Study on the Train Timetable Rescheduling of High-speed Railway Considering the Satisfaction of Transfer Passengers

Aoran Dong, Bin Liu, Zhiqiang Tian, Zhiwen Deng

***Abstract*—The rescheduling of train timetables is a crucial task in the scheduling of railway transport, known as the Train Timetable Rescheduling (TTR) problem. In order to increase passenger satisfaction with transfer and reduce the impact of delayed trains on transfer succession and railway operation, a high-speed railway multiobjective optimization model for train timetable rescheduling is constructed with station operating time, transfer station track utilization rate, and train operating time as constraints, and maximizing passenger satisfaction, minimizing total train delay time, and minimizing the number of failed passengers in transfer as optimization objectives. A multiobjective solution algorithm based on hierarchical sequence theory was designed, and finally, the model was solved using Gurobi. Taking the example of the railway network comprising of Beijing-Shanghai high-speed railway and Xuzhou-Lanzhou high-speed railway, two adjustment strategies have been formulated to validate the model. The results show that the train timetable rescheduling model considering transfer passenger satisfaction can significantly reduce the delay time of transfer passengers and the possibility of transfer failure while maintaining high transfer passenger satisfaction, which provides a new idea for real-time train operation scheduling considering transfer succession.**

***Index Terms*—High-speed railway, Train timetable rescheduling, Multiobjective optimization, Passenger satisfaction, Hierarchical sequence method**

I. Introduction

As with any mode of transport, high-speed railway is subject to delays. When delays occur, train operations are disrupted, which can result in train conflicts or congestion of track resources. Therefore, it is essential to reschedule train operations promptly to ensure safety. Train operations are reflected in the timetable, once the train operation has been rescheduled, the originally planned timetable is no longer feasible, as a new timetable is created by the rescheduling process. For this reason, train operation rescheduling is also known as train timetable rescheduling (TTR).

The responsibility of TTR generally lies with the dispatcher, which means that the process is a manual rescheduling of train operations. On lines with slow trains and low train numbers, dispatchers can do this job perfectly, but on high-speed railways the opposite is true: when delays occur, dispatchers simply cannot bring trains back on schedule in a short period of time. If train operations are not resumed quickly, delays will spread from train to train, affecting a significant number of passengers. This will have a serious impact on the commercial competitiveness of high-speed railways. As a result, train rescheduling on high-speed railways needs to be more intelligent.

As is generally known, there is a significant overlap between the passengers of the high-speed railway and the civil aviation. If passengers are dissatisfied with a service, they will naturally choose its alternatives. Allen et al. (2019) noted that 'Critical Incidents', such as delays, have a significant negative impact on passenger satisfaction, which in turn reduces passenger loyalty and willingness to promote the service[1]. Therefore, to increase passenger loyalty on high-speed railway, it is crucial to handle delays effectively. Specifically, by maintaining a high level of passenger satisfaction during the TTR process.

Delays do not directly affect passenger satisfaction, but they can disrupt passengers' plans after getting off the train, which is the reason behind the decrease in passenger satisfaction. Monsuur et al. (2021) found that passengers' perceptions of train delays vary considerably, due to the different impact of delays on the subsequent journeys of passengers[2]. For example, transfer passengers reacted more strongly to delays than regular passengers. This was because they had to change trains. If the delay is too long, they may not be able to do so. The situation is particularly serious for high-speed railways. As high-speed railways provide medium and long-distance services, a failed passenger transfer means that the passenger's journey is cancelled on the same day, the impact is significant. In recent years, high-speed railway networks have become increasingly interconnected, passengers are more likely to transfer. With this trend, if higher satisfaction levels are to be maintained, the TTR process cannot ignore transfer passengers.

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Many scholars have conducted extensive research on the train timetable rescheduling (TTR) problem[3]. Mixed integer programming is frequently used to solve TTR problems. In order to solve the main difficulties of the TTR problem, some papers set a single optimization objective[4]-[7]. Meng et al. (2022) constructed a TTR model with the objective of minimizing the total late arrival and departure times of the train at each station[4]. Zhan et al. (2015) minimizes the number of cancelled trains and the total weighted delay in the TTR model[5]. Xu et al. (2021) integrated the train delay time and the number of changes of arrival and departure tracks into one objective, solve the TTR problem under multiple disturbances[6]. D'Ariano et al. (2006) optimized the TTR problem with the objective of minimizing the deviation of the rescheduled timetable from the planned timetable[7].

In addition to setting a single objective, more studies are taking a synergistic optimization approach with multiple objectives. This can balance operational metrics and service quality. Zhang et al. (2023) solved the track usage problem in the TTR process by combining timetable volatility with track usage volatility[8]. Dollevoet et al. (2012) used event-activity networks to construct a TTR model, consider the rerouting of passengers, and improved quality of service in the TTR process[9]. Binder et al. (2017) developed a TTR model to increase passenger satisfaction and reduce operating costs, achieving an optimal balance between the two in the TTR process[10]. Zhang et al. (2020) proposed a method for the combined planning of train timetables with platforms and routes, this method has the capacity to significantly reduce operating costs during the TTR process[11]. Hong et al. (2021) considered passenger reassignment in the TTR process, ensure a smooth journey for passengers affected by train disruptions during the TTR process[12]. Zhang et al. (2016) constructed a TTR collaborative optimization model to minimize total delay time and total dwell time, demonstrates the applicability of the model under large scale real-world scenarios[13].

The continuity of passenger transfers is also an important factor to be considered in the TTR problem. Wen et al. (2022) considering that passengers' journey is disrupted if they miss the last train, constructed a transfer based TTR optimization model for the last train[14]. Li et al. (2023) integrated the TTR process into the CTC system and developed an intelligent TTR model. The model is passenger oriented. It considers the transfer process of the passenger[15]. Zhang et al. (2022) added the objective of minimizing the number of passengers with failed transfers, constructed a TTR model that included transfers. It maintains a balance between passenger transfer and the restoration of traffic order[16].

The scale of the TTR problem is huge, making it difficult to solve quickly with general algorithms. Therefore, algorithm design is also an important direction of research for the TTR problem. Qin and Meng (2023) designed a new particle swarm algorithm to solve the TTR problem[17]. Wang et al. (2019) also designed a particle swarm algorithm based on a genetic algorithm to solve the TTR problem[18]. Meng and Zhou (2014) designed a Lagrangian relaxation algorithm that can efficiently solve the TTR problem in complex scenarios[19]. Zhan et al. (2016) designed a rolling solution method for the characteristics of the TTR model, which achieved better results in complex scenarios[20].

With the advent of intelligent methods such as reinforcement learning and machine learning, some scholars have used them to overcome the TTR problem. Tikhonov et al. (2015) were the first to use SVM for train delay analysis and used the machine learning technique to study the relationship between train delays and railway and railway systems[21]. Wang et al. (2022) proposed a method for intelligent train rescheduling in delay scenarios using a combination of Monte Carlo tree search and reinforcement learning. The efficiency of emergency response for delayed trains was improved by offline training and online adaptation [22]. Zura et al. (2016) introduced the Q-learning method to the TTR problem, which was found to be more suitable for solving the TTR problem than common heuristic algorithms [23]. Khadilkar (2019) designed a TTR algorithm based on reinforcement learning, which is more scalable and has a higher solution quality than traditional heuristic algorithms[24].

This paper proposes a multiobjective optimization model for train timetable rescheduling, where optimization objectives are passenger transfer and train operation. The model aims to ensure the quality of service for transfer passengers, which in turn improves the competitiveness and customer loyalty of high-speed railways. By introducing passenger satisfaction, the TTR process is no longer limited to satisfying operational metrics, providing a new approach to solving TTR problems. In reality, the rescheduling process in different scenarios is a process of trade-offs between multiple objectives, so it is necessary to analyze the Pareto frontiers of multiple objectives in our model. We have analyzed the model results in a real case. The results show that the model constructed in this paper can significantly improve the satisfaction of transferring passengers during rescheduling and reduce the number of failed transfer passengers, while the results of the Pareto analysis also show the adaptability of the model.

