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Yong Qin · Limin Jia · Jianwei Yang ·
Lijun Diao · Dechen Yao ·
Min An *Editors*

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Rail Transportation Operation Management Technologies

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Contents

Study on the Compilation of Train Diagram and Transportation Capacity of Urban Rail Transit

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Abstract. The train diagram of urban rail transit is the concentrated embodiment of the transportation organization of the whole urban rail transit system. By analyzing the passenger flow data of a metro line in a city, the section passenger flow in peak hours and the maximum section passenger flow in time period in the whole day are calculated from the OD matrix. The number of running trains and the running interval are also calculated, and fine-tuning is carried out, so as to get the full-time driving plan. On the basis of determining the train routing, stop plan, turn back plan and vehicle operation plan, the train diagram shall be prepared. In order to ensure the subway operation enterprises to arrange transportation production reasonably, through the analysis of subway line capacity and train capacity, the transportation capacity is analyzed and studied.

Keywords: Train diagram · OD matrix · Full-time driving plan · Transportation capacity

1 Introduction

The dispatch and command work of urban rail transit is an important part of the operation and management of urban rail transit systems. The important foundation of its work is that the train operates well according to the train diagram. The train diagram is a graphical explanation of the spatial and temporal relationship of train operation. It interprets the order in which each train occupies the section, train operation time, the arrival and departure or passing time of each station, the dwell time at the station and the turnaround time at the turnaround station and train routing and the inbound and outbound time at the vehicle depot. It is an important foundation for subway operation enterprises to organize train operations [1]. Zhou Zhengduo [2] et al. established an optimization model for redundant time layout of train operation diagrams of high-speed railway. It has positive significance in ensuring the order of transportation organization and improving the quality of passenger transportation services. Wang [3] et al. established a state space model that considers the evolution of train departure time and changes in passenger capacity inside the train. Jovanović [4] et al. fixed the train interval operation time and dwell time, and abstracted the optimal allocation of train interval redundancy time as a

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knapsack problem. Shi Xiaojun [5] analyzed the elements and steps of preparation of train operation diagram based on his practical experience in preparing Tianjin Metro No.1, and summarized the preparation techniques. Xu Ruihua [6] et al. analyzed the design concept and overall structure of computer compilation of train operation diagrams for urban rail transit, and studied a series of issues related to the operation and management of urban rail transit systems. Du Yijia [7] et al. analyzed the functional characteristics of train operation diagram compilation systems for domestic and foreign railway networks, providing a platform and tool for the development of train operation diagram compilation systems for networked railway lines. Rong Jian [8] conducted research on management optimization strategies for train operation diagram preparation to improve the level of train operation diagram preparation. Guo, H. [9] built a mathematic model to characterize the time-varying demand on passengers arriving at the platform of a metro station linking to an intercity railway station. Zhang Kun [10] briefly analyzed the factors and strategies of subway transportation capacity to improve the transportation efficiency of urban rail transit. Kang Liujiang [11] achieved collaborative compilation of network operation diagrams.

The above literature has not studied the most basic method of compiling train diagrams. So, the peak hour OD matrix (7:00~8:00) of a certain line in a city is given. The process of compiling train operation diagrams is calculated and studied. In general, the given 14 stations are named A, B, C, D, E, F, G, H, I, J, K, L, M and N. The average station spacing is 1543 m, with one end being the depot and the other end being the parking lot. A $\rightarrow$ N is the downlink, and N $\rightarrow$ A is the uplink.

2 Technical Route

Compiling a train diagram is a complex task that requires maintaining certain principles. On the premise of ensuring safety and reliability, the train speed is increased and the running time of the train is reduced for the convenience of passengers. Appropriate turn back methods are selected to fully utilize train and line capabilities. For economic reasons, the number of vehicles in operation should be minimized as much as possible [12]. The technical route for preparing train operation diagram is shown in Fig. 1.

