The Optimization Study of Operation Schemes for Intercity Trains Considering the Periodicity of Passenger Flow Direct Access Rate

Juhua Yang, Tao Wang, Lei Liu, Dongyao Qi

***Abstract* - With the advancement of high-speed rail technology and the expansion of intercity railway networks in China, improving the service quality of train schedules has become crucial. Currently, some intercity railways have the conditions for periodic transportation, but relevant research is still incomplete. This paper establishes an optimization model for the formulation of periodic intercity train schedules based on the PESP model. The model investigates the rationality of passenger flow demand under different direct access rates, with the objective of minimizing the total operation time of trains. It solves the relationship between the total operation time and the direct access rate for periodic intercity trains. An example study of the Chengdu-Mianyang-Lezhi intercity railway is conducted to validate the rationality and effectiveness of the model. This study provides a method for addressing the relationship between train operation schedules and passenger flow demand under the periodic model.**

***Index Terms* - Intercity trains; Periodic train operation schemes; Integer programming model; Passenger flow direct access rate**

I. Introduction

The train operation plan is the foundation of railway train operation organization. The quality of its formulation directly impacts the safety of railway operations and the utilization of railway line transportation capacity. A periodic timetable refers to a schedule in which the train operating patterns within each cycle are identical. In simple terms, it means that within a given cycle, trains of the same type and class depart, pass through, or arrive at stations along the route at fixed intervals, denoted by the cycle time (T). Within each time period (T), trains of the same type and class have the same origin and destination stations, the same intermediate station stops, identical operating speeds, and the same departure frequency.

Compared to non-periodic timetables, periodic timetables exhibit a stronger regularity and rhythm. This makes them more conducive to more efficient train flow organization at stations. They also make it easier for passengers to remember train departure times, thus enhancing the convenience of travel. Currently, countries with well-developed high-speed rail networks widely use periodic train timetables, such as Japan, France, and Germany. In China, some scholars have also conducted extensive research on the application of periodic timetables in domestic rail transport. However, most of the research focuses on high-speed rail for long-distance transport. Periodic schedules are more suitable for intercity railways than long-distance transportation. They are designed for short-distance passenger transport. The shorter transport duration allows for shorter cycles. It enhances the rhythm and efficiency of the periodic timetable system.

II. Literature review

In recent years, the periodic timetable model has been widely applied in the railway systems of Japan and Europe. Peeters[1] provided a comprehensive review of the modeling methods for periodic timetables and the related PESP (Periodic Event Scheduling Problem) and CPF (Cycle Planning Framework) issues. Cordone et al.[2], based on a determined train schedule, established a mixed-integer nonlinear programming model to analyze the impact of periodic transportation modes on passenger flow demand. Kroon et al.[3] focused on the train connection flexibility problem under the PESP model, aiming to optimize passengers' transfer times. Research has shown that when the proportion of periodic trains reaches 75% and non-periodic trains account for 25%, passenger satisfaction increases by approximately 18.5%. Heydar[5] and Sparing[6] explored optimization problems of periodic train timetables with the objective of minimizing the cycle length.

Recently, many scholars in China have begun to focus on the development, formulation, and optimization methods of periodic train operation schemes. Wang Bo et al.[7] argue that the passenger flow characteristics of intercity railways make them suitable for periodic timetables, and they established a multi-objective chance-constrained model based on peak-hour passenger flow to formulate train schedules. Xie Meiquan et al.[8] proposed a sequencing-based periodic timetable model aimed at reducing the solution size of the PESP (Periodic Event Scheduling Problem). Yan Ying et al.[9] divided the formulation process of periodic train schedules into three stages: creating the profile schedule, drawing the periodic cycle lines, and formatting the timetable. Nie Lei et al.[10] successfully

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generated periodic train schedules for peak hours by optimizing train arrival and departure sequences, combining periodic and non-periodic models. Li Dewei et al.[11] solved the problem of large-scale periodic timetable formulation by utilizing variable inter-station travel times.

The aforementioned literature primarily focuses on optimizing the timetable preparation for cyclic operations, specifically regarding the optimization of the scheduling period and operation time. However, there is a certain lack of research on the rationality of passenger demand in cyclic timetables. In contrast, there has been some research on the optimization of non-cyclic timetables with consideration of passenger demand. In terms of dynamic passenger demand, Ding Shishun[12] studied the characteristics and principles of timetable preparation under dynamic passenger demand conditions. He developed an integrated optimization model for station stops and train schedules. Zhang Jun et al.[13] conducted evaluations and optimizations on the overall coordination and developmental capability of train schedules based on passenger flow data. Regarding the matching degree between train timetable capacity and passenger demand, Li Sijie et al.[14] proposed a multi-level evaluation method for assessing the matching degree between train timetable capacity and passenger demand.

