increasing revenue. Flagship trains enhance economic benefits through improved efficiency and optimized organization.

(3) Structural value

In timetables, flagship trains exhibit hourly pseudo-periodic patterns that provide structural value for overall timetable layout and compilation, significantly impacting capacity optimization.

The value of flagship trains encompasses brand significance, economic benefits, and structural contributions, providing efficient travel options while serving as references for system planning and management to improve timetable efficiency and capacity utilization.

3. Throughput capacity utilization optimization model with flagship train considerations

3.1 Problem description and assumptions

This chapter addresses the throughput capacity utilization problem for high-speed railways considering the operation of flagship trains. Flagship trains, characterized by their fixed departure times at round hours and premium service levels, represent a critical component of brand value in railway operations. The model optimizes the selection and scheduling of trains from a candidate set while ensuring flagship trains operate at their designated hourly departure times.

The following assumptions are made for the capacity utilization model:

(1) Known candidate train set: The candidate train set is predetermined and serves as input to the optimization problem. The set includes trains of different speed grades (300km/h and 350km/h) with various stopping patterns, where flagship trains represent a premium subset with mandatory whole-hour departures and limited stops. Each candidate train is defined by its origin-destination pair, stopping scheme, and service characteristics.

(2) Sufficient rolling stock and crew resources: The model assumes adequate availability of train units and crew, without explicitly optimizing their allocation.

(3) Train-kilometer conversion coefficient as objective: The optimization uses weighted train-kilometer conversion coefficients instead of simple train counts, allowing proper consideration of short-haul services converted to long-haul equivalent capacity.

3.2 Mathematical formulation

As shown in Figure 1, train b has the longest running distance. Without considering other factors, the train-kilometer coefficient of train b should be 1, while the train-kilometer coefficients of train a and train c are converted to 0.4 and 0.6 respectively.

The sets, indices, parameters, and decision variables used in the model are shown in Table 1 and Table 2.

The capacity utilization optimization model considering flagship trains proposed in this section is an integer programming model based on transportation resource request conflicts. The model is constructed using the Big M method, which has certain similarities with the capacity calculation model based on train diagram optimization graphical methods. The optimization objective is adjusted from the number of trains to maximizing the weighted train-kilometer conversion coefficient, that is, establishing the optimization objective function by maximizing the sum of weighted train-kilometer conversion coefficients of selected trains to be operated.

$$Z = max\sum_{k\in K_c} Lsv_k \cdot z_k \quad (1)$$

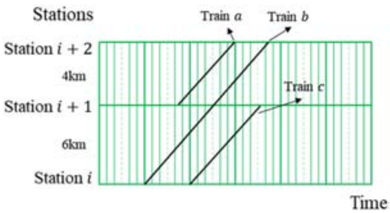

Figure 1. Illustration of the train-kilometer conversion coefficient. Source: Author’s own work

Table 1. Set, indexes, parameters of the model

Symbols	Definitions
N	Set of stations on the line
K	Set of trains
K_n	Set of low-speed grade trains (300km/h) $K_n \subset K$
K_b	Set of high-speed grade trains (350km/h) $K_b \subset K$
K_j	Set of flagship trains, $K_j \subset K_b$
i, j	Station index, $i, j \in N$
m	Total number of trains running on the line
k, k'	Train index, $k, k' \in K$
$N_{kk'}$	Set of stations commonly passed by trains k and k', $k, k' \in K$
o_k	Origin station of train k
d_k	Terminal station of train k
ST_{ki}	Stopping status of train k at station i, 0 means passing without stopping, 1 means stopping
F_i	Minimum number of stops required at station i within the specified time
$Tr^k_{i,i+1}$	Pure running time of train k in section $(i, i+1)$
ti_k	Departure time of train k, generally taken as whole hours, i.e. 420min, 480min, etc., $ti_k \in TI$
S_{ki}	Starting additional time of train k at station i
B_{ki}	Stopping additional time of train k at station i
Ts_i^{min}	Minimum dwell time of trains at stations
Ts_i^{max}	Maximum dwell time of trains at stations
T_i^{min}	Upper limit of operation time window at station i
T_i^{max}	Lower limit of operation time window at station i
I_{dd}	Minimum train departure interval
I_{dp}	Maximum train passing interval
I_{pd}	Minimum passing-to-departure interval
I_{aa}	Minimum arrival-to-arrival interval
I_{ap}	Minimum arrival-to-passing interval
I_{pa}	Minimum passing-to-arrival interval
I_{pp}	Minimum passing-to-passing interval
M	A large positive number
Lsv_k	Train-kilometer conversion coefficient for train k
TI	Set of whole hour times

