Collaborative Optimization of High-Speed Railway Timetabling and Stop Planning under Integrated Passenger and Freight Transportation

Juhua Yang, Junfeng Zhang, Zhiqiang Tian, Guofeng Sun,Hui Lian

***Abstract*—To improve the utilization of surplus capacity and enhance both economic efficiency and service quality in integrated high-speed railway passenger and freight operations, this study develops a coordinated optimization framework for train timetabling and stop planning. The framework explicitly integrates time-sensitive express freight demand with passenger flow requirements, aiming to align heterogeneous service needs within a unified scheduling structure. A nonlinear mixed-integer programming model is formulated to jointly determine train schedules and stop patterns, with the objective of maximizing total system revenue while maintaining service quality and optimizing train utilization. The model is linearized through the introduction of auxiliary variables and solved efficiently using the commercial solver GUROBI. Numerical experiments based on real-world data from the Wuhan–Guangzhou high-speed rail corridor demonstrate that the proposed method increases the express freight delivery rate to 90.32% and total revenue to 6.93 million yuan, while improving transport capacity utilization without compromising passenger service quality. Sensitivity analyses reveal that higher passenger demand raises total revenue but results in more stops and longer travel times, whereas increased stop costs reduce service frequency and overall system gains. These findings confirm the practical applicability of the proposed method and offer actionable insights for integrated scheduling and resource allocation in high-speed rail systems.**

***Index Terms*—High-speed railway; Mixed transportation; Timetabling; Stop planning; Express allocation**

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Juhua Yang is a professor in the School of Traffic and Transportation, Lanzhou Jiaotong University, Lanzhou 730070, China (e-mail: yangjuhua@mail.lzjtu.cn).

Junfeng Zhang is a postgraduate student in the School of Traffic and Transportation, Lanzhou Jiaotong University, Lanzhou 730070, China (e-mail: 11230012@stu.lzjtu.edu.cn).

Zhiqiang Tian is a professor in the School of Traffic and Transportation, Lanzhou Jiaotong University, Lanzhou 730070, China (corresponding author to provide e-mail: tianzq@mail.lzjtu.cn).

Guofeng Sun is a lecturer in the School of Traffic and Transportation, Lanzhou Jiaotong University, Lanzhou 730070, China (e-mail: guofengsun01@126.com).

Hui Lian is a postgraduate student in the School of Traffic and Transportation, Lanzhou Jiaotong University, Lanzhou 730070, China (e-mail: 11230038@stu.lzjtu.edu.cn).

I. INTRODUCTION

In recent years, the rapid expansion of e-commerce has fueled a substantial increase in demand for fast and reliable interregional freight transportation. According to national statistics, China's postal industry handled 193.68 billion parcels in 2024, representing a year-on-year growth of 19.2%, with express deliveries accounting for 175.08 billion parcels—an increase of 21.5%. This explosive growth in freight activity has become a key driver of sustained economic development. However, several challenges remain in meeting the evolving requirements of fast freight services. First, there is an increasing imbalance between the surging demand for express cargo transportation and the available transport capacity, particularly as urban-to-urban shipments continue to rise. Second, road transportation remains the predominant mode for express freight, yet it significantly contributes to environmental pollution and suffers from growing congestion in many regions due to network saturation.

To overcome these supply-side constraints, many countries have begun integrating freight services into high-speed railway (HSR) networks, with the goal of improving transport efficiency and fostering greener, more economically sustainable logistics systems. With inherent advantages such as high speed, low environmental impact, and substantial transport capacity, HSR systems play a critical role in enhancing both national and regional connectivity. Countries such as Germany and France have successfully implemented HSR-based express freight services, yielding significant economic and social benefits. In China, the continuous expansion of the HSR network has enabled pilot programs that utilize passenger electric multiple units (EMUs) for express cargo transportation, offering highly time-sensitive services such as same-day, next-day, and two-day delivery. These initiatives have significantly improved regional logistics efficiency and enhanced the economic performance of railway operators.

Nevertheless, the planning of HSR timetables and stop patterns remains predominantly driven by passenger demand, often overlooking the freight-carrying potential of high-speed railways. In both academic research and real-world operations, freight allocation is typically treated as a secondary adjustment under predetermined schedules and stop patterns, resulting in substantial express cargo demand being unserved or inefficiently accommodated. This disconnect underscores the necessity for an integrated planning approach that simultaneously accounts for both passenger and freight demand in high-speed rail scheduling and operations.

This study aims to optimize high-speed railway timetables, stop patterns, and carriage allocation schemes to maximize the synergy between freight demand and train operational planning, thereby enhancing the overall service capacity of railway enterprises. By focusing on the spatiotemporal coupling of express cargo demand with train schedules and stop decisions, we propose a demand-driven, integrated optimization strategy for timetable and stop planning. The proposed framework supports the dynamic adjustment of carriage configurations in response to evolving passenger and freight requirements, significantly improving the utilization efficiency of HSR transport resources. Ultimately, this approach seeks to increase the profitability of railway operations while promoting environmental sustainability by shifting a greater share of express freight from road to rail.

II. Literature review

The efficient organization of high-speed railway (HSR) operations fundamentally depends on the quality of train timetables and stop planning (Yao et al., 2023 [1]). Timetables define the temporal structure of train services, while stop patterns directly determine whether transport demand can be effectively accommodated along a given route. Together, these elements represent the core temporal and spatial decision variables in HSR operational planning, and their optimization is essential for ensuring high service quality and effective cost control. Traditionally, railway operations have been managed through a hierarchical decision-making framework that includes network design, line planning, timetable generation, rolling stock scheduling, and crew assignment (Narayanaswami et al., 2011 [2]). In early studies, stop planning was typically treated as a subcomponent of line planning. However, with growing recognition of its operational significance, recent research increasingly emphasizes the integrated optimization of stop planning in conjunction with other planning stages.

Chang et al. (2000) formulated a multi-objective optimization model to determine service types, frequencies, and fleet sizes for intercity HSR, based on a set of candidate stopping patterns [3]. Building on this foundational work, Qi et al. (2018) proposed a mixed-integer programming framework that jointly optimizes train segments and stop patterns, thereby improving the alignment between service design and operational feasibility [4]. More recently, Zhao et al. (2021) developed a bilevel line planning model grounded in Stackelberg game theory, which explicitly captures the strategic interactions between planners and passengers within HSR networks [5].

Timetable optimization has also been a central research focus, typically addressed after line plans have been determined. Two main research streams are commonly identified: periodic timetabling (Zhang and Nie, 2016 [6]) and non-periodic timetabling (Cacchiani and Toth, 2012 [7]). While periodic timetables are relatively easy to construct and implement, they often lack the flexibility to accommodate fluctuating passenger demand, leading to capacity shortages during peak periods and underutilization during off-peak times. In contrast, non-periodic timetables provide greater adaptability and responsiveness. Recent studies have further advanced this area. For instance, Robenek et al. (2018) [8] integrated demand elasticity into timetable design by employing a probabilistic passenger demand model to determine optimal departure times and ticket prices. Tian and Niu (2019) [9] proposed a bilevel optimization model that explicitly accounts for passenger transfers, aiming to minimize total transfer waiting time and improve network-level service coordination.

In recent years, increasing research efforts have focused on the integrated optimization of interdependent operational components within railway systems. For example, Dong et al. (2020) proposed a simultaneous optimization framework for train timetabling and stop planning, and developed an enhanced adaptive large neighborhood search (ALNS) algorithm to efficiently solve the resulting large-scale problem [10]. Building on this work, Xie et al. (2021) [11] expanded the model by incorporating train energy consumption as a key decision factor alongside passenger demand. Yue et al. (2016) [12] developed a column generation heuristic to jointly optimize stop strategies and timetable scheduling. Similarly, Xu et al. (2021) [13] introduced a unified modeling approach that integrates passenger flow considerations, enabling the simultaneous optimization of timetable construction, skip-stop policies, and platform assignments using a Lagrangian relaxation technique. Yang et al. (2016) [14] focused on the stop-or-skip decision-making process by introducing binary variables for station stops and formulated a comprehensive model aimed at minimizing both origin station delays and dwell times at intermediate stations.

