

# Cooperative Optimization of High-Speed Railway Train Stop Planning and Timetabling

JiaXin Wang, Xu Zhang, JiaMing Gan

**Abstract**—With the rapid and advanced development of high-speed railway (HSR) in China, enhancing the coordinated adaptability of HSR train stop planning and timetabling while improving operational precision has become increasingly critical. To address this, this paper tackles the limitations of existing collaborative optimization approaches. Most conventional methods rely on two-stage models—an approach prone to goal misalignment and local optima. Therefore, this paper resolves the aforementioned issues by integrating the two stages into a single optimization phase. Specifically, it takes into account the impacts of train types and stop-start additional time on the optimization scheme, adopts inter-station origin-destination (OD) accessibility to indirectly characterize the demand for passenger flow exchange, and formulates departure time rules to maintain the stability of the train timetable structure. A multi-objective collaborative optimization model is developed, considering constraints such as station service frequency and safety intervals, with objectives including minimizing total train travel time, total number of stops, and the deviation between actual and expected departure times at the origin station. An empirical study was conducted on the 58 downbound trains of the Wuhan-Guangzhou HSR in June 2025, using solver Gurobi. Results indicated reductions in total train travel time and total stops by 2.6% and 3.5%, respectively, and a reduction of 13 overtaking events. This optimization improves accessibility between lower-tier nodes while maintaining service stability at higher-tier nodes, leading to enhanced operational efficiency, service quality, and safety. It provides valuable guidance for high-speed railway operators in developing integrated stop plans and timetables.

**Index Terms**—high-speed railway(HSR), train stop planning, timetabling, collaborative optimization, inter-station origin-destination (OD) service accessibility, departure time rules.

## I. INTRODUCTION

By the end of 2024, China's high-speed railway (HSR) network had reached an operating mileage of 48,000 kilometers, accounting for over two-thirds of the world's total HSR mileage. Endowed with core advantages of high speed, high punctuality, high safety, and high-density operations, HSR has emerged as the core capacity carrier in the passenger transport market. With the continuous growth of passenger travel demand and the increasing passenger flow density, maintaining HSR's competitive edge in the passenger transport market hinges on enhancing transport efficiency and passenger travel convenience through refined

operations. Notably, the collaborative optimization of train stopping plans and timetables stands as the core means to achieve this objective.

In existing studies, the optimization of train stopping plans and timetables has usually been treated as two independent issues. In the field of stopping plan research, some scholars have incorporated it into the train operation plan system and analyzed it in coordination with other sub-issues. For instance, Fan et al. (2021) constructed an optimization model for train operation plan from the perspective of improving passenger satisfaction, focusing on service quality and demand matching. Qin et al. (2020) and Sun et al. (2022) developed HSR train operation plan optimization models based on the space-time network theory and designed a two-layer algorithm for solution, but neither considered train classification nor the additional time for train acceleration and deceleration. Zhou et al. (2024) further expanded the research scope by integrating the collaborative optimization of ticket prices, ticket quotas, and the train operation plan. Meanwhile, other scholars have explored the stopping plan as an independent research focus. Huang et al. (2018) proposed a customer-oriented dynamic cyclic adjustment method to optimize the HSR stopping plan, improving passenger transfer efficiency through the cyclic process of "passenger flow allocation - plan evaluation - plan adjustment". Yan et al. (2019) established a 0-1 programming model for HSR stopping plan with the objective of minimizing the time occupied by train routes on the operation diagram, and solved it using the built-in algorithm of Lingo, without considering train classification. Xu et al. (2020) put forward a strategy of reducing the number of stops at medium and small stations while increasing trains that stop at every station between adjacent large stations; they also constructed a stopping plan optimization model to minimize passenger time loss, and designed a genetic algorithm for solution. Cha et al. (2022) built a multi-objective stopping plan optimization model based on the principle of prioritizing passenger flow allocation for large passenger volumes. Xu et al. (2023) explored the integrated optimization of train stopping plans and seat allocation, and verified the advantages of integrated optimization over separate optimization through comparisons. In the field of train timetable research, scholars have also achieved fruitful results. Zhang et al. (2019) and Tian et al. (2023) constructed timetable optimization models based on the space-time network theory. Niu et al. (2021) systematically summarized the current status and existing problems of existing train timetable research, pointing out that timetable optimization needs to be deeply integrated with processes such as rolling stock scheduling and stopping plans. Wang et al. (2023) further realized the collaborative optimization of rolling stock composition and timetables,

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effectively reducing the number of stranded passengers and the number of rolling stocks used.

However, the phased and independent research on stopping plans and timetables has largely weakened the connection between them. Superficially, a train stopping plan can be determined based on the arrival and departure times in the timetable; but from the perspective of hierarchical planning, the stopping plan is an upper-level route planning issue-its settings directly affect the foundation and boundaries of timetable optimization, while timetable optimization in turn exerts a reverse impact on the feasibility of the stopping plan. Therefore, the collaborative optimization of stopping plans and timetables is an inevitable requirement for maximizing the overall efficiency of the HSR system. A number of scholars have conducted relevant research on their collaborative optimization. Yue et al. (2016) proposed a novel method based on the train generation algorithm, integrating passenger demand and train scheduling to optimize stop planning and train timetabling in two steps. Altazin (2017) addressed train scheduling under minor disruptions by constructing a linear integer programming model. This model considers train skipping and vehicle constraints, aiming to minimize system recovery time, passenger waiting time, and weighted skipping frequency. Yan (2019) and Li (2023) employed a two-stage iterative approach, first determining the optimal stop planning, then using it as input for the second stage to derive the optimal timetabling. Dong et al. (2020) proposed a combined optimization model integrating both approaches by considering time-varying passenger demand. Hao et al. (2020) introduced a flexible minimum headway train control system, constructing a mixed-integer linear programming model to maximize total train revenue while accounting for symmetric transportation demand, and designed a genetic algorithm for the solution. Zhang et al. (2023) addressed passenger demand uncertainty by constructing an ILP model based on scenario-based demand and spatiotemporal networks, jointly optimizing total travel time for trains and passengers alongside passenger supply-demand matching. Gao et al. (2025) proposed a two-stage solution algorithm for the collaborative optimization model, first solving the train stop plan before generating the train timetable.