The main contributions of this paper are as follows:

(1) We analyzed the key difficulties of the TTR problem considering the transfer process, and derive the TTR optimization objective and optimization method considering the satisfaction of the transfer passengers

(2) A mixed integer programming model is proposed to solve TTR problem, which considers three objectives: transfer passenger satisfaction, the degree of deviation from the operation diagram, and the continuity of passenger transfers.

(3) To solve a multiobjective optimization model, we have designed a method based on the idea of hierarchical sequence, which grades multiple objectives in terms of priority, solving one objective at a time, and the next solving is based on the results of the previous one. This solution method proved to be very suitable for solving the TTR model considering passenger satisfaction.

II. The Problem of Train timetable Rescheduling considering Transfer

To facilitate the description of the problem, we define the following terms: the total time it takes a passenger to complete the transfer process is defined as the transfer time;

the train on which the passenger first travels is defined as the forward train, and the train to which the passenger changes at the transfer station is defined as the successor train.

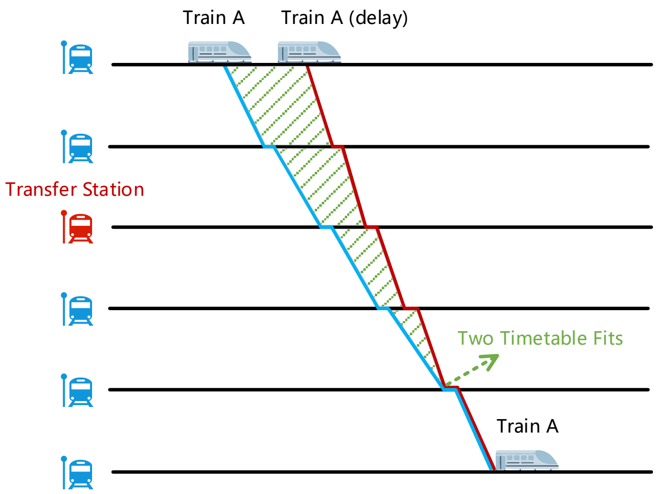

Fig. 1. TTR process with the objective of minimizing the deviation of the rescheduled timetable from the planned timetable

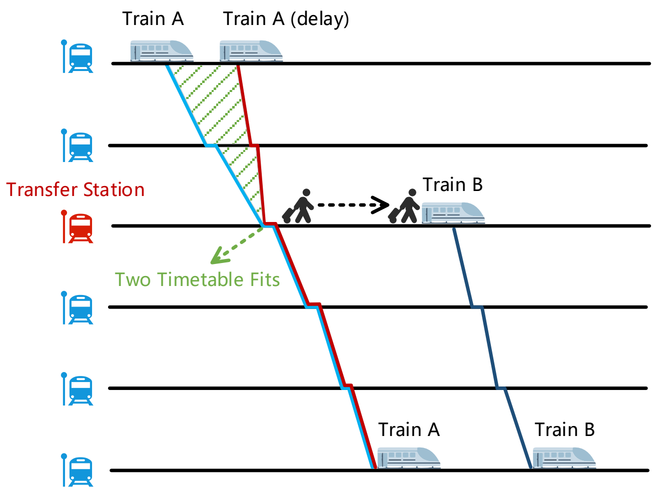

Fig. 2. TTR process considering passenger transfer scenario

When a train is delayed, the timetable rescheduling becomes a top priority. The railway dispatching department follows a principle when performing TTR: to allow delayed trains to return to their originally planned service as much as possible, and if this principle is abstracted into a specific optimization objective, this can be expressed as minimizing the deviation of the rescheduled timetable from the planned timetable. In fact, this objective is the key to solving the TTR problem, so most research has considered this objective when solving the TTR problem. Fig. 1 shows the role of this objective in the TTR process. In Fig. 1, the blue line represents the running path of **Train A** between two neighboring stations; the red line represents the running path of **Train A** after a delay. When **Train A** is delayed at a station, in order to minimize the deviation of the rescheduled timetable from the planned timetable, it is necessary to compress the gap between the delayed running path and the planned running path, and finally to achieve a fit between the rescheduled timetable and the planned timetable at a station, this station is located before the terminal station and after the station where the delay occurred. However, if the situation is very complicated, **Train A** may not be able to fit the two timetables even at the terminal station. In summary, the range of train rescheduling is the journey from the station where the delay occurs to the terminal station. The task of rescheduling is to return the train to its planned operating condition as soon as possible during this journey.

In the above discussion, we have not considered the transfer of passengers, which is different when we take it into account. Fig. 2 shows the TTR process considering passenger transfers. In Fig. 2, Train A is the forward train and Train B is the successor train. When passengers transfer on a train, it is essential to ensure that the rescheduled timetable and the planned timetable fit at the transfer station, or that there is a small deviation between the two timetables, which is necessary to ensure a smooth transfer of passengers. If the rescheduling is carried out as shown in Fig. 1, the train will be able to fit the two timetables after the transfer station, but the passengers will miss the transfer, this is obviously very unsatisfactory for transfer passengers.

The difference between considering passenger transfers and not considering passenger transfers is apparent. The reason for this difference is that when considering passenger transfers, the train journey becomes two parts, one between the station where the delay occurs and the transfer station, which belongs to the transfer passengers, and the other between the station where the delay occurs and the terminal station, which belongs to the regular passengers. Since the journeys of transfer passengers are shorter, priority must be given in the TTR process of considering transfers to ensuring that the two timetables are fitted at the transfer station or before the transfer station, which of course does not affect the feelings of regular passengers, on the contrary, the sooner train operations return to normal, the less time regular passengers are delayed in their journeys. There is also a question here: if the optimization objective is to minimize the deviation between the rescheduled timetable and the planned timetable, then the train will still achieve the objective at the station further ahead as much as possible, and whether it is necessary to achieve the fit between the two timetables as a priority objective at the transfer station. The answer is yes, because multiple trains are affected when there is a delay on the line and not all of these trains are involved in transfers. During the TTR process, the affected groups of trains are uniformly rescheduled, rather than rescheduling each train individually. Furthermore, to avoid conflicts between trains, rescheduling tends to change the original sequence of trains. Due to the reasons mentioned above, the train rescheduling results may not be as 'good ' as imagined but will show both good and bad results. Therefore, when considering passenger transfers in TTR optimization, the objective of minimizing the deviation of the rescheduled timetable from the planned timetable at the transfer station must be given priority.

Maintaining high levels of satisfaction among transfer passengers is essential to improving the service level of the TTR process. The satisfaction of transfer passengers is affected not only by the success of the transfer, but also by the change in transfer time. Fig. 3 shows the flow of passenger transfers. From Fig. 3 we can see that when passengers transfer from **Train A** to **Train B**, they have to walk from **Platform A** to **Platform B**. The distance that passengers walk is called the transfer walking distance, and the time it takes passengers to walk this distance is called the passenger walking time. Passengers often set aside extra time for their transfer due to unfamiliarity with the station layout or fear of missing their train, this extra time is called redundant time, so the transfer time of a passenger is the sum of the transfer walking time and redundant time. The transfer time a passenger reserves when purchasing a transfer combined ticket is the transfer time with the highest level of passenger satisfaction.

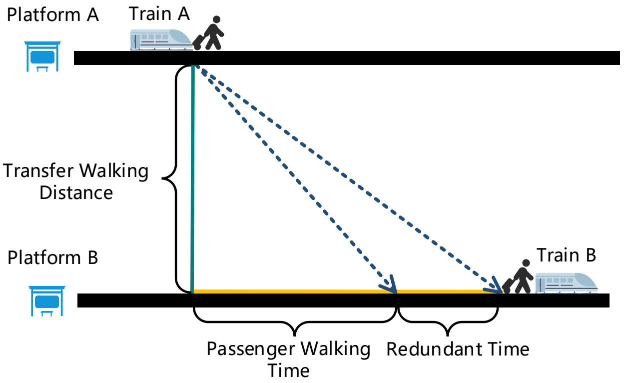

Fig. 3. Schematic diagram of the passenger transfer process

When the arrival time of **Train A** at the transfer station is delayed, the transfer time of the passenger will be compressed, at this time, the satisfaction of the passenger will decrease, when the transfer time is compressed to be less than passenger walking time, the passenger will fail to transfer, at this time, the satisfaction of the passenger will be reduced to the minimum, therefore, to maintain the satisfaction of transfer passengers during rescheduling, it is crucial to preserve their reserved transfer time. If this is not possible, it should be ensured that the transfer time is not less than the passenger walking time to ensure a successful transfer. When rescheduling is carried out, normally only **Train A** is rescheduled and not **Train B**. This is done to avoid the spread of delays. However, if rescheduling **Train A** does not allow passengers to transfer successfully, rescheduling the departure time of **Train B** at the transfer station may be feasible. After all, for the medium and long-distance journeys, the failure of the transfer is unacceptable for the passengers.

