

Research on Maintenance Window Scheduling for Plateau Passenger-Freight Mixed Traffic Railways

Lei Liu, Zhiqiang Tian, Bin Liu, Fuxia Wang, Guofeng Sun

Abstract—Addressing the impact of plateau railways' hypoxic and severely cold environments on maintenance efficiency, this study emphasizes the critical role of maintenance window configuration in resolving conflicts between train operations and maintenance, ensuring safety, and improving efficiency. Analyzing constraints and optimization methods specific to plateau conditions, it proposes pre-positioning maintenance vehicles to enhance window utilization. An optimization model maximizing train frequency and minimizing travel time, subject to maintenance duration and operational constraints, was developed and solved with Gurobi to compare vertical rectangular windows and segmented rectangular windows. Case studies show both meet basic passenger demand: vertical windows suit balanced bidirectional demand, while segmented windows better accommodate predominant unidirectional demand. Optimization principles for setting windows during off-peak/peak seasons and transitional periods are also proposed, providing a scientific basis for plateau railway maintenance window selection.

Index Terms—Plateau railway, Maintenance window, Window configuration patterns, Train diagram, Gurobi

I. INTRODUCTION

With the continuous advancement of plateau railway planning and construction, the railway network is rapidly evolving as the primary channel for material transportation in high-altitude regions. The efficient organization of passenger and freight transport plays a pivotal role in accelerating regional economic development and integrating plateau areas into national economic development strategies. In this context, scientifically

optimizing maintenance window scheduling to enhance line capacity has become a critical operational challenge. The unique geographical environment and complex line conditions in plateau regions mean that maintenance window configuration not only affects transportation efficiency but also directly impacts operational safety and sustainable development.

Research on plateau railway transportation organization has achieved significant progress in existing literature. Q. Yao [1] demonstrated the feasibility of dynamic programming-based transportation organization models for passenger-freight mixed lines in plateau mountainous areas through comparative analysis of domestic and international operational practices. X. Peng [2] proposed a comprehensive maintenance zone layout methodology and corresponding window scheduling schemes tailored to long steep gradient characteristics in alpine regions. Y. Zhu [3] systematically investigated the alignment between transportation mode capacity and passenger-freight demand patterns. L. Liu et al. [4] developed an integrated scheduling model for train diagrams and maintenance windows to address train crossing conflicts on double-track passenger-freight mixed lines, providing critical references for optimizing plateau railway operations.

Regarding collaborative optimization of train diagrams and maintenance windows, T. Zhang et al. [5] established a linear programming model for overnight train operations and window scheduling in high-speed railways, considering differential constraints between power supply sections and operating zones. Z. Zhang et al. [6] solved a bi-objective mixed-integer programming model with Pareto optimality using constraint transformation methods. B. Yuan et al. [7] quantitatively analyzed the impact mechanisms of window phase-shifting and station siding capacity on diagram compilation. C. Xu et al. [8] innovatively introduced train operation state variables to construct a dynamic co-optimization model under undetermined service patterns, effectively characterizing the interaction between window scheduling and train movements. Luan et al. [9] formulated maintenance windows as virtual trains within a mixed-integer programming framework considering station track availability, proposing Lagrangian relaxation solutions. Zhang et al. [10] investigated night-train routing strategies between high-speed and conventional lines to resolve scheduling conflicts with maintenance windows. Zhang et al. [11] developed an integer linear programming model for dual-track networks with Lagrangian relaxation heuristics. Yang et al. [12] created a distributionally robust optimization framework to enhance adaptability against operational

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uncertainties through robust integration of maintenance windows and timetables. A. Dong et al. [13] proposed a multi-objective model to tackle timetable rescheduling due to high-speed train delays, aiming to maximize passenger transfer satisfaction, minimize delays, and reduce transfer failures. They developed a hierarchical sequential theory-based algorithm and validated its effectiveness through case studies.

In theoretical research on maintenance window configuration, K. Li et al. [14] proposed optimization strategies by analyzing cross-line operation disruptions caused by overlapping window phases in adjacent sections. L. Chen [15] conducted quantitative analysis revealing an inverse proportionality between window duration and both line capacity and train speed. Z. Tian et al. [16] pioneered the incorporation of maintenance window constraints into train diagram optimization objectives for long steep gradient lines. Furthermore, Y. Wang [17] refined window configurations through microscopic workflow analysis of maintenance operations. J. Li [18] demonstrated the economic feasibility of winter daytime windows via cost-benefit analysis. X. Cai [19] established a coordinated optimization model aligning window scheduling with passenger train departure times. Y. Wei [20] compared vertical vs. segmented rectangular windows applicability using Beijing-Guangzhou high-speed railway case data. L. Yu [21] developed a dual-objective framework balancing window duration and operational regularity. H. Shi [22] validated segmented windows' cross-network compatibility under dual-network integration scenarios.

Existing research on maintenance window scheduling primarily focuses on plain areas and conventional railways, with limited studies addressing plateau railways' unique environmental challenges. This paper develops a geographically adaptive optimization model for plateau railways by analyzing operational constraints and window configuration requirements, proposing tailored solutions to improve transport efficiency.

II. PROBLEM ANALYSIS

A. Constraints on Maintenance Window Utilization Rate

The enhancement of comprehensive maintenance window utilization on plateau railways is constrained by multiple factors, mainly including line environment limitations, auxiliary operation time consumption, and conflicts between operation and maintenance. In terms of line environment, relevant research shows that reduced oxygen levels due to rising altitude significantly affects manual work efficiency, with the working efficiency of non-acclimatized workers

declining progressively as elevation increases. Additionally, the severe cold climate brings challenges: the region sees continuous snowfall from October to May annually, with snow cover lasting up to eight months, obstructing mountain road access and making routine vehicle maintenance operations impracticable, thereby exacerbating maintenance difficulties.

B. Optimizing Maintenance Window Scheduling

To mitigate conflicts between train operations and maintenance activities, four methods listed in Table II can generally be adopted to improve the comprehensive maintenance window utilization rate in plateau railways, thereby enhancing line capacity.