Source(s): Author's own work

Table 2. Variables of the model

Symbols	Definitions
z_k	Binary variable, indicating whether train k is operated. If operated, $z_k = 1$; otherwise$z_k = 0$
a_i^k	Integer variable, the arrival time of train k at station i
d_i^k	Integer variable, the departure time of train k at station i
$y_i^{k,k'}$	Binary variable, indicating the running order of trains k and k' in section $(i-1, i)$. If $y_i^{k,k'} = 1$, train k is the preceding train of train k'; if $y_i^{k,k'} = 0$, train k is the following train of train k'

Source(s): Author's own work

The model includes the following constraints:

(1) Station Service Frequency Constraint

To ensure passengers' basic travel needs are met, it is necessary to limit the total number of trains stops at each station. The minimum service frequency at each station should be set based on passenger demand, using either passenger boarding/alighting numbers or passenger travel demand as approximation methods.

$$\sum_{k\in K}ST_{ki}\cdot z_k \geq F_i, \forall i\in N \tag{2}$$

(2) Train Dwell Time Constraint

To ensure smooth passenger boarding/alighting and necessary technical operations, minimum dwell times must be established for trains at each station. To minimize negative impacts on passenger experience, train dwell times should also not be excessive. Therefore, both minimum and maximum time limits are necessary. Since train k's operation is uncertain, both sides of the equation are multiplied by z_k.

$$z_k\cdot\left(d_i^k - a_i^k\right) \geq z_k\cdot ST_{ki}\cdot t_i^{min}, \forall k\in K, i\in N/\{o_k, d_k\} \tag{3}$$

$$z_k\cdot\left(d_i^k - a_i^k\right) \leq z_k\cdot ST_{ki}\cdot t_i^{max}, \forall k\in K, i\in N/\{o_k, d_k\} \tag{4}$$

$$z_k * \left(d_i^k - a_i^k\right) = 0, \forall k\in K, i\in \{o_k, d_k\} \tag{5}$$

Due to the binary decision variable for train operation, the constraints are linearized using the Big-M method:

$$\left(d_i^k - a_i^k\right) \geq ST_{ki}\cdot Ts_i^{min} - M\cdot(1-z_k), \forall k\in K, i\in N/\{o_k, d_k\} \tag{6}$$

$$\left(d_i^k - a_i^k\right) \leq ST_{ki}\cdot Ts_i^{max} + M\cdot(1-z_k), \forall k\in K, i\in N/\{o_k, d_k\} \tag{7}$$

$$\left(d_i^k - a_i^k\right) \leq M\cdot(1-z_k), \forall k\in K, i\in \{o_k, d_k\} \tag{8}$$

$$\left(d_i^k - a_i^k\right) \geq -M\cdot(1-z_k), \forall k\in K, i\in \{o_k, d_k\} \tag{9}$$

(3) Inter-station Running Time Constraint

The inter-station running time includes the travel time between adjacent stations. For train k in section $(i, i+1)$, the running time equals the pure running time plus the starting additional time at station i and the stopping additional time at station $(i+1)$.

$$z_k\cdot\left(a_{i+1}^k - d_i^k\right) = z_k\cdot\left(ST_{k,i}\cdot s_{k,i} + t_{i,i+1}^k + x_{i+1}^k\cdot b_{k,i+1}\right), \forall k\in K, i\in N/\{d_k\} \tag{10}$$

Similarly, linearized using the Big-M method:

$$\left(a_{i+1}^k - d_i^k\right) \leq \left(ST_{k,i}\cdot S_{k,i} + Tr_{i,i+1}^k + ST_{k,i+1}\cdot B_{k,i+1}\right) + M\cdot(1-z_k), \forall k\in K, i\in N/\{d_k\} \tag{11}$$

$$\left(a_{i+1}^k - d_i^k\right) \geq \left(ST_{k,i}\cdot S_{k,i} + Tr_{i,i+1}^k + ST_{k,i+1}\cdot B_{k,i+1}\right) - M\cdot(1-z_k), \forall k\in K, i\in N/\{d_k\} \tag{12}$$

(4) Train Departure Interval Constraint

To ensure safe operating distances between trains, adjacent trains must maintain specified minimum departure intervals. These intervals are affected by the stopping strategies of adjacent trains at stations. Four types of intervals must be considered: minimum stop-to-stop departure interval I_{dd} (preceding train stops, following train stops); minimum stop-to-pass departure interval I_{ap} (preceding train stops, following train passes); minimum pass-to-stop departure interval I_{pa} (preceding train passes, following train stops); minimum pass-to-pass departure interval I_{pp} (both trains pass). The specific interval type depends on both trains' stopping decisions at the station and their sequence order in the section.