Combined with the above analysis, it can be seen that when solving the TTR problem, if the satisfaction of transfer passengers is considered, then priority must be given to optimizing the trains involved in the transfer, and trying to ensure that the rescheduled timetable of these trains has the smallest possible deviation from the planned timetable when arriving at the transfer station, so as to maintain a higher level of satisfaction of transfer passengers, and in special situations, in order to allow more passengers to make successful transfers, a small rescheduling of the successor train is also allowed. In this paper, the multiobjective linear mixed integer programming model is constructed with three optimization objectives. The primary objective is to minimize the change in satisfaction of transfer passengers, the secondary objective is to minimize the total deviation of the rescheduled timetable from the planned timetable, and the third objective is to minimize the number of failed transfer passengers. This method of setting ensures that transfer passengers are given priority, and at the same time, the feelings of general passengers are fully considered.

III. Train Timetable Rescheduling Model Considering the Satisfaction of Transfer Passengers

A. Problem assumptions and symbol description

Before constructing the model, we make the following assumptions:

1) In this paper, only the situation where the forward train is delayed is considered, and as the role of TTR is very small in the situation where the successor train is delayed, this situation is not studied.

2) In this paper, we only consider the problem of late train delays caused by disturbances in train operations, and we do not consider the impact of shunting operations.

3) In this paper, we do not consider the effects of the maintenance time window settings, the train utilization plan, or the crew scheduling plan on the model.

The parameters and variables used to construct the model in this paper are shown in Table I and Table II:

TABLE I
Description of Parameters

Symbol	Description
L	Set of all lines, $l \in L$
I	Set of all trains, $i \in I_l$
I_{delay}	Set of trains affected by the initial delay
S	Set of all stations, particularly, the transfer station is s_t ,The station with the initial delay is s_{delay}
K	Set of all tracks in transfer station, $k \in K$
$T^a_{i,s,l}$	Planned arrival time of train i at station s in line l
$T^d_{i,s,l}$	Planned departure time of train i at station s in line l
N_{i,j,s_t}	Number of passengers transfer from train i to train j at transfer station s_t
$AD_{s_t,l,k}$	Binary parameter, take 1 if the arrival and departure track k connecting the transfer station s_t in line l is allowed to be occupied, 0 otherwise
$S_{i,s,l}$	Binary parameter, take 1 if train i stops at station s in line l , 0 otherwise
$W^t_{i,s_t,l}$	Binary parameter, take 1 if train i has a special operation at station s_t in line l , 0 otherwise
$W^l_{s_t,l,k}$	Binary parameter, take 1 if the arrival and departure track k have special operational stopping conditions for trains, 0 otherwise
T^{walk}	Minimum transfer time
$T^{\max}$	Maximum transfer time
$T^{\min}$	Minimum dwell time of train i at station s
$t_{s,s+1}$	Minimum pure running time of train i on the section between stations s and $s+1$
I^{run}	Tracking interval time between trains i and $i+1$
T^{aa}	Minimum station arrival interval time
T^{dd}	Minimum station departure interval time
T^{lose}_s	Delay time for trains initially late at station s
M	A very large constant

TABLE II
DESCRIPTION OF VARIABLES

Symbol	Description
$t_{i,s,l}^{a}$	Actual arrival time of train i at station s within line l
$t_{i,s,l}^{d}$	Actual departure time of train i at station s within line l
y_{i,j,s_t}	Binary variable, take 1 if the transfer process between train i and train j is valid, 0 otherwise
$E_{i,s_t,l,k}$	Binary variable, take 1 if train i occupies arrival and departure track k at station s_t, 0 otherwise
$x_{i,j,s,l}$	Binary variable, take 1 if train i departs before train j at station s within line l, 0 otherwise

B. Objective function

1) Maximizing transfer passenger satisfaction

In the previous section, we analyzed the variation in transfer passenger satisfaction, from which we can conclude that maximizing transfer passenger satisfaction is equivalent to minimizing the deviation of the rescheduled timetable from the planned timetable at the transfer station. In practical scenarios, deviation between two timetables is represented by the deviation of the actual arrival and departure times of the train at the station from the planned arrival and departure times. In the transfer process, the arrival time of the train at the station belongs to the forward train; the departure time of the train at the station belongs to the successor train; therefore, maximizing transfer passenger satisfaction can be expressed as minimizing the sum of the deviation times of these two trains at the transfer station.

$$\min Z_1 = \sum_{i\in I_l}\sum_{j\in I_{l'}}\sum_{l\in L}[(t_{i,s_t,l}^{a}-T_{i,s_t,l}^{a})+(t_{j,s_t,l'}^{d}-T_{j,s_t,l'}^{d})]y_{i,j,s_t} \quad (1)$$

2) Minimizing total train delay time

Minimizing total train delay is a key optimization objective of the TTR problem, expressed as minimizing the deviation between the actual arrival and departure times of all trains at the station and the planned arrival and departure times.

$$\min Z_2 = \sum_{i\in I_l}\sum_{s\in S_l}\sum_{l\in L}[(t_{i,s,l}^{a}-T_{i,s,l}^{a})+(t_{i,s,l}^{d}-T_{i,s,l}^{d})] \quad (2)$$

3) Minimizing the number of failed transfer passengers

The TTR process should ensure that as many passengers as possible are successfully transfer, expressed as minimizing the number of failed transfer passengers.

$$\min Z_3 = \sum_{i\in I_l}\sum_{j\in I_{l'}} N_{i,j,s_t}(1-y_{i,j,s_t}) \quad (3)$$

C. Constraints

1) Station operation constraints

Constraint (4) ensures that at the transfer station the interval between the arrival time of the forward train and the departure time of the successor train shall be at least the minimum transfer time for the passenger. T^{walk} is the passenger walking time, which can be considered as the minimum transfer time.

$$(t_{j,s_t,l'}^{d}-t_{i,s_t,l}^{a}) \ge T^{walk}-M(1-y_{i,j,s_t})$$
$$\forall i\in I_l, j\in I_{l'}, l\in L, l'\in L \quad (4)$$

Constraint (5) ensures that at the transfer station, the interval between the forward train and the successor train is at most T^{max}. If the transfer time is greater than T^{max}, the transfer is considered to have failed for the passenger travelling in that transfer combination.

$$(t_{j,s_t,l'}^{d}-t_{i,s_t,l}^{a})-M(1-y_{i,j,s_t}) \le T^{max}$$
$$\forall i\in I_l, j\in I_{l'}, l\in L, l'\in L \quad (5)$$

A significant passenger station, capable of transfer will connect at least two or more different lines. Constraint (6) ensures that trains coming from different directions will stop at specific yards or fixed arrival and departure tracks, rather than at random.

$$\sum_{l\in L}\sum_{k\in K} E_{i,s_t,l,k} AD_{s_t,l,k} = 1, \ \forall i\in I_l \quad (6)$$

Constraint (7) ensures that trains stopping at transfer stations should select the available arrival and departure tracks; constraint (8) ensures that trains passing through should travel on the main line without occupying the arrival and departure tracks; and constraint (9) ensures that trains carrying out special operations such as watering or vacuuming within the station should stop on the arrival and departure tracks with the appropriate capacity.

$$\sum_{l\in L}\sum_{i\in I_l} E_{i,s_t,l,k} S_{i,s_t,l} = 1, \ \forall k\in K \quad (7)$$

$$S_{i,s_t,l} = \sum_{k\in K} E_{i,s_t,l,k}, \ \forall i\in I_l, l\in L \quad (8)$$

$$\sum_{i\in I_l} S_{i,s_t,l} W_{i,s_t,l}^{t} \le \sum_{k\in K} W_{s_t,l,k}^{l}, \ \forall l\in L \quad (9)$$