The growing demand for express freight in high-speed railway (HSR) operations has introduced new complexities and heightened the importance of integrated planning. As e-commerce continues to expand, HSR is increasingly regarded as a strategic mode for time-sensitive freight, offering both economic and environmental advantages. Pazour et al. (2010) [15] explored the efficiency gains achievable by integrating freight into underutilized off-peak passenger services, demonstrating significant improvements in system revenue. Bi et al. (2019) [16] assessed the feasibility of HSR-based express services in China and identified supply–demand mismatches as a key challenge for future development. In the context of passenger–freight integrated operations, Li et al. (2023) [17] proposed optimization models incorporating penalty parameters to discourage freight assignments on high-occupancy passenger trains, thereby mitigating negative impacts on passenger service quality. Zhang et al. (2025) [18] developed a robust optimization model for flexible train composition, jointly considering passenger and uncertain freight demand. By integrating a space–time network and an advanced decomposition algorithm, their approach significantly enhances solution robustness and computational efficiency. Qi et al. (2025) [19] jointly optimized variable train compositions, timetables, and stop patterns, solving the resulting model using a variable neighborhood search (VNS) heuristic. In the domain of urban rail, Li et al. (2021) [20] formulated a mixed-integer linear programming model to maximize operator profits by flexibly inserting dedicated freight trains and efficiently utilizing residual capacity, supported by scalable preprocessing and heuristic solution methods.

Building on the existing body of research, this study develops a collaborative optimization model for high-speed railway timetabling and stop planning that simultaneously considers both passenger and express freight demand. The model is formulated as a nonlinear mixed-integer programming problem with the objective of maximizing combined passenger and freight revenue while minimizing total stopping costs. To enable efficient computation, the model is linearized through the introduction of auxiliary variables, allowing it to be solved as a mixed-integer linear programming (MILP) problem. Numerical experiments based on a case study of the Wuhan–Guangzhou HSR corridor validate the model's effectiveness and demonstrate its potential for practical application in real-world railway operations.

III. PROBLEM STATEMENTS

In high-speed railway mixed transportation systems, train timetabling and stop planning have a direct impact on the allocation of express freight services. The timetable determines the precise loading and unloading windows for express cargo and whether shipments can depart on schedule, while the stop plan dictates whether a particular train can accommodate specific freight tasks. In this study, we address the high time-sensitivity requirements of express rail freight while ensuring the travel needs of passengers are met. Our objective is to maximize the satisfaction of express freight demand and to enhance both the profitability and service quality of railway operators.

For the high-speed railway under study, we define the set of stations along the considered operating direction as S, and the set of trains as I.The set of freight service classes is denoted by G, where each class has distinct time-sensitivity requirements. In the high-speed rail system, freight demand is expressed in terms of "express freight boxes," and the set of shipment requests is denoted by F.For each freight class, there exist both soft and hard time window constraints at the origin station. Let g represent the freight service class and s the loading station; the soft time window for a shipment is denoted as $[te1_s^g, te2_s^g]$, and the hard time window as $[te1_s^g, te3_s^g]$. The soft time window determines whether the maximum transportation revenue can be achieved, while the hard time window dictates whether a shipment can be transported by a given train. For each shipment, the earliest and latest allowable loading times at the station are defined accordingly. If a train's departure time at the station falls outside the hard time window, the shipment cannot be assigned to that train. Conversely, if the departure time falls within the hard window, the shipment may be carried by the train, but revenue will be reduced if the loading time is outside the soft window. As illustrated in Figure 1, if freight f is dispatched by a train departing within the interval $[t_1, t_2]$, the transportation revenue is maximized. If the shipment is dispatched by a train departing within $[t_2, t_3]$, the revenue is subject to a penalty. If the freight cannot be dispatched by any train within the interval $[t_1, t_3]$, the revenue is zero, indicating that the shipment cannot be transported.

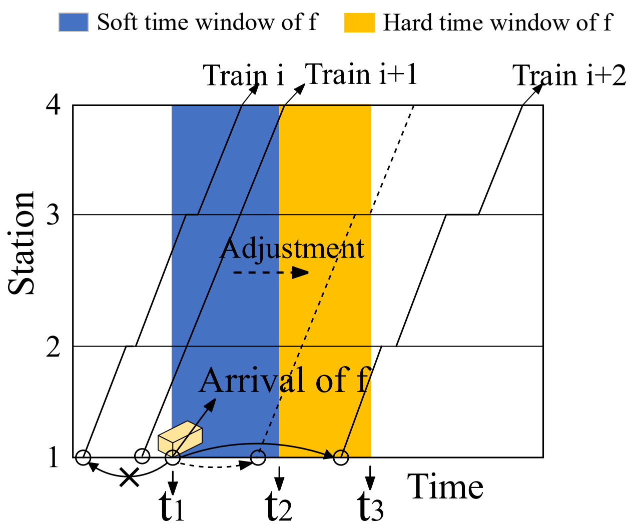


Fig. 1. High-Speed Rail Express Freight Allocation Diagram

For rigorous modeling, some assumptions are considered in this study.

Assumption 1. To avoid potential safety risks in mixed passenger and freight operations, a separated carriage strategy is adopted, whereby passengers and freight must be allocated to different carriages.

Assumption 2. Given that high-speed rail express freight primarily targets high-value, small-sized items (such as perishable gifts and business documents), it is assumed that all shipments are handled, loaded, and distributed in standardized express boxes.

IV. MATHEMATICAL FORMULATION

A. Notation and Variable Definitions

First, we present all relevant symbols and parameters used in the formulation, some of which have been introduced previously and are formally defined in Table 1.

The decision variables and auxiliary variables required for the model are defined in Table 2.

B. Constraints

(1) Timetable constraints

Trains must perform stopping operations at designated stations, and the dwell time must satisfy both passenger boarding and alighting needs as well as overtaking requirements between different train classes. Therefore, the stopping time for each train should be allowed to flexibly vary within a specified range.

$$d_{i,s}^{min} x_s^i \le t_{i,s}^d - t_{i,s}^a \le d_{i,s}^{max} x_s^i, \quad \forall i \in I, s \in S_i \backslash \{o_i, d_i\} \tag{1}$$

To optimize the utilization of high-speed railway resources and enhance transportation services, train departure times are permitted to be adjusted only within specified time windows.

$$A_i \le t_{i,o_i}^d \le B_i, \quad \forall i \in I \tag{2}$$

TABLE I
NOTATIONS AND PARAMETERS USED IN THE FORMULATION.

