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Optimization of Urban Rail Transit Connection Scheme for Evacuating Large Volumes of Arriving Railway Passengers

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ABSTRACT Urban rail transit (URT) is an essential mode of travel used for evacuating passengers from railway stations. To provide timely and safe connecting services for passengers arriving at railway hubs, it is recommended for URT operators to develop a coordinated connection scheme considering the periodic incoming volume of railway passengers. According to the fluctuation characteristics of the large passenger flows in railways, this paper presents a reasonable scheme for increasing the capacity of URT trains. First, a method for calculating the effective evacuation capacity of URT trains and determining the time range that should be optimized according to the transportation capacity matching degree is proposed. The dwell time and departure interval are taken as decision variables in this adjustment period. Two constraints are considered: capacity convergence and the maximum safe capacity of the platform. Based on the consideration of reserved capacity for subsequent sections, the objective is to optimize the degree of matching between the effective evacuation capacity of the URT and the transfer demand of the arriving railway passengers. A multi-objective nonlinear integer-programming model is established for the coordinated connection of URT trains with large passenger flows, and a solution process of a train connection scheme is designed that involves a genetic algorithm. Finally, the effectiveness of the proposed model and algorithm is analyzed and verified by considering the Shanghai Hongqiao Hub—a transfer station between a high-speed railway and URT—as an example.

INDEX TERMS Urban rail transit, connection scheme, passenger evacuation, integer programming, genetic algorithm.

I. INTRODUCTION

Urban rail transit (URT) is the most important evacuation mode for railway hubs. With the continuous expansion of the Chinese high-speed rail network, the passenger flow in railway hubs is increasing. At present, URT is operated in a growing number of Chinese cities. An important aspect of urban planning is the design of connections between the URT and railway hub stations. According to previous studies [1]–[5], in China, nearly 50% of the passengers arriving at a railway hub choose URT to transfer for economic and convenience reasons, representing a large demand (Table 1). An insufficient capacity of URT at a railway station may lead to crowding in transfer corridors or on URT platforms, creating a capacity bottleneck and increasing the safety risk. Additionally, the passenger flow of the railway can significantly increase in a short period of time, and this duration within which increase occurs is unpredictable. Most of the passengers require the URT to evacuate, but URT schedules often fail to consider these sudden large incoming passenger flows, which ultimately results in increased passenger transfer times. Passengers may even have to wait for a second train on the URT platform, which affects their travel efficiency. Therefore, owing to the large passenger flow demand of railway hubs, it is necessary to optimize the train connection scheme of URT and rationally allocate

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TABLE 1. Transfer sharing rate for passengers in Major Railway Hubs in China.

Railway Station \ Sharing Rate	URT	Bus	Taxi	Private car
Beijing South Railway Station	50%	30%	12%	8%
Beijing West Railway Station	48.61%	43.52%	4.57%	3.30%
Xian North Railway Station	58.09%	17.58%	12.99%	11.34%
Chengdu East Railway Station	53.5%	23.5%	10%	13%
Shanghai Hongqiao Railway Station	42.5%	15.1%	23.2%	19.2%

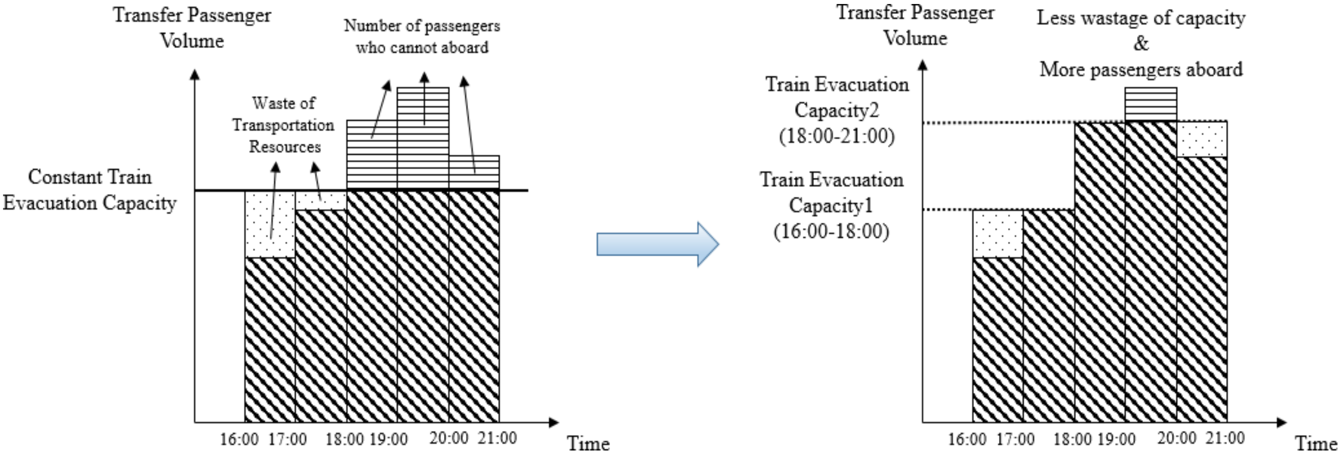

FIGURE 1. Comparison of capacity matching before and after adjustment.

the system capacity resources to alleviate crowding in transfer corridors and on URT platforms and realize the best match between the passenger flow demand and the transport capacity.