2) Train running constraints

Constraint (10) ensures that the actual departure time of a train at a station is not less than the planned departure time; constraint (11) ensures that the actual arrival time of a train at a station is not less than the planned arrival time; and constraint (12) ensures that the actual dwell time of a train at a station is not less than the minimum dwell time.

$$t_{i,s,l}^{d} \ge T_{i,s,l}^{d}, \ \forall i\in I_l, s\in S_l, l\in L \quad (10)$$

$$t_{i,s,l}^{a} \ge T_{i,s,l}^{a}, \ \forall i\in I_l, s\in S_l, l\in L \quad (11)$$

$$(t_{i,s,l}^{d}-t_{i,s,l}^{a}) \ge T^{min}-M(1-S_{i,s,l}), \ \forall i\in I_l, s\in S_l, l\in L \quad (12)$$

Constraint (13) ensures that the actual running time of a train between two stations is not less than the minimum pure running time of a train between two stations; constraints (14)-(16) ensure that the following interval between two neighboring trains between two stations is not less than the minimum following interval of a train.

$$(t_{i,s+1,l}^{a}\text{-}t_{i,s,l}^{d}) \ge t_{s,s+1}, \ \forall i\in I_l, s\in S_l, s+1\in S_l, l\in L \quad (13)$$

$$t_{j,s,l}^{a}-t_{i,s,l}^{a} \ge I^{run}-M(1-x_{i,j,s\text{-}1,l})$$
$$\forall i\in I_l, j\in I_l, s-1\in S_l, s\in S_l, l\in L \quad (14)$$

$$t_{j,s,l}^{d}-t_{i,s,l}^{d} \ge I^{run}-M(1-x_{i,j,s,l})$$
$$\forall i\in I_l, j\in I_l, s\in S_l, l\in L \quad (15)$$

$$x_{i,j,s,l}+x_{j,i,s,l} = 1, \ \forall i\in I_l, j\in I_l, s\in S_l, l\in L \quad (16)$$

Constraints (17)-(18) ensure that two adjacent trains arriving at or departing from the same station must respect the minimum time interval between arrivals or departures from the station.

$$t_{j,s,l}^{a}-t_{i,s,l}^{a} \ge T^{aa}-M(1-x_{i,j,s-1,l})$$
$$\forall i\in I_l, j\in I_l, s\in S_l, l\in L \quad (17)$$

$$t_{j,s,l}^{d}-t_{i,s,l}^{d} \ge T^{dd}-M(1-x_{i,j,s,l})$$
$$\forall i\in I_l, j\in I_l, s\in S_l, l\in L \quad (18)$$

3) Disturbance and disruption constraints

Constraint (19) ensures that the actual dwell time of a train at a disturbed station is not less than the sum of the planned dwell time and the delay caused by the disturbance; furthermore, constraint (20) ensures that when a train is disturbed at a station, the actual departure time of the train is not less than the sum of the planned departure time and the delay. If a disruption occurs between station s and station $s+1$, the disruption time of the section between station s and station $s+1$ can be virtualized as a train. The departure time of the virtual train at Station A and its arrival time at Station B, designated as $t^{d}_{ivir,s,l}$ and $t^{a}_{ivir,s+1,l}$ respectively, represent the beginning and end times of the disruption. Constraints (19)-(21) ensure that if a train operates within the disruption time of the section, the departure time of the train at station s must not be less than $t^{a}_{ivir,s+1,l}$.

$$(t^{d}_{i,s,l}-t^{a}_{i,s,l})\geq T^{d}_{i,s,l}-T^{a}_{i,s,l}+T^{lose}_{s},\ \forall i\in I_{delay}, s\in s_{delay}, l\in L \quad (19)$$

$$t^{d}_{i,s,l}\geq T^{d}_{i,s,l}+T^{lose}_{s},\ \forall i\in I_{delay}, s\in s_{delay}, l\in L \quad (20)$$

$$t^{d}_{i,s,l}>T^{a}_{ivir,s+1,l},\ \forall i\in I_{break}, (s,s+1)\in hitch_{s,s+1}, l\in L \quad (21)$$

Where I_{break} is the train directly affected by the disruption between station s and $s+1$; $hitch_{s,s+1}$ is the section between station s and $s+1$ with the disruption.

D. The expression of transfer *passenger satisfaction*

In the previous section, we derived the maximum objective function for transfer passenger satisfaction, but the calculation could not quantify passenger satisfaction. Subsequently, we use triangular fuzzy variables to represent the change in passenger satisfaction. The passenger satisfaction equation is denoted as formula (22).

$$S(t)=\begin{cases}\dfrac{t-T^{walk}}{T-T^{walk}}, & if\ \ T^{walk}\leq t\leq T\\ \dfrac{t-T^{\max}}{T-T^{\max}}, & if\ \ T\leq t\leq T^{\max}\\ 0, & otherwise\end{cases} \quad (22)$$

Where T is the transfer time chosen by the passenger, denoted by $T^{d}_{j,s_t,l'}-T^{a}_{i,s_t,l}$; t is the transfer time of the passenger after TTR, denoted by $t^{d}_{j,s_t,l'}-t^{a}_{i,s_t,l}$.

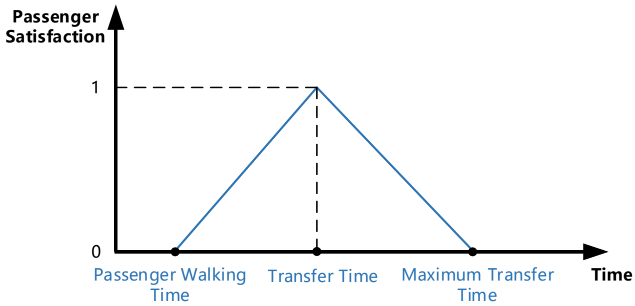

Fig. 4. Quantification of transfer passenger satisfaction

Formula (22) provides a specific score between 0 and 1 to quantify the satisfaction of the passenger during transfer. Fig. 4 shows the quantification of transfer passenger satisfaction. From Fig. 4, it can be seen that passengers determine their transfer time, denoted by T, when purchasing a ticket, at which time passenger satisfaction is 1. When rescheduling is performed, a new transfer time, denoted by t, is generated and passenger satisfaction decreases regardless of whether the transfer time is increased or decreased. If the transfer time is less than the passenger walking time or greater than the maximum transfer time, passenger satisfaction decreases to 0.

E. Model construction

For the convenience of example verification, the above formula is reconstructed into two TTR models:

Model M1: (TTR model considering passenger satisfaction):

Objective function (1) - (3).

Subject to constraints (4) - (21).

Model M2: (TTR model without considering passenger satisfaction):

Objective function (2) - (3).

Subject to constraints (4) - (21).

F. Model solution method

For solving the constructed multiobjective optimization model, we designed a solution method based on the idea of hierarchical sequence. This method involves differentiating the objective functions in the model according to their importance, solving the single objective model sequentially, and using the solution result as the input for the next solution. The main advantage of this approach is the ability to prioritize the optimization of transfer passenger satisfaction and has little impact on the macroscopic TTR process.

The steps for the solution method designed in this paper are as follows:

Step 1: The three objective functions in the model are sorted according to the priority of the solution, and the solution priorities are as follows: $Z_1>Z_2>Z_3$.

Step 2: Solve the model with Z_1 as the objective to obtain the optimal objective value $Z_1^{\min}$, and change the first objective function to the following constrained form:

$$\sum_{i\in I_l}\sum_{j\in I_{l'}}\sum_{l\in L}[(t^{a}_{i,s_t,l}-T^{a}_{i,s_t,l})+(t^{d}_{j,s_t,l'}-T^{d}_{j,s_t,l'})]y_{i,j,s_t}\leq Z_1^{\min} \quad (23)$$

Step 3: Add the constraint created in Step 2 to the model.