Synthesizing the optimization methods in Table II, all four approaches can improve maintenance window utilization. However, the first three methods require additional investments and may reduce equipment/personnel utilization efficiency. In contrast, the fourth method enhances utilization without economic costs by optimizing maintenance vehicle scheduling. Specifically, the train-style deployment strategy involves pre-scheduling maintenance vehicles into designated window segments while ensuring operational safety. This approach leverages the idle time-space buffer zones between maintenance windows and train operation lines to extend effective maintenance duration, thereby maximizing window utilization.

C. Analysis of Optimal Scheduling Periods for Maintenance Windows

To ensure maintenance operation efficiency, it is necessary to determine reasonable maintenance periods for plateau railways. Sunrise and sunset times at two locations along the railway line are collected and summarized in Tables III-IV for further analysis.

Based on the analysis of annual sunrise and sunset data, the effective operational daytime window for railway maintenance has been determined to be 07:00–20:00. Compared to the conventional 00:00–06:00 maintenance window typically used for plain or low-altitude high-speed railways, it is recommended that the maintenance window for plateau railways be adjusted to 07:00–22:00. This adjustment thus achieves the following:

- (1) Covers the daytime maintenance period (07:00–20:00) to fully utilize natural lighting;
- (2) Extends the window to 22:00, providing a 1-hour buffer period to address sudden climatic changes in plateau regions;
- (3) Naturally aligns with human circadian rhythms, thereby synchronously improving mechanical maintenance efficiency and personnel work efficiency.

TABLE I
IMPACT OF ELEVATION VARIATION ON LABOR EFFICIENCY

Elevation Range	Atmospheric Oxygen Partial Pressure	Human Arterial Oxygen Saturation	Labor Efficiency Loss
2000-3000m	80%	91%	25%
3000-4000m	70%	88%	50%
4000-5000m	60%	80%	75%
≥5000m	≤50%	≤75%	≥90%

TABLE II
OPTIMIZATION METHODS FOR MAINTENANCE WINDOW UTILIZATION

Optimization Method	Advantages	Limitations
Improve equipment mechanization	Directly enhances operational efficiency	Limited adaptability to alpine environments
Augment human and equipment resources	Reduces task completion time	High costs and low resource utilization efficiency
Minimize auxiliary operation duration	Increases effective maintenance time	Requires infrastructure upgrades and complex scheduling
Train-style maintenance vehicle deployment	Zero-cost solution, extends effective time	Demands precise scheduling and safety protocols

TABLE III
SUNRISE AND SUNSET TIMETABLE FOR LOCATION A

Date	Sunrise	Solar Noon	Sunset	Daylight Duration	Dawn	Dusk
2024.1.1	08:24:34	13:30:11	18:35:48	10:11:14	07:58:08	19:02:15
2024.4.1	07:15:10	13:30:39	19:46:09	12:30:59	06:50:57	20:10:22
2024.7.1	06:27:31	13:30:53	20:34:16	14:06:45	05:59:54	21:01:52
2024.10.1	07:20:44	13:16:26	19:12:09	11:51:25	06:56:43	19:36:10

TABLE IV
SUNRISE AND SUNSET TIMETABLE FOR LOCATION K

Date	Sunrise	Solar Noon	Sunset	Daylight Duration	Dawn	Dusk
2024.1.1	08:37:26	13:45:50	18:54:14	10:16:48	08:11:22	19:20:18
2024.4.1	07:31:23	13:46:17	20:01:12	12:29:49	07:07:28	20:25:06
2024.7.1	06:46:04	13:46:32	20:46:59	14:00:55	06:18:56	21:14:07
2024.10.1	07:36:02	13:32:04	19:28:07	11:52:05	07:12:18	19:51:50

D. Problem Statement on Maintenance Window Configuration

Currently, domestic railway maintenance windows mainly take two forms: rectangular windows and V-shaped windows. A V-shaped window involves closing only one line for maintenance while the other remains in operation, creating a V-shaped blank in the train operation diagram. However, given the high operating speed of high-speed railway trains and the long duration required for maintenance windows, using V-shaped windows significantly impacts the safety of train operation and maintenance operations. Thus, rectangular windows are adopted as the opening form in the practical application of comprehensive maintenance windows for China's high-speed railways: a rectangular window refers to a specific period during which both up and down lines are closed for maintenance, with trains prohibited from entering the relevant section, forming a rectangular blank in the train operation diagram. As rectangular windows are the sole form for China's high-speed railway comprehensive maintenance, subsequent research will focus on their optimization; specifically, rectangular windows can be categorized into vertical and segmented vertical types, and assessing their adaptability to plateau railway conditions as well as their impacts on train operations and maintenance safety is key to optimizing window design.

(1) Vertical Rectangular Window

When a vertical rectangular Window is adopted for a railway line, the maintenance of all sections along the line starts at the same time and ends at the same time. Figure 1 shows an example of a vertical rectangular Window. The figure includes 4 stations: k_1, k_2, k_3, k_4 , and divides the line into 3 sections: $k_1 - k_2, k_2 - k_3, k_3 - k_4$.

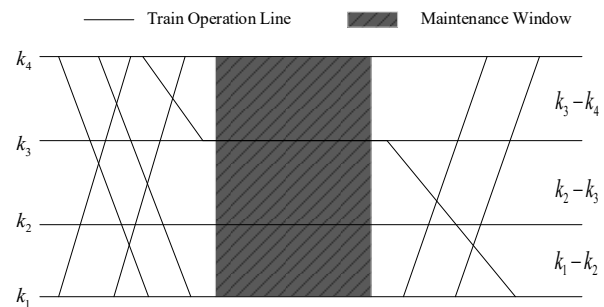


Fig. 1. Configuration of the Vertical Rectangular Window

(2) Segmented Rectangular Window

When a segmented rectangular Window is adopted for the line, the maintenance of the entire line section is divided into different time periods for maintenance, thus forming interlaced rectangular Windows. Figure 2 shows an example of a segmented rectangular Window.