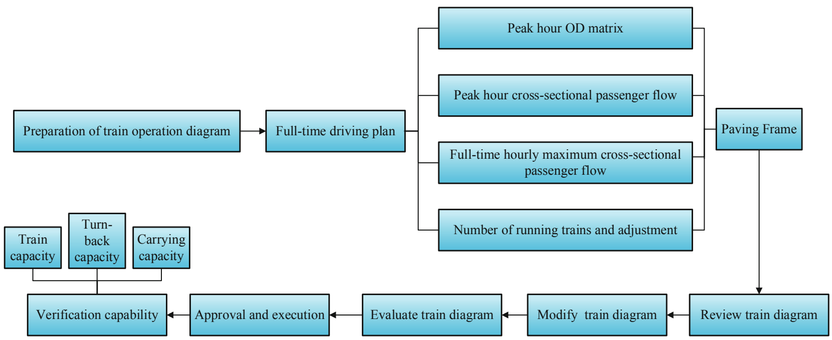

Fig. 1. Compilation process of train operation diagram

3 Process Exploration

3.1 Calculation of Cross-Sectional Passenger Flow

According to the peak hour OD matrix, the cross-sectional passenger flow during peak hours can be calculated. As shown in Table 1 below. The number of downlink people and the number of uplink people in the table refer to the cross-sectional passenger flow during peak hours.

$$P_j = P_i - P_x + P_s \tag{1}$$

where, P_j is passenger flow of the jth cross section. P_i is passenger flow of the ith cross section. P_x is number of passengers getting off at the station. P_s is number of passengers boarding at the station.

Table 1. Peak hour (7:00~8:00) cross-sectional passenger flow (unit: person)

The number of downlink people	The number of downlink people boarding	The number of downlink people getting off	Station name	The number of uplink people boarding	The number of uplink people getting off	The number of uplink people
13461	13461	0	A	0	11486	11486
19474	6145	132	B	105	5232	16613
24294	5174	354	C	382	5027	21258
26764	3273	803	D	859	4347	24746
30387	4703	1080	E	1180	4290	27856
31145	3617	2859	F	2189	3443	29110
27282	7064	10927	G	11784	5637	22963
26376	2907	3813	H	6519	2464	18908
23012	1928	5292	I	4057	1622	16473
19875	1485	4622	J	4830	998	12641
14263	1041	6653	K	3236	534	9939
9018	716	5961	L	3829	288	6398
4475	103	4646	M	3895	330	2833
	0	4475	N	2833	0	

There is a peak period, which occurs at the F-G section. The other sections gradually decrease from the peak section to both sides. Therefore, it can be inferred that two ends of the line are in the suburbs, with less passenger flow, and the middle is in the city center. The commercial community and other areas have a larger passenger flow, and most people are in the city center.

3.2 Division of Working Day Periods

The operating time of urban rail transit systems in China is generally 18 h. From 5:00 to 23:00. Due to the fact that the OD matrix is obtained from research on weekdays, only the weekday train diagram and capability are discussed. The division of time periods and the distribution proportion of full-time hourly maximum cross-sectional passenger flow are shown in Table 2 below. From Table 1, it can be seen that the maximum section passenger flow during peak hours is 31145 passengers, which can be calculated as full-time hourly maximum cross-sectional passenger flow.

Table 2. Full-time hourly maximum cross-sectional passenger flow

Time	Distribution ratio (%)	Passenger flow	Time	Distribution ratio (%)	Passenger flow (%)
5:00–6:00	17	5295	14:00–15:00	58	18064
6:00–7:00	45	14015	15:00–16:00	69	21490
7:00–8:00	1	31145	16:00–17:00	85	26473
8:00–9:00	75	23359	17:00–18:00	62	19310
9:00–10:00	5	15573	18:00–19:00	42	13081
10:00–11:00	53	16507	19:00–20:00	34	10589
11:00–12:00	63	19621	20:00–21:00	29	9032
12:00–13:00	6	18687	21:00–22:00	26	8098
13:00–14:00	6	17441	22:00–23:00	16	4983

3.3 Determination of Train Formation Plan

In urban rail transit, three types of vehicle A, B, and C are specified. According to the situation, Type A vehicles are selected. The commonly used 6-vehicle formation scheme in urban rail transit has been adopted. That means six A-type vehicles are coupled to form a train. Length of each carriage of type A vehicle is 24.4 or 22.8 m. Its width is 3 m. Vehicle capacity is 310 persons.

3.4 Preparation of A Full Day Driving Plan

The full day driving plan is the plan for the number of trains that will operate in each hour during the operating hours of the urban rail transit system. The daily operation tasks of urban rail transit lines are specified.

$$n_i = \frac{P_{\max}}{P_{train}\beta} \tag{2}$$

where, n_i is number of hourly trains operating throughout the day. P_{train} is number of train personnel quota. $P_{\max}$ is one-way maximum cross-sectional passenger flow. β is full load rate of line section.

$$\beta = \frac{P_{\max}}{C_{\max}} \times 100\% \tag{3}$$

where, $C_{\max}$ is the transportation capacity of the line during peak hours.