Step 4: Take the solution result of Step 2 as input to the model, solve the model with Z_2 as the objective to obtain the optimal objective value $Z_2^{\min}$, and change the second objective function to the following constraint form:

$$\sum_{i\in I_l}\sum_{s\in S_l}\sum_{l\in L}[(t^{a}_{i,s,l}-T^{a}_{i,s,l})+(t^{d}_{i,s,l}-T^{d}_{i,s,l})]\leq Z_2^{\min} \quad (24)$$

Step 4: Solve the model with the constraints in Step 3 attached with Z_3 as the objective, and finally produce the results of the TTR model.

Step 5: Add the constraint created in Step 4 to the model.

Step 6: Take the solution result of Step 4 as input to the model, solve the model with Z_3 as the objective, and finally to get the results of the TTR model.

IV. CASE SETTINGS

A. Basic information

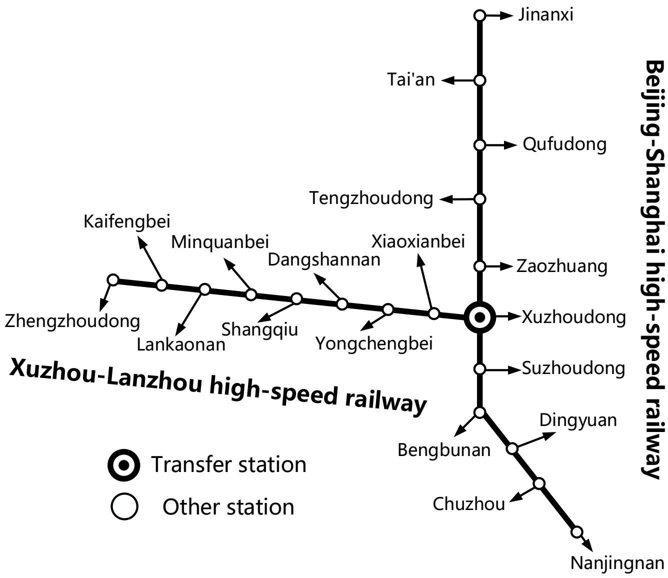

Fig. 5. Schematic diagram of Beijing-Shanghai high-speed railway from Jinanxi to Nanjingnan and Xuzhou-Lanzhou high-speed railway from Xuzhoudong to Zhengzhoudong

We select the section from Jinanxi Station to Nanjingnan Station of the Beijing-Shanghai high-speed railway; the section from Xuzhoudong Station to Zhengzhoudong Station of the Xuzhou-Lanzhou high-speed railway as the background lines for model testing, of which there are 11 stations in the section from Jinanxi Station to Nanjingnan Station. There are 14 stations in the section from Nanjingnan Station to Zhengzhoudong Station. Fig. 5 shows a schematic diagram of the two lines above.

B. Data setting

We selected 30 trains in both directions of the selected lines in the 10:00-17:00 time period, which has the highest transfer passenger flow on a specific day in April 2023, among which there are 15 trains in the direction of Nanjingnan from Jinanxi, numbered 1-15, and 15 trains in the direction of Zhengzhoudong from Nanjingnan, numbered 16-30, according to the actual train connection relationship to determine a total of twelve pairs of transfer train combinations. Transfer passengers first take a train from Jinanxi to Nanjingnan and change at Xuzhoudong Station to a train from Nanjingnan to Zhengzhoudong.

The values of various parameters involved in the model are as follows: the minimum transfer time is 15 min; the maximum transfer time is 60 min; the minimum dwell time is 2min; the minimum tracking interval time of two trains is 4min; the minimum time between arrival and departure from the station between the two trains is 2 min. Python randomly generates the number of transfer passengers of twelve pairs of transfer train combinations, and since the Beijing-Shanghai high-speed railway and Xuzhou-Lanzhou high-speed railway are the high-speed railway lines with more significant passenger flow in China, the interval of random number generation is defined as (60-300); The minimum pure running time between stations are shown in the table below.

TABLE III
MINIMUM PURE RUNNING TIME FOR THE SECTION FROM JINANXI TO NANJINGNAN

Section	Minimum pure running time (min)
Jinanxi-Tai'an	7
Tai'an -Qufudong	12
Qufudong-Tengzhoudong	9
Tengzhoudong-Zaozhuang	6
Zaozhuang -Xuzhoudong	10
Xuzhoudong-Suzhoudong	13
Suzhoudong-Bengbunan	13
Bengbunan-Dingyuan	9
Dingyuan -Chuzhou	10
Chuzhou-Nanjingnan	10

TABLE IV
MINIMUM PURE RUNNING TIME FOR THE SECTION FROM XUZHOUDONG TO ZHENGZHOUDONG

Section	Minimum pure running time (min)
Xuzhoudong -Xiaoxianbei	8
Xiaoxianbei-Yongchengbei	7
Yongchengbei-Dangshannan	4
Dangshannan -Shangqiu	12
Shangqiu -Minquanbei	8
Minquanbei -Lankaonan	6
Lankaonan-Kaifengbei	10
Kaifengbei-Zhengzhoudong	10

In this case, we assume that the section between Tengzhoudong and Zaozhuang is disrupted at 15:00 and returns to normal after 30 minutes. During this time, no train can pass through this section. To solve the problem, we use two TTR methods, **Model M1** and **Model M2**. The effectiveness of model M1 will be tested by comparison. We used a computer with Intel(R) Core (TM) i7-8750H CPU, 16G RAM, and Python software to solve the above models using Gurobi, and the results are shown below.

V. RESULT ANALYSIS

A. Comparison of passenger satisfaction between Model M1 and Model M2

In the case study there are a total of twelve pairs of train transfer combinations, which we have labelled combinations 1-12, and their planned arrival and departure times, as well as the transfer times at the transfer stations, are shown in Table V. The transfer times in Table V are determined by the combination ticket purchased by the passenger, which is the transfer time chosen by the passenger for maximum satisfaction, therefore passenger satisfaction for all train combinations in Table V is 1.

TABLE V
THE PLANNED ARRIVAL AND DEPARTURE TIME AND TRANSFER TIME OF TRAIN TRANSFER COMBINATION AT THE TRANSFER STATION

Forward train	Arrival time	Successor train	Departure time	Transfer time(min)
G129	14:24	G1925	14:39	15
G325	15:19	G1929	15:40	21
G2573	15:10	G1929	15:40	30
G135	15:35	G1811	16:03	28
G1227	15:44	G1811	16:03	19
G137	15:48	G1811	16:03	15
G135	15:35	G1815	16:22	47
G1227	15:48	G1815	16:22	38
G137	15:48	G1815	16:22	34
G183	15:53	G1815	16:22	29
G185	16:27	G1932	16:51	42
G185	16:27	G2809	17:09	24

TABLE VI
PASSENGER SATISFACTION LEVELS FOR MODEL M1

Forward train	Arrival time	Successor train	Departure time	$S(t)$
G129	14:24	G1925	14:39	1
G325	15:19	G1929	15:40	1
G2573	15:10	G1929	15:40	1
G135	*15:48*	*G1811*	*16:03*	*0.385*
G1227	*15:52*	*G1811*	*16:03*	*0*
G137	*16:00*	*G1811*	*16:03*	*0*
G135	*15:48*	*G1815*	*16:23*	*0.676*
G1227	*15:52*	*G1815*	*16:23*	*0.842*
G137	*16:00*	*G1815*	*16:23*	*0.542*
G183	*15:56*	*G1815*	*16:23*	*0.895*
G185	16:27	G1932	16:51	1
G185	16:27	G2809	17:09	1

TABLE VII
PASSENGER SATISFACTION LEVELS FOR MODEL M2

Forward train	Arrival time	Successor train	Departure time	$S(t)$
G129	14:24	G1925	14:39	1
G325	15:19	G1929	15:40	1
G2573	15:10	G1929	15:40	1
G135	*15:52*	*G1811*	*16:03*	*0*
G1227	*15:56*	*G1811*	*16:03*	*0*
G137	*16:00*	*G1811*	*16:03*	*0*
G135	*15:52*	*G1815*	*16:23*	*0.567*
G1227	*15:56*	*G1815*	*16:23*	*0.0.391*
G137	*16:00*	*G1815*	*16:23*	*0.421*
G183	*16:04*	*G1815*	*16:23*	*0.285*
G185	16:27	G1932	16:51	1
G185	16:27	G2809	17:09	1

We solved the case with **Model M1** and **Model M2**. Inserting the solved transfer time into formula 22 enables the determination of the transfer passenger satisfaction change. Table VI and Table VII shows the values of passenger satisfaction for **Model M1** and **Model M2**. Fig. 6 shows the comparison of passenger satisfaction between **Model M1** and **Model M2**.