Symbols	Definition
S	Set of stations, and total number of stations is $\|S\|$
I	Set of trains, and the total number of train is $\|I\|$
G	Set of express freight service classes, and the total number is $\|G\|$
F	Set of express freight demands, and the total number of freight is $\|F\|$
$[te1_s^g, te2_s^g]$	The soft time window for express freight of service class g and shipment s
$[te1_s^g, te3_s^g]$	he hard time window for express freight of service class g and shipment s
$[d_{i,s}^{min}, d_{i,s}^{max}]$	The minimum dwell time and maximum operation time for train i at station s
A_i, B_i	The allowable departure time window for train i at the origin station.
$t_{i,s}^{run}$	The running time of train i on segment s
t_i^{start}	The required start-up time for train i
t_i^{stop}	The required stopping time for train i
T^{dd}, T^{aa}	The minimum headway time between two consecutive trains depart from and arrive at the same station
o_i, d_i	The origin and destination stations for train i
N_i	The maximum number of station stops allowed for train i
C_i	The total number of carriages assigned to train i
b^p	The passenger capacity of a single carriage.
b^{fr}	The freight capacity of a single carriage.
q_{sv}	The number of passengers traveling from station s to station v
o_f, d_f	The origin and destination stations of freight demand f
$n_{s,v}^g$	The unit freight revenue per box for express cargo of service class g transported from station s to station v
α_g	The transportation time penalty coefficient for freight of service class g
ρ_i	The loading and unloading time per box for train i
$z_{s,v}^i$	The ticket fare of train i from station s to station v
M	A sufficiently large positive constant
δ	The stop cost of a train

TABLE II
THE VARIABLES USED IN THE MODEL

Symbols	Definition
$td_{i,s}$	The departure time of train i at station s
$ta_{i,s}$	The arrival time of train i at station s
x_s^i	A binary variable indicating whether train i stops at station s
p_s^i	The number of carriages assigned to passenger service by train i on segment s
fr_s^i	The number of carriages assigned to express freight service by train i on segment s
$q_{s,v}^i$	The number of passengers transported by train i from station s to station v
y_f^i	A binary variable equal to 1 if freight f is transported by train i, and 0 otherwise
$w_{i,j}^s$	A binary variable $w_{i,j}^s$ equals 1 if train i departs from station s before train j; otherwise, $w_{i,j}^s = 0$
m_f^i	The express freight revenue obtained by train i for transporting freight f
μ_f^i	A binary auxiliary variable
ν_f^i	A binary auxiliary variable
τ_f^i	A continuous auxiliary variable
ϕ_f^i	A continuous auxiliary variable
κ_f^i	A continuous auxiliary variable
$\psi_{s,v}^i$	A binary auxiliary variable
$\gamma_{s,v}^i$	A binary auxiliary variable

To calculate the arrival and departure times of trains at each station, it is necessary to introduce train running time constraint.

$$t_{i,s+1}^a = t_{i,s}^d + t_{i,s}^{run} + x_i^s t_i^{start} + x_i^{s+1} t_i^{stop}, \quad \forall i \in I, s \in (S \setminus \{m\}) \tag{3}$$

To ensure the feasibility of the optimized train timetable, constraints (4)–(6) are introduced to guarantee the operational safety of train movements.

$$t_{i,s}^{d} + T_{s}^{d} \le t_{j,s}^{d} + \left(1 - w_{i,j}^{s}\right) \cdot M, \quad \forall i \ne j, i, j \in I, s \in (S_i \backslash \{d_i\}) \cap \left(S_j \backslash \{d_j\}\right) \tag{4}$$

$$t_{i,s+1}^{a} + T_{s}^{a} \le t_{j,s+1}^{a} + \left(1 - w_{i,j}^{s}\right) \cdot M, \quad \forall i \ne j, i, j \in I, s \in (S_i \backslash \{d_i\}) \cap \left(S_j \backslash \{d_j\}\right) \tag{5}$$

$$w_{i,j}^{s} + w_{j,i}^{s} = 1, \ \forall i < j, i, j \in I, s \in (S_i \backslash \{d_i\}) \cap \left(S_j \backslash \{d_j\}\right) \tag{6}$$

(2) Stop-Related Constraints

Trains are required to stop at both the origin and terminal stations. Additionally, to ensure an adequate level of service, the total number of intermediate station stops for each train must not exceed a specified maximum.

$$x_{i}^{o_i} = 1, \quad \forall i \in I \tag{7}$$

$$x_{i}^{d_i} = 1, \quad \forall i \in I \tag{8}$$

$$\sum_{s \in S} x_{i}^{s} \le N_i, \quad \forall i \in I \tag{9}$$

(3) Train Capacity Constraints

Considering the strict capacity limitations of trains, the overall transport capacity is divided into passenger and express freight capacities. The allocation of carriages for passenger and freight services on each segment ensures that the train's capacity constraints are satisfied.

$$p_{s}^{i} + fr_{s}^{i} \le C_i \quad \forall i \in I, l \in L \tag{10}$$

$$\sum_{s \in S, s \le l} \sum_{v \in S, v > l} q_{s,v}^{i} \le p_{l}^{i} \cdot b^{p} \quad \forall i \in I, l \in L \tag{11}$$

$$\sum_{f \in F, o_f \le l, d_f > l} y_{f}^{i} \le fr_{l}^{i} \cdot b^{fr} \quad \forall i \in I, l \in L \tag{12}$$

(4) Passenger flow conservation constraints

All passenger demands must be served, and the passenger flow conservation constraint is given by:

$$\sum_{i \in I} q_{s,v}^{i} = q_{sv}, \forall (s,v) \in RS \tag{13}$$

(5) Express Freight Constraints

To ensure that the train stop plan satisfies the origin-destination and time window requirements of express freight, the freight assignment scheme can be formulated as follows:

$$t_{i,o_f}^{\,d} \ge te1_{o_f}^{g_f} - M \cdot (1 - y_{f}^{i}) \ \ \forall i \in I, f \epsilon F \tag{14}$$

$$t_{i,o_f}^{\,d} \le te3_{o_f}^{g_f} + M \cdot (1 - y_{f}^{i}) \ \ \forall i \in I, f \epsilon F \tag{15}$$

$$y_{f}^{i} \le x_{i}^{o_f}, \forall i \in I, f \epsilon F \tag{16}$$

$$y_{f}^{i} \le x_{i}^{d_f}, \forall i \in I, f \epsilon F \tag{17}$$

$$\sum_{i \in I} y_{f}^{i} \le 1, \forall f \in F \tag{18}$$

Equations (14) and (15) characterize the coupling relationship between trains and freight. For any train i, it can undertake the transportation task of express box f only if its departure time falls within the specified time window for that freight. Equations (16)–(17) ensure that a train can transport express box f only if it stops at both the origin and destination stations of the shipment.

For express box f, if it departs from the origin station within the specified soft time window, the shipment can reach the consignee as soon as possible. However, if it is dispatched within the hard time window, the delivery time will be delayed. Therefore, the revenue obtained from transporting express box f is defined as follows.

$$m_{f}^{i} = \begin{cases} n_{o_f,d_f}^{g_f} & , te1_{o_f}^{g_f} \le t_{i,o_f}^{\,d} \le te2_{o_f}^{g_f} \\ n_{o_f,d_f}^{g_f} \cdot \alpha_{g_f} & , te1_{o_f}^{g_f} \le t_{i,o_f}^{\,d} \le te2_{o_f}^{g_f} \end{cases}, \forall i \in I, f \epsilon F \tag{19}$$

The dwell time of a train at a station must not only satisfy overtaking constraints, but also meet the loading and unloading time requirements for express freight operations at the station.

$$t_{i,s}^{\,d} - t_{i,s}^{\,a} \ge \rho_i \cdot \sum_{f \epsilon F, o_f = s \| d_f = s} y_{f}^{i}, \forall i \in I, s \in S_i / \{o_i, d_i\} \tag{20}$$

C. *Objective function*

The optimization objectives for train timetabling and stop planning in high-speed rail mixed transportation systems are to increase operator revenue and reduce operational costs. The first objective is passenger revenue, as shown in Equation (21).

$$Z_1 = \sum_{(s,v) \in RS} \sum_{i \in I_{s,v}} q_{s,v}^{i} \cdot z_{s,v}^{i} \tag{21}$$

The express freight revenue for box f is determined by the binary variable y_{f}^{i}, indicating whether box f is transported by train i, and the revenue variable m_{f}^{i} for box f transported by train i. Therefore, the total express freight revenue Z_2 in the high-speed railway system can be expressed as follows:

$$Z_2 = \sum_{\forall i \in I, f \epsilon F} y_{f}^{i} \cdot m_{f}^{i} \tag{22}$$

The train stop plan directly affects both traction energy consumption and the service quality of high-speed rail operations. Therefore, minimizing the total number of train stops is considered to avoid unnecessary stops. The total stop cost Z_3 can thus be expressed as follows:

$$Z_3 = \delta \cdot \sum_{i \in I} \sum_{s \in S_i} x_{i}^{s} \tag{23}$$

In summary, the objective function of the model, Z, is given by:

$$\max Z = \sum_{(s,v) \in RS} \sum_{i \in I_{s,v}} q_{s,v}^{i} \cdot z_{s,v}^{i} + \sum_{\forall i \in I, f \epsilon F} y_{f}^{i} \cdot m_{f}^{i} - \delta \cdot \sum_{i \in I} \sum_{s \in S_i} x_{i}^{s} \tag{24}$$

D. *Model linearization*

(1) Linearization of express box revenue constraints.