When both trains k and k' operate and stop at station i: if $y_{i+1}^{k,k'} = 1$ (train k precedes k' in section $(i, i+1)$), equation (13) applies; if $y_{i+1}^{k,k'} = 0$ (train k follows k'), equation (14) applies.

$$d_i^{k'} - d_i^k \geq I_{aa} - M \cdot \left(1 - y_{i+1}^{k,k'}\right) - M \cdot (1 - z_k) - M \cdot (1 - z_{k'}), \forall k, k' \in K(k \neq k'), i \in N_{kk'} \tag{13}$$

$$d_i^k - d_i^{k'} \geq I_{aa} - M \cdot y_{i+1}^{k,k'} - M \cdot (1 - z_k) - M \cdot (1 - z_{k'}), \forall k, k' \in K(k \neq k'), i \in N_{kk'} \tag{14}$$

When train k stops at station i while k' passes:

$$d_i^{k'} - d_i^k \geq I_{ap} - M \cdot \left(1 - y_{i+1}^{k,k'}\right) - M \cdot (1 - z_k) - M \cdot (1 - z_{k'}), \forall k, k' \in K(k \neq k'), i \in N_{kk'} \tag{15}$$

$$d_i^k - d_i^{k'} \geq I_{pa} - M \cdot y_{i+1}^{k,k'} - M \cdot (1 - z_k) - M \cdot (1 - z_{k'}), \forall k, k' \in K(k \neq k'), i \in N_{kk'} \tag{16}$$

When both trains pass station i:

$$d_i^{k'} - d_i^k \geq I_{pp} - M \cdot \left(1 - y_{i+1}^{k,k'}\right) - M \cdot (1 - z_k) - M \cdot (1 - z_{k'}), \forall k, k' \in K(k \neq k'), i \in N_{kk'} \tag{17}$$

$$d_i^k - d_i^{k'} \geq I_{pp} - M \cdot y_{i+1}^{k,k'} - M \cdot (1 - z_k) - M \cdot (1 - z_{k'}), \forall k, k' \in K(k \neq k'), i \in N_{kk'} \tag{18}$$

(5) Train Arrival Interval Constraint

Similar to departure intervals, adjacent trains must maintain specified arrival intervals at stations. Four types of arrival intervals are considered: I_{aa}, I_{ap}, I_{pa}, and I_{pp}.

$$a_i^{k'} - a_i^k \geq I_{aa} - M \cdot \left(1 - y_{i+1}^{k,k'}\right) - M \cdot (1 - z_k) - M \cdot (1 - z_{k'}), \forall k, k' \in K(k \neq k'), i \in N_{kk'} \tag{19}$$

$$a_i^k - a_i^{k'} \geq I_{aa} - M \cdot y_{i+1}^{k,k'} - M \cdot (1 - z_k) - M \cdot (1 - z_{k'}), \forall k, k' \in K(k \neq k'), i \in N_{kk'} \tag{20}$$

$$a_i^{k'} - a_i^k \geq I_{ap} - M \cdot \left(1 - y_{i+1}^{k,k'}\right) - M \cdot (1 - z_k) - M \cdot (1 - z_{k'}), \forall k, k' \in K(k \neq k'), i \in N_{kk'} \tag{21}$$

$$a_i^k - a_i^{k'} \geq I_{pa} - M \cdot y_{i+1}^{k,k'} - M \cdot (1 - z_k) - M \cdot (1 - z_{k'}), \forall k, k' \in K(k \neq k'), i \in N_{kk'} \tag{22}$$

$$a_i^{k'} - a_i^k \geq I_{pp} - M \cdot \left(1 - y_{i+1}^{k,k'}\right) - M \cdot (1 - z_k) - M \cdot (1 - z_{k'}), \forall k, k' \in K(k \neq k'), i \in N_{kk'} \tag{23}$$

$$a_i^k - a_i^{k'} \geq I_{pp} - M \cdot y_{i+1}^{k,k'} - M \cdot (1 - z_k) - M \cdot (1 - z_{k'}), \forall k, k' \in K(k \neq k'), i \in N_{kk'} \tag{24}$$