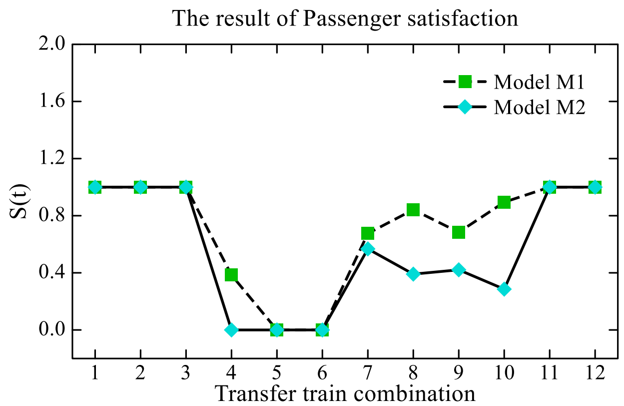

Fig. 6. Comparison of passenger satisfaction between Model M1 and Model M2

The results show that seven train combinations (4-10) are affected by delays. Passenger satisfaction comparison between **Model M1** and **Model M2** solutions is illustrated in Fig. 6. From the seven rescheduled combinations, five of them were solved with better results using **Model M1**, in these five combinations, **Model M1** achieves an average of 74.9% higher passenger satisfaction than **Model M2**. The remaining two combinations were failed transfer combinations, which were solved with the same results using **Model M1** and **Model M2**.

It is shown that **Model M1** is effective in maintaining a high level of passenger satisfaction in the case of train delays. Compared to **Model M2**, **Model M1** boosts passenger satisfaction by at least 19% and, in some cases, up to 100%. Additionally, **Model M2** has three failed train combinations, while **Model M1** has only two failed train combinations, indicating that **Model M1** allows more passengers to transfer successfully.

B. Comparison of other objectives between Model M1 and Model M2

In the constructed model, there are two objectives: minimize total train delay time (objective 2) and minimize the number of failed transfer passengers (objective 3). These objectives exist in both **Model M1** and **Model M2**. We should analyze the advantages and disadvantages of **Model M1** and **Model M2** in these two objectives. In addition, in real cases, TTR problems need to be solved quickly, so we need to consider the model solving speed. Table VIII shows the comparison between **Model M1** and **Model M2** in terms of the values of the above two objectives and the model solving speed.

TABLE VIII
COMPARISON OF OBJECTIVE VALUES AND SOLVING SPEED

Model	Objective 2 value	Objective 3 value	Solving time
Model M1	1442 min	113 people	21.58 s
Model M2	1097 min	305 people	33.63 s

Table VIII shows that the total train delay in **Model M2** is less than that in **Model M1**. This is attributed to **Model M2** not considering the contentment of transferring passengers, thus, lowering the delay by reducing transfer time. In contrast, **Model M1** takes into consideration the satisfaction of transfer passengers, therefore, increasing the total delay time to satisfy the transfer needs of more passengers than **Model M2**. A comparison between **Model M1** and **Model M2** shows that **Model M1** reduces the number of failed transfer passengers by 63%. In the real case, this is an acceptable and satisfactory solution, because when a passenger fails to make a transfer, the passenger's travel is irreversibly affected, which cannot be solved by reducing the delay of a fraction of the train.

Table VIII also shows that the total solution time of **Model M1** is 35.8% faster than that of **Model M2**. This is because **Model M1** prioritizes the objective of passenger satisfaction, the constraint of the degree of deviation of the actual arrival and departure time of the forward train and the successor train at the transfer station from the original plan is added in the second step of solving the objective of total delay time. In the solution of a mixed integer programming model, the more compact the constraints of the model, the easier it is to converge to an optimal solution and the faster the solution time. This improved speed makes **Model M1** better suited for the real-world TTR problem.

C. Analysis of TTR model results considering passenger satisfaction

In the above section, we compared the results of **Model M1** and **Model M2** and proved that the results of **Model M1** are better than **Model M2**. We will now analyze the results of **Model M1**. Fig. 7 and Fig. 8 shows the planned train operation diagrams of the Beijing-Shanghai high-speed railway and the Xuzhou-Lanzhou high-speed railway; Fig. 9 and Fig. 10 shows the train operation diagrams after the rescheduling of **Model M1**. The departure order at Jinanxi Station is G129, G1223, G11, G133, G325, G2573, G135, G1227, G13, G137, G183, G139, G1251, G185, G141; the departure order at Nanjingnan Station is G1806, G1920, G3165, G1476, G1948, G1925, G1929, G3103, G1811, G1815, G1932, G2809, G1818, G1822, G1936.

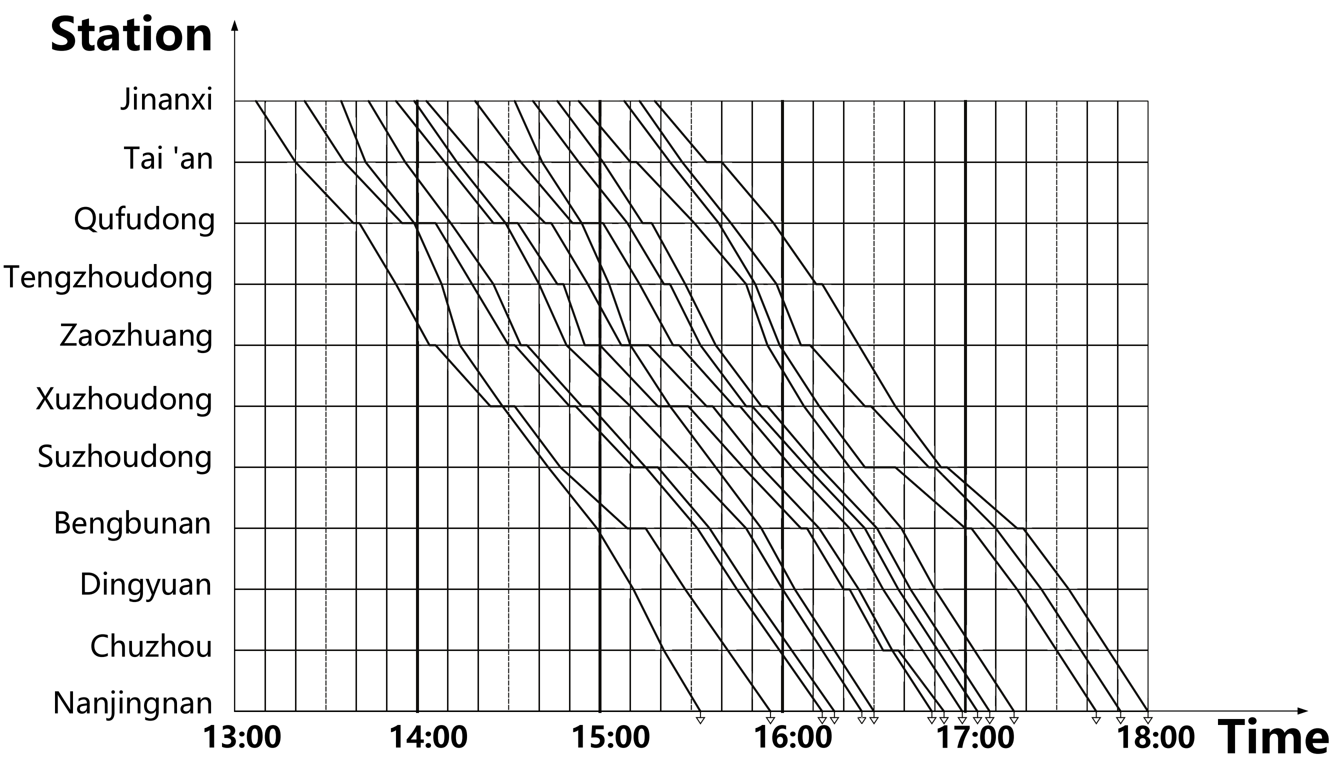

Fig. 7. Planned train operation diagram of the Beijing-Shanghai high-speed railway