III. PROBLEM DESCRIPTION

Existing research has laid the foundation for solving the problem of compiling periodic train schedules in China's railway system. It has become an industry consensus to use the PESP model to compile periodic train schedules. The quality of a periodic schedule can be described from two perspectives. For railway operators, the goal is to minimize the total running time of trains within a period in order to reduce operating costs and achieve greater profit margins. For passengers, the aim is to maximize the direct passenger flow rate within the period to minimize transfers and improve passenger satisfaction. The impact of passenger flow rate on the total running time of periodic train schedules is illustrated in Figures 1 and 2. For example, for passengers traveling directly from Station A to Station D, in the timetable shown in Figure 1, there is only one option, which is to take Train C1. In the timetable shown in Figure 2, there are two options: taking Train C1 or Train C7. For example, for transfer passengers traveling from Station A to Station D, in the timetable shown in Figure 1, there are only two options: first take Train C5 and transfer to Train C1 in the next cycle at Station B, or first take Train C7 and transfer to Train C1 in the next cycle at Station C. In the timetable shown in Figure 2, there are four transfer options: first take Train C5 and transfer to either Train C7 or Train C1 in the next cycle at Station B, or transfer to Train C1 in the next cycle at Station C, or first take Train C3 and transfer to Train C1 in the next cycle at Station C. Figures 1 and 2 show that operating more high-speed direct trains results in shorter travel times and lower operating costs for the railway. However, it also leads to a lower direct travel rate, fewer transfer options, and lower passenger satisfaction. On the other hand, operating more low-speed section trains increases travel times and operating costs. But it provides a higher direct travel rate, more transfer options, and higher passenger satisfaction.

The above analysis shows that there is a negative correlation between the total running time of trains and the passenger flow direct rate. This study investigates how to optimize the types and quantities of trains in the periodic schedule. The goal is to maximize satisfaction for both running time and direct passenger flow service demands. The study aims to balance the relationship between the two factors.

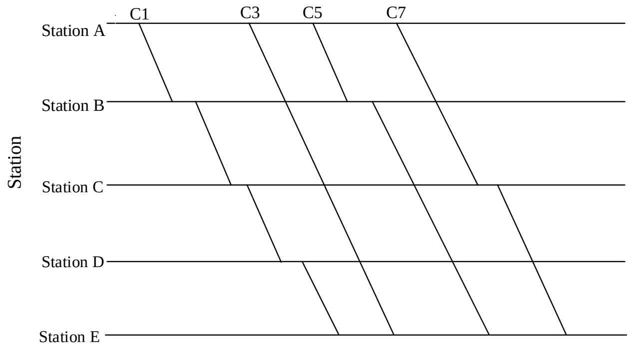

Fig 1 Multi-time unit cycle train timetable of direct trains.

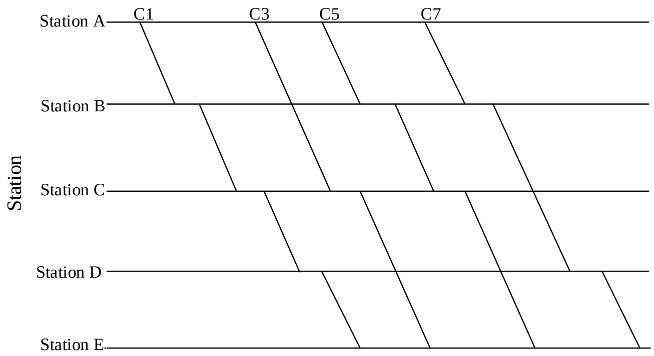

Fig 2 Direct train timetable with few unit cycles.

The optimization process of the periodic schedule is shown in Figure 1. First, the starting and ending points of the periodic trains (major routes) and the station stop plan are determined. This is based on the passenger flow characteristics of the line, such as OD passenger flow and OD levels, as well as the current operation plan. Next, passenger flow boarding and alighting at each starting and ending point and station are analyzed. The stations are then classified into different levels. Different stopping frequencies and limits for consecutive stops are set for each level of station. An alternative train set is generated using an enumeration method. During model optimization, trains are selected from the alternative set based on different direct travel rate requirements. This results in the final periodic train operation plan.

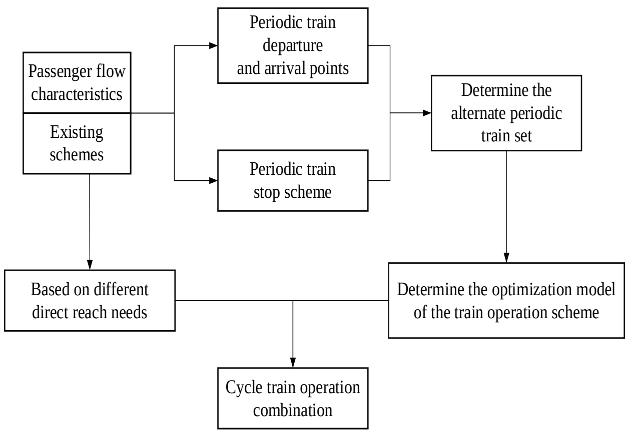

Fig 3 Cycle mode optimization process

IV. METHODOLODY

A. PESP Model

In the PESP model, let the occurrence time of each event i be denoted as t_i. T is the period of the event cycle. In the periodic planning model, the occurrence of all events must satisfy the time window constraints $[E_{ij}, L_{ij}]$. The E_{ij} and L_{ij} represent the upper and lower bounds of the periodic time window constraint. The conditions for E_{ij} and L_{ij} are as follows: $0 < E_{ij} < T$ and $0 < L_{ij} - E_{ij} < T$. Ensure that the occurrence of events is within the period T.