By reviewing existing collaborative optimization studies, we have identified several shortcomings. First, most scholars adopt a two-stage approach to optimize stopping plans and timetables sequentially. However, phased optimization tends to lead to target disconnection and local optimality; moreover, cross-stage iteration increases computational complexity, making it difficult to adapt to the high-density operation requirements of HSR. Second, in actual line operations, there are many types of trains, such as flagship trains and ordinary trains, as well as through trains and regional trains. Nevertheless, few studies have considered the relationship between different train types and the formulation of stopping plans or timetables. Third, the additional time for train acceleration and deceleration is a critical factor in the train operation process, yet most scholars often overlook this factor to simplify their models. Finally, each train has a corresponding expected departure time at the origin station. However, if trains depart strictly according to the expected departure time in actual operation, conflicts between trains

may occur due to unreasonable setting of such times. As a result, most scholars usually set an allowable delay range for trains, only permitting departures later than the expected time. This constraint is too strict and contradicts the need for flexibility in actual operation and dispatching.

To address the aforementioned shortcomings in existing research, this study integrates the optimization of stopping plans and timetables into the same stage, constructing a multi-objective collaborative optimization model to fundamentally avoid the inherent defects of two-stage models. The framework for train stop planning and timetabling optimization is illustrated in Figure 1. First, train types are classified based on train grades and operating sections, and designs targeted optimization strategies. Meanwhile, constraints on departure times are relaxed, allowing trains to depart within a reasonable range around the expected departure time to align with actual operation scenarios. To minimize modifications to the timetable structure and accommodate passengers' travel time habits, this study formulates rules for selecting train departure times. In addition, to address the difficulty in obtaining origin-destination (OD) data, the indicator of inter-station service accessibility is introduced to indirectly characterize the demand for passenger flow exchange. This study aims to provide more practical theoretical support and decision-making references for the refined operation and management of HSR.

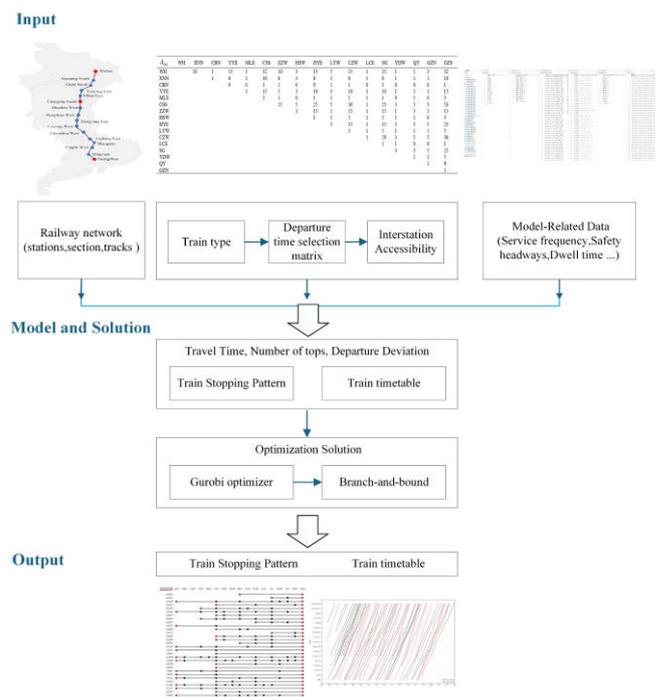


Figure 1. Framework of the train stop planning and timetabling optimization methodology

The main contributions of this study are as follows:

- (1) A novel collaborative optimization model for HSR stopping plans and timetables is proposed. This model abandons the traditional "two-stage" method that tends to cause target disconnection, and jointly solves the stopping plan and timetable in the same stage.
- (2) Train types are classified based on train grades and operation sections, and departure time selection rules are

formulated. A multi-objective nonlinear integer programming (MNIP) model is constructed by comprehensively considering complex constraints such as station service frequency and safety intervals.

(3) The indicator of inter-station OD service accessibility is innovatively introduced, effectively addressing the industry pain point of difficulty in obtaining actual passenger flow data (OD).

(4) A large number of experiments are conducted with 58 local trains in the downward direction of the Wuhan-Guangzhou HSR line in June 2025 as the optimization object.

## II. PROBLEM DEFINITION

This study examines a HSR line, as shown in Figure 2. The line connects multiple stations, which are categorized into hub stations and intermediate stations based on the political positioning and economic development levels of their respective cities. These stations divide the entire line into several continuous operational sections. To meet diverse passenger demands, two train types operate on the line: flagship trains and regular trains. Flagship trains, characterized by higher service levels and faster speeds between stations, primarily serve long-distance passengers by stopping only at hub stations. Regular trains constitute the main operational capacity, stopping at hub stations as required while also serving select intermediate stations to accommodate local passenger flows. Train stop patterns are flexible and diverse, including non-stop service, major-station stopping, alternating major/minor-station stopping, and local stopping. In Figure 2, “a” denotes a non-stop flagship train, “b” represents a flagship train stopping at major stations, “c” indicates a regular train alternating between major and minor stations, and “d” stands for a local regular train stopping at all stations.

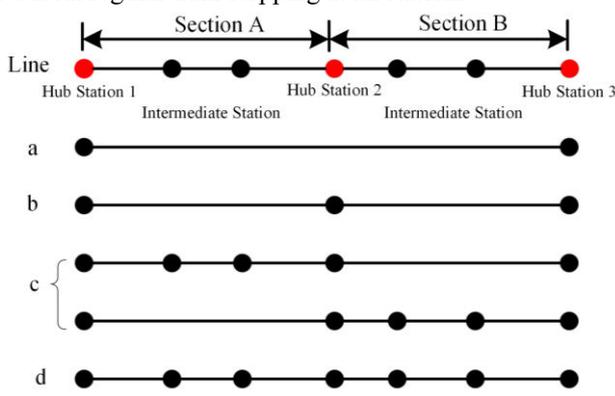


Figure 2. Stop Scheme Diagram.