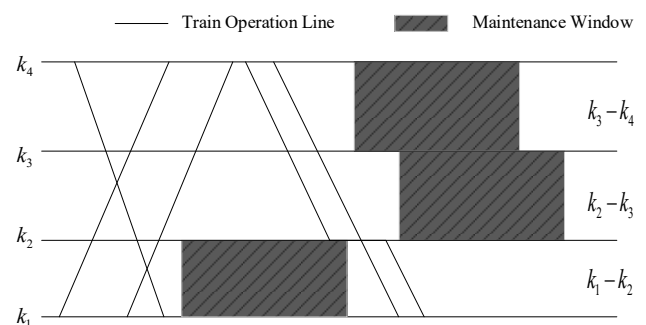


Fig. 2. Configuration of the Segmented Rectangular Window

To sum up, based on the above - mentioned analysis of the opening duration and time period of the maintenance Window for the plateau railway, this paper systematically integrates the train operation constraints and the Window maintenance constraints, and constructs a bi - objective programming model with the maximization of the number of train operations and the minimization of the total train travel time as the objectives, so as to realize the quantitative decision - making of the maintenance Window opening scheme.

III. MODEL FORMULATION

A. Problem Assumptions

The following assumptions are adopted during the modeling process:

- (1) Train service plans are predetermined in advance before the modeling begins.
- (2) Two main train types are considered in the model: conventional-speed passenger trains and freight trains.
- (3) All stations along the line possess sufficient receiving and departure track capacity as well as scheduling capability, enabling them to handle simultaneous train arrivals and departures without congestion.
- (4) When upstream sections are under maintenance windows, trains will operate in a holding mode at stations, remaining stationary until the maintenance window is closed before proceeding onward.

B. Notation Definition

Key model parameters and decision variables are explicitly defined in Tables V and VI, systematically facilitating both the construction and practical implementation of the proposed methodology.

TABLE V
PARAMETER DEFINITIONS

Parameter	Definition
L	Set of trains
K	Set of stations
Q	Set of track sections
k_1	Origin station
k_m	Destination station
E_m	Set of track sections in the m-th power supply zone
$D_{\min}$	Earliest departure time at origin station
$D_{\max}$	Latest departure time at origin station
$A_{\min}$	Earliest arrival time at destination station
$A_{\max}$	Latest arrival time at destination station
$T_{\min}^{\text{stop}}$	Minimum dwell time at stations (min)
$T_{\max}^{\text{stop}}$	Maximum dwell time at stations (min)
$T_{\min}^{\text{run}}$	Minimum running time for sections (min)
$T_{\max}^{\text{run}}$	Maximum running time for sections (min)
T_a	Minimum arrival interval at stations (min)
T_d	Minimum departure interval at stations (min)
$T_{\min}^{\text{win}}$	Earliest maintenance window opening time
$T_{\max}^{\text{win}}$	Latest maintenance window closing time
T_{safe}	Safety buffer period before/after windows
$N_{\max}$	Maximum number of train departures
M	A large positive integer

TABLE VI
PARAMETER DEFINITIONS

Variable	Definition
$d_{i,k}$	Integer variable: Departure time of train i at station k
$a_{i,k}$	Integer variable: Arrival time of train i at station k
t_k^{start}	Integer variable: Start time of the maintenance window in section k
t_k^{end}	Integer variable: End time of the maintenance window in section k
z_i	Binary variable (0-1): 1 if train i is scheduled, 0 otherwise
$n_{i,k}$	Binary variable (0-1): 1 if train i departs before the maintenance window closure in section k , 0 otherwise
$x_{i,j,k}$	Binary variable (0-1): 1 if train i departs from station k before train j , 0 otherwise
$y_{i,j,k}$	Binary variable (0-1): 1 if train i arrives at station k before train j , 0 otherwise

C. Objective Functions

As a critical transportation corridor for regional economic development, plateau railways necessitate maximized line capacity to fulfill passenger and freight demands. This study establishes a dual-objective optimization model that simultaneously maximizes the number of train services and minimizes total travel time, explicitly addressing maintenance safety and operational efficiency through spatiotemporally coordinated transportation organization. By reducing maintenance window occupation of line capacity, the formulation ensures balanced resource allocation between transportation and maintenance requirements, mitigates capacity bottlenecks induced by suboptimal scheduling, and avoids resource waste through scientific time-space coordination. The objectives are mathematically expressed as:

$$\max F_1 = \sum_{i \in L} z_i \quad (1)$$

$$\min F_2 = \sum_{i \in L} (a_{i,k_m} - d_{i,k_1}) \quad (2)$$

D. Constraints

(1) Scheduling Variable Linkage Constraints

$$D_{\min} \cdot z_i \leq d_{i,k_1} \leq D_{\max} \cdot z_i, \forall i \in L \quad (3)$$

$$A_{\min} \cdot z_i \leq a_{i,k_1} \leq A_{\max} \cdot z_i, \forall i \in L \quad (4)$$

Equations (3)-(4) ensure that scheduled train i adheres to a feasible departure time window.

(2) Dwell Time Constraints

$$T_{\min}^{\text{stop}} \cdot z_i \leq d_{i,k} - a_{i,k} \leq T_{\max}^{\text{stop}} \cdot z_i, \forall i \in L, \forall k \in K_i \quad (5)$$

Equation (5) ensures the dwell time of trains at stations remains within permissible limits.

(3) Section Running Time Constraints

$$T_{\min}^{\text{run}} \cdot z_i \leq a_{i,k+1} - d_{i,k} \leq T_{\max}^{\text{run}} \cdot z_i, \forall i \in L, \forall k \in K, k \neq k_1 \quad (6)$$

Equation (6) ensures the running time of trains in each section remains between the minimum and maximum allowable thresholds.