The objective of the PESP model is to find a feasible solution that satisfies the constraints of condition (1).

$$E_{ij} < t_j - t_i + p_{ij}T < L_{ij} \quad (1)$$

p_{ij} is the periodic adjustment parameter between events i and j. By adjusting the values of p_{ij}, the periodic difference between different events can be modified, allowing the events to occur within a single period in the periodic planning problem.

Based on the nature of the PESP problem, under the premise of satisfying conditions $0 < E_{ij} < T$ and $0 < L_{ij} - E_{ij} < T$.

The values of p_{ij} can be one of the following two cases:

(1) When $L_{ij} < T$,if $t_j > t_i$ then $p_{ij} = 0$; if $t_j < t_i$, then $p_{ij} = 1$. In this case, p_{ij} is a binary variable (0 or 1).

(2) When $L_{ij} > T$, p_{ij} can take the values 0,1 or 2.

In the problem studied in this paper, condition $L_{ij} < T$ is satisfied, so p_{ij} takes the values 0 or 1.

B. Model assumptions

(1)The operation plan of the intercity trains, the train running routes, and the composition details of similar trains are known.
(2)The turnaround time and the connection time range of the high-speed train sets at the destination station are known.
(3)The stop time for trains at each intermediate station is known.
(4)The stopping plans for different levels of trains are known. When overtaking occurs at stations with overtaking conditions, only one train is allowed to wait.
(5)Only higher-level trains are allowed to overtake lower-level trains. Within the same level of trains, a passing train can overtake a stopping train.
(6)According to literature 11, the traditional model in the past imposes strict equality constraints on the travel time between train sections. Due to the limited solution space, this often leads to infeasible solutions. In this paper, to ensure a feasible solution, there are no strict constraints on the section travel time.

C. Mathematical model

C.1 Description of parameters and variables

The model in this article involves multiple variables and parameters. In order to facilitate description and understanding, a systematic and detailed explanation of each parameter and variable in the model has been provided. The specific definitions, descriptions, and interrelationships of parameters and variables are shown in Tables 1 and 2.

TABLE I Parameter definitions table

parameters	Description
N	A set of stations, with each station denoted as n_i $i \in \{1,2,3,\ldots\ldots, n\}$
N_s	The set of originating stations where departure trains can be operated
N_e	The set of terminating stations where train arrival operations can be carried out.
N_p	The set of intermediate stations where only train passing operations are carried out.
k_N	The number of arrival and departure tracks at the station.
T	The unit cycle time of the periodic timetable.
G	The set of high-speed train sets, with each train represented by g_{ij}, $i \in \{1,2,3,\ldots\ldots, n\}, j \in \{1,2,3,\ldots\ldots, n\}$
S	The set of sections, with each section represented by s_{ij}, $i \in \{1,2,3,\ldots\ldots, n\} j \in \{1,2,3,\ldots\ldots, n\}$
L_s^T	The maximum capacity of section s within the unit cycle time T.
Q_s^T	The passenger flow through the section s within the cycle time T.
C	The train capacity, where the capacity for each type of train is C_i, $i \in \{1,2,3,\ldots\ldots, n\}$
D_s	The number of sections that need to be served directly within the cycle time T
$T_{\min}^n$	The minimum stopping time of the train at the station.
$T_{\max}^n$	The maximum stopping time of the train at the station.
T_g	The ideal departure time of the train g.
$J_{\min}^n$	The minimum transfer time between trains g and g'.
$J_{\max}^n$	The maximum transfer time between trains g and g'.
$Z_{\min}^n$	The minimum turnaround time for the high-speed train set.
$Z_{\max}^n$	The maximum turnaround time for the high-speed train set.
θ	The train's occupancy rate
Δ	The redundancy of the train's total passenger capacity.

TABLE II Variable definitions table

variables	Description
x_i	The decision variable, the number of trains of the i-th type to be operated.
s_i	0-1 variable, where the value is 1 if train i passes through section S, otherwise it is 0.
Z_s^i	0-1 variable, where the value is 1 if train i can provide direct service for section S, otherwise it is 0.
x_{ij}	0-1 variable, where the value is 1 if the j-th train of the i-th type is operated, otherwise it is 0.
C_{ijs}	The actual passenger capacity of the j-th train of the i-th type on the section.
x_{ijn}	0-1 variable, where the value is 1 if the j-th train of the i-th type can provide service for station$n$, otherwise it is 0.
A_s^g	The departure time of train g at station S
D_e^g	The arrival time of train g at station n
t_s^g	The departure operation time of train g at station S
t_e^g	The arrival operation time of train g at station S.
x_g^n	The train g that needs to stop at station n.
x_i	The decision variable, the number of trains of the i-th type to be operated.

C.2 Objective function

In the cyclic timetable, the train completes its transportation tasks within each unit cycle. The scheduling and operation structure in each cycle are generally similar. Therefore, the optimization objective in this paper is to minimize the total running time of the train within each unit cycle.