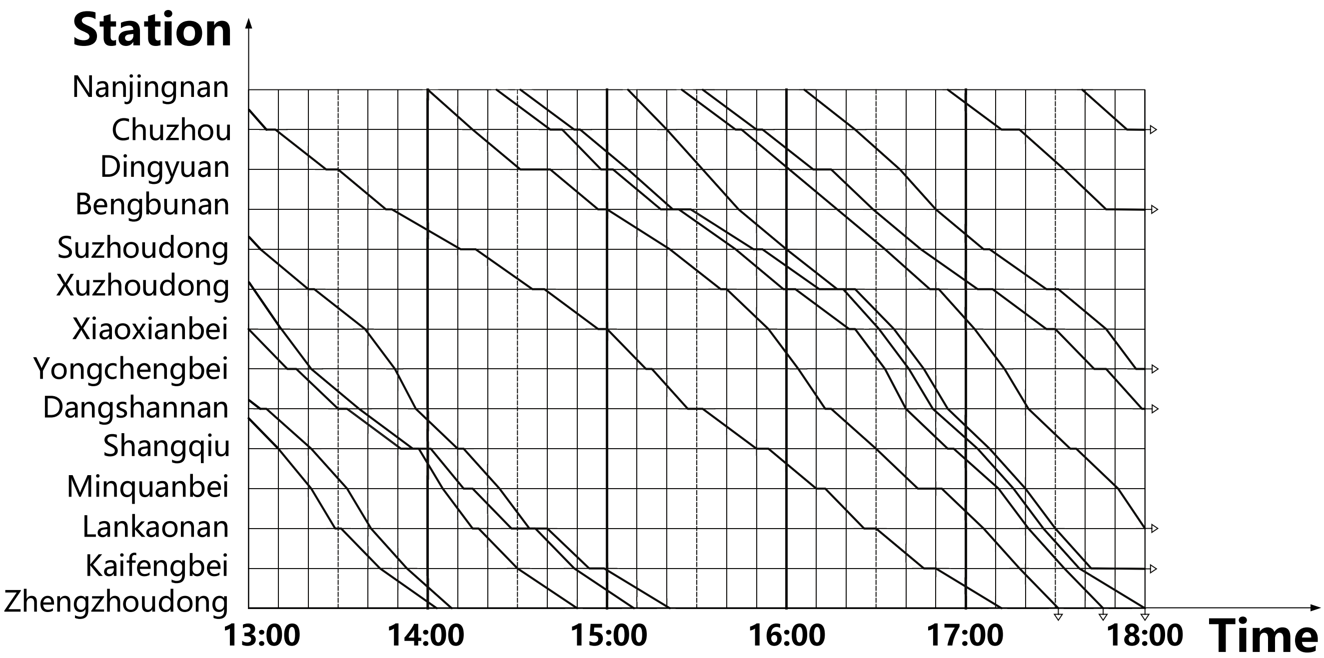

Fig. 8. Planned train operation diagram of the Xuzhou-Lanzhou high-speed railway

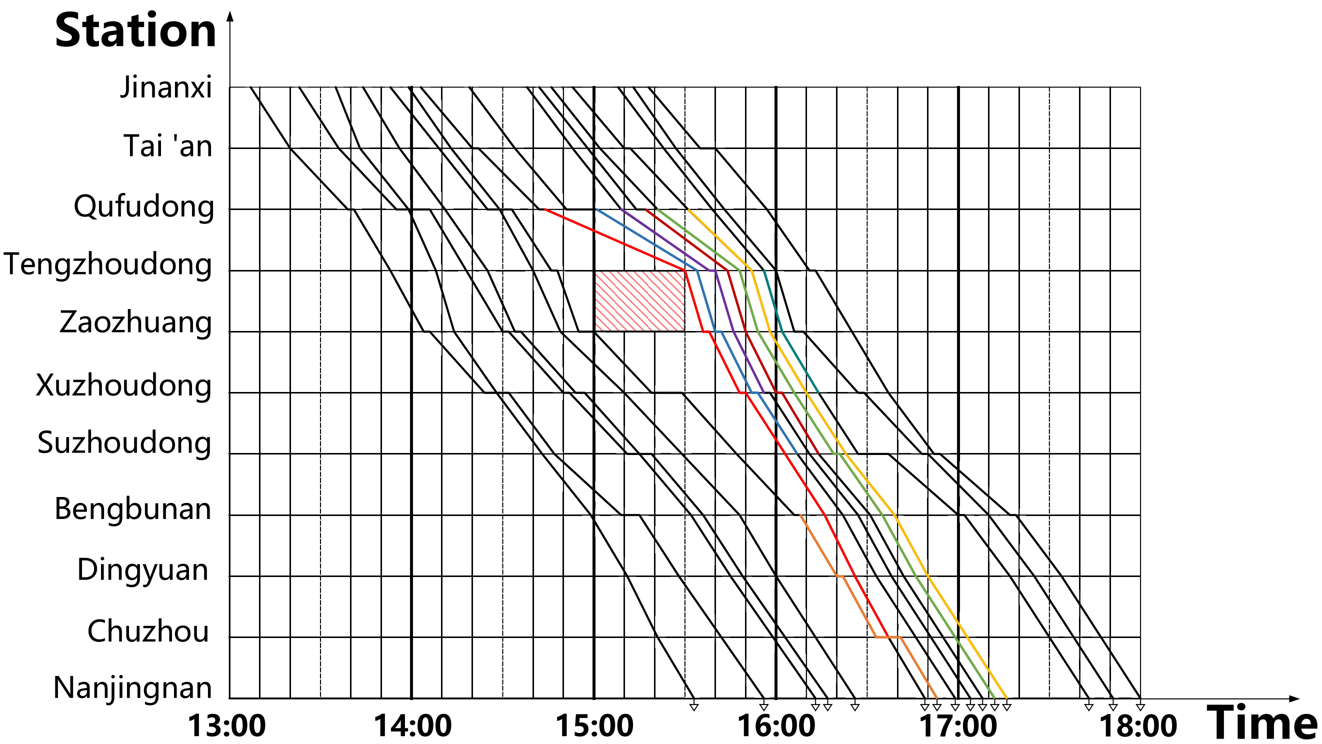

Fig. 9. Rescheduled train operation diagram of the Beijing-Shanghai high-speed railway (The colored train indicates that it has been rescheduled)