The value of β can be determined based on different time periods. During peak hours of passenger flow, it can be greater than 1, and at other times it can be lower than 1. Its function can determine the basic balance of the number of trains running, without causing frequent train entry and exit. Therefore, 110% is used during peak hours, and 90% is used during other operating hours. The number of train personnel quota during peak and off-peak hours is respectively 2046 and 1674.

The number of trains running is calculated, and the departure interval also needs to be calculated. The calculated driving interval during a certain period of time may be relatively long. If it is too long, the waiting time for passengers will be increased, and the quality of service will be reduced. Therefore, considering all factors, the driving interval should be between 9:00 and 21:00. Generally, it should not exceed 6 min. During off-peak operating hours, it is generally not recommended to exceed 10 min. The calculation results and the final number of trains are shown in Table 4 below. As shown in Table 3 below

$$t_{interval} = 60/n_i \tag{4}$$

where, $t_{interval}$ is interval time of trains running.

3.5 Determination of Train Stop Time

The main purpose of subway trains stopping at stations is to carry out passenger transportation operations, such as passengers boarding and disembarking. When calculating the train dwell time, it is necessary to minimize the train dwell time and improve transportation efficiency while meeting the requirements of train dwell operations to the greatest extent possible.

$$t_{station} = \frac{h\left(P_{boarding} + P_{disembarking}\right)t_{boarding}(disembarking)}{nmd} + t_{onandoff} - t_{\Delta} \tag{5}$$

Where, $P_{boarding}, P_{disembarking}$ is number of people boarding or disembarking at stations during peak hours. $T_{boarding(disembarking)}$ is the average time required for each passenger to board or disembark (Acceptable 1.2 s). $T_{on\ and\ off}$ is time for opening and closing the door (Acceptable 18 s) [13]. $t_{\Delta}$is overlapping time between opening and closing doors and passenger boarding (Acceptable 3 s). h is peak hour coefficient (Acceptable 1.15). n is number of trains operating during peak hours (Acceptable 16). m is number of train formations (Acceptable 6). D is number of doors on each side of each vehicle (Acceptable 5).

According to the above formula, the stopping time of the train can be calculated. To consider a certain amount of surplus, an upward floating treatment should be carried out, usually an integer multiple of 5. As shown in Table 4 below.

Table 3. The number of hourly trains operating throughout the day

Time	Interval time of trains running after adjustment	Number of running trains	Number of running trains after adjustment	Time	Interval time of trains running after adjustment	Number of running trains	Number of running trains after adjustment
5:00–6:00	10 min	4	6	14:00–15:00	5 min 30 s	11	11
6:00–7:00	6 min 42 s	9	9	15:00–16:00	4 min 36 s	13	13
7:00–8:00	3 min 45 s	16	16	16:00–17:00	4 min 36 s	13	13
8:00–9:00	4 min 18 s	14	14	17:00–18:00	5 min	12	12
9:00–10:00	6 min	10	10	18:00–19:00	6 min	8	10
10:00–11:00	6 min	10	10	19:00–20:00	6 min	7	10
11:00–12:00	5 min	12	12	20:00–21:00	6 min	6	10
12:00–13:00	5 min	12	12	21:00–22:00	10 min	5	6
13:00–14:00	5 min 30 s	11	11	22:00–23:00	10 min	3	6

Table 4. Stopping time at each station

Station	Number of passengers boarding and disembarking	Stopping time (s)	Correction of stop time (s)	Station	Number of passengers boarding and disembarking	Stopping time (s)	Correction of stop time (s)
A	13461	53.70	55	H	6720	34.32	35
B	6277	33.05	35	I	7220	35.76	40
C	5528	30.89	35	J	6107	32.56	35
D	4076	26.72	30	K	7694	37.12	40
E	5783	31.63	35	L	6677	34.20	35
F	6476	33.62	35	M	4749	28.65	30
G	17991	66.72	70	N	4475	27.87	30

3.6 Determination of Interval Operation Time

Nowadays, trains generally run under the moving block signal system. The average operating speed of the section is 50 km/h. According to the distance between stations, the running time between trains is calculated as shown in Table 5.