The running time of the train within a unit cycle is mainly composed of the train's running time on the track, station dwell time, and the start and end station operation time. The optimization objective function 1 can be expressed as Equation 2.

$$Z_1 = min \sum_{g=1}^{n}(A_s^g - D_s^g + t_s^g + t_e^g) + \sum p_t T \quad (2)$$

Trains of the same type have the same operating speed and station stopping patterns, and they serve the same group of passengers. To ensure balanced train service, it may be necessary to limit the departure frequency of the same type of trains. This should be done within a given cycle to improve passenger service quality. This ensures that the trains of the same type dispatched from the same station to the same section are evenly distributed within the cycle.

Assume there are b trains of the same type within one cycle. To evenly distribute the departure times of these trains, the ideal departure frequency f is such that one train departs every T/b minutes. This paper minimizes the difference between the calculated departure times and the ideal departure times. This approach achieves optimal balanced departure timings. The optimization objective function 2 is shown in Equation 3.

$$Z_2 = min \frac{\sum_{i=1}^{m}(t_i - T_i)}{m-1} \quad (3)$$

C.3 Constraint condition

A. Passenger capacity constraint.

The total passenger capacity of the trains operating on the section should not be less than the passenger flow passing through the section, that is:

$$\sum_{i=1}^{n}\sum_{j=1}^{n} x_{ij} \cdot C \cdot \theta \ge Q_s^T \quad (4)$$

The passenger load of the operating trains cannot exceed the passenger capacity of the trains.

$$\sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{s} C_{ijs} \le C \cdot \theta \quad (5)$$

The total passenger capacity of the trains serving station n should be no less than the passenger flow at station n during the cycle. This ensures enough capacity to meet the demand. Additionally, the total passenger capacity should include a certain degree of redundancy. This helps accommodate transfer passenger flow and sudden surges.

$$\sum_{i=1}^{a}\sum_{j=1}^{b} x_{ijn} \cdot C \cdot \theta \ge Q_n^T (1 + \Delta) \quad (6)$$

B. The line passes through capacity constraint.

The total number of trains operating on the section within the cycle time T should not exceed the maximum passing capacity of the section during the cycle time T.

$$\sum_{i=1}^{n} x_i \cdot s_i \le L_S^T \quad (7)$$

C. Train stop time constraints.

The station stop constraint time for intercity trains includes the passenger boarding and alighting time at each station. It also includes the technical operation time at technical stations.

The minimum stop time for passenger boarding and alighting should be based on the passenger flow at each station. It must be enough to accommodate the needs of passengers boarding and alighting.

$$T_{\min}^n \le D_e^g - A_e^g + p_e T \le T_{\max}^n \quad (8)$$

The technical stop time at intercity train stations is different from that of other trains. It is caused only by the overtaking operations of the train. In this context, it mainly refers to two situations. One is when a higher-level train overtakes a lower-level train. The other is when a train of the same level overtakes a stop-bound train. Additionally, a train can only overtake one train at a time.

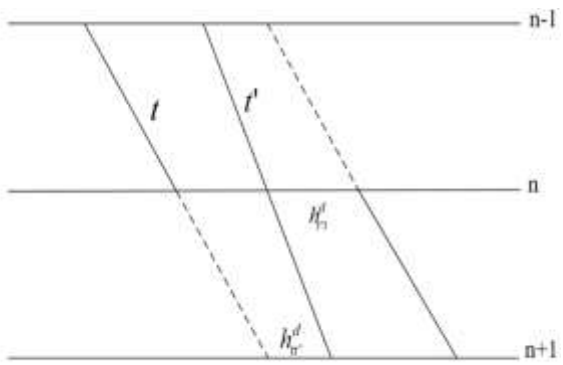

Fig 4 Schematic diagram of the train crossing

$$T_{\min}^n \le D_e^g - A_e^g + p_e T \le T_{v1} - T_{v2} + h_{tt'}^d + h_{t't}^d \quad (9)$$

D. Train safety interval time constraint.

Most of the stations for intercity trains are lower-level stations, such as third-class or fourth-class stations. When considering train safety intervals, it is simplified. The goal is to ensure that the number of trains stopping at the same station does not exceed the number of arrival and departure tracks available..

$$k_N \le \sum x_g^n \quad (10)$$

E. The transfer connection time constraint.

The operating routes of intercity trains are usually fixed. Some trains skip certain stations or operate on shorter routes. As a result, there may be no direct trains between certain stations. This leads to a demand for transfer services from passengers.

$$J_{\min}^n \le D_e^g - A_e^{g'} + p_e T \le J_{\max}^n \quad (11)$$

F. The turnover time constraint for train sets.

The operating sections of intercity trains are fixed. The train sets perform fixed transportation tasks. They adopt a fixed train set schedule. To improve the turnover efficiency of the train sets, the goal is to maximize the transportation capacity of the trains within a given cycle. The EMU train sets should satisfy the following relationship.

$$Z_{\min}^n \le D_e^g - A_e^{g'} + p_e T \le Z_{\max}^n \quad (12)$$

This constraint is similar to the train transfer and connection time constraint. The difference is that trains g and g' use the same set of train units. Train g is the return train following train g'.