To avoid nonlinear constraints in the model, constraint

(19) is reformulated by introducing two continuous auxiliary variables, τ_f^i and ϕ_f^i, and two binary auxiliary variables, μ_f^i and ν_f^i. The reformulated constraint can then be represented by the following set of linear constraints:

$$\mu_f^i + \nu_f^i = y_f^i, \forall i \in I, f \epsilon F \tag{25}$$

$$\tau_f^i \le n_{o_f,d_f}^{g_f} \cdot \mu_f^i, \forall i \in I, f \epsilon F \tag{26}$$

$$\tau_f^i \ge n_{o_f,d_f}^{g_f} \cdot \mu_f^i, \forall i \in I, f \epsilon F \tag{27}$$

$$\phi_f^i \le n_{o_f,d_f}^{g_f} \cdot \alpha_{g_f} \cdot \nu_f^i, \forall i \in I, f \epsilon F \tag{28}$$

$$\phi_f^i \ge n_{o_f,d_f}^{g_f} \cdot \alpha_{g_f} \cdot \nu_f^i, \forall i \in I, f \epsilon F \tag{29}$$

$$t_{i,o_f}^{d} \ge te1_{o_f}^{g_f} \cdot \mu_f^i + te2_{o_f}^{g_f} \cdot \nu_f^i - (1 - y_f^i) \cdot M, \forall i \in I, f \epsilon F \tag{30}$$

$$t_{i,o_f}^{d} \le te2_{o_f}^{g_f} \cdot \mu_f^i + te3_{o_f}^{g_f} \cdot \nu_f^i + (1 - y_f^i) \cdot M, \forall i \in I, f \epsilon F \tag{31}$$

$$m_f^i = \tau_f^i + \phi_f^i, \forall i \in I, f \epsilon F \tag{32}$$

μ_f^i and ν_f^i are used to determine whether freight f is transported by train i and whether the shipment incurs a penalty when assigned to train i. When $y_f^i = 0$, it indicates that freight f cannot be transported by train i, and thus $\mu_f^i = \nu_f^i = 0$. In this case, constraints (26)–(29) and (32) ensure that $m_f^i = 0$.

When freight f is transported by train i, $y_f^i = 1$, and either μ_f^i and ν_f^i must be equal to 1. In this case, constraints (31)–(32) determine the relationship between the departure time of train i and the time windows for the shipment. If the departure time falls within the soft time window, then $\mu_f^i = 1$, and constraints (26)–(27) ensure that the maximum revenue is achieved, i.e., $m_f^i = \tau_f^i = n_{o_f,d_f}^{g_f}$. If the departure time falls within the hard time window, then $\nu_f^i = 1$, and constraints (28)–(29) ensure that the freight revenue is penalized, i.e., $m_f^i = \phi_f^i = n_{o_f,d_f}^{g_f} \cdot \alpha_{g_f}$.

(2) Linearization of the objective function.

To address the product of binary and continuous variables in Equation (22), a new variable κ_f^i and several auxiliary constraints are introduced to replace the nonlinear expression in the objective function.

$$\kappa_f^i \le M \cdot y_f^i, \forall i \in I, f \epsilon F \tag{33}$$

$$\kappa_f^i \le m_f^i, \forall i \in I, f \epsilon F \tag{34}$$

V. Numerical Experiments

A. Basic Data

A case study is conducted on the Wuhan–Guangzhou high-speed railway (HSR), one of the busiest passenger corridors in China, consisting of 17 stations in the downbound direction from Wuhan to Guangzhou South. This corridor is chosen for its large passenger volume and diverse station characteristics, making it representative for evaluating passenger–freight integrated operations. Figure 2 shows the spatial distribution of passenger demand, with stations indexed from 1 to 17.

Operational data, including ticket fares and sectional travel times, are collected from the 12306 platform. A total of 56 downbound trains are considered, reflecting heterogeneous service patterns. To capture realistic operational constraints, dwell times at intermediate stations are bounded between 2 and 10 minutes, with an additional 2 minutes of start-up and 3 minutes of stopping time. The minimum headway for both arrivals and departures is set to 3 minutes. Each train is composed of 8 carriages, with a passenger capacity of 100 persons or 50 standardized express boxes per carriage. The average handling time per express box is 0.01 minutes, and the cost of each additional stop is assumed to be 500 RMB.

On the freight side, owing to the limited availability of actual operational data, synthetic demand is generated based on regional express market characteristics along the corridor. As illustrated in Figure 3, the dataset consists of 5,650 express boxes distributed across categories and stations, which serves as a representative basis for model evaluation. The express demand is classified into three categories with distinct delivery time requirements. The corresponding soft time windows are depicted in Figure 4, where revenue discounts are imposed if deliveries occur outside the specified windows (penalty coefficients of 0.75, 0.66, and 0.88, respectively).

This case setting reflects the essential operational features of the Wuhan–Guangzhou HSR and ensures that the subsequent computational results are representative of real-world passenger–freight integration challenges.

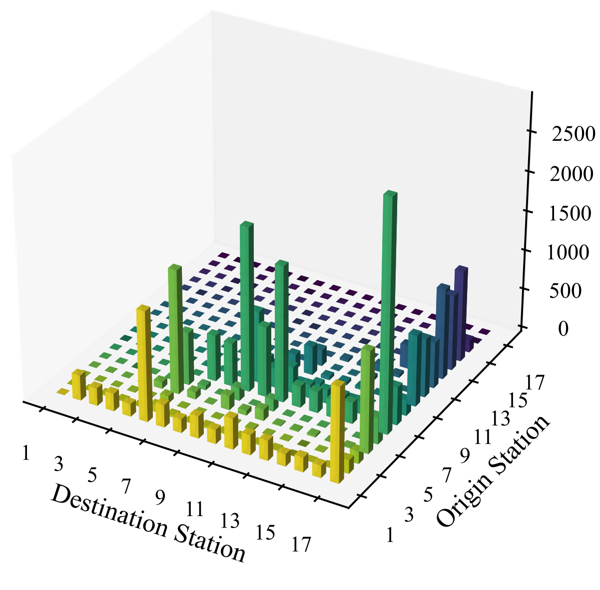
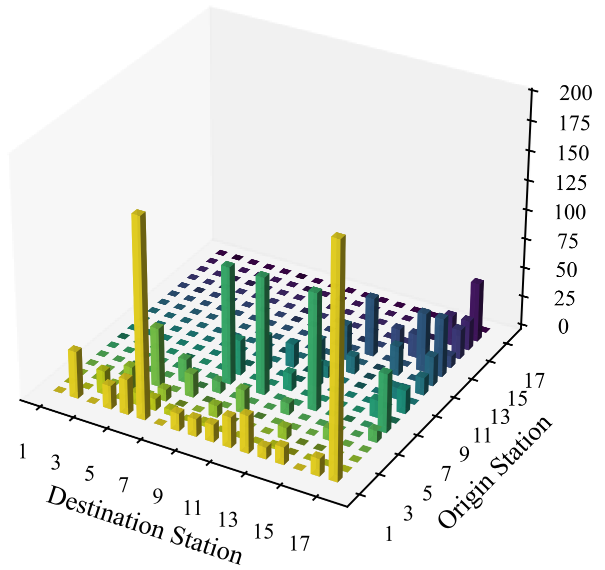