Due to the significant speed difference between benchmark trains and regular trains, regular trains must yield to allow benchmark trains to overtake- to ensure the efficient operation of benchmark trains. However, this overtaking process can prolong the travel time of regular trains and even trigger operational conflicts. As illustrated in Figure 3 (where Train A represents the benchmark train and Train B represents a regular train), when Train A overtakes Train B, Train B experiences extended stopping times. Given that actual routes may involve dozens or even hundreds of trains, overtaking scenarios are commonplace, leading to increased

travel times for a greater number of trains. This paper proposes a solution by moderately adjusting train departure sequences and times. This approach reduces conflicts and time losses caused by benchmark train overtaking while satisfying stop constraints and service requirements.

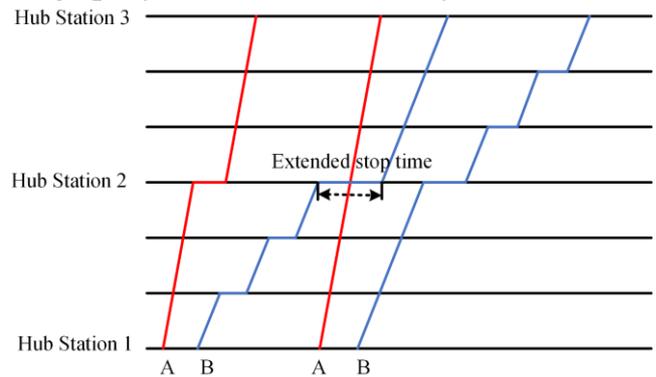


Figure 3. Operational Diagram.

## III. COLLABORATIVE OPTIMIZATION MODEL CONSTRUCTION

### 1) Model Assumptions and Symbolic Definitions

To simplify the problem, the following assumptions are made in this paper.

- (1) The high-speed railway (HSR) line operates symmetrically in both directions, thus, only one train direction is considered.
- (2) The number of trains and their respective operating sections are known and fixed.
- (3) The pure running time between stations is identical for trains of the same class.
- (4) Optimization focuses solely on stop patterns and timetables for trains operating exclusively on this line, disregarding the impact of cross-line trains.
- (5) All passengers can reach their destinations via direct trains, ignoring the effects of transfers.

The primary variables and parameters involved in the model are shown in Table 1.

Table 1 .Key Variables and Parameters of the Model.

Variables and Parameters	Symbol	Definition
Assembly	$S$	Meet at the station, $s, m, n \in S = \{1, 2, \dots,  S \}$

Decision variable	$S_i$	Set of stations the train $i$ passes through, $S_i = \{1, 2, \dots,  S_i \} \subseteq S$
	$T$	Train Assembly, $i, j \in T = \{1, 2, \dots,  T \}$
	$x_i^m$	0-1 variable: If the train $i$ stops at the $m$ station, this variable is 1; otherwise, it is 0.
	$a_i^m$	Train $i$ arrival time at the station $m$ .
intermediate variable	$d_i^m$	Departure time of the train $i$ at the station $m$ .
	$t_i^e$	Expected departure time of the train $i$ .
	$y_{ij}^m$	Variable 0-1: If Train $i$ departs from Station $m$ before Train $j$ , this variable is 1; otherwise, it is 0.
	$z_{ij}$	0-1 variable: If the train $i$ selects the departure time $t_j$ as the expected departure time, this variable is 1; otherwise, it is 0.
Parameters	$t_f$	Additional time for vehicle start-up
	$t_d$	Additional parking time
	$t_i^s$	Pure running time of the train from station $m$ to station $m+1$ .
	$t_i^{\min} / t_i^{\max}$	Minimum/maximum dwell time for the train $i$ at the station.
	$f_m^{\min} / f_m^{\max}$	Minimum/Maximum Service Frequency at the station $m$ .
	$t_j$	Departure time of the train $j$ from its starting station in the actual timetable.
	$\Delta t$	Maximum permitted variation time for train departure at the originating station.
	$l_i^{\min} / l_i^{\max}$	Minimum/Maximum Number of Stops for the train $i$ .
	$h^{dep} / h^{arr}$	Minimum departure/arrival interval between adjacent trains
	$A_{m,n}$	Inter-station OD service accessibility metric, along with the minimum number of trains stopping at both the station $m$ and the station $n$ .
	$Zmatrix_{i,j}$	Select departure time from the 0-1 matrix. When the train $i$ can choose departure time $t_j$ , $Zmatrix_{i,j}$ is 1; otherwise, it is 0.
	$\alpha_1$	Weighting coefficients for total travel time and total number of stops
	$\alpha_2$	Weighting Coefficient for Total Departure Time Variation

### 2) Objective function

From the perspective of railway authorities, the primary goal is to reduce operational costs while improving passenger satisfaction. Train travel time is closely linked to operational

costs and the quality of the passenger experience, whereas the number of stops directly affects travel duration. Consequently, train travel time and the number of stops are identified as the first two optimization objectives. Furthermore, considering passengers' time preferences, maintaining train departures as close as possible to their scheduled times is prioritized. Therefore, minimizing deviations in train departure times is selected as the third optimization goal. The specific operations are as follows:

$$\min Z_1 = \sum_{i=1}^{|T|} (a_i^{|S_i|} - d_i^1) \quad (1)$$

$$\min Z_2 = \sum_{i=1}^{|T|} \sum_{s=1}^{|S_i|} x_i^s \quad (2)$$

$$\min Z_3 = \sum_{i=1}^{|T|} |d_i^1 - t_i^e| \quad (3)$$

The linear weighting method is employed to convert the multi-objective function into a single-objective function. The objective function of the collaborative optimization model is presented as follows:

$$\min Z = \alpha_1 \left( \sum_{i=1}^{|T|} (a_i^{|S_i|} - d_i^1) + \sum_{i=1}^{|T|} \sum_{s=1}^{|S_i|} x_i^s \right) + \alpha_2 \sum_{i=1}^{|T|} |d_i^1 - t_i^e| \quad (4)$$

Where  $\alpha_1$  and  $\alpha_2$  denote the weights of train travel time, number of stops, and departure time deviation, respectively; the sum of these weights is equal to 1.