In summary, the optimization model for the scheduling of periodic intercity trains takes equations (2) and (3) as the objective functions, and equations (4) to (12) as the constraints.

The optimization model for the scheduling of periodic intercity trains is a linear integer programming model. It is typically solved using integer programming solvers. Examples of solvers include CPLEX, COPT, Gurobi, and others.

D. The steps for solving

Step 1: Based on the characteristics of the actual intercity lines, determine the required periodic operation scheme. Also, determine the stopping plans for different types of trains. Use these as the foundation to arrange the train arrival and departure sequence. Solve the model under the premise of a defined sequence.

Step 2: Develop the train arrival and departure sequence for different stopping plans. Arrange the arrival and departure order at stations for different train services based on their specific stopping requirements.

Step 3: Use software to build the model. Identify and define the various parameters in the model. Use real-world operational data to convert these parameters into model variables. Ensure the variables can be recognized by the software.

Step 4: Use the software to solve the model. Read the data and complete the solution process.

V. Optimization Algorithm

Based on the solved periodic operation scheme, the corresponding train operation plan can be obtained. From this, the proportion of direct passenger flow that can be provided can be determined. The objective function in the optimization model only considers the shortest train running time and the optimal departure frequency. To better evaluate passenger satisfaction, the model is assessed based on the direct passenger flow rate. If the direct passenger flow rate under the periodic mode is high, it means the periodicized OD (origin-destination) passenger flow is high. In this case, it can be concluded that the periodic operation mode meets the service level requirements for passenger travel.

Within the periodic time frame, based on the solved train schedule combination, the corresponding passenger direct flow rate can be obtained. Here, a slack variable y_u^T is introduced to represent the deficit in the direct service frequency for the OD pair to u within the periodic time T. When the service meets the demand, y_u^T takes the value of 0; otherwise, it takes a positive integer.

To achieve the highest direct flow rate, the objective function is to minimize the sum of y_u^T, as follows.

$$\min Z_u = \sum_{u\in U} y_u^T \tag{13}$$

VI. Numerical experiments

This paper selects the Chengdu-Mianyang-Leshan intercity railway as a case study. It optimizes the train operation plan for a periodic time of 1 hour. The paper also determines the passenger flow synchronization level, which is the passenger direct flow rate..

The Chengdu-Mianyang-Leshan intercity railway starts at Jiangyou Station in Mianyang City, in the north, and ends at Yibin West Station in Yibin City, in the south. The total length of the railway is 428 km, with 11 stations along the route. Two speed levels of trains are selected for operation, based on the current train operation points and the station stop plan. The schedule is shown in Table III. There are five stop schemes in total: three for lower-level trains and two for higher-level trains. These are shown in Table IV. The minimum tracking interval between trains is 5 minutes.

After determining the example data, the problem is solved using Gurobi 10.0.2.

When passenger flow demand is not considered, the model solves for the periodic train operation plan of the Chengdu-Mianyang-Lezhi intercity railway at (T = 1h), as shown in Fig 5. A total of 6 trains are operated. The total travel time for the upward-bound trains is 1073 minutes, while the total travel time for the downward-bound trains is 1069 minutes. At this point, the direct passenger flow rate is 75.98%.

Table III The operation timetable for the two speed levels of trains on each section.

Interval	Interval running time (min)	
	High-class trains	Low-class trains
Jiangyou-Mianyang	17	19
Mianyang-Deyang	17	19
Deyang-Xindudong	17	19
Xindu East - Chengdu East	12	13
Chengdu East -Shuangliu Airport	15	17
Shuangliu Airport - Meishan East	20	22
Meishan East - Leshan	19	21
Leshan-Nixi	28	31
Nixi-Pingshan	9	10
Pingshan-Yibing West	12	13

Table IV Train stop plan

Time(min) / Station	plan1	plan2	plan3	plan4	plan5
Mianyang		2	2	7	
Deyang	2	5	2	2	
Xindu East				2	
Chengdu East	2	7	7	7	2
Shuangliu Airport				2	3
Meishan East	2	2	2	2	5
Leshan	2	2	2	2	2
Nixi				2	2
Pingshan				2	2

To improve the synchronization level of passenger flow, a direct service constraint is introduced. This constraint explores the relationship between the direct passenger flow rate and the travel time.

$$\sum_{u\in U} y_u^T \le z \tag{14}$$

After introducing the direct rate constraint, for example, ensuring a direct rate of no less than 85%, compare it with the initial timetable. The operating diagram with a direct arrival rate of no less than 85% is shown in Figure 6.

The comparison of the cyclical level, passenger flow direct reach rate, and proportion of under-frequency for the two schemes over 1 hour is shown in Table V.

By comparison, although the initial plan has a higher direct reach rate, it has a larger proportion of under-frequency. The new plan increases the total running time by 53 minutes, but the direct reach rate increases by 9.84%, and the cyclical level improves by 14.64%. This significantly improves passenger satisfaction. Therefore, introducing the direct reach rate constraint is crucial for the practical application quality of the timetable.