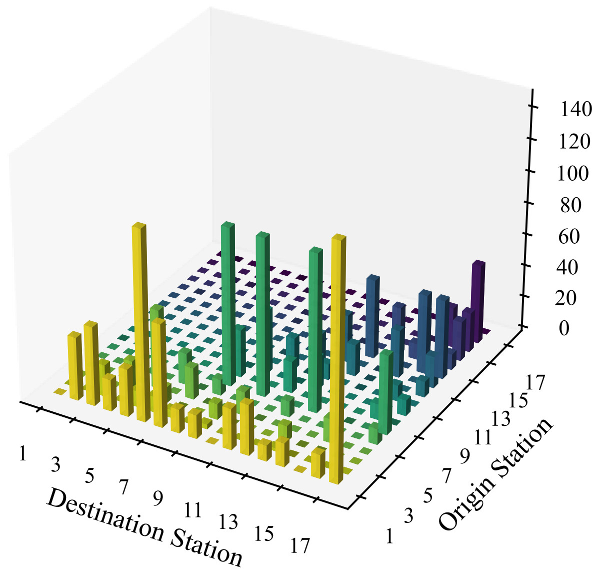
Fig. 2. Passenger Demand

B. Results analysis

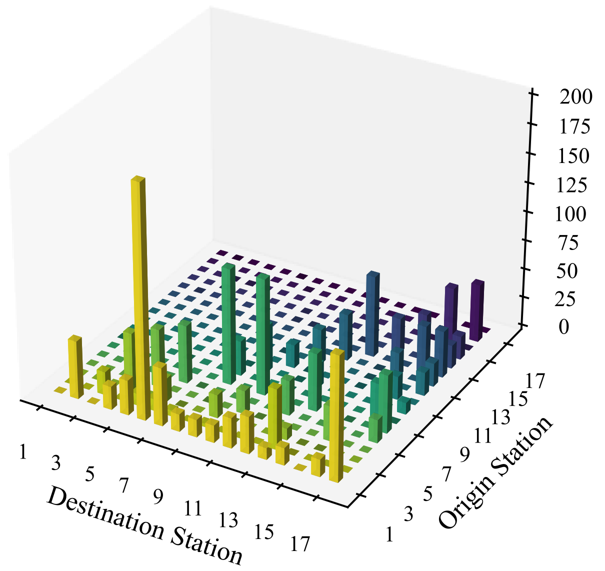
The model was solved using GUROBI, yielding a solution after 409 seconds with an objective value of 6,931,302.29 (comprising passenger revenue of 6,811,206 yuan and express freight revenue of 403,646.03 yuan) and a gap of 3.9398%. A total of 5,103 express boxes were transported, achieving a completion rate of 90.32%. The optimized train timetable is illustrated in Figure 5. Most trains operate within the maximum revenue time windows for express shipments at each station, with only a few trains scheduled outside these optimal windows. This arrangement ensures that the time-sensitivity requirements of express shipments are effectively met, thereby improving the quality of high-speed rail express services. At the same time, the influence of the express freight time windows ensures that train travel times are well controlled, maintaining a high level of passenger service quality. The total number of train stops after optimization is 594. The train stop patterns are influenced by factors such as ticket prices, passenger demand, express freight requirements, time window constraints for express shipments, and operational safety considerations, resulting in variability in stop patterns among different trains.



(a) Express Freight Demand of Class 1



(b) Express Freight Demand of Class 2



(c) Express Freight Demand of Class 3

Fig. 3. Express Freight Demand

The optimized express freight allocation scheme is shown in Figure 6. A total of 5,103 express boxes were served by trains, resulting in a transportation rate of 90.32%. Many express shipments exhibit OD connectivity; for example, Train 1 delivers express boxes from Wuhan, Xianning North, Chibi North, and Changsha South to Shaoguan for unloading, while simultaneously loading new shipments at Shaoguan for subsequent stations along the route. At Shaoguan Station, Train 1 performs both loading and unloading operations, maximizing the utilization of station dwell time, increasing train operating revenue, and improving the load factor of express freight carriages.

A comparison of Figures 4 and 5 reveals that although Train 2 only transports express boxes with OD pair (1, 17), it satisfies a large volume of passenger demand, resulting in a higher number of stops. Additionally, considering the impact of train stop costs in the model, passenger and express freight demands with the same origin or destination stations are preferentially assigned to the same train, thereby maximizing the utilization of high-speed railway transport resources.

The passenger carriage occupancy rates and express freight carriage load factors are shown in Figure 7. For trains 11 to 16 and trains 26 to 31, the passenger carriage occupancy rates are close to 1, indicating that the passenger carriage capacity is fully utilized. Trains transporting express boxes also demonstrate high load factors for express freight carriages, further reflecting the efficient utilization of express freight capacity.

C. Sensitivity Analysis

(1) Analysis of Passenger Demand Variations

Passenger demand is a direct factor influencing the allocation of train transportation capacity, train timetabling, and stop planning. A case study was conducted to analyze the impact of passenger demand variations on the optimization results, as shown in Figure 8. As passenger demand increases, both the objective function value and passenger revenue rise, with the latter exhibiting a linear growth trend. However, express freight revenue and the total volume of transported express boxes show an overall decline as passenger demand increases, since more carriages are allocated for passenger transport, thereby reducing freight capacity. The decline in freight revenue displays fluctuations, which are primarily attributable to the influence of train stop costs.

As passenger demand grows, both the number of train stops and the total travel time gradually increase. When passenger demand reaches 1.5 times the base level, the number of stops and total travel time tend to stabilize. This is because, as long as the demand remains within the maximum transport capacity of the trains, boarding and alighting will occur at the corresponding stops. Therefore, when the number of stops stabilizes, the total travel time also tends to stabilize. Notably, the trends of total travel time and the number of stops do not completely coincide, as total travel time is also affected by operational safety requirements and the loading and unloading time for express boxes.