(6) Time Window Constraint

To ensure safe train operations on high-speed railways, time window constraints such as maintenance windows must be established. This study uses parallelogram (diamond) shaped time windows, where each train's arrival and departure times at each station must fall within the time window.

$$T_i^{min} - M\cdot(1-z_k) \le d_i^k \le T_i^{max} + M\cdot(1-z_k), \forall k \in K, i \in N \tag{25}$$

$$T_i^{min} - M\cdot(1-z_k) \le a_i^k \le T_i^{max} + M\cdot(1-z_k), \forall k \in K, i \in N \tag{26}$$

(7) Section Running Order Constraint

This constraint defines the running order of any two trains in a specific section. On the same track section, one train must be the preceding train while the other follows.

$$y_i^{k,k'} + y_i^{k',k} = 1, \forall k, k' \in K, i \in N_{kk'} \tag{27}$$

(8) Flagship Train Hourly Departure Constraint

Flagship trains provide new approaches for brand value-oriented capacity optimization. All flagship trains belong to high-grade train categories and must depart at the top of the hour.

$$d_{o_k}^k = ti_k, \forall k \in K_j \tag{28}$$

$$z_k = 1, \forall k \in K_j \tag{29}$$

(9) Decision Variable Constraints

$$z_k \in \{0,1\}, \forall k \in K \tag{30}$$

$$y_i^{k,k'} \in \{0,1\}, \forall k, k' \in K, i \in N_{kk'} \tag{31}$$

4. Capacity optimization case study considering flagship trains

4.1 Case parameter settings

The Beijing-Shanghai High-Speed Railway is one of the busiest high-speed rail lines in China, comprising 23 stations in total. This case study focuses on the southbound Beijing-Jinan section (from Beijing South Station to Jinan West Station), which includes 6 stations. The time range selected is a two-hour daytime period from 7:30 to 9:30.

The minimum dwell time for trains at intermediate stations is set at 2 minutes, with a maximum of 10 minutes. The departure headway between trains at each station is 5 minutes, the arrival headway is 4 minutes, the passing headway is 3 minutes, the passing-departure headway is 3 minutes, the departure-passing headway is 5 minutes, the arrival-passing headway is 4 minutes, and the passing-arrival headway is 3 minutes.

Two speed categories of trains operate on this line: high-speed trains (350 km/h) and low-speed trains (300 km/h). The running times of trains with different speed levels in each section are shown in Table 3.

The models proposed in this paper are implemented using Python 3.11 with the Branch-and-Cut algorithm. The computing environment consists of a personal computer with an Intel Core i7-11700 CPU @ 2.50 GHz and 32 GB of RAM. The construction of candidate train sets follows the approach of Zhang *et al.* (2022), whose research was based on a quarterly timetable from 2022. After providing a basic set of candidate trains, the candidate stopping patterns were continuously supplemented, using a 2-h time range as the research example. This case study

Table 3. Jingji section line and parameter information

Station	Mileage (km)	Section pure running time (min)		Additional time for train starting/topping (min)		Min service frequency
		350km/h	300km/h	Starting	Stopping	
BJN	0	–	–	2	3	10
LF	59	15	16	2	3	1
TJN	131	11	13	2	3	5
CZX	219	16	18	2	3	3
DZD	327	18	20	2	3	5
JNX	419	17	19	2	3	10

Source(s): Author’s own work

establishes 20 different candidate train sets, each maintaining a fixed number of 22 candidate trains without further increases. Among these, 3 are high-speed train candidates and 19 are low-speed train candidates. The main difference between each candidate train set lies in the low-speed train candidate sets, which are configured based on different schemes derived from actual operational timetables. The specific generation rules are shown in Figure 2, with low-speed train stopping patterns detailed in Appendix A.

4.2 Numerical experiments

This study examines 3 high-speed trains, with 2 designated as flagship trains scheduled to depart on the hour. A capacity optimization case considering flagship trains (FO) is designed, with 20 experimental groups named FO1, FO2, ..., FO20, to further analyze the capacity results.