Table 5. Train interval operation time

Interval	Interval distance (m)	Running time (s)	Interval	Interval distance (m)	Running time (s)
A—B	1569	113	H—I	1258	91
B—C	1235	89	I—J	1496	108
C—D	1458	105	J—K	1789	129
D—E	1469	106	K—L	1691	122
E—F	2103	152	L—M	1854	134
F—G	1256	91	M—N	1395	101
G—H	1479	107			

3.7 Determination of Train Turnback Time

The turn back operation of trains on this line at destination stations A and H belongs to the post station turn back operation. Train stopping at platform 1 handles passenger disembarking operations within a certain stopping time. After completion, the train enters turn back line 2 from the main line, and the shunting route can be processed. The train is within the turn back line, and the drivers of the front and rear trains change their heads. After staying for a certain period of time, the previous train leaves the station. At the same time, the switch is opened on the main line and the shunting signal is open, entering the downlink platform 3, and the train completes the turn back operation.

The calculation formula is:

$$h_{departure} = t_{leave} + t_{operation}^{exit} + t_{confirm} + t_{departure} + t_{stop} \quad (6)$$

where, t_{leave} is the time when the departing train leaves the station block zone (Acceptable 1.5 min). $t_{operation}^{exit}$ is time for handling exiting turn back line (Acceptable 0.5 min). $T_{confirm}$ is time for confirming the signal (Acceptable 0.5 min). $T_{departure}$ is time the train runs from the station's turn back line to the departure line (Acceptable 1.5 min). T_{stop} is train stop time including passenger boarding (Acceptable 1 min).

Therefore, the final turnback time of the train is 5 min, or 300 s.

3.8 Preparation of Vehicle Allocation Plan

To complete the passenger transportation task, the urban rail transit system must maintain a certain number of vehicles. According to usage, it can be divided into three categories: operating vehicles, maintenance vehicles and backup vehicles.

For operational vehicles:

$$N = \frac{n_{peak\ hours}\theta_{train} m}{3600} \quad (7)$$

where, N is Number of operating vehicles. $N_{peak\ hours}$ is number of operating trains during peak hours. θ_{train} is train turnover time. m is number of train formations.

Among them:

$$\theta_{train} = \sum t_{running} + \sum t_{station} + \sum t_{turnback\ station\ stop} \quad (8)$$

where, $t_{running}$ is the sum of the running time of trains traveling back and forth between different sections on the line. $T_{station}$ is the total stopping time of each intermediate station for a train traveling back and forth on the line. $T_{turnback\ station\ stop}$ is the total dwell time of the train at the turnaround station.

Based on the above dwell time, interval operation time and turnaround time, adding an additional 20 s for train start and 10 s for parking, train turnover time θ_{train} is 4306 s namely 71.77 min. So, the number of operating vehicles is 115. The number of maintenance vehicles and the number of backup vehicles are generally determined based on 10% of the number of operating vehicles. So the total number of maintenance vehicles and backup vehicles is 23. The final total number of vehicles was determined to be 138.

4 Preparation of Train Diagram

For the drawing of train diagrams, manual drawing can be used. But with the continuous development of computer technology, major simulation software has been launched one after another. For example, there is Matlab, AutoCAD, etc. Nowadays, China's urban rail system adopts the internationally advanced Automatic Train Control (ATC). This system can lay out train diagrams. Therefore, ATC Train Dispatch Simulation System of Urban Rail Transit is used for development.

Based on the data determined above, they are input into the software. Train diagram is drawn. The results are shown in Fig. 2 (partial view).

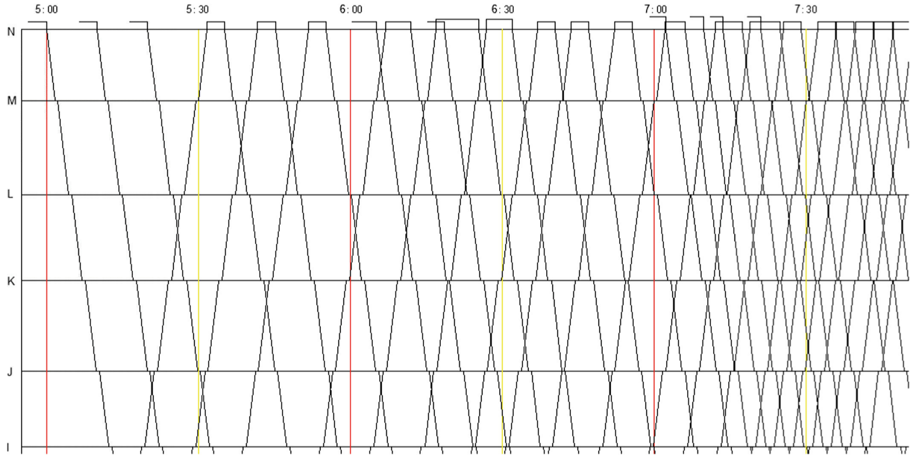

Fig. 2. Partial enlarged view of train diagram

4.1 Exploration of Train Transportation Capacity

For train passing capacity, that is the maximum number of trains that can pass in a certain direction within 1 h on a certain route.