### 3) Constraints

**Station Service Frequency Constraints.** Passenger demand differs across stations of varying grades, and each station is equipped with distinct platform capacities and track configurations. To match passenger flow requirements, service frequencies must be regulated accordingly. The service frequency constraints applicable to this station are expressed as follows:

$$f_m^{\min} \leq \sum_{i=1}^{|T|} x_i^m \leq f_m^{\max}, \forall m \in S \quad (5)$$

**Constraints on the Maximum and Minimum Number of Stops per Train.** The number of stops varies by train class and operating section. Higher-class trains make fewer stops, while lower-class trains make more. To meet diverse passenger needs, restrictions must be imposed on the number of stops for each train. The constraints defining the maximum and minimum number of stops per train are expressed as follows:

$$l_i^{\min} \leq \sum_{m=1}^{|S_i|} x_i^m \leq l_i^{\max}, \forall i \in T \quad (6)$$

**Inter-Station OD Service Accessibility Constraints.** The frequency of inter-station OD services is a key indicator for evaluating the intensity of passenger demand between two stations. Stations with more frequent passenger exchanges generally have a higher demand for direct trains. The relationship between inter-station OD service frequency and train stop schemes is showed in Figure 4. As a critical constraint for optimizing stop plans, the inter-station OD service accessibility indicator is defined by the minimum total number of trains stopping at both stations simultaneously. By setting a lower bound for this total, the constraint avoids scenarios where inappropriate stop arrangements lead to the absence of direct trains between stations—thus preventing passengers from being forced to transfer—and fundamentally safeguards the basic passenger

exchange demand between stations. Given the difficulty in obtaining OD passenger flow data, determining the value of  $A_{m,n}$  is challenging. After reviewing extensive literature, this study determines this value by integrating station hierarchy with the actual inter-station OD frequency. The constraints on inter-station OD service accessibility indicators are expressed as follows:

$$\sum_{i \in T} x_i^m \cdot x_i^n \geq A_{m,n}, \forall m, n \in S_i, m < n \quad (7)$$

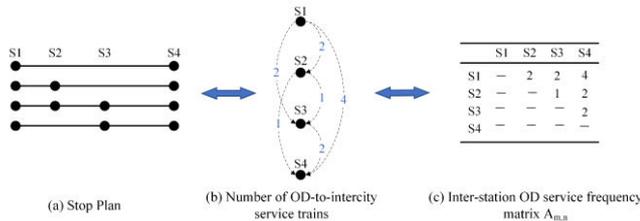


Figure 4. Relationship Diagram Between Inter-Station OD Service Frequency and Train Stop Plans.

**Start-End Point Mandatory Stop Constraint.** Logically, all trains are required to make mandatory stops at both their origin station and the destination station; this requirement is expressed as follows:

$$x_i^1 = x_i^{|S_i|} = 1, \forall i \in T \quad (8)$$

**Constraints on Train Scheduled Departure Time Selection.** To align with passenger travel habits and minimize disruption to the existing timetable structures, train departure times must be constrained. Trains may only select their departure times from the departure time options corresponding to their own type. Formulas (9) to (12) specify two key rules: first, a train's departure time can only be selected from the set of actual departure times of existing trains; second, each selected departure time must be unique. Specifically, each time point in the departure time set can be assigned to only one train, establishing a one-to-one mapping between the train set and the departure time set. The relationship between train departure time selection and train type is illustrated in Figure 5.

$$t_i^e = \sum_{j=1}^{|T|} z_{ij} t_j, \forall i \in T \quad (9)$$

$$\sum_{i=1}^{|T|} z_{ij} = 1, \forall j \in T \quad (10)$$

$$\sum_{j=1}^{|T|} z_{ij} = 1, \forall i \in T \quad (11)$$

$$z_{ij} \leq Zmatrix_{ij}, \forall i, j \in T \quad (12)$$

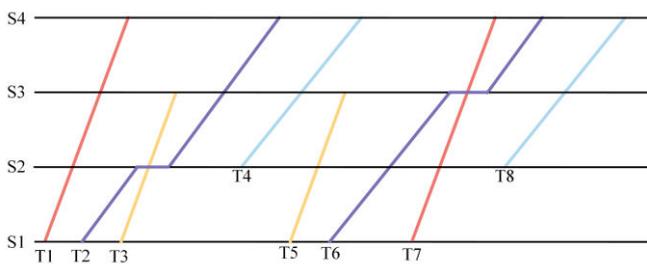


Figure 5. Timetables for Four Types of Trains.