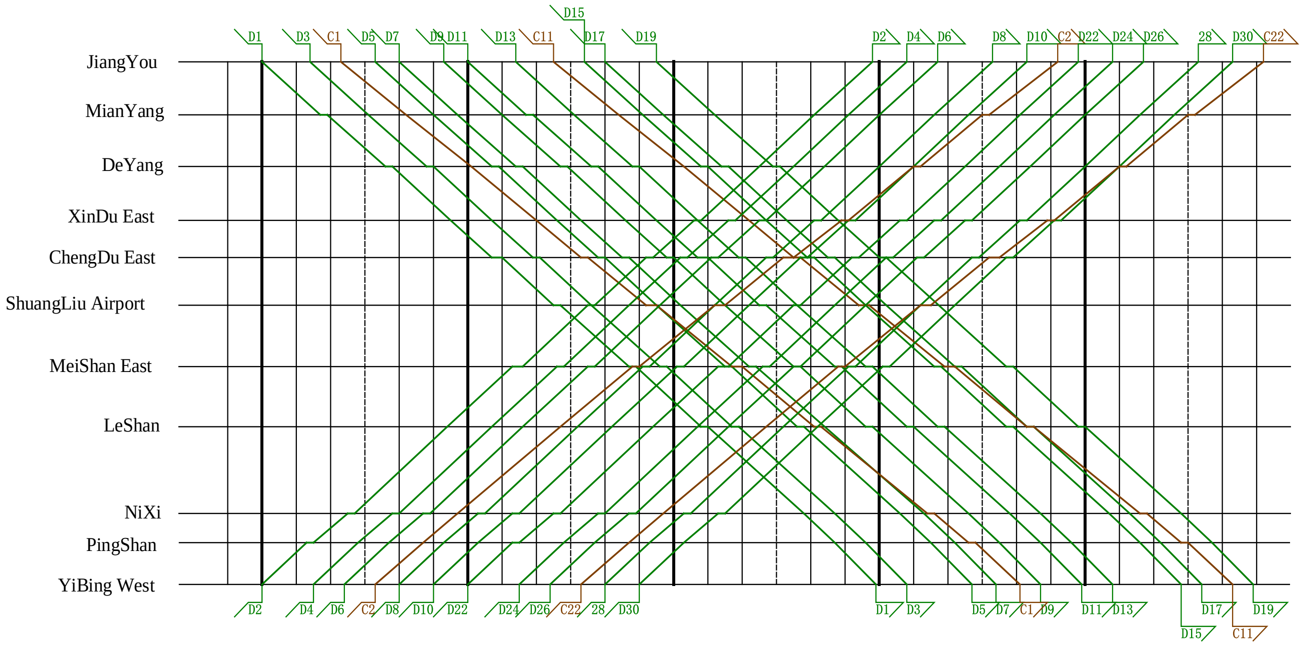

Fig 5: Basic periodic train operation plan.

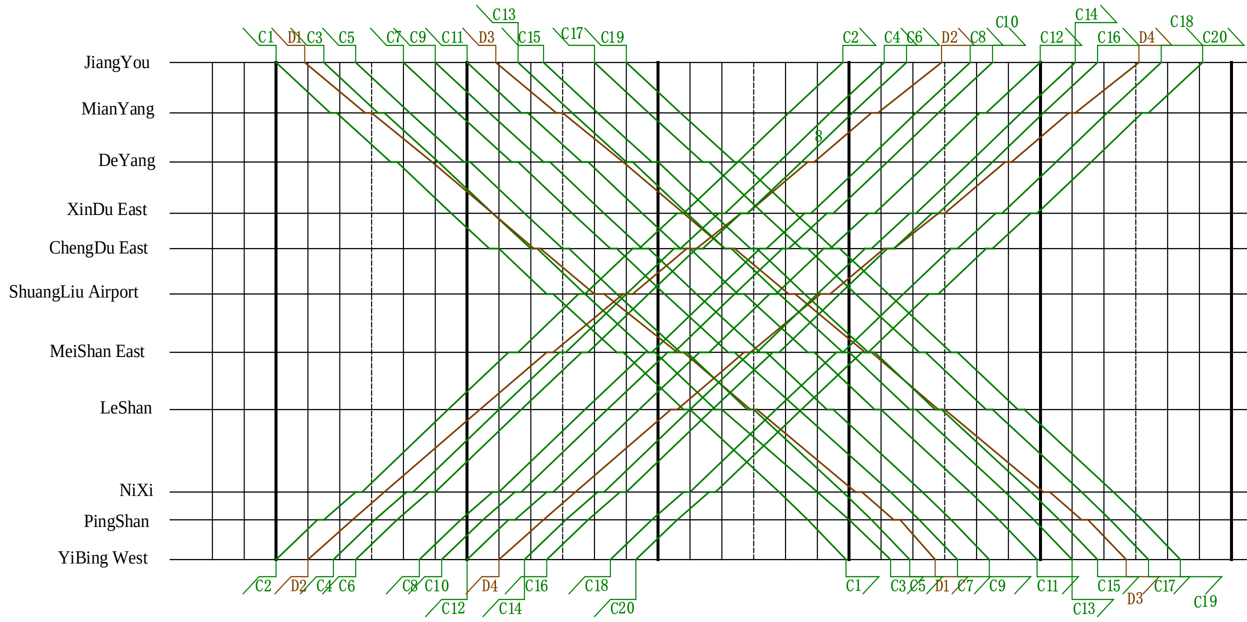

Fig 6: The timetable with a direct rate of no less than 85%.