(4) Train Headway Constraints

$$a_{j,k} - a_{i,k} + M(1 - y_{i,j,k}) \geq T_a \cdot z_i \cdot z_j, \quad (7)$$

$$\forall i, j \in L, \forall k \in K, k \neq k_1$$

$$y_{i,j,k} + y_{j,i,k} = 1, \forall i, j \in L, \forall k \in K, k \neq k_1 \quad (8)$$

Equations (7)-(8) enforce the minimum arrival interval between trains at stations.

$$d_{j,k} - d_{i,k} + M(1 - x_{i,j,k}) \geq T_d \cdot z_i \cdot z_j, \quad (9)$$

$$\forall i, j \in L, \forall k \in K, k \neq k_l$$

$$x_{i,j,k} + x_{j,i,k} = 1, \forall i, j \in L, \forall k \in K, k \neq k_l \quad (10)$$

Equations (9)-(10) enforce the minimum departure interval between trains at stations.

(5) Maintenance Window Time Frame Constraints

$$t_k^{start} \geq T_{win}^{min}, \forall k \in Q \quad (11)$$

$$t_k^{end} \leq T_{win}^{max}, \forall k \in Q \quad (12)$$

Equations (11)-(12) ensure the maintenance windows are scheduled within permissible time frames.

(6) Maintenance Window Start-End Time Constraints

$$t_k^{start} = t_{k'}^{start}, \forall k, k' \in E_m \quad (13)$$

$$t_k^{end} = t_{k'}^{end}, \forall k, k' \in E_m \quad (14)$$

Equations (13)-(14) enforce uniform start and end times for maintenance windows within the same power supply zone.

(7) Maintenance Window Duration Constraints

$$t_k^{end} - t_k^{start} \geq T_{min}, \forall k \in Q \quad (15)$$

Equation (15) ensures the maintenance window duration in each section meets the minimum required operating time.

(8) Maintenance Window-Train Conflict Constraints

$$a_{i,k+1} \leq t_k^{start} - T_{safe} + M(1 - n_{i,k}) + M(1 - z_i), \quad (16)$$

$$\forall i \in L, \forall k \in Q, k \neq k_m$$

$$d_{i,k} \leq t_k^{end} + T_{safe} - M(1 - n_{i,k}) + M(1 - z_i), \quad (17)$$

$$\forall i \in L, \forall k \in Q, k \neq k_m$$

Equations (16)-(17) prevent operational conflicts between maintenance windows and train movements, ensuring both operational safety and maintenance feasibility. For scheduled trains ($z_i = 1$), they must enter sections either before the maintenance window starts or after it ends.

(9) Maximum Departure Quantity Constraint

$$\sum_{i \in L} z_i \leq N_{max} \quad (18)$$

Equation (18) limits the total number of train departures based on line capacity and maintenance window duration.

(10) Additional Logical Constraints

$$n_{i,k}, z_i \in \{0, 1\}, \forall i \in L \quad (19)$$

$$x_{i,j,k}, y_{i,j,k} \in \{0, 1\}, \forall i \in L, \forall k \in K \quad (20)$$

The complete model comprises constraints (1)-(20), integrating all aforementioned operational and maintenance requirements.

E. Model Analysis

The optimization model for the opening form of maintenance windows of plateau railways constructed in this paper belongs to a bi - objective linear mixed - integer programming model. Under the special operating environment and high safety standards of plateau railways, the model aims to accurately coordinate the opening of maintenance windows and the organization of train operations. It needs to additionally handle the two objectives of maximizing the number of operated trains and minimizing the train travel time, while strictly satisfying a

series of complex constraints such as the safe interval of train operations and the requirements for window blocking.

To specifically illustrate the complexity of the model and the feasibility of solution, a typical section of a double - track railway including 50 alternative trains ($|I| = 50$) and 11 stations ($|Q| = 11$) is taken as the object of case analysis. The detailed variable and constraint scales of the model are shown in Table VII.

TABLE VII
PARAMETER MODEL COMPLEXITY

Variable/Constraint	Scale	Count
Integer Variables	$2 I \cdot K + 2 Q $	1120
0-1 Variables	$ I + I \cdot Q + I ^2 \cdot K $	28050
Constraints	$2 Q (I +1) + I \cdot K (K +1)$	29070

According to Table VII, the model contains a total of 29,170 variables (including 28,050 key 0-1 decision variables) and 29,070 linear constraints. All objective functions and constraint conditions established in the model are linear expressions without nonlinear terms, which is a key prerequisite for using efficient Mixed-Integer Linear Programming (MILP) solvers. Despite the large model scale (29,170 total variables and 29,070 total constraints), according to the official benchmark tests of the commercial solver Gurobi (version 12.0.1) and extensive engineering practices, such well-structured MILP problems are generally within the range of its efficient solving capabilities. Therefore, the Python programming language can be used to accurately solve the model by calling the Gurobi 12.0.1 solver.

For the dual-objective function of the model, linear weighted summation can be performed, and the two objective functions are merged into a comprehensive objective function through weights:

$$\max F = \alpha \sum_{i \in I} z_i - \beta \sum_{i \in I} (a_{i,k_m} - d_{i,k_l}) \quad (21)$$

The setting of weight coefficients α and β in the objective function is based on the following key considerations:

(1) Objective priority: When evaluating the window operation form based on transportation capacity, maximizing the number of trains in operation is given the primary priority, so the weight α is set as the benchmark value of 1.

(2) Magnitude Balance: The two objectives differ significantly in dimension and numerical range (the number of train services is about dozens, and the total travel time reaches tens of thousands of minutes). The setting of $\beta = 0.001$ is aimed at effectively balancing the magnitude difference, avoiding the total travel time term completely dominating the optimization process in terms of numerical value, and ensuring that both objectives can affect the quality of the solution. Preliminary sensitivity analysis supports that this value can effectively optimize the travel time on the premise of giving priority to ensuring the number of train services.

In the case study of this paper, the objective function of equation (21) and the weight coefficients set as $\alpha = 1$ and $\beta = 0.001$ are used for specific calculations and scheme evaluation.