$$n_{\max} = \frac{3600}{t_{interval}} \tag{9}$$

where, $n_{\max}$ is the maximum number of trains that the line can pass through within 1 h. t_{interval} is minimum train interval.

For this line, the moving block control principle is adopted. Under the moving block system, the tracking point of the following train is the tail of the preceding train. Tracking interval of moving block train:

$$I = \frac{V_{\max}}{3.6a} + 3.6 \times \frac{L_F + L_A}{V_{\max}} \tag{10}$$

where, $V_{\max}$ is maximum running speed of the train (Acceptable 80 km/h). a is train braking deceleration (Acceptable 1.3 m/s^2). L_F is distance of train travel within the confirmation signal and braking response time $L_F = (30\,s + 1.5\,s) \times \frac{50000\,m}{3600\,s} \approx 438\,m$. L_A is the safe distance from the target stopping point of the following train to the starting point of the track circuit occupied by the preceding train (Acceptable 200 m).

After analysis, it can be concluded that the minimum tracking interval of the train is 108 s.

For turn back capability, it refers to the maximum number of trains that can be turned back at a turn back station within a unit hour.

$$n_{turnback} = \frac{3600}{h_{depart}} \tag{11}$$

where, $n_{turnback}$ is the maximum number of trains that can turn back within 1 h at the turn back station. H_{depart} is Time for train turn back departure interval.

So, the turnback capacity of this line is 12 trains.

For train capacity, it refers to the amount of space that a train can transport passengers when fully loaded.

$Traincapacity = Numberofpassengerspervehicle \times Numberoftrainformations$ For the transportation capacity of the line, it is equal to the product of the passing capacity and the train capacity.

$$p = n_{\max} m p_{train} \tag{12}$$

where, p is maximum conveying capacity per unit time of the line. N_{max} is the maximum number of trains that the line can pass through within 1 h. m is number of train formations. P_{train} is vehicle personnel quota.

So, the transportation capacity of this line is 63240 people.

5 Conclusion

By peak hour OD matrix for a specific route through the city, peak hour cross-sectional passenger flow and full-time hourly maximum cross-sectional passenger flow are calculated. So, the full-day driving plan can be obtained. The departure interval has been fine-tuned, resulting in a feasible full-day driving plan. The stopping time and interval running time are calculated ulteriorly. After determining the turn back method, turn back time, train routing, stop plan, and vehicle allocation plan, ATC simulation software is used to draw train diagrams to obtain the planned train diagram, and transportation capacity is explored. When preparing the train diagram, it is necessary to conduct a comprehensive analysis of the system. Comprehensive planning should be achieved, constantly summarizing experience to improve drawing quality. In the later stage, further research should be conducted on the crew plan, which refers to the use of the plan by crew members.

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Research on High-Speed Railway Timetable Rescheduling Based on Genetic Algorithm

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Abstract. This paper presents an effective approach to address the challenge of rapidly restoring train operation order and automatically generating scheduling optimization schemes during abnormal events. The study focuses on high-speed railway, and establishes a high-speed railway train operation adjustment model, with the primary objective of minimizing the weighted total arrival delay time while satisfying various time and capacity constraints. To overcome the NP-hard nature of the problem, we propose a genetic algorithm approach with an appropriate coding mode, fitness function, crossover, and mutation rules. To validate the proposed model and algorithm, we use the operational data from the Beijing-Shanghai high-speed railway. The results of comparing the advantages and disadvantages of the genetic algorithm with the interval-only accelerated operation method demonstrate the feasibility and effectiveness of genetic algorithm, which can provide decision support for dispatching high-speed railway train operation scheduling.