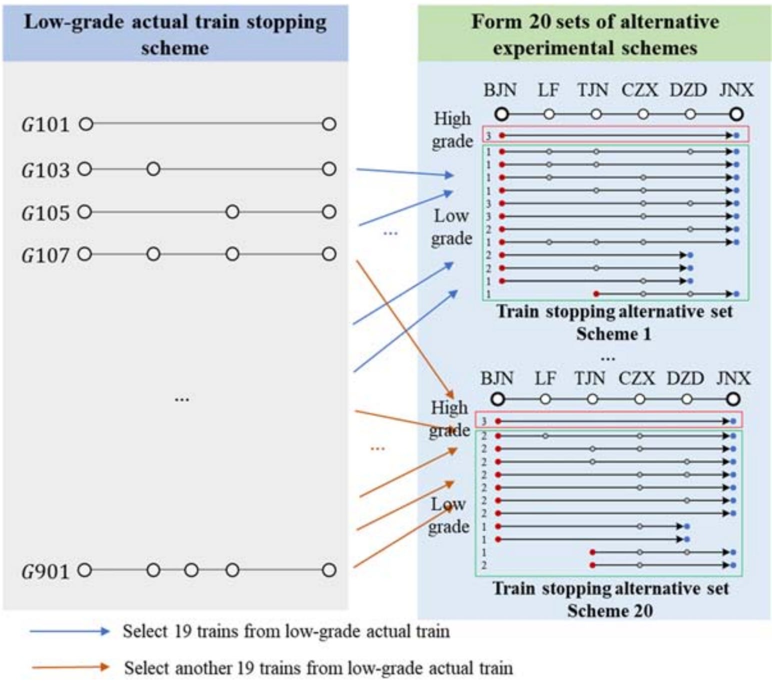

Figure 2. Candidate train set generation rules. Source: Author’s own work

Under the condition of scheduling 2 flagship trains, the optimization results are shown in Figure 3. The figure illustrates that two high-speed trains operate as flagship trains departing at 8:00 and 9:00 sharp. In subfigures 3(1), (3), and (6), the third high-speed train is not selected for operation. The specific solution results for case FO are presented in Table 4.

To compare the optimization results with those considering flagship trains, a capacity utilization optimization model without flagship train considerations (NFO) is designed using the same candidate train sets. Twenty experimental groups are conducted, named NFO1, NFO2, ..., NFO20, to further analyze the capacity results. The optimization outcomes are shown in Figure 4.

In the capacity utilization optimization case NFO without flagship train considerations, trains are scheduled within the parallelogram time window (2-h pink area) with the objective of maximizing the weighted train-kilometer conversion coefficient. Analysis reveals that in Figure 4(b) and (c), high-speed trains appear in “paired” tracking patterns, which is a common approach demonstrating reasonable capacity utilization. In Figure 4(a), (d), (e), and (f), high-