Table V Comparison of cyclical mode evaluation indicators.

	Proportion of under-frequency	Cyclical level	Passenger flow direct reach rate
Initial scheme	25.05%	65.98%	75.98%
Optimized scheme	15.24%	80.66%	85.86%

After introducing the direct flow rate constraint, the train's direct flow rate is gradually increased. This helps obtain the relationship between travel time and direct flow rate. The relationship is plotted in Figure 7.

As shown in Figure 7, as the direct flow rate increases, the total travel time of the trains also gradually increases. The two are linearly positively correlated. In practical applications, one should not blindly pursue the highest direct flow rate to improve passenger service quality. This could lead to excessively long total travel times and high railway operation costs. To balance the relationship between the two, this paper converts the deficiency in direct service into time. This time is then added to the total travel time to form a new objective function.

$$Z = (min\alpha \sum_{g=1}^{n} (A_s^g - D_s^g + t_s^g + t_e^g) + \sum p_t T) + \beta \frac{\sum_{i=1}^{m}(t_i - T_i)}{m-1} + \sum_{u \in U} y_u^T \cdot \gamma \tag{15}$$

γ: Represents the conversion ratio between the deficiency in direct flow rate and travel time.

The curve showing how the total travel time changes with the direct flow rate after adding the direct flow time penalty, based on the new objective function, is shown in Figure 8.

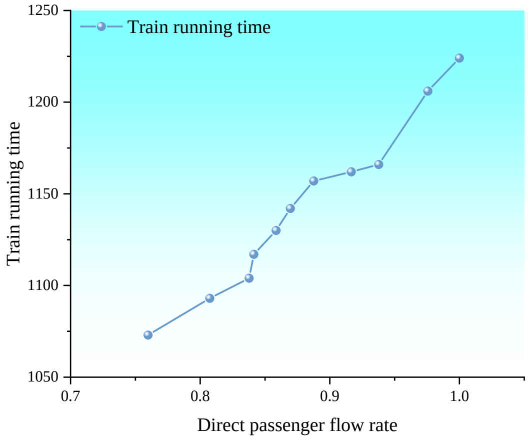

Fig 7: Relationship between travel time and direct flow rate

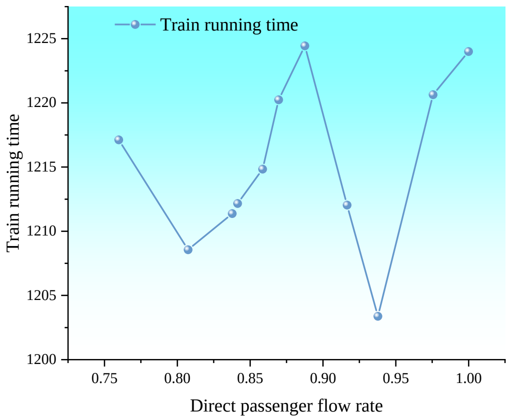

Fig 8: Relationship between travel time and direct flow rate after adding time penalty.

As can be seen from Figure 8, the total time is optimal when the direct flow rate is 93% and 77%. At this point, without considering the penalty time, the total travel time of the trains is 1166 minutes.

The relationship between the running time and directness rate for two operating schemes is compared in a single graph, as shown in Figure 9. It can be clearly observed that after the time penalty is added, the running time no longer increases as the directness rate rises. From Figures 9 and 8, it is evident that when the directness rate is 93.77%, the total running time is the shortest, which is 1166 minutes without considering the penalty time.

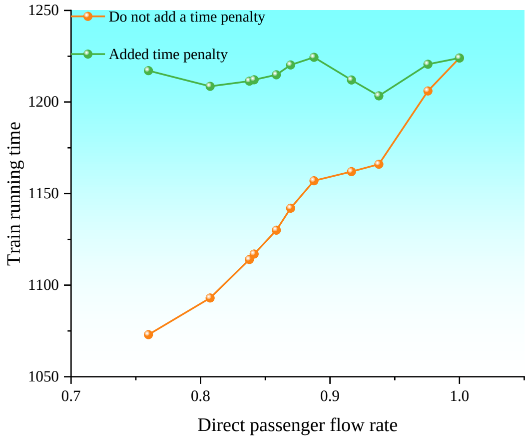

Fig 9 Comparison chart of running time

To describe the service quality of the trains under different operating schemes more clearly, the running time with the added penalty time is calculated for various operating schemes, showing the relationship with passenger flow directness rate and synchronization level (percentage of periodic passenger flow), as shown in Figure 10. From Figure 10, it can be seen that the optimal running time is 1166 minutes, with a directness rate of 93.77% and a synchronization level of 92.68%.