Keywords: Timetable Rescheduling · High-speed Railway · Genetic Algorithm

1 Introduction

According to the Statistical Bulletin of China State Railway Group Co., Ltd. in 2021 [1], by the end of 2021, the mileage of China's high-speed rail operation had exceed 40,000 km, and the number of trains had reached 4,153, ranking first in the world. Adjustment of train operation is also called real-time scheduling, which means that under emergency conditions, according to the length of delay time and the number of trains affected by delay propagation, the normal operation of delayed trains can be resumed and the influence of delay propagation can be reduced as much as possible, so as to ensure the high punctuality rate of trains.

Emergency events can be divided into slight disturbance and severe disturbance [2]. Train real-time scheduling optimization under slight disturbance is mainly aimed at the scene where the train has slight initial delay, and the model complexity increases exponentially with the complexity of the study scene, which cannot solve the problem of large-scale serious disturbance [3]. Shuguang Zhan [4] proposed a train operation

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adjustment model based on event activity network for the complete or partial interruption of the interval. Ruhu Gao et al. [5] proposed an optimization algorithm of running diagram based on ADMM (Alternating Direction Method of Multipliers). Zhiwen Liao et al. [6] proposed a train operation adjustment model based on priority. Considering transfer, Pengcheng Wen et al. [7] established a linear integer programming model of train operation adjustment suitable for the last train period. Considering passenger transfer, Pu Zhang et al. [8] established a multi-objective mixed integer linear programming model to minimize the total train delay time and the number of passengers who failed to transfer. Considering severe initial delay and interval speed limit conditions, Mingming Wang et al. [9] constructed a multi-objective nonlinear train scheduling optimization model based on event activity network. Based on global conflict analysis, Jun Zhang et al. [10] constructed a bi-objective programming model for schedule adjustment, which was solved by the algorithm of Pareto optimality and Nash equilibrium. Mingming Wang et al. [11] proposed a hybrid heuristic algorithm of genetic and particle swarm optimization to solve the train operation adjustment model under slight initial delay, but the gap between the feasible solution and the optimal solution in an acceptable time was 19.6%. Ming Lei et al. [12] applied the idea of co-evolutionary genetic algorithm to solve the train operation adjustment model.

2 Definition of Problem

Train real-time scheduling problem is a NP-hard problem, in order to simplify the research, the following assumptions are put forward:

(1) Taking a single railway line as the research object, trains in different directions of line run independently, and one of directions is selected for research.
(2) Assuming that the number of arrival and departure lines and staff at each station are sufficient.

3 Model Construction

3.1 Model Parameters & Decision Variables

Before building the model, it is necessary to define the known parameters and unknown variables. The symbolic meanings of sets, indexes, parameters and variables used in mathematical models are shown in Table 1.

3.2 Model Construction

In this paper, the goal is to minimize the weighted total arrival delay time, which mainly measures the total delay time of trains arriving at each station.

$$\min \ z = \sum_{k \in K} \sum_{u \in U} a_k \times \left(A_u^k - A\prime_u^k \right) \tag{1}$$

In order to ensure the feasibility of the train operation adjustment scheme, the adjustment should be carried out under certain constraints.

Table 1. The meanings of the parameters and decision variables

Symbols	Meanings
K	Set of train services, indexed by k, $k \in \{1, 2, \ldots, n\}$
U	Set of stations, indexed by u, $u \in \{1, 2, \ldots, m\}$
τ_{start}	Additional time caused by starting at station
τ_{stop}	Additional time caused by stopping at station
t_{arr}	The headway of arrival at station
t_{dep}	The headway of departure from station
T_u^k	Minimum dwell time of train k at station u
$A_u^{\prime k}$	Scheduled arrival time of train k at station u
$D_u^{\prime k}$	Scheduled departure time of train k from station u
A_u^k	Actual arrival time of train k at station u
D_u^k	Actual departure time of train k from station u
$r_{u,u+1}$	Minimum interval time of the same track occupied by adjacent train
I	Time interval between trains spaced by automatic block signals

- The Constraint of Dwell Time

The dwell time of trains at each station must be longer than the minimum dwell time.

$$D_u^k - A_u^k \geq T_u^k, k \in K, u \in U \tag{2}$$

- The Constraint of Interval Time of Track

Adjacent trains need to meet the constraint of minimum interval time of the same track.

$$\begin{cases} \left|A_u^{k+1} - A_u^k\right| \geq I \\ \left|D_u^{k+1} - D_u^k\right| \geq I \\ k \in K, u \in U \end{cases} \tag{3}$$