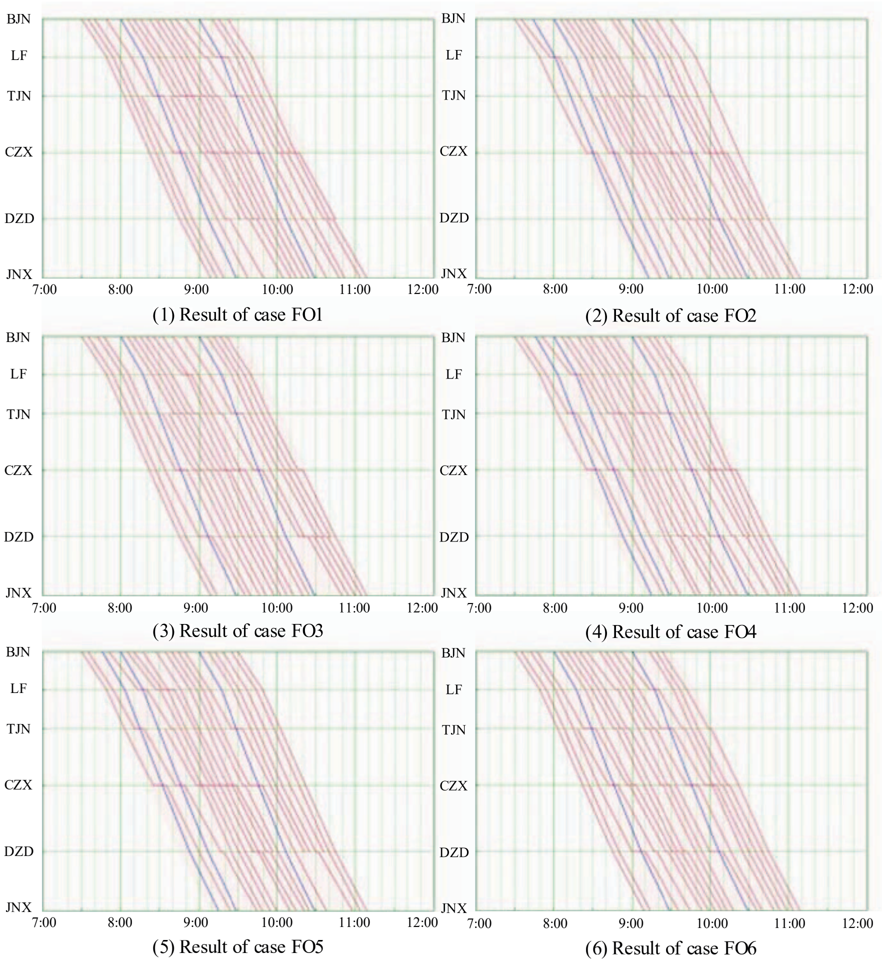

Figure 3. Timetable example of the Case FO. Source: Author’s own work

Table 4. Analysis of the results of the case FO

Case	Number of trains	Number of high-priority trains	Number of low-priority trains	Number of constraints	Number of variables	Objective function	Solution time (s)
FO1	20/22	2/3	18/19	10,550	2,582	18.71	212.24
FO2	19/22	3/3	16/19	9,641	2,572	17.94	246.67
FO3	20/22	2/3	18/19	10,734	2,584	19.17	218.19
FO4	18/22	3/3	15/19	10,763	2,584	17.77	193.42
FO5	20/22	3/3	17/19	10,367	2,580	18.78	186.38
FO6	19/22	2/3	17/19	11,529	2,592	18.7	238.88
FO7	20/22	3/3	17/19	9,641	2,572	18.71	208.99
FO8	19/22	3/3	16/19	9,997	2,576	18.24	204.35
FO9	19/22	3/3	16/19	10,734	2,584	18.47	262.39
FO10	20/22	2/3	18/19	10,546	2,582	18.94	250.49
FO11	19/22	3/3	16/19	10,589	2,582	18.24	226.73
FO12	19/22	3/3	16/19	11,126	2,588	18.47	250.7
FO13	19/22	3/3	16/19	10,176	2,578	18.4	256.71
FO14	19/22	2/3	17/19	11,137	2,588	18.4	215.31
FO15	18/22	2/3	16/19	11,348	2,590	18	252.84
FO16	19/22	3/3	16/19	10,546	2,582	18.47	248.43
FO17	18/22	3/3	15/19	10,589	2,582	17.47	189.02
FO18	19/22	3/3	16/19	10,738	2,584	18.47	242.74
FO19	19/22	3/3	16/19	10,561	2,582	18.7	279.33
FO20	19/22	3/3	16/19	10,176	2,578	18.4	254.33

Source(s): Author's own work

speed and low-speed trains make reasonable use of spatial-temporal resources through stopping patterns and overtaking arrangements. These cases typically feature more low-speed trains with high-speed trains appearing in a dispersed manner. Detailed calculation results are shown in Table 5.

In the headers of Tables 4 and 5, the numbers to the left of the slash in the fields for train count, high-speed train count, and low-speed train count represent the number of trains selected by the model optimization, while the numbers to the right represent the provided candidate train count. Comparative analysis between case FO (considering flagship trains) and case NFO (without flagship train considerations) reveals that cases with flagship train operating constraints select fewer trains on average. The following sections provide a comparative analysis of the two cases based on train count and capacity utilization rate indicators.

4.3 Results discussion and analysis

(1) Changes in Train Numbers

As shown in Figure 5, the average number of trains in case FO is lower than that in case NFO. The average number of trains in case NFO is 20, while case FO has an average of 19.1 trains, representing a decrease of 0.9 trains on average. In experiments 1, 3, 5, 6, 10, 12, and 14, the number of trains remains equal, indicating that under identical stopping pattern alternatives, both models select the same number of trains. Research analysis reveals that under a given set of alternative train options, operating flagship trains may reduce the total number of trains. In the 20 experimental groups, under the given stopping pattern alternatives and other case parameters, when two flagship trains with hourly departures are operated within a 2-h period, the number of trains decreases by an average of 0.9.