IV. CASE STUDIES

A. Basic Data

(1) Line Configuration

This study empirically validates the effectiveness of the proposed model using an actual double-track plateau railway line A–K. The line comprises exactly 11 stations with a total length of 572.11 km. It primarily operates two distinct speed-class trains: conventional-speed passenger trains and freight trains. The minimum running times for different train types across sections are comprehensively detailed in Table VIII, while the power supply zone configuration along the entire line is graphically illustrated in Table IX.

(2) Additional Parameters

The operational study period is formally defined from 07:00 to 22:00. The train departure interval for scheduled services is standardized at 10 minutes.

TABLE VIII
MINIMUM SEGMENT RUNNING TIMES BY TRAIN TYPE
(MINUTES)

Section	Passenger Train		Freight Train	
	Up	Down	Up	Down
A-B	23	27	40	43
B-C	30	31	50	51
C-D	30	28	50	48
D-E	29	32	50	53
E-F	25	20	41	37
F-G	18	23	35	38
G-H	32	33	54	56
H-I	41	38	69	65
I-J	31	30	52	53
J-K	29	27	48	43

Based on established existing line operational practices, a standard safety buffer period of 10 minutes is consistently applied before and after maintenance windows, with the maintenance window duration typically configured specifically as 240 minutes. To better align with passenger travel preferences and coordinate effectively with other transportation modes, the optimal train operation period is scheduled strictly between 07:00 and 22:00. The minimum dwell times at stations are conventionally established at 4

minutes for conventional-speed passenger trains and 10 minutes for freight trains.

TABLE IX
POWER SUPPLY ZONE DIVISION

Power Supply Zone	Sections
1	A-B, B-C
2	C-D, D-E
3	E-F, F-G
4	G-H, H-I
5	I-J, J-K

B. Results Analysis

This study compares the applicability of vertical rectangular windows and segmented rectangular windows under two operational modes—centralized train operation and grouped train operation—by integrating line data and parameters while meeting basic passenger train demand and maximizing freight train operations.

(1) Centralized Train Operation

Under the condition of operating 10 passenger trains in each direction and adopting a centralized operation mode for both conventional-speed passenger trains and freight trains, the Gurobi solver was employed to generate a timetable using vertical rectangular windows (as shown in Fig. 4). The maintenance window was scheduled from 18:00 to 22:00, with a total of 40 trains operating in both directions: 20 trains in the upward direction (10 passenger trains and 10 freight trains, totaling 8,281 minutes of travel time) and 20 trains in the downward direction (10 passenger trains and 10 freight trains, totaling 8,270 minutes of travel time). This configuration satisfies basic passenger travel demands, enables appropriate freight train operations, and achieves balanced passenger-freight train distribution across both directions.

Using identical parameters, the model generated the segmented rectangular window train diagram (Fig. 5), with maintenance periods in Table X. Maximum bidirectional trains reached 42, 32 upward (10 conventional-speed passenger and 22 freight trains, total travel time 14,296 minutes) and 10 downward (10 conventional-speed passenger and 0 freight trains, total travel time 3,177 minutes). This configuration satisfies basic passenger demand and fully accommodates upward freight operations, but operates no downward freight trains. These results indicate segmented rectangular windows suit lines with extremely high unidirectional freight demand.

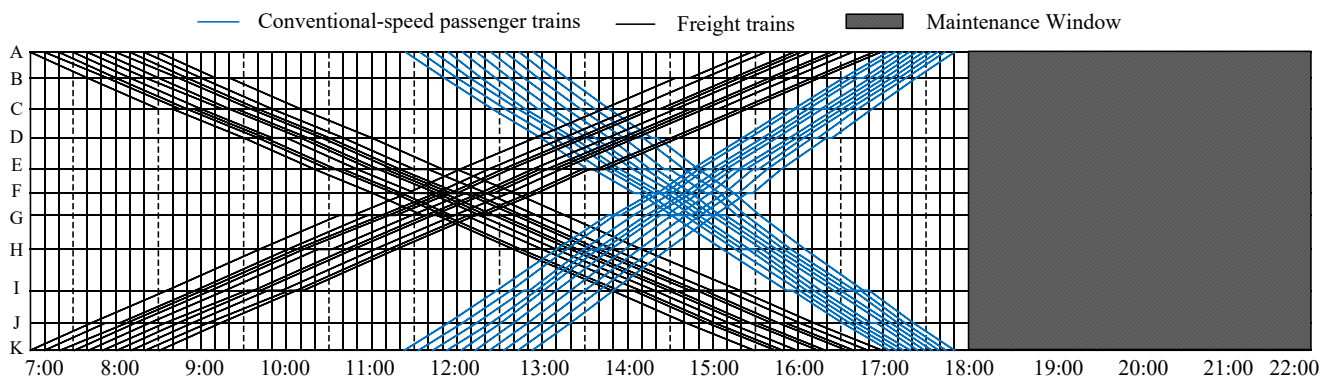


Fig. 4. Train Diagram for Centralized Operation Under Vertical Rectangular Window

TABLE X
SCHEDULED PERIODS OF SEGMENTED RECTANGULAR WINDOWS UNDER CENTRALIZED TRAIN OPERATION

Section	Maintenance Window Period	Section	Maintenance Window Period
A-B	18:00-22:00	F-G	18:00-22:00
B-C	18:00-22:00	G-H	7:00-11:00
C-D	18:00-22:00	H-I	7:00-11:00
D-E	18:00-22:00	I-J	7:00-11:00
E-F	18:00-22:00	J-K	7:00-11:00