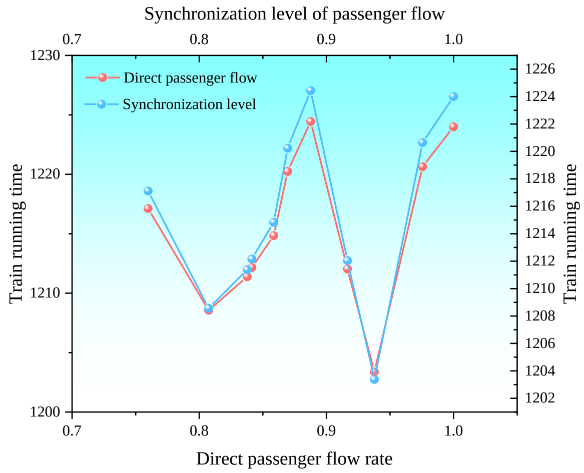

Fig 10 Comparison of the direct reach rate with the level of contemporaneity

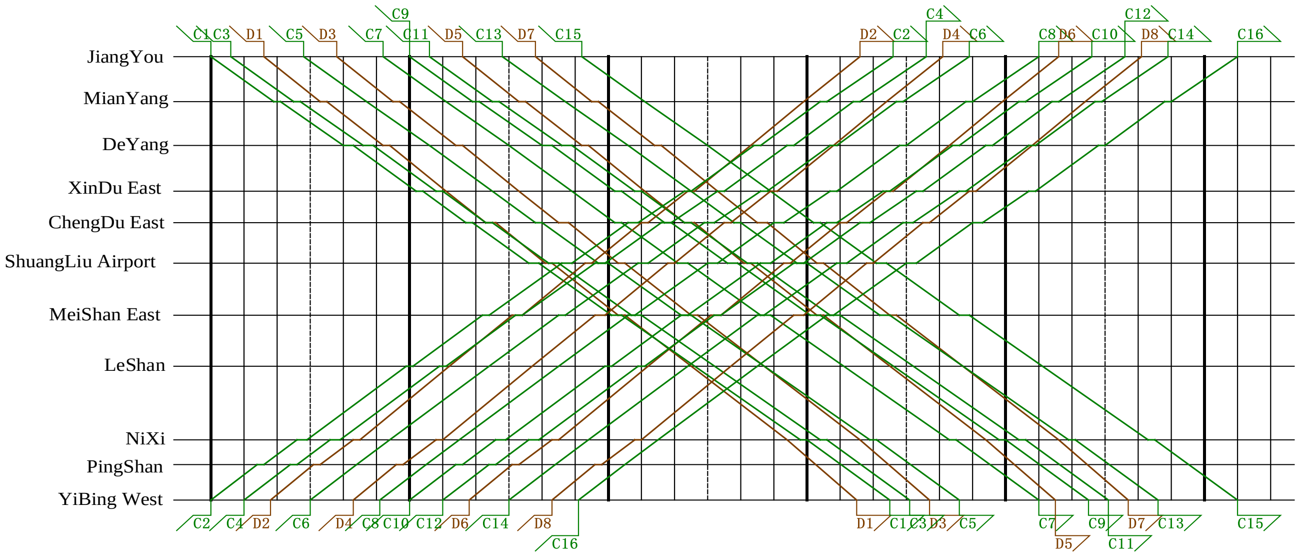

Fig 11 Optimal train scheduling plan

Table VI Comparison of cyclical mode evaluation indicators.

	Proportion of under-frequency	Cyclical level	Passenger flow direct reach rate
Initial scheme	25.05%	65.98%	75.98%
Optimized scheme	7.13%	92.68%	93.77%

At this point, a total of 6 trains are operating, with the total travel time for the upward trains being 1166 minutes and the total travel time for the downward trains being 1169 minutes. The direct flow rate for passenger traffic at this time is 93.77%. The optimal operation diagram at this time is shown in Figure 11.

We compared the initial plan with the optimal plan, as shown in Table VI. The total operation time of the optimal plan is 93 minutes longer than the initial plan. However, the under-frequency weight is reduced by 17.92%. The passenger synchronization level increased by 26.7%, and the direct passenger rate increased by 17.79%. In the optimal plan, railway operating costs increased, but passenger satisfaction was higher, resulting in better service quality.

VII. CONCLUSION

This paper investigates the rationality of passenger flow demand in periodic timetables. It establishes an optimization model for compiling periodic intercity train schedules based on the PESP model. The goal is to minimize the total train operating time. The model considers constraints such as safe departure and arrival times for adjacent trains, passenger capacity constraints, station stop time constraints, train turnover constraints, and section capacity constraints. The model is solved using Gurobi 10.0.2. Based on theoretical research, a periodic train timetable for the Chengdu-Mianyang intercity trains, in both upward and downward directions, is developed. Finally, the relationship between passenger flow directness rate and total train operating time is examined to assess the rationality of passenger flow demand. Based on this, a method for selecting the optimal periodic train operation plan is proposed.

In practice, this paper only considers the operation of intercity trains on a specific line. It does not account for the operation of other high-speed trains. Further research is needed on the periodic scheduling of trains on the entire high-speed rail network. Additionally, only the safe time intervals for train arrivals and departures are considered. The issue of platform occupancy at stations is not fully addressed. Future research can focus on this issue. This study focused solely on the collaborative optimization of train route planning and schedules for single-direction express rail link operations. Future research could expand this to include bidirectional operations or entire railway networks.

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