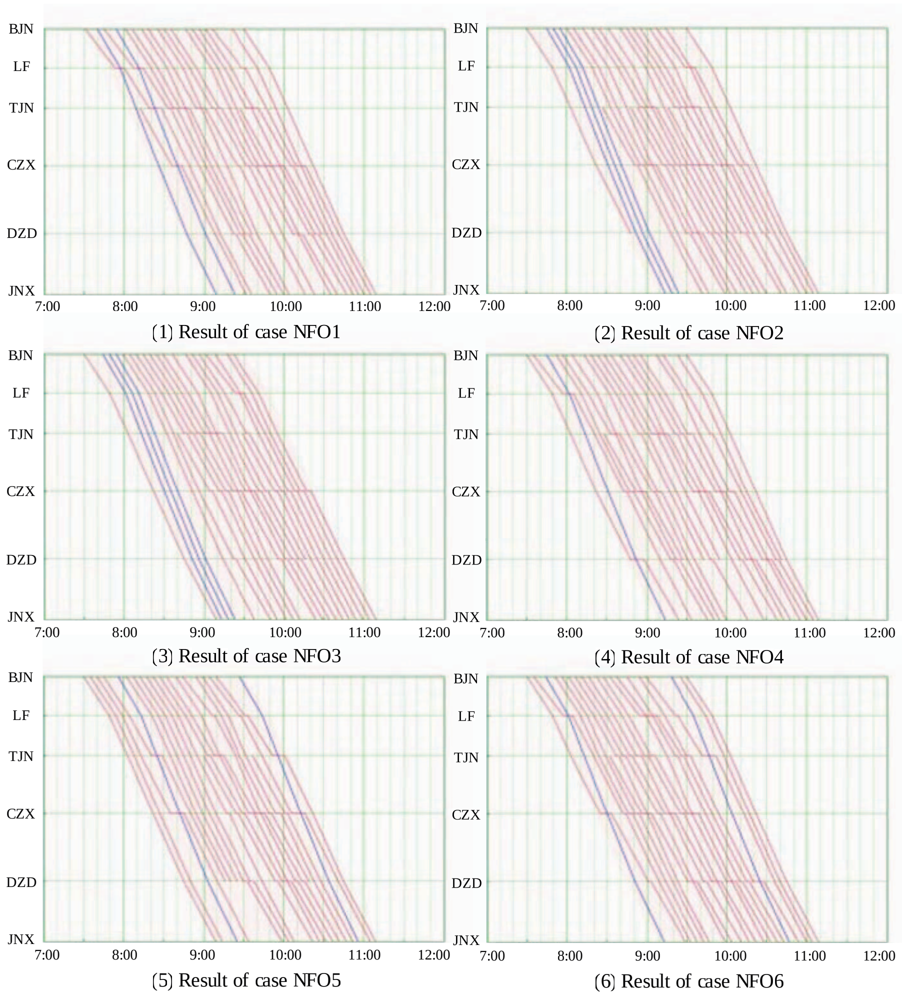

Figure 4. Timetable example of the Case NFO. Source: Author's own work

(2) Changes in Capacity Utilization Rate

The capacity utilization rate here is calculated as the current weighted train-kilometer conversion coefficient divided by the total number of alternative stopping trains, which equals the model's optimization objective value divided by the upper limit of alternative stopping trains. As shown in Figure 6, the capacity utilization rate of the optimization model considering flagship trains is lower on average than that of the capacity utilization model without value distinction. The average capacity utilization rate for case NFO is 86.43%, while case FO achieves 83.73%, showing an average decrease of 8.4% in capacity utilization rate when flagship trains are considered. In experimental cases FO3, FO6, and FO14, the capacity utilization rates remain identical, indicating that under these experimental parameters, both models produce consistent train operation optimization schemes. The capacity utilization rate calculated using train-kilometer conversion coefficients can reflect capacity changes in long and short routes that cannot be distinguished by train numbers alone. Research analysis