- The Constraint of Departure Time

The passenger train can only depart from the railway station after ensuring that all passengers who purchase tickets have completed boarding and landing, and it is usually not allowed to depart earlier than the scheduled departure time.

$$\begin{cases} D_u^k \geq D\prime_u^k \\ D_u^{k+1} - D_u^k \geq t_{dep} \\ A_u^{k+1} - A_u^k \geq t_{arr} \\ k \in K, u \in U \end{cases} \tag{4}$$

- The Constraint of Minimum Interval Time

In order to ensure the safety of train operation, the running speed of trains cannot exceed the maximum running speed specified according to the line design conditions, that is, it meets the requirement of minimum interval time of the same track occupied by adjacent train.

$$A_{u+1}^k - D_u^k - \tau_{\text{start}} - \tau_{\text{stop}} \geq r_{u,u+1}, k \in K, u \in U \tag{5}$$

- The Constraint of Crossing

Trains in the same direction cannot appear in the same space at the same time. Even at the station, one arrival and departure line can only be occupied by one train at the same time.

$$\begin{cases} D_u^k > D_u^g \Rightarrow A_u^k > A_u^g \\ k \in K, u \in U, k \neq g \end{cases} \tag{6}$$

4 Model Solving

Genetic algorithm is a random search algorithm and can solve combinatorial optimization problems well. The basic idea of solving the problem of timetable rescheduling by genetic algorithm is as follows:

- Chromosome Coding

In order to make chromosomes correspond to the adjustment results better, this paper adopts integer coding, the gene is the number of delayed trains, and the chromosome length is the number of all delayed trains.

- Population Initialization

The departure sequence of 50 delayed trains is randomly generated, and the randomly generated departure sequence is likely to be an infeasible solution. The method adopted is to directly eliminate the infeasible solution by using constraints.

- Constructing Fitness Function

The fitness function designed in this paper is the reciprocal of the total weighted arrival delay time of the next station of the adjustment station, that is, the higher the chromosome fitness with the smallest total weighted arrival delay time when the train arrives at the next station according to the adjusted departure sequence.

$$\begin{cases} f_u^i = \frac{1}{\sum_{k \in K'} a_k \times \left(A_{u+1}^k - A_{u+1}'^k\right)} \\ i = 1, 2 \ldots n \end{cases} \tag{7}$$

- Choice

The better parental chromosomes were screened out by selection operation, and the chromosomes with low fitness were eliminated. According to the principle that the higher the fitness of the parental chromosome, the greater the probability of inheritance to the next generation, this paper uses roulette to select the better parental chromosome.

$$P_i = \frac{f_u^i}{\sum_{i=1}^{n} f_u^i} \times 100\% \tag{8}$$

- Crossing

Because the chromosomes encoded in this paper are the departure sequence of delayed trains, no matter what way the two parental chromosomes cross, it will inevitably produce infeasible solutions, so the diversity of population depends on mutation operation.

- Mutation

In order to make the new individual produced feasible solution, the genes of the two positions are randomly exchanged, so as to increase the diversity of population and prevent falling into local optimal solution.

- Stop

When the iteration number reaches the maximum iteration number, the adjustment is stopped, which is manually input, and the default maximum iteration number is 100 generations.

5 Example Analysis

5.1 Example Description

There are 24 stations along the Beijing-Shanghai high-speed railway (see Fig. 1). Because TianjinXi Station is not on the main line of Beijing-Shanghai high-speed railway, this paper selects the remaining 23 stations except TianjinXi Station as the research object.

5.2 Delay Condition Setting

This paper selects 19 trains from BeijingNan to Shanghai Hongqiao from 7:00 to 12:00 one day. In order to facilitate the subsequent adjustment of train departure sequence, the trains are numbered as 1~19 from small to large according to the departure sequence of the departure station. When scheduling the train timetable, it can be found that G1, G3, G5, G7, G9 and G11 trains have few stops, high slope of train running line, high travel speed and overtake other trains at some stations. Therefore, it is determined that these six trains are all high-grade trains and the remaining 13 trains are low-grade trains. The adjustment weight of high-grade trains is 0.3, and that of low-grade trains is 0.2.

Assuming that all trains start on time, the research scope of this paper is the delay of arrival of a single train, that is, the delay of a single train in 22 sections of Beijing-Shanghai high-speed railway. Set the delay situation as G113 arrives at CangzhouXi Station 16 min later, and use only interval accelerated operation and genetic algorithm to output adjustment results for this situation.