Figure 5 illustrates four distinct train types: T1 and T7 represent benchmark trains originating from S1 and terminating at S4, while T4 and T8 denote regular trains departing from S2 and arriving at S4. A departure time selection matrix was formulated based on train departure

time selection rules, clearly demonstrating the choice of departure times for each train.

$$Zmatrix_{ij} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \end{bmatrix}$$

**Train station dwell time constraints.** When trains stop at a station, their dwell time must not exceed the specified maximum value nor fall below the specified minimum value; this constraint is expressed as follows:

$$x_i^m \cdot t_i^{\min} \leq d_i^m - a_i^m \leq x_i^m \cdot t_i^{\max}, \forall i \in S_i, \forall i \in T \quad (13)$$

**Travel time constraints between train stations.** The relationship between a train's travel time between two adjacent stations, its pure running time, and the additional start-stop time is expressed by the following formula:

$$a_i^{m+1} - d_i^m = t_{i,m}^p + x_i^m \cdot t_f + x_i^{m+1} \cdot t_d, \forall i \in T, \forall m \in \{1, 2, \dots, |S_i| - 1\} \quad (14)$$

**Train Safety Interval Constraints.** Train safety intervals are a critical design factor for ensuring operational safety of HSR. By setting minimum arrival and departure intervals between adjacent trains, these intervals ensure safe separation distances and mitigate potential safety risks. The specific constraints for the safe operational headway of trains are expressed as follows:

$$d_i^m + h^{dep} \leq d_j^m + U(1 - y_{ij}^m), \forall i, j \in T, i \neq j, \forall m \in S_i \cap S_j \quad (15)$$

$$a_i^{m+1} + h^{arr} \leq a_j^{m+1} + U(1 - y_{ij}^m), \forall i, j \in T, i \neq j, \forall m \in S_i \cap S_j \quad (16)$$

$$y_{ij}^m + y_{ji}^m = 1, \forall i, j \in T, i \neq j, \forall m \in S_i \cap S_j \quad (17)$$

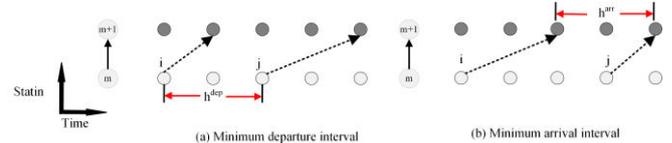


Figure 6. Train Safety Operating Interval.

**Train Departure Time Adjustment Constraints.** To minimize train conflicts, scheduled departure times may be adjusted appropriately, but such adjustments must not exceed the maximum permissible variation range. The constraints on train departure time adjustments are expressed as follows:

$$t_i^e - \Delta t \leq d_i^1 \leq t_i^e + \Delta t, \forall i \in T \quad (18)$$

**Variable Value Constraints.** Certain decision variables and intermediate variables are binary, taking values of either 0 or 1. These constraints are expressed as follows:

$$x_i^m, y_{ij}^m, z_{ij} \in \{0, 1\} \quad (19)$$

#### IV. CASE STUDY

This study focuses on the Wuhan-Guangzhou HSR, which forms the southern section of the Beijing-Guangzhou HSR and constitutes one of the vertical corridors in China's "Eight Vertical and Eight Horizontal" HSR network. With a total length 1068.8 kilometers, the line traverses three provinces and serves 17 stations. The route map is presented below,

where Guangzhou North Station and Guangzhou South Station are consolidated into a single “Guangzhou Station” for simplicity in the diagram.



Figure 7. Stations along the Wuhan-Guangzhou HSR Line.

V. BASIC DATA

This study analyzes 58 downbound trains on the Wuhan-Guangzhou HSR in June 2025, encompassing both full-route and sectional services. Among these trains, 19 are benchmark trains and 39 are regular trains. The origin stations include Wuhan Station, Yueyang East Station, Changsha South Station, Hengyang East Station, Chenzhou West Station, and Shaoguan Station, with all trains terminating at Guangzhou South Station. Stations along the southbound route from Wuhan Station to Guangzhou South Station are sequentially numbered as shown in Table 2.

The expected departure times of the trains are determined based on actual timetable data, and the trains are numbered according to their departure sequence in the operational schedule as presented in Table 3. Based on train class and operating section, the 58 trains are categorized into nine types, as shown in Table 4.

For example, “A(1,17)” denotes the benchmark train traveling from Wuhan Station(Station 1) to Guangzhou South Station(Station 17), while “B(4,17)” represents a regular train operating from Yueyang East Station(Station 4) to Guangzhou South Station(Station 17). Due to differing speeds between benchmark and regular trains, trains do not travel at constant speeds during actual operations. Therefore, this study uses the average pure running time of benchmark and regular trains in each section as the pure running time for that section, as shown in Table 5.

Table 2. Stations Along the Wuhan-Guangzhou HSR Line.

Station ID	Station	Station ID	Station	Station ID	Station
1	Wuhan	7	Zhuzhou West	13	Shaoguan
2	Xianning North	8	Hengshan West	14	Yingde West
3	Chibi North	9	Hengyang East	15	Qingyuan
4	Yueyang East	10	Leiyang West	16	Guangzhou North
5	Miluo East	11	Chenzhou West	17	Guangzhou South
6	Changsha South	12	Lechang East		

Table 3 Actual Train Schedule Information.

Train ID	Train	Origin Station	$t_j$	Train ID	Train	Origin Station	$t_j$
1	G6023	9	6:38	30	G6107	6	11:31
2	G6231	13	6:44	31	G1007	1	11:56
3	G1103	1	6:48	32	G77	1	12:07
4	G6113	6	7:08	33	G879	1	12:12
5	G6119	4	7:13	34	G6037	6	12:47
6	G1001	1	7:17	35	G881	1	12:56
7	G1003	1	7:31	36	G1189	1	13:07
8	G6013	6	7:38	37	G6183	6	13:12
9	G6015	4	7:38	38	G335	1	13:17
10	G6035	11	7:45	39	G6153	6	13:31
11	G871	1	8:00	40	G79	1	13:59
12	G6029	6	8:05	41	G1175	1	14:09
13	G6175	13	8:08	42	G341	1	14:19
14	G6041	6	8:30	43	G1579	1	14:25
15	G6209	6	8:44	44	G6005	6	15:00
16	G6361	9	8:47	45	G883	1	15:18
17	G1135	1	8:49	46	G6089	6	15:31
18	G875	1	9:00	47	G885	1	16:03
19	G6001	6	9:00	48	G6171	4	16:15
20	G1109	1	9:05	49	G337	1	16:23
21	G1005	1	9:23	50	G6011	6	16:36
22	G6109	6	9:31	51	G543	1	16:44

23	G6003	6	10:00	52	G1009	1	17:28
24	G809	1	10:04	53	G1117	1	17:38
25	G877	1	10:09	54	G6007	6	18:00
26	G541	1	10:14	55	G889	1	18:10
27	G6103	6	10:33	56	G81	1	18:15
28	G1185	1	10:45	57	G339	1	18:20
29	G547	1	11:11	58	G6027	4	18:45

Table 4. Nine Different Types of Trains.