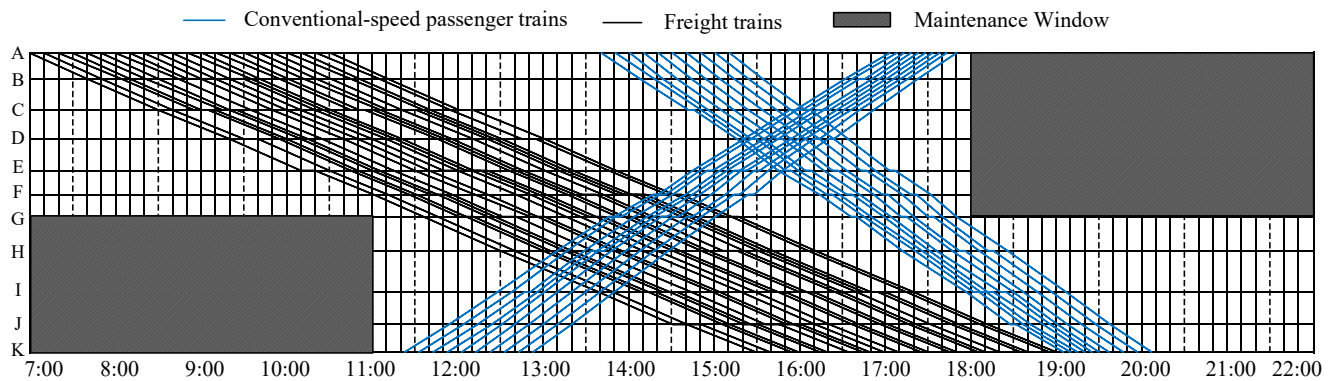


Fig. 5. Train Diagram for Centralized Operation Under Segmented Rectangular Window

(2) Grouped Train Operation

To ensure basic passenger transportation demands while operating passenger and freight trains in grouped formations with unchanged parameters, the vertical rectangular window configuration was applied. The solver-generated timetable is illustrated in Fig. 6, where the maintenance window is scheduled from 18:00 to 22:00, and the maximum number of trains in both directions totals 40. Specific results include 20 trains in the upward direction (15 conventional-speed passenger trains and 5 freight trains operating during 07:00–08:00 and 11:00–13:00, with a total travel time of 7,206 minutes) and 20 trains in the downward direction (15 conventional-speed passenger trains and 5 freight trains operating during 07:00–08:00 and 11:00–13:00, with a total travel time of 7,200 minutes). This configuration not only fulfills basic passenger demand but also adds 10 extra conventional-speed passenger trains, achieving balanced passenger-freight service distribution across both directions.

With other parameters unchanged, the model was further solved using the segmented rectangular window configuration, generating the train diagram shown in Fig. 7. In this configuration, the maintenance window periods are detailed in Table XI, with a maximum of 35 trains operating in both directions. Specifically, 24 trains in the upward direction (10 conventional-speed passenger trains and 14 freight trains operating during 07:00–08:00 and 13:00–14:00, with a total travel time of 10,186 minutes) and 11 trains in the downward direction (11 conventional-speed passenger trains and 0 freight trains operating during 11:00–13:00, with a total travel time of 3,465 minutes). This configuration satisfies basic passenger demand and adds 1 extra conventional-speed passenger train but fails to operate freight trains in the downward direction, further validating the segmented rectangular window's suitability for lines with unidirectional freight dominance.

The case study analysis demonstrates that both vertical rectangular windows and segmented rectangular windows can fulfill basic passenger transportation demands. In terms

of freight operations, vertical rectangular windows can moderately satisfy freight requirements while maintaining balanced bidirectional freight distribution. In contrast, segmented rectangular windows are only suitable for lines with unidirectional heavy freight demand, failing to ensure balanced bidirectional freight capacity. Therefore, for railway lines requiring balanced bidirectional transportation capacity, the vertical rectangular window configuration proves more adaptable to integrated passenger and freight operational demands compared to the segmented rectangular window configuration.

(3) Short-Distance Train Operations

When designing maintenance window configurations (whether utilizing vertical or segmented rectangular time blocks), timetables exclusively focused on long-distance train operations inevitably result in the inherent creation of significant idle time-space buffer zones along the line. These unused segments represent substantially underutilized capacity within the available infrastructure. To strategically optimize the utilization of critical line resources and enhance overall transportation capacity, a proven solution involves proactive scheduling of short-distance or regional trains within these otherwise idle buffer zones. This integrated approach effectively addresses local transportation demands while filling the resultant operational gaps.

Taking the vertical rectangular maintenance window model with grouped long-distance train operation as a representative case, Fig. 8 demonstrates the practical implementation of this strategy. The figure clearly illustrates the resulting timetable layout where short-distance trains have been effectively inserted into the previously idle buffer zones (visually highlighted within the red boxes). This synergistic integrated scheduling methodology maximizes infrastructure utilization efficiency. It serves as a conclusive demonstration of how the deliberate integration of short-distance services can significantly improve the leveraging of existing line capacity resources, thereby extracting considerably greater value from the entire rail network.

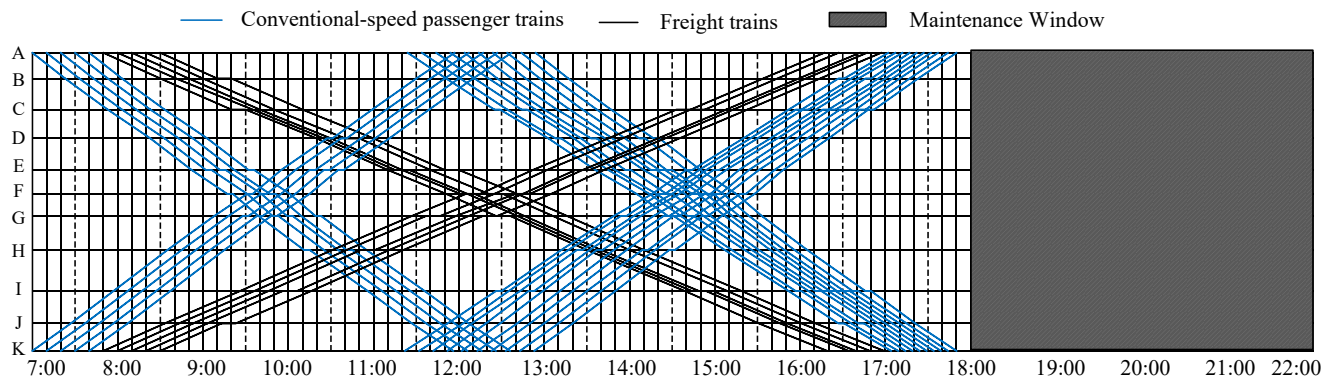


Fig. 6. Train Diagram for Grouped Operation Under Vertical Rectangular Window

TABLE XI

MAINTENANCE WINDOW PERIODS FOR SEGMENTED RECTANGULAR WINDOWS UNDER GROUPED TRAIN OPERATION

Section	Maintenance Window Period	Section	Maintenance Window Period
A-B	18:00-22:00	F-G	18:00-22:00
B-C	18:00-22:00	G-H	18:00-22:00
C-D	18:00-22:00	H-I	7:00-11:00
D-E	18:00-22:00	I-J	7:00-11:00
E-F	18:00-22:00	J-K	7:00-11:00