Fig. 1. Beijing-Shanghai high-speed railway route map

5.3 Analysis of Results

Train G113 was originally scheduled to arrive at CangzhouXi Station at 9:30, but actually arrived at 9:46. The subsequent high-grade train G5 was originally scheduled to cross G113 at CangzhouXi Station at 9:40. However, due to the delay of the train, the train G5 was forced to slow down in TianjinNan-CangzhouXi Section. The delayed time of arriving at CangzhouXi Station is the actual arrival time of train G113 plus the minimum arrival interval. As scheduled, the train G5 does not need to stop at CangzhouXi Station. Train G113 runs on time between CangzhouXi Station and DezhouDong Station, and resumes on time at DezhouDong Station at 10:12. Train G5 runs in the next interval and resumes punctual operation at Zaozhuang Station at 11:07. There are 2 late trains involved in this adjustment, with a total arrival delay of 60.15 min and 6 late stations. All late trains resume punctual operation before arriving at the terminal. The scheduled train timetable and the actual train timetable are adjusted by interval acceleration method and genetic algorithm (see Fig. 2).

The adjustment result is that the total arrival delay time is 504.05 min only by interval acceleration operation, while the total arrival delay time is 67.15 min by genetic algorithm adjustment, which is 86.7% less than the delay time of only interval acceleration operation; The number of delay stations only for interval acceleration operation is 20, and the total number of stations with delay is adjusted to 6 by genetic algorithm. Therefore, the calculation result of genetic algorithm is better, which is mainly reflected in the better results of total arrival delay time, total number of late trains and terminal delay time, and the output result is also more stable. Under the condition of small delay time, all delayed trains can resume punctual operation, ensuring that the total delay time and adjustment time are within an acceptable range, and the objective function value is better.

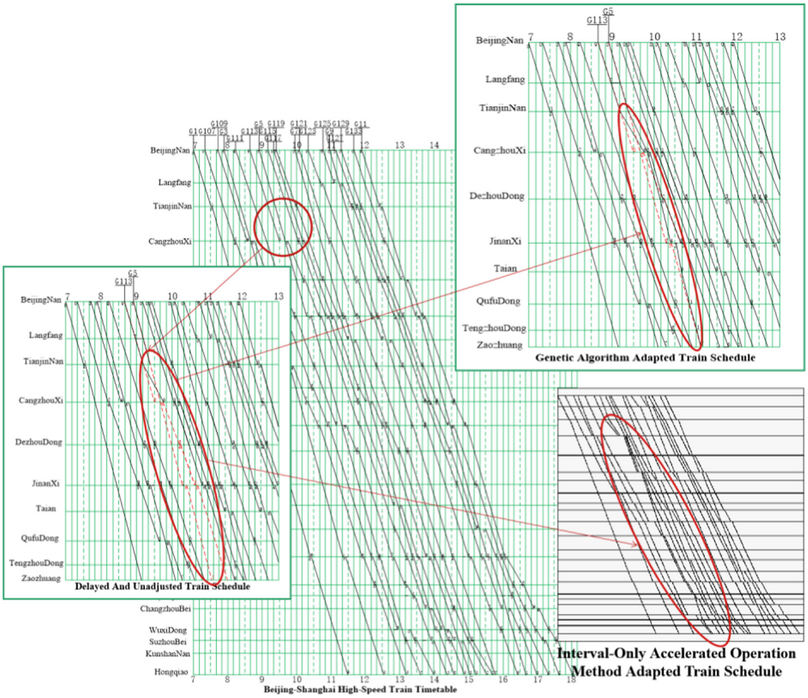

Fig. 2. The best rescheduled time-distance diagram based on the proposed GA and interval-only accelerated operation method respectively.

6 Conclusion

In this paper, aiming at minimizing the total weighted arrival delay of trains and satisfying various time interval constraints, a train operation adjustment model is established, and genetic algorithm is used to solve the model. By calculating the arrival and departure time of delayed trains at each delayed station, their arrival and departure times are determined by using constraints, so that all the generated solutions are feasible solutions, which improves the operation efficiency and shortens the time for finding satisfactory solutions. Compared with the adjustment scheme of only accelerating operation in interval, the calculation result of genetic algorithm is better, which is mainly reflected in the better results of total arrival delay time, total number of late trains and terminal delay time, and the output result is also more stable.

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