Table 5. Analysis of the results of the case NFO

Case	Number of trains	Number of high-priority trains	Number of low-priority trains	Number of constraints	Number of variables	Objective function	Solution time (s)
NFO1	20/22	2/3	18/19	10,546	2,582	18.94	232.43
NFO2	20/22	2/3	18/19	9,637	2,572	18.41	342.7
NFO3	20/22	2/3	18/19	10,730	2,584	19.17	225.25
NFO4	20/22	2/3	18/19	10,759	2,584	19.01	201.2
NFO5	20/22	3/3	17/19	10,363	2,580	19.01	266.67
NFO6	19/22	1/3	18/19	11,525	2,592	18.7	183.19
NFO7	22/22	3/3	19/19	9,637	2,572	19.88	89.52
NFO8	20/22	2/3	18/19	9,993	2,576	18.71	216.92
NFO9	20/22	2/3	18/19	10,730	2,584	19.17	211.38
NFO10	20/22	2/3	18/19	10,542	2,582	19.01	223.35
NFO11	20/22	3/3	17/19	10,585	2,582	19.01	240.16
NFO12	19/22	2/3	17/19	11,122	2,588	18.7	187.4
NFO13	20/22	2/3	18/19	10,172	2,578	18.64	252.18
NFO14	19/22	0/3	19/19	11,133	2,588	18.4	276.3
NFO15	20/22	1/3	19/19	11,344	2,590	19.31	224.44
NFO16	20/22	3/3	17/19	10,542	2,582	19.17	245.33
NFO17	20/22	1/3	19/19	10,585	2,582	18.55	257.22
NFO18	20/22	2/3	18/19	10,734	2,584	19.17	228.65
NFO19	20/22	3/3	17/19	10,557	2,582	19.4	261.31
NFO20	21/22	3/3	18/19	10,172	2,578	19.94	219.08

Source(s): Author’s own work

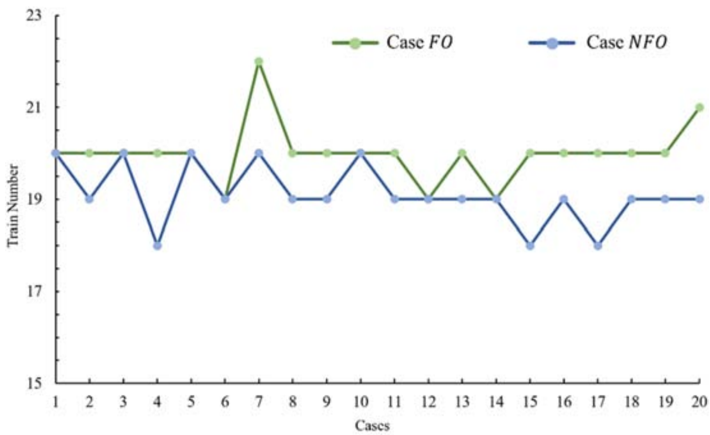

Figure 5. Train Number Change of the Case FO and NFO. Source: Author’s own work

indicates that under a given set of alternative trains, operating flagship trains as a brand value behavior may reduce capacity utilization rate by 8.4%.

5. Conclusions

This paper focuses on solving the capacity utilization optimization problem under the condition of flagship train hourly departure scheduling, supporting research on capacity

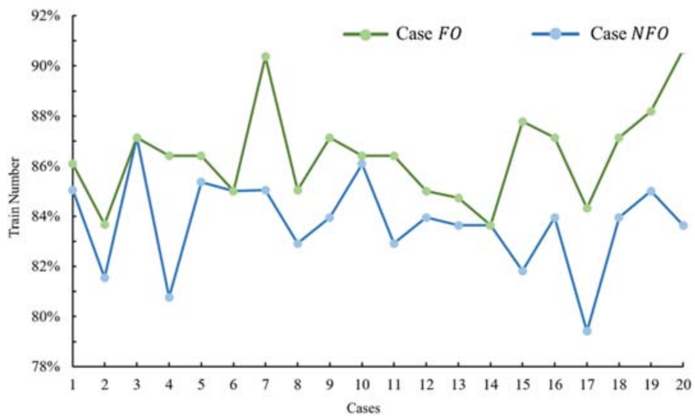

Figure 6. Capacity utilization of the case FO and NFO. Source: Author's own work

utilization with brand value considerations. The study identifies brand value with the operation of "flagship trains" as high-value popular services, and based on the operational characteristics of flagship trains, treats the scheduling of fast hourly trains as a means of brand value enhancement. A brand value-oriented capacity utilization optimization model for flagship train operation is constructed and compared with high-speed rail capacity utilization models that do not consider flagship trains as the benchmark for value-oriented capacity utilization optimization results. Analysis of cases NFO and FO demonstrates that under given alternative train sets, operating 2 flagship trains within a 2-h timeframe results in an average capacity utilization rate decrease of 8.4%. This finding provides decision support for brand value-oriented high-speed rail capacity utilization research.

Supplementary material

The supplementary material for this article can be found online.

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