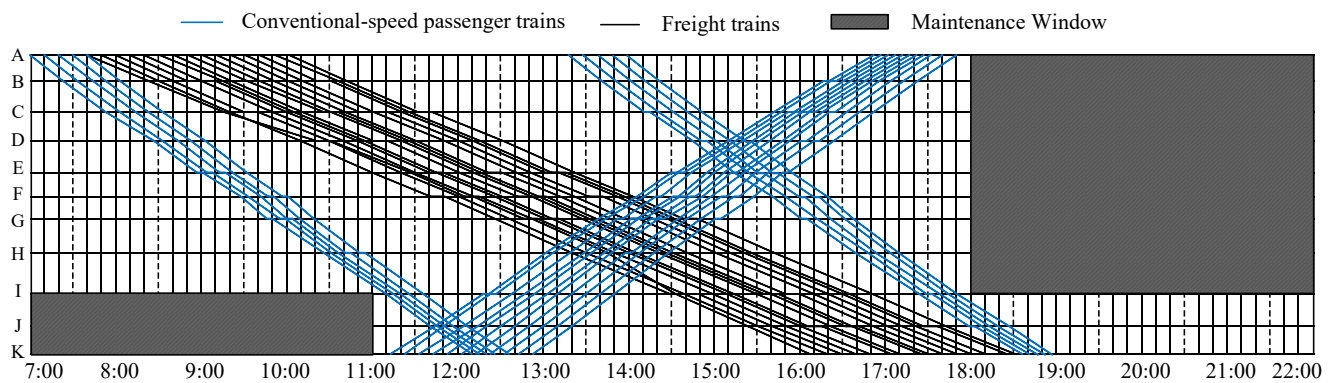


Fig. 7. Train Diagram for Grouped Operation Under Segmented Rectangular Window

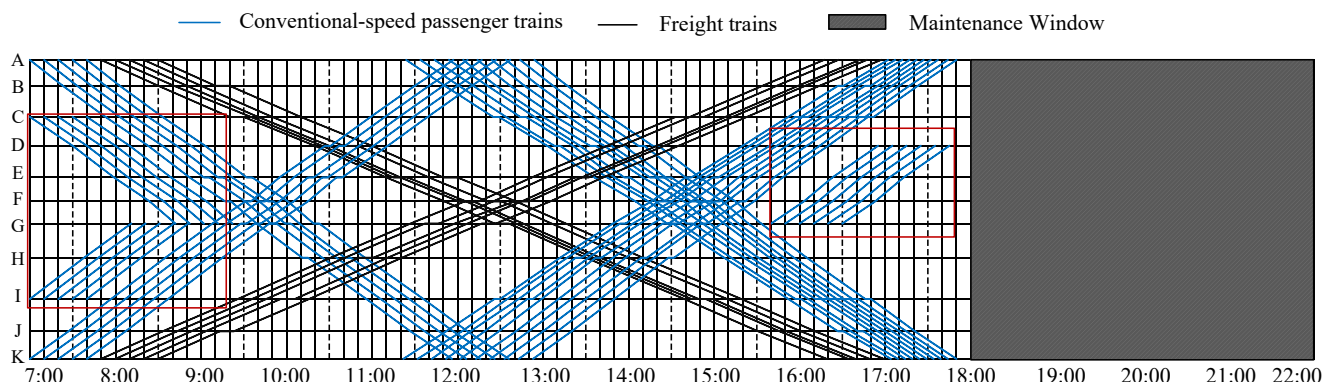


Fig. 8. Train Diagram for Short-Distance Operations Under Vertical Rectangular Window

C. Analysis on Maintenance Window Setting in Different Transportation Seasons of Plateau Railways

In the case study, the predetermined duration of the maintenance window is fixed at 240 minutes. The results conclusively show that the vertical rectangular window has more advantages in ensuring the balance of two-way passenger and freight transportation capacity of the line. However, the natural environment of plateau railways, such as significant climate changes and complex geological

conditions, has strong seasonal differences, which puts forward dynamic and higher requirements for the setting of maintenance windows. The fixed window strategy is difficult to maintain year-round applicability, and it is necessary to strategically optimize and adjust according to the characteristics of transportation seasons to balance maintenance needs, transportation efficiency and operational safety.

(1) Analysis of Transportation Seasonal Characteristics and Window Setting Requirements for Plateau Railways

The climatic environment and geological conditions along plateau railways change significantly with seasons, directly affecting the timeliness of Window setting, operation intensity, and matching with transportation demands.

1) Off-season of Passenger and Freight Transport (November to April of the following year)

Frequent low-temperature freeze-thaw cycles occur, and diseases such as subgrade frost heave and mud boiling, tunnel lining leakage, etc., are prone to occur during the spring thaw period (March-May). The passenger and freight volume is relatively low in this stage. It is necessary to extend the Window duration, and it is recommended to set 270-300 minutes per day. Vertical rectangular Windows or centralized segmented forms are preferentially adopted to facilitate time-consuming concentrated and preventive overhauls, such as frost damage treatment, drainage system maintenance, etc.

2) Peak Season of Passenger and Freight Transport (May to October)

Tourist passenger flow and material transportation demand surge. Overlaying the rainy season (June to September), the risks of geological disasters such as debris flows and slope collapses increase. Transportation efficiency becomes the priority consideration. It is necessary to significantly compress the Window duration, and it is recommended to set 120-150 minutes per day, and adopt a more flexible “short Window + dynamic compensation” mode. Focus on arranging fast and precise basic maintenance, and reserve elastic time for responding to sudden geological disasters.