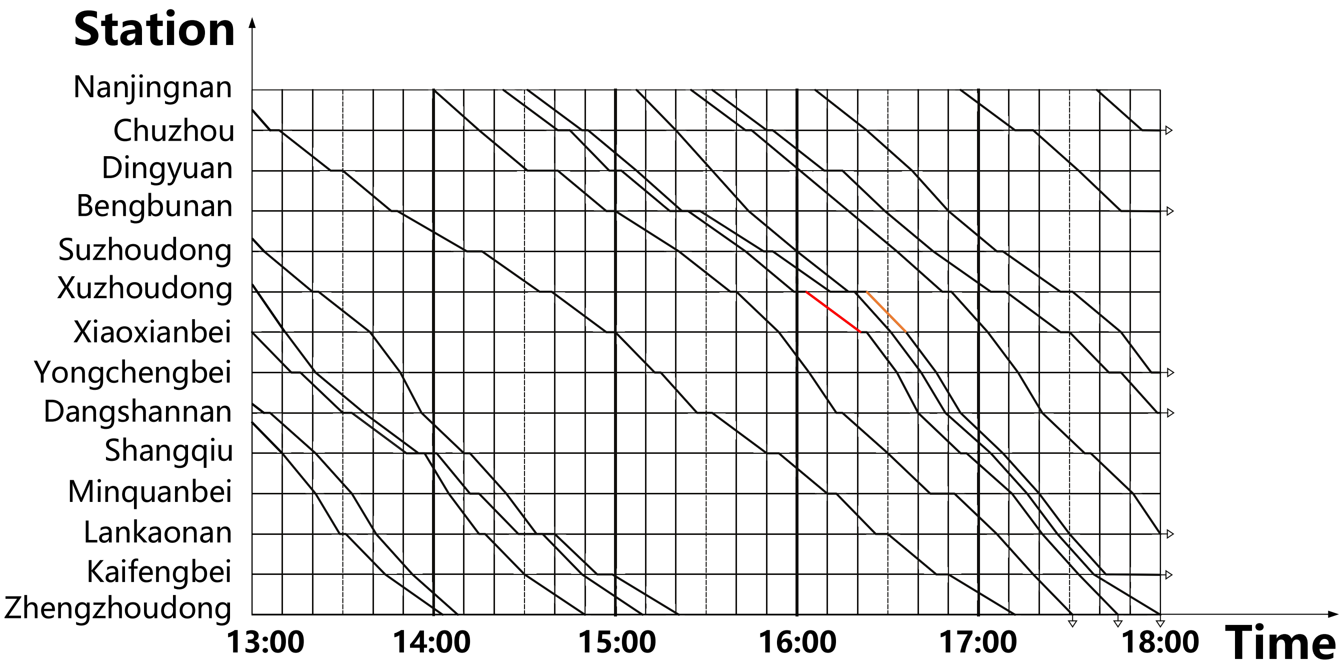

Fig. 10. Rescheduled train operation diagram of the Xuzhou-Lanzhou high-speed railway (The colored train indicates that it has been rescheduled)

Fig. 9 shows that the section between Tengzhoudong and Zaozhuang is disrupted between 15:00 and 15:30 and the trains G135, G1227, G137, G183, G13 and G139 cannot pass as planned. To prevent the above trains from entering the Tengzhoudong to Zaozhuang section during the interval disruption time, **Model M1** has rescheduled the operation of these trains. In addition, to prevent train conflicts, G325 was forced to run delayed on the Bengbunan to Nanjingnan section and G1251 was forced to run delayed on the Tengzhoudong to Xuzhoudong section. As shown in Fig. 10, only two trains, G1811 and G1815, are rescheduled on the Xuzhou-Lanzhou high-speed railway, and the rescheduling of these two trains only delayed the departure time from Xuzhoudong station by 1 minute.

Model M1 has proved to be effective in solving the railway delay problem. In the case, **Model M1** successfully restored train operations to normal by rescheduling only 33% of the trains and 11.6% of the train paths. Additionally, most of the rescheduled trains operate on the line where the disruption occurred, on neighboring lines, only two trains were slightly rescheduled, and delays were largely not spread between lines.

In the real world, TTR needs to minimize the number of passengers affected by delays, which is manifested by reducing the number of rescheduled trains. From Fig. 9 at most nine trains (G135, G1227, G137, G183, G13, G139 and G1251) can be affected by the delay, but **Model M1** only reschedules seven of them (G135, G1227, G137, G183, G13, G139 and G1251) to bring the line back to normal. In this case, only nine trains can be affected by the disruption on the Tengzhoudong to Zaozhuang section, but in the real situation the number is up to more than eighty trains, so when **Model M1** is applied to reality, the performance will be better.

The distribution of the Pareto solution set must be considered when solving the multiobjective programming model. We will analyze the Pareto solution set of **Model M1** under the delay scenario set by the case. When solving the model, we transform the solved objective function into constraints whose upper bound is the optimal value of that objective. So, we can perform a Pareto analysis by simply increasing the upper bound of the constraint.

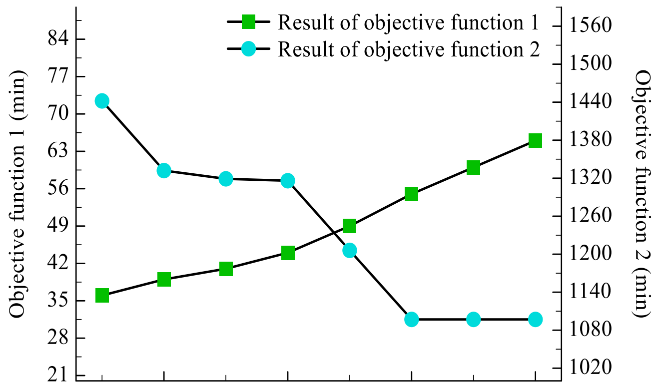

Fig. 11. Pareto solution set distribution diagram for objective 1 and objective 2

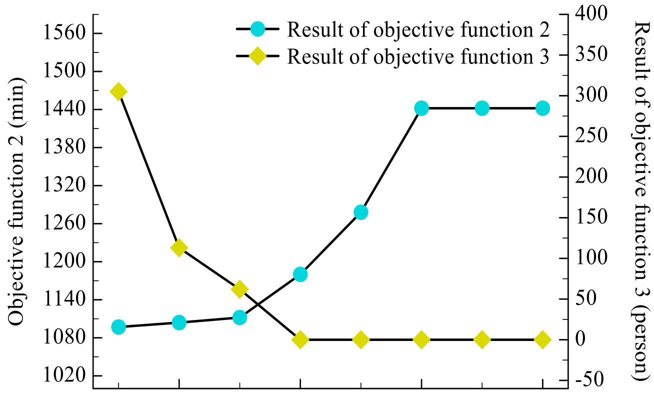

Fig. 12. Pareto solution set distribution diagram for objective 2 and objective 3

Fig. 11 shows the Pareto solution set distribution for objective 1 and objective 2. As the value of objective 1 gradually increases from 36 mins, the value of objective 2 decreases from 1442 mins, which indicates that the greater the deviation of the actual arrival and departure time of the forward train and the successor train at the transfer station from the planned timetable, the smaller the total delay time of the line. When the value of objective 1 exceeds 55 minutes, the total delay time of the line remains constant at 1097 minutes. Therefore, if the value of objective 1 falls between 36-55 minutes and objective 2 falls between 1097-1442 minutes, the Pareto optimal solution set of objectives 1 and objective 2 can be obtained.

Fig. 12 shows the Pareto solution set distribution for objective 2 and objective 3. As the value of objective 2 gradually increases from 1097min, the value of objective 3 gradually decreases from 305, indicating that the greater the total delay time of the line, the smaller the number of passengers who fail to transfer. When the value of objective 2 is between 1112min-1472min, the number of passengers who fail to transfer is close to zero, so when the value of objective 2 is between 1097min-1112min and the value of objective 3 is between 0 and 305, we can obtain the Pareto optimal solution set of objectives 2 and objective 3.

Combining the above two Pareto optimal analyses, **Model M1** provides a set of solution spaces for the dispatcher to choose from, and the dispatcher can choose the global optimal solution according to the actual situation in terms of improving the satisfaction of transfer passengers, reducing the total delay time, and reducing the number of failed transfers. When the number of transfer passengers is small, the dispatcher can choose to reduce the total delay time of the line as the primary objective; when the number of transfer passengers is large, the dispatcher can choose to improve passenger satisfaction as the primary objective.

VI. CONCLUSION

In this paper, we designed a high-speed railway TTR model considering the satisfaction of transfer passengers and designed a kind of hierarchical sequence algorithm used to model solving, achieved good results in the example.

(1) In complex delay scenarios, the TTR model constructed in this paper can achieve accurate train operation rescheduling considering passenger satisfaction, reduce the negative impact of delayed trains on passengers and the railway department, at the same time greatly improve the satisfaction of transfer passengers, which strongly to increase the commercial competitiveness of high-speed railways.

(2) The TTR model constructed in this paper, considering transfer passenger satisfaction, can propose different solutions according to the actual case. When special situations occur, the dispatcher can flexibly determine the importance of multiple objectives according to the actual passenger flow of the day, to ensure the minimum total delay time of the line while improving passenger satisfaction and allowing more passengers to transfer smoothly.

(3) The TTR model constructed in this paper, considering passenger satisfaction, can reach the optimal solution in a short time. In the computational case, the solution time of **Model M1** is 35.8% faster than that of **Model M2**. The efficient solution can help the dispatcher to make quick decisions and reduce the impact of delay spread.

(4) In constructing the model, we only emphasized the passenger transfer process and did not consider the coupling relationship between the total mileage of different transfer passengers and passenger satisfaction in the operation adjustment. Subsequent research work will concentrate on segmenting and incorporating transfer passengers with varying travelling mileage into the model, with the aim of enhancing the accuracy of transfer operation adjustment.

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