Train Type	Train ID
A(1,17)	11,18,24,25,29,32,33,35,40,45,47,55,56
B(1,17)	3,6,7,17,20,21,26,28,31,36,38,41,42,43,49,51,52,53,57
B(4,17)	5,9,48,58
A(6,17)	19,23,44,50,54
B(6,17)	4,8,12,14,15,22,27,30,34,37,39,46
A(9,17)	1
B(9,17)	16
B(11,17)	10
B(13,17)	2,13

Table 5. Pure Running Time Between Stations for Trains of Different Classes (min).

Section	ClassA	ClassB	Section	ClassA	ClassB
WH-XNN	17	19	HYE-LYW	11	12
XNN-CBN	8	9	LYW-CZW	12	14
CBN-YYE	18	20	CZW-LCE	17	18
YYE-MLE	12	14	LCE-SG	8	9
MLE-CSS	13	15	SG-YDW	13	14
CSS-ZZW	9	10	YDW-QY	11	12
ZZW-HSW	12	14	QY-GZN	6	7
HSW-HYE	8	9	GZN-GZS	12	13

Similarly, due to variations in train grades and operating sections, the number of stops per train varies. Specific data is presented in Table 6.

Table 6. Maximum and Minimum Number of Stops for Different Train Types.

Train Type	Minimum Number of Stops	Maximum Number of Stops
A(1,17)	3	5
B(1,17)	6	11
B(4,17)	5	7
A(6,17)	2	3
B(6,17)	4	7
A(9,17)	2	3
B(9,17)	3	5
B(11,17)	3	5
B(13,17)	3	5

By compiling the number of stops made by 58 trains at each station and integrating node classification results from other scholars, the node classification results for this study are determined and shown in Table 7.

Wuhan Station, Changsha South Station, and Guangzhou South Station are designated as mandatory stop hub stations for all passing trains; thus, their service frequencies are fixed. For other stations, service frequencies are set based on node levels, with minimum and maximum

service frequencies defined. Notably, Guangzhou North Station requires special handling due to its specific operational characteristics. Detailed service frequencies for all stations are presented in Table 8, while values of other train-related parameters are listed in Table 9.

Table 7. Node Level Classification Results.

Node Level	Relevance	Hub Station
Level 1	0.8~1	Wuhan, Changsha South, Guangzhou South
Level 2	0.4~0.8	Yueyang East, Zhuzhou West, Hengyang East, Chenzhou West, Shaoguan, Guangzhou North
Level 3	0~0.4	Xianning North, Chibi North, Miluo East, Hengshan West, Leiyang West, Lechang East, Yingde West, Qingyuan

Station.

Table 8. Maximum and Minimum Service Frequency at the

Station	Minimum	Maximum	Station	Minimum	Maximum
Wuhan	32	32	Leiyang West	8	10
Xianning North	8	10	Chenzhou West	30	35
Chibi North	1	3	Lechang East	1	3
Yueyang East	15	20	Shaoguan	25	30
Miluo East	3	5	Yingde West	5	8
Changsha South	53	53	Qingyuan	8	10
Zhuzhou West	15	20	Guangzhou North	8	10
Hengshan West	5	8	Guangzhou South	58	58
Hengyang East	25	30			

Table 9. Values for Other Relevant Train Parameters.

Parameters	value	Parameters	value
$t_f$	2min	$h^{arr}$	5min
$t_d$	3min	$h^{dep}$	5min
$t_i^{min}$	2min	$\alpha_1, \alpha_2$	0.8, 0.2
$t_i^{max}$	Class A: 3min Class B: 20min	Gap	5%
$\Delta t$	10min	$U$	1000

origin-destination (OD) passenger flow data, this study employs the inter-station OD service accessibility indicator—defined as the number of direct OD trains—as an indirect measure of passenger exchange between stations. This indicator represents the minimum number of trains that must stop at both stations simultaneously; meeting this threshold is essential to ensure basic passenger travel demand and adequate service quality. The indicator’s values are determined by integrating accessibility requirements between nodes of different grades and actual OD service frequencies, with the results provided in Table 10.

Given the difficulty in acquiring actual

Table 10. Inter-Station OD Service Accessibility Indicators.

$A_{m,n}$	WH	XNN	CBN	YYE	MLE	CSS	ZZW	HSW	HYE	LYW	CZW	LCE	SG	YDW	QY	GZN	GZS
WH		10	1	15	1	32	10	3	15	5	15	1	15	1	1	3	32
XNN			1	8	1	10	8	3	8	3	8	1	8	1	1	1	10
CBN				0	0	1	1	0	0	1	1	0	1	0	0	0	1
YYE					1	15	5	3	10	3	10	1	10	1	1	1	15
MLE						3	1	0	1	1	1	1	1	0	1	0	3
CSS							15	5	25	5	30	1	25	3	5	5	53
ZZW								1	15	1	15	1	15	1	3	1	15
HSW									1	1	5	1	3	1	1	0	5
HYE										3	15	1	15	3	5	5	25
LYW											3	1	5	1	1	1	5
CZW												1	20	3	5	5	30
LCE													1	1	0	0	1
SG														3	5	5	25
YDW															1	1	5
QY																1	8
GZN																	5

Note: For convenience, in some tables, Wuhan is abbreviated as WH, and the same abbreviation rule applies to other stations.