(2) Window Optimization under the Coupling Effect of Multiple Factors

The seasonal characteristics of the plateau environment impose multiple constraints on Window setting, which need to be comprehensively considered in the optimization.

1) Influence of climatic environment: Low temperature and hypoxia in winter significantly reduce the operational efficiency of personnel, requiring the adoption of a shift-based operation system in different time periods; strong ultraviolet rays in summer accelerate equipment aging, requiring the shortening of the detection cycle. These factors directly affect the effective operation time and Window efficiency.

2) Topographic and Geological Risks

During the rainy season, especially in complex mountainous areas such as the Hengduan Mountains, the seepage pressure of rock masses increases, and the risk of slope instability rises. Window periods should prioritize targeted emergency or preventive operations such as slope radar monitoring and cable reinforcement.

3) Equipment and Personnel Adaptability

In low temperatures, construction machinery has a high failure rate, and long Windows in the off-season need to reserve time for equipment preheating and debugging. Oxygen supply and cold protection facilities should be dynamically adjusted with the seasons to ensure operational safety standards.

4) Fluctuations in Transport Demand

The vigorous passenger and freight transport demand in the peak season requires that Window setting must be efficient and precise, minimizing the occupation of effective transport time.

(3) Principles for Optimized Seasonal Window Setting of Plateau Railways

Based on the seasonal characteristics of plateau railways, the following differentiated Window setting principles are

proposed, aiming to adapt to environmental changes and maximize transportation efficiency.

1) Off-season: “Centralized Maintenance + Preventive Maintenance” Principle

Make full use of the window with low transportation pressure, extend the Window duration to 270-300 minutes, and mainly adopt vertical rectangular Windows to support the “daytime + nighttime” segmented maintenance mode. This is more consistent with the characteristics of vertical Windows in the off-season in case studies, allowing more than 70% of annual overhauls and renovation projects to be completed during the long closure period.

2) Peak Season: “Precision Maintenance + Condition-based Maintenance” Principle

Significantly compress the Window duration to 120-150 minutes, and adopt a flexible and efficient “short Window + dynamic compensation” mode. Segmented rectangular Windows may play a greater role in this stage, especially for rapid maintenance of high-risk sections, but special attention should be paid to their possible impact on the freight capacity of the downlink (or specific direction). Relying closely on the monitoring data beside the track, dynamically adjust the position, duration and form of the Window, prioritize the treatment of the most urgent diseases, minimize the interference with the golden transportation period, and ensure the transportation capacity in the peak season.

3) Cross-season: “Elastic Buffer” Principle

In the transition period (April and October) of climate and transportation demand conversion, set an elastic cycle of about 15 days. The Window duration and form can be smoothly transitioned within this window, gradually adjusted from 270 minutes to 150 minutes and vice versa, and the maintenance plan and Window strategy are dynamically adjusted according to the actual weather, passenger and cargo flow, and equipment status to provide a buffer for the system to adapt to seasonal changes.

V. CONCLUSION

This study investigates maintenance window configurations for double-track passenger-freight mixed-traffic railways in plateau environments by analyzing constraint factors and optimization methods for window utilization efficiency. Integrating train diagram compilation principles, we establish a bi-objective mixed-integer programming model that simultaneously maximizes train service frequency and minimizes total travel time, incorporating both operational and maintenance constraints. Case study validation confirms the model’s feasibility, yielding the following conclusions:

(1) To mitigate conflicts between train operations and maintenance windows, maintenance vehicles can be pre-scheduled to enter designated window segments under the premise of operational safety. By leveraging the idle time-space buffer zones between maintenance windows and train operating lines, this strategy extends the effective maintenance duration, thereby improving maintenance window utilization efficiency.

(2) Unlike high-speed rail lines in plain and low-altitude regions that schedule maintenance windows during nighttime hours (00:00–06:00), plateau regions require specialized scheduling of maintenance windows due to their unique natural climatic conditions. In practical operational planning,

maintenance schedules must be closely aligned with local climatic conditions to ensure optimal operational efficiency of maintenance machinery and personnel.

(3) The optimization model for the maintenance window configuration forms of plateau railways established in this paper can provide reference for the comparison and selection of maintenance window implementation schemes. Case analysis demonstrates that both vertical rectangular windows and segmented rectangular windows can satisfy basic passenger transport demands of railway lines. Under the concentrated departure mode of passenger and freight trains, the segmented rectangular window shows better performance than the vertical rectangular window in terms of the number of train operations on the line, but exhibits significant differences in transportation capacity between upward and downward directions. When balanced bidirectional transportation capacity is required on the line, the vertical rectangular window better adapts to transportation demands; when greater unidirectional transportation capacity is needed, the segmented rectangular window becomes more suitable. Therefore, in practical maintenance window scheduling processes, reasonable adjustments of window configurations can be made according to actual transportation requirements of specific railway lines.

(4) Traditional deduction coefficient methods estimate capacity loss by converting maintenance window occupancy time but struggle to precisely resolve spatial-temporal conflicts between train diagrams and window settings. This study addresses this limitation by developing an optimization model to compare maintenance window configurations. Unlike conventional qualitative comparison methods, the proposed model simultaneously coordinates train operations and maintenance window scheduling. In contrast to capacity evaluation using deduction coefficients, our model meticulously incorporates complex factors including train inter-station running times, dwell times, and headway constraints. The solution can directly inform the development of train diagrams, facilitating operational decisions.

(5) This paper finally analyzes the setting of maintenance windows in different transportation seasons in combination with the seasonal differences of plateau railway transportation, and accordingly puts forward the optimized setting principles for maintenance windows in off-season, peak season and cross-season.

(6) In subsequent research processes, coordinated optimization between train operation diagrams and maintenance windows could be further investigated by incorporating more actual operational requirements of plateau railways.

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