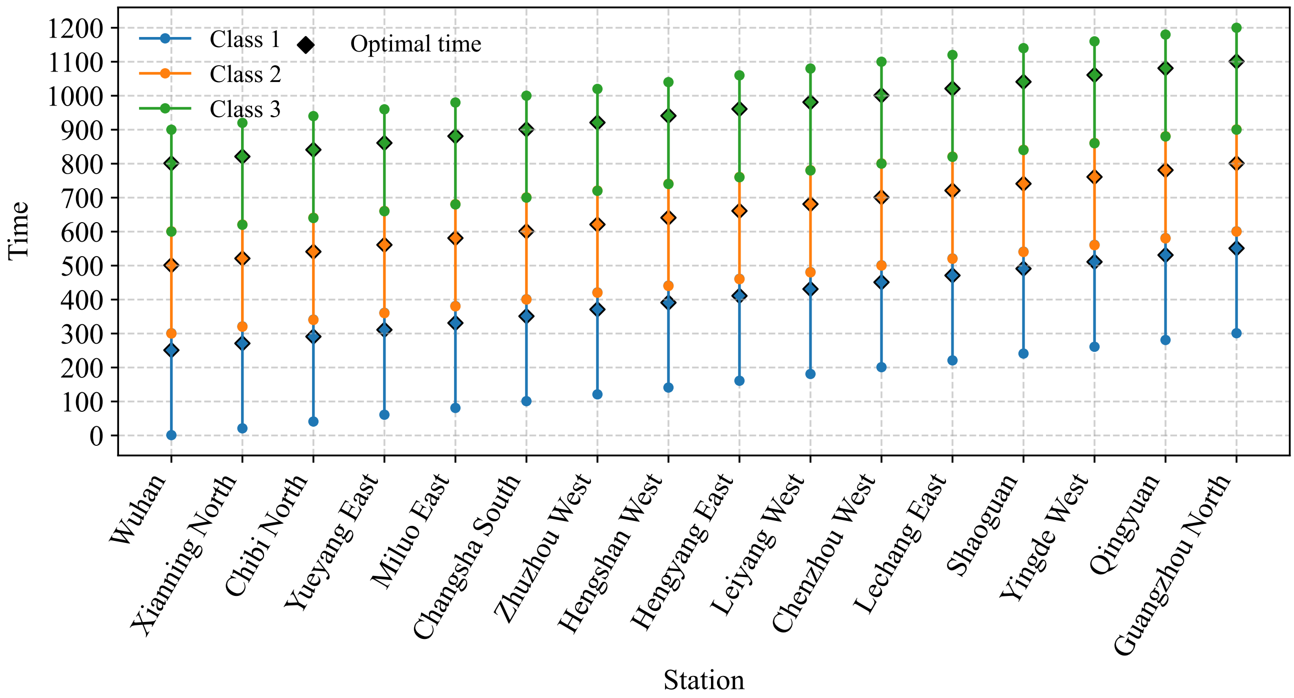


Fig. 4. Time Windows for Different Levels of Express Delivery Demand

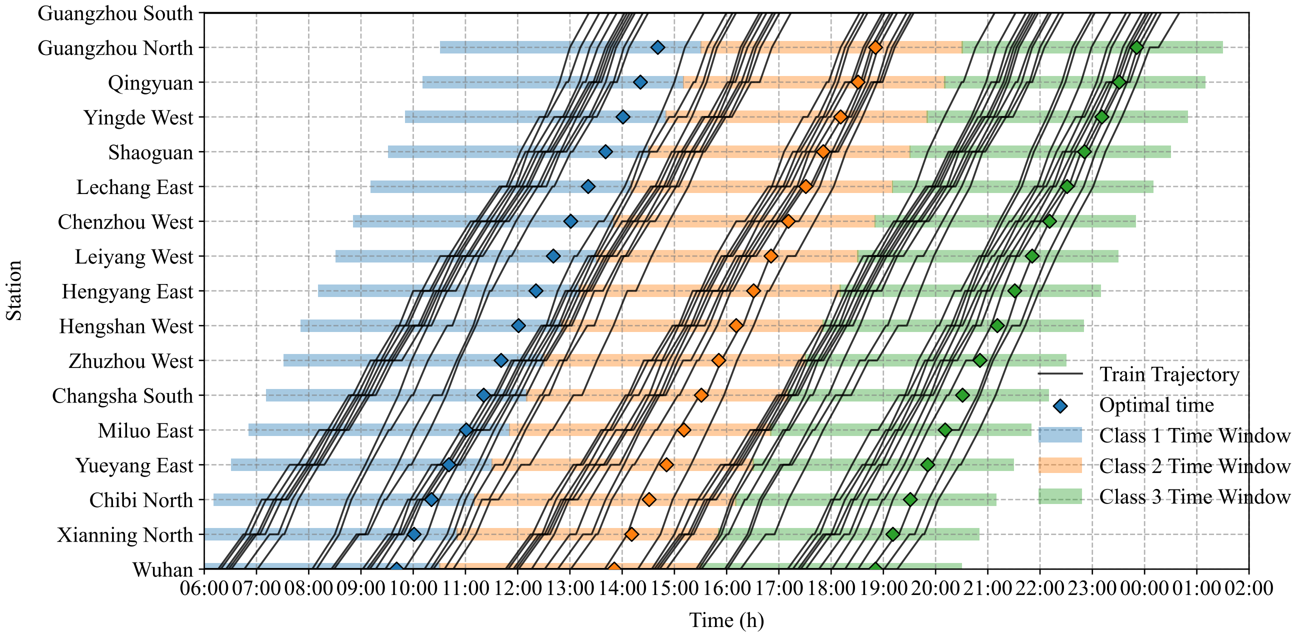


Fig. 5. Optimized Train Timetabling and Stop Planning

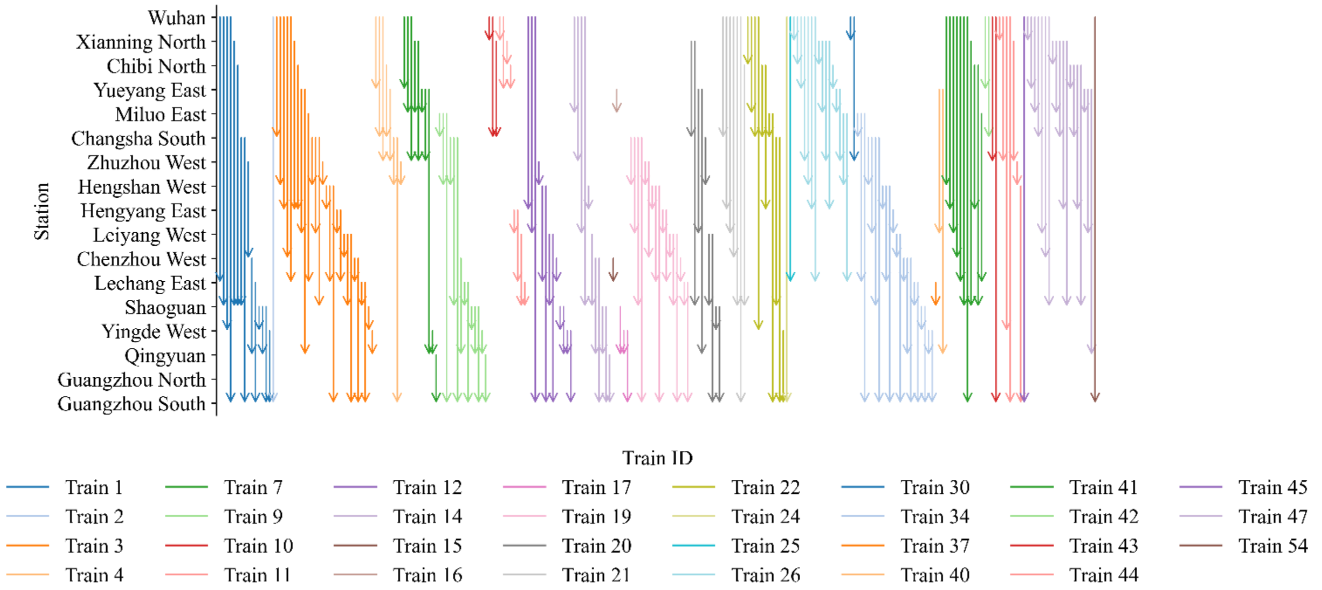
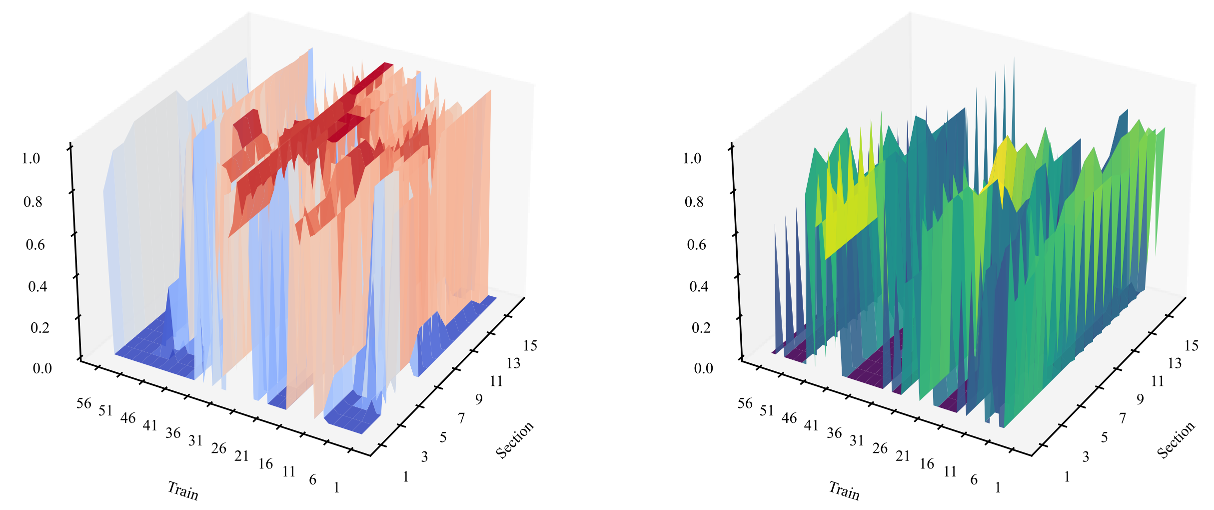