VI. RESULTS ANALYSIS

The model solution in this study was implemented using Python 3.10 and invoked the commercial solver Gurobi 10.0.1. Gurobi demonstrates significant advantages in handling large-scale, highly complex optimization problems,

particularly for integer programming problems, where it can achieve exact solutions through branch-and-bound algorithms. The collaborative optimization model results were generated within 14,400 seconds, with a convergence rate of 1.2%. The optimized stop-station plan and train timetable obtained through the solution are presented in Figures 8 and 9, respectively.



Figure 8. Optimized Stop Plan.

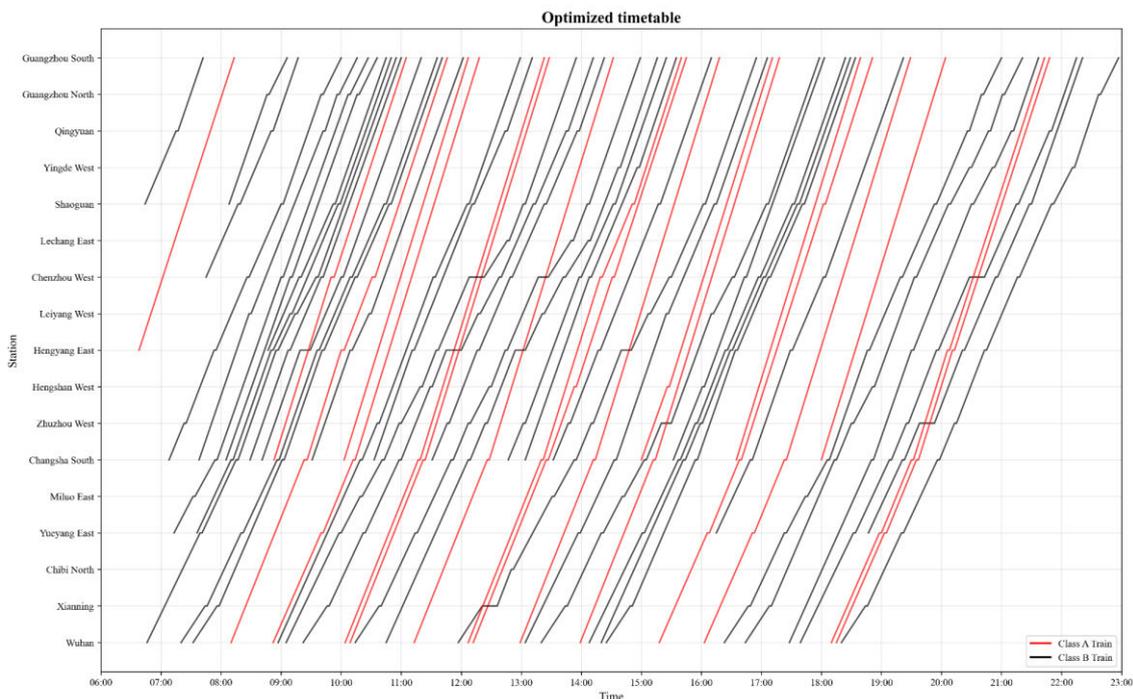


Figure 9. Optimized Timetable.

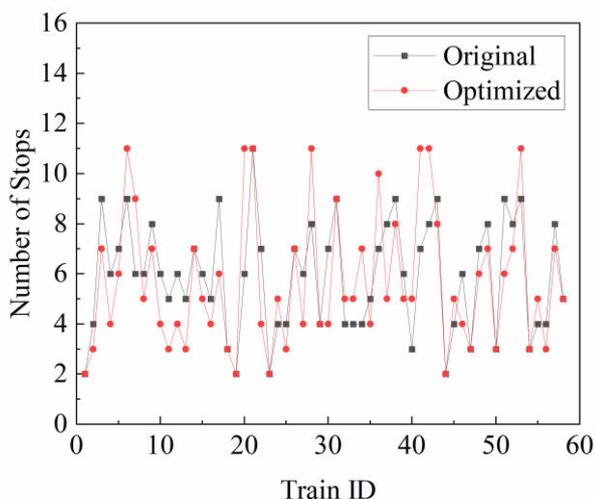


Figure 10. Comparison of Train Stops Between the Original and the Optimized Scheme.

As shown in Figure 10, the number of stops for most trains has decreased, with only a few trains experiencing an increase in stops due to constraints imposed by inter-station OD service accessibility metrics. Comparing the data before and after optimization in Table 11, the total number of train stops decreased from 343 to 331, a reduction of 3.5%, while the average number of stops per train decreased from 5.91 to 5.70. Total stop time shortened from 698 min to 539 min, total start-stop overhead time decreased from 1425 min to 1365 min, and total train travel time fell from 11790 min to 11483 min, saving 307 min. This optimization plan directly reduces train idle time and start-stop time losses, decreases rolling stock occupancy time, and effectively controls operating costs while enhancing line throughput efficiency.

Table 11. Comparison of Data Between Original Scheme and Optimized Scheme.

	Stops	Stops Time	Additional Time	Travel Time	Departures Time Deviation
Original	343	698	1425	11790	-
Optimized	331	539	1365	11483	77
difference	12	159	60	307	-
Percentage	3.5%	22.78%	4.2%	2.6%	-

Table 12. Comparison of Station Service Frequency Between Original Scheme and Optimized Scheme.

Station	Original	Optimized	Station	Original	Optimized	Station	Original	Optimized
WH	32	32	XNN	12	10	CBN	1	1
YYE	20	20	MLE	5	5	CSS	53	53
ZZW	19	16	HSW	7	7	HYE	31	30
LYW	9	9	CZW	36	34	LCE	3	3
SG	31	28	YDW	7	7	QY	11	10
GZN	8	8	GZS	58	58			

Table 13. Comparison of Service Frequency Between Nodes Between Original Scheme and Optimized Scheme.