Fig. 6. Express Box Allocation Scheme



(a) Passenger Carriage Load Factors of Trains

(b) Freight Carriage Load Factors of Trains

Fig. 7. Utilization of Passenger and Freight Carriage Capacity

(2) Analysis of Stop Cost Variations

Train stopping is a critical determinant of both revenue generation and the balance between passenger and freight services in high-speed rail operations. Figure 9 presents the sensitivity analysis with respect to stop cost variations. As stop cost increases, the objective function value exhibits a clear downward trend, driven by simultaneous reductions in both passenger and freight revenues. Passenger revenue, jointly determined by ticket prices and passenger allocations, generally decreases with higher stop costs, though with greater volatility, since some passengers are shifted to higher-fare trains while the system adjusts to maximize overall revenue. Express freight revenue shows a similar declining pattern but is strongly influenced by both transported volumes and time-dependent delivery windows; for instance, when the stop cost is set at 300, freight volume peaks, yet revenue is lower than at 500 due to misalignment with profitable dispatch periods. Meanwhile, higher stop costs reduce the number of stops, thereby shortening total travel time. Once stops and travel time decline to certain thresholds, the system stabilizes to ensure that all passenger demand is fully satisfied. These results highlight the trade-off imposed by stop costs: while higher costs can enhance operational efficiency by limiting stops and reducing travel times, they simultaneously erode total revenue and induce non-monotonic fluctuations in passenger and freight performance due to discrete adjustments in train stopping patterns.