OD Service Frequency	Original Plan	Optimized	Difference
Level 1~Level 1	117	117	0
Level 1~Level 2	354	354	0
Level 1~Level 3	140	136	-4
Level 2~Level 2	176	173	-3
Level 2~Level 3	168	171	+3
Level 3~Level 3	31	36	+5

As shown in Table 12, the service frequency at primary nodes remains unchanged, aligning with the rigid travel demands of high-density passenger flows at hub stations and ensuring the stability and reliability of transportation services at core stations. While meeting basic passenger flow requirements, the service frequency at some secondary and tertiary nodes has decreased compared to pre-optimization. This achieves a streamlined allocation of stop resources at non-core stations without compromising basic transportation service capacity. Further analysis of Table 13 reveals that OD

service frequencies between primary nodes and between primary and secondary nodes remain unchanged, safeguarding transportation efficiency on high-demand routes. Meanwhile, OD service frequencies between secondary and tertiary nodes, as well as between tertiary nodes, have increased compared to pre-optimization levels. This significantly improves travel accessibility for passengers at lower-tier nodes while minimizing unnecessary train stops, preventing excessive resource allocation toward higher-tier nodes, and effectively enhancing the overall fairness of transportation services.

Table 14. Adjusted Departure Times for Selected Trains at Origin Stations Following Optimization.

Train	$t_i^e$	$d_i^1$	Deviation	Train	$t_i^e$	$d_i^1$	Deviation
G6023	6: 38	6: 38	0	G6107	8: 44	8: 41	-3
G6113	8: 05	8: 05	0	G879	18: 10	18: 10	0
G6119	7: 38	7: 36	-2	G6037	11: 31	11: 31	0
G1003	17: 38	17: 39	1	G1189	13: 17	13: 20	3
G6013	13: 31	13: 32	1	G6183	10: 33	10: 33	0
G6015	18: 45	18: 47	2	G335	14: 09	14: 08	-1

Due to space constraints, Table 14 lists partial train departure time adjustments. The total departure time variation at the origin station was 77 minutes, with the maximum deviation per train controlled within 10 minutes, causing no significant disruption to passenger travel plans. Compared to the original timetable, train overtaking incidents decreased by 13 instances. This demonstrates that moderate adjustments to departure times effectively mitigated operational conflicts arising from speed differences between trains of varying grades, enhancing line operational safety and fully validating the model's feasibility.

In summary, the collaborative optimization model achieves synergistic improvements in operational efficiency, service quality, and operational safety while satisfying constraints such as station service frequency and inter-station accessibility. It provides valuable reference for refined operations on the Wuhan-Guangzhou HSR.

### VII. SENSITIVITY ANALYSIS

This paper considers the objective of minimizing train departure time deviation at the origin station because the original timetable may result in numerous train conflicts and excessive overtaking due to unreasonable departure times. Allowing train departure times to vary from the original schedule aims to reduce train conflicts. To investigate the impact of different values on each objective, this study sets to

0, 5, 10, 15, and 20 minutes. The results obtained for different values are shown in Table 15.

Table 15. Results for Different Permitted Departure Deviation Times.

$\Delta t$	Deviation Time	Dwell time	Gap	Maximum Deviation Time
0	0	644	2.6%	0
5	46	622	3.2%	5
10	77	539	1.2%	10
15	187	555	3.7%	15
20	275	523	1.2%	20

Based on the solution results, 10 minutes represents the optimal value for the permissible departure deviation time. This parameter achieves a three-dimensional balance between passenger travel time habits, operational efficiency improvements, and model solution stability. Regarding passenger travel time habits, a 10-minute adjustment corresponds to a total departure time variation of 77 minutes at the origin station. This keeps the maximum deviation within 10 minutes, avoiding train conflicts and overtaking issues caused by zero adjustment space at 0 minutes, while also preventing significant deviations from expected departure times at 15 and 20 minutes that could disrupt passenger travel plans. This aligns with the optimization goal of minimizing departure time variations to match passenger time habits. From an operational efficiency perspective, the 10-minute interval corresponds to a total stop time of 539

minutes—significantly lower than both 0-minute and 5-minute intervals. While slightly higher than the 20-minute interval, it achieves an optimization effect of reducing total travel time by 307 minutes compared to the original plan. This reduction in stop duration and operational costs is balanced with enhanced service frequency between lower-tier nodes, ensuring both efficiency and service equity. From the model solution perspective, the 10-minute interval corresponds to a relative gap of 1.2%, matching the 20-minute interval and significantly lower than both the 5-minute and 15-minute intervals. This indicates higher solution quality and stability at this parameter, effectively avoiding local optima and meeting the reliability demands of high-density operations. Therefore, selecting a 10-minute interval yields an optimal solution.

#### CONCLUSION

This study focuses on the coordinated optimization of high-speed railway (HSR) stop plans and timetables. Considering variations in train grades and operating sections, an inter-station origin-destination (OD) service accessibility metric is introduced to indirectly characterize passenger exchange demands between stations. To overcome the limitations of traditional two-stage models, this study integrates stop plan optimization and timetable adjustment into a single-stage framework, constructing a multi-objective optimization model.

The proposed model is validated using 58 downbound trains on the Wuhan-Guangzhou High-Speed Railway (Wuhan-Guangzhou HSR) as the research sample. Results indicate that the optimized scheme achieves notable improvements: the total number of train stops is reduced by 12, and the total train travel time is shortened by 307 minutes. Additionally, service frequency between high-grade nodes remains stable, while OD service frequency between low-grade nodes is effectively improved. Meanwhile, departure time adjustments are kept within manageable limits, and the incidence of overtaking conflicts is reduced—collectively realizing a balance among operational efficiency, service equity, and operational safety.

Nevertheless, this study has certain limitations. It only considers trains operating on a single line, neglecting cross-line trains and the impact of dynamic changes in passenger flow. For future research, three directions could be explored: (1) integrating the spatiotemporal characteristics of OD passenger flow to develop a dynamic optimization model; (2) incorporating cross-line train demand and schedule optimization into the existing framework; and (3) refining constraint conditions to further enhance the adaptability of the optimization scheme to large-scale HSR network operations.

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