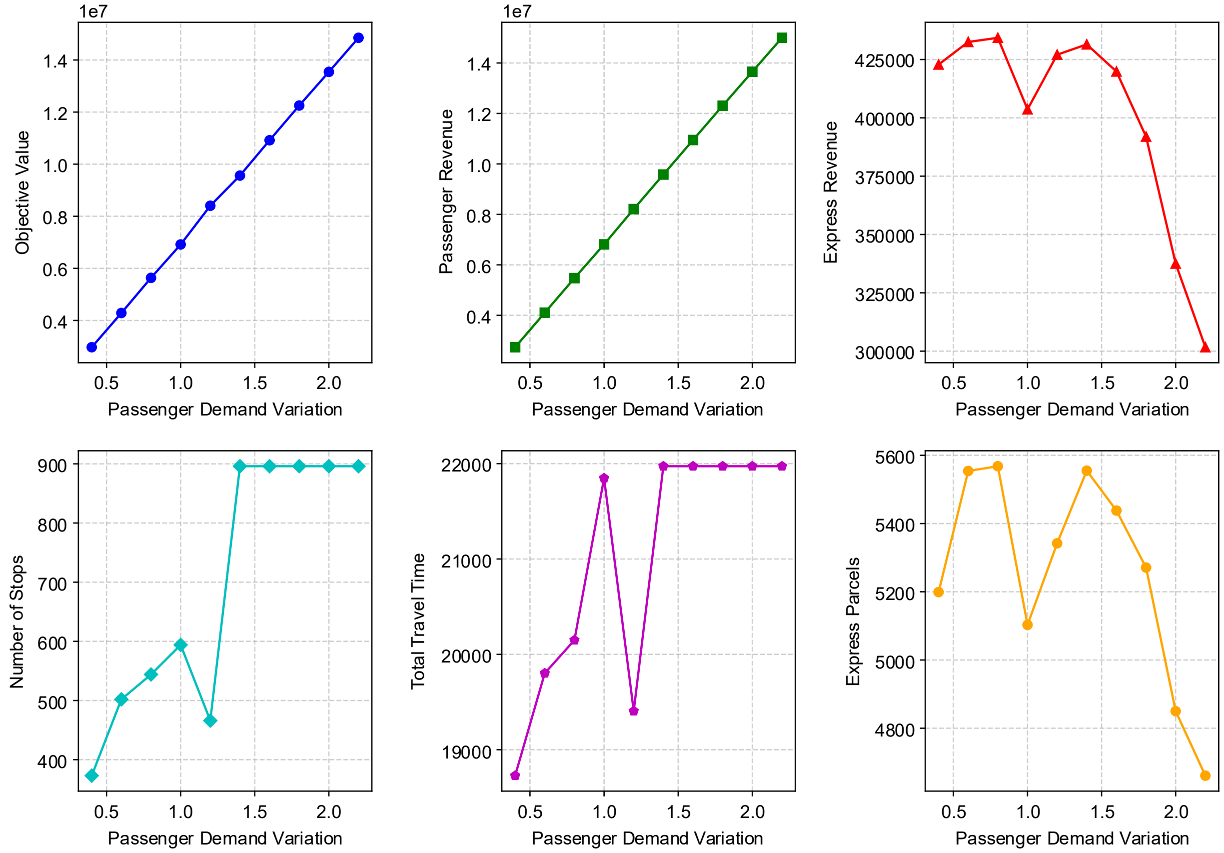


Fig. 8. Sensitivity Analysis of Passenger Demand

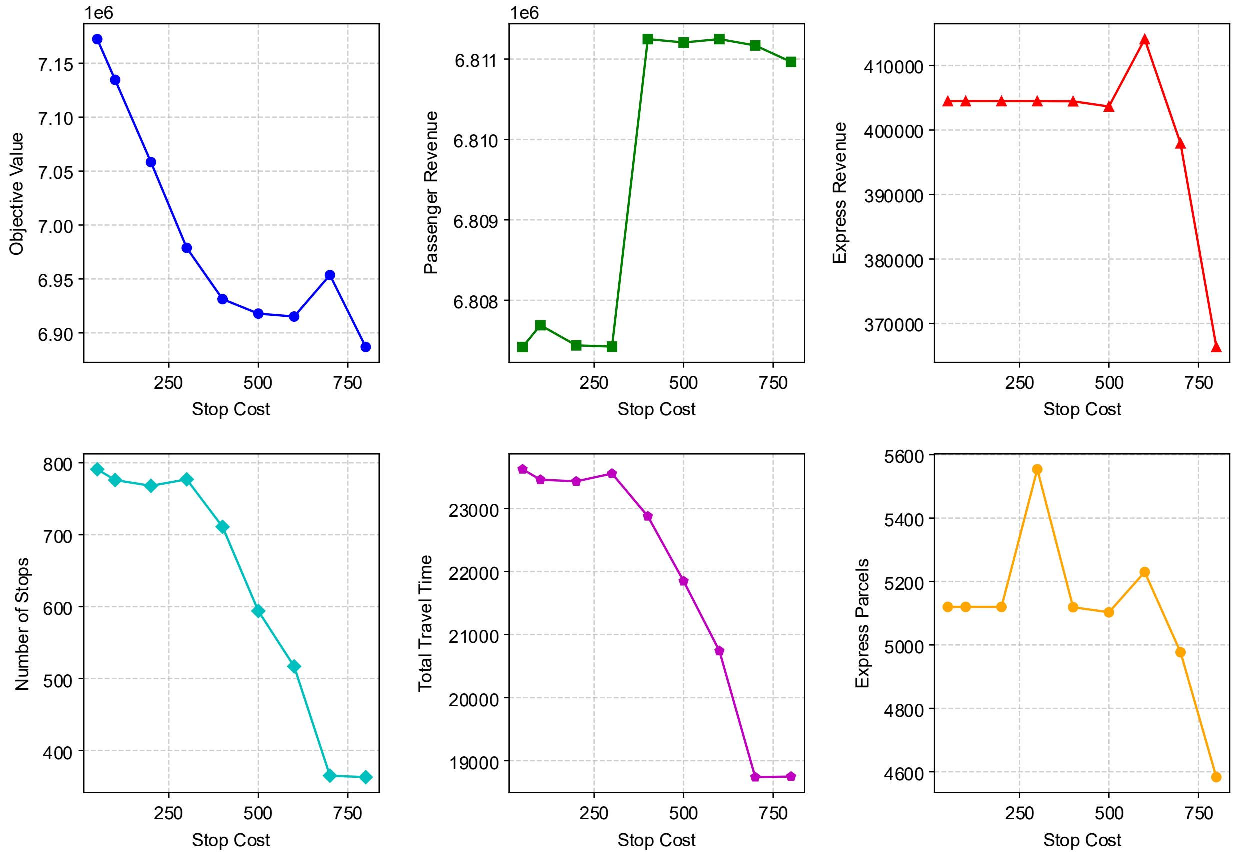


Fig. 9. Sensitivity Analysis of Train Stop Cost

D. Comparison with phased optimization

To compare integrated and sequential optimization for high-speed rail express freight services, we design a two-stage optimization framework. In the first stage, the Train Planning Model (TPM) is formulated to optimize train timetables, stop patterns, and passenger flow allocation. Using the resulting timetable, stop plan, and passenger assignment as inputs, the second stage develops the Cargo Allocation Model (CAM) to optimize express freight loading. The sequential approach thus optimizes passenger services first and freight services subsequently, whereas the integrated approach coordinates both simultaneously. Table 3 reports the comparative results of the two approaches.

$$TPM\begin{cases}\max & Z_1+Z_3\\ s.t. & Constraints(1)-(11),(13)\end{cases} \tag{35}$$

$$CAM\begin{cases}max\ \kappa_f^i\\ s.t.\ \ Constraints(12),(14)-(18)\\ \qquad\qquad ,(20),(25)-(34)\end{cases} \tag{36}$$

TABLE III
THE VARIABLES USED IN THE MODEL

Optimization	Passenger Revenue	Freight Revenue	Express Box
phased	6725792	250600	3269
collaborative	6811206	403646	5103

As shown in Table 3, the phased optimization approach focuses solely on satisfying passenger demand through timetable and stop pattern planning, without accounting for express freight requirements. Consequently, this approach results in a substantial reduction in freight volumes and corresponding revenue relative to the collaborative optimization model. In addition, the phased approach leaves a considerable portion of the available carriage capacity unused, reflecting inefficiencies in resource utilization.

In contrast, the collaborative optimization model simultaneously considers both passenger and freight demands when determining timetables, stop patterns, and allocation decisions. By coordinating these elements, it not only increases total operational revenue but also achieves more balanced and efficient use of carriage capacity. This joint optimization further enhances the adaptability of train services to varying market conditions, ensuring that passenger service quality is preserved while freight demand is effectively accommodated. The results highlight the practical value of collaborative optimization in improving overall system performance and providing decision support for high-speed rail operators facing multimodal service demands.

VI. CONCLUSIONS

(1) This study proposes a collaborative optimization framework for high-speed railway timetabling and stop planning, explicitly driven by the time-window constraints associated with express freight services. The developed model simultaneously optimizes train stop patterns, departure and arrival schedules, freight container allocations, and passenger flow assignments. By thoroughly incorporating the time-sensitive characteristics of express freight alongside passenger service quality considerations, the proposed framework systematically integrates various operational constraints, effectively addressing the complexity inherent in multi-time-window coordination within high-speed railway operations.

(2) With dual objectives of maximizing total system revenue and ensuring timely delivery of express freight, the optimized timetable and stop plan achieve a balanced integration of passenger and freight transportation demands. Through strategically adjusting train stops and schedule allocations, the model effectively ensures that the majority of express consignments satisfy their respective time-window constraints, without compromising passenger comfort and service punctuality. This coordinated approach results in notable enhancements in overall operational profitability and resource utilization efficiency.

(3) The model not only enhances train transport revenue but also guarantees passenger convenience and the timely fulfillment of express freight demand, thereby unlocking the full potential of high-speed rail transport systems. The integrated optimization approach provides railway operators with a more scientific and effective decision-making tool for operational management, particularly under scenarios involving multiple, sometimes conflicting, constraints.

(4) This paper employs a single high-speed rail corridor as a case study. Future research will extend the proposed methodology to address the organizational and operational optimization challenges inherent in integrated passenger–freight transportation systems across more complex, multi-line high-speed railway networks. Such extensions will further enhance the generalizability and practical applicability of the optimization approach developed in this study.

(5) Compared to traditional optimization frameworks driven solely by passenger demand, the proposed collaborative optimization approach—driven jointly by passenger needs and time-sensitive freight requirements—generates timetables and stop plans that better align with the integrated demands of high-speed passenger–freight transportation. By explicitly incorporating freight time-window constraints into scheduling decisions, the framework effectively accommodates heterogeneous service priorities, thereby achieving superior system coordination, enhanced operational performance, and improved service quality across both passenger and freight domains.

(6) Beyond its methodological and empirical contributions, this research also provides important managerial insights. It demonstrates that collaborative optimization can serve as a practical tool for railway operators to reconcile the competing demands of passenger and freight services, improve utilization of scarce network capacity, and enhance the resilience of operations under varying market conditions. These findings offer a valuable reference for the future design of high-speed railway systems that aspire to function as integrated passenger–freight service providers.

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Juhua Yang was born in Gansu, China. She obtained her Ph.D. degree from the School of Traffic and Transportation, Lanzhou Jiaotong University. She is now a professor at the same school. She has rich scientific research achievements and has published numerous papers in domestic academic journals and international conferences.

Junfeng Zhang was born in Dingxi, Gansu Province, China. He obtained his Bachelor of Engineering degree from Lanzhou Jiaotong University in June 2023. In September 2023, he began his postgraduate studies at the School of Transportation, Lanzhou Jiaotong University. His research focuses on railway transportation organization and high-speed rail passenger–freight integrated operation. He has published one EI-indexed paper in this field.

Zhiqiang Tian was born in Gansu, China, in 1981. In October 2011, he obtained his Ph.D. degree in Traffic and Transportation Planning and Management from Southwest Jiaotong University. He is now a professor at the School of Traffic and Transportation, Lanzhou Jiaotong University. He has rich scientific research achievements and has published numerous papers in domestic academic journals and international conferences.

Guofeng Sun was born in Dingxi, Gansu Province, China. He received his Ph.D. degree from Beijing Jiaotong University in 2025. He is currently a lecturer at Lanzhou Jiaotong University. His research interests include optimization of railway transportation organization and train service planning.

Hui Lian was born in Datong, Shanxi Province, China. She is currently pursuing her postgraduate studies at the School of Traffic and Transportation, Lanzhou Jiaotong University. Her research interests include urban rail transit operation organization and optimization.