Based on the aforementioned research, we investigated the situation of large passenger flows in railway hubs. To reduce the risk of passenger jams and secondary queuing on the platform, the URT transport organization must be able to handle the passenger flow from the railway station. Additionally, the URT operator must be able to identify the times of large passenger flows in advance. The operator should identify the period when the capacity does not match the demand to achieve matching between the two transport modes. Using the railway operation plan and historical passenger flow data, the period of large passenger flows in the railway hub can be analyzed. Then, according to the AFC (Automatic Fare Collection System) data of URT, the periods of mismatch between the URT and railway are identified. Within this time range, considering the train transportation capacity and the limited capacity of the station, two constraints are identified: the connections and the passenger safety. To improve the efficiency of URT, an optimization model of the train connection plan is established. The model optimizes the degree of matching between the URT capacity and the transfer demand and achieves the minimum transfer waiting time for all the passengers.

At present, the URT operation plan only considers the characteristics of its own passenger flow and disregards the impact of the large passenger flow of the railway, and the conditions considered in URT are relatively simple. As shown in Fig. 1(a), the URT operation plan is often periodic, and the capacity of the trains passing through the railway station in the entire day is relatively constant with only consideration of the internal passenger of URT. The capacity cannot satisfy the fluctuation of the large passenger flow demand in the railway hub. If the URT operation plan can be adjusted flexibly according to the fluctuation of the passenger flow in the railway hub and the train operation interval, the amount of transport resources wasted can be reduced, and situations of insufficient transport capacity can be avoided, as shown in Fig. 1(b).

II. RELATED WORKS

With the development of URT, scholars have investigated the transfers and connections between URT and many other transport modes. The transfers and connections between URT and buses is a popular research topic in passenger multimodal transport. The two main research areas are a) optimization of the layout of station or transfer facilities [6]–[8] and b) optimization of the lines or schedules of the bus for connecting to URT [9]–[12]. In view of the unexpected interruption of URT, Jin *et al.* [13] proposed optimizing the bus-bridge service to

TABLE 2. Comparison of related publications on URT–railway services with our work.

Publication (Year)	Topic	Model/solution	Consideration		
			Capacity connection	Facility capability	Transfer waiting time
[16] Zhen et al. (2013)	Optimization of integrative passenger rail transit station layout	Bi-level programming model			√
[17] Chen et al. (2013)	Comprehensive evaluation of the service level of evacuating passengers in high-speed railway station	Fuzzy mathematics comprehensive evaluation method		√	√
[18] Chen et al. (2014)	Evaluation on transfer in large transport terminals	MGE and TOPSIS	√	√	√
[19] Zong et al. (2011)	Evaluation of connection model of intercity railway and suburban rail transit	Rough-set and gray-clustering evaluation			√
[20] Liu et al. (2012)	Joint operation among regional rail transit, URT, and major bus lines	Genetic algorithm			√
[21] Li et al. (2019)	Optimization of one-direction URT connection timetable considering waiting time and energy efficiency	Multi-objective programming model	√		√
This Paper	Optimization URT connection timetable considering railway large passenger flow and capacity reservation	Nonlinear multi-objective integer programming model	√	√	√

better evacuate stranded passengers. Gu *et al.* [14] proposed a two-stage integer programming model to formulate flexible bridge routes and allocate buses. Kang *et al.* [15] addressed the connection between the last URT train and the bus. A mixed-integer linear programming model was established for maximizing the number of transfer passengers on the last train and minimizing the waiting times for URT-to-bus passengers. Optimization results for the last train timetable and bus-bridge services were obtained to improve the transfer success rate of URT-to-bus passengers.

Research on URT–railway service mainly focuses on facility layout, design planning, and transfer scheme evaluation. Zhen *et al.* [16] proposed the construction of an integrated urban passenger rail transit system. A bi-level programming model of the layout of the integrative urban rail transit line station based on the alternative use mode was established to optimize the layout of the integrative URT station. Scholars [17]–[19] have comprehensively evaluated the interchange performance and passenger evacuation capacity service level of railway hubs and optimized the hub infrastructure design, transfer flow lines, etc. The objective of aforementioned research is typically the internal structure and transportation organization of the hub; only the capacity of the transfer facilities is studied. These scholars could only evaluate the transfer service of railway stations qualitatively; they could not solve the problem of unbalanced supply and demand between the URT and railway. Few scholars have investigated the cooperative operation between URT and railway. To achieve joint operation among regional rail transit, URT, and major bus lines, Liu [20] developed a joint operation coordination model to optimize the joint operation, which reduces the waiting and transfer costs for passengers. Li *et al.* [21] considered the dynamic passenger flow distribution and established a multi-objective programming model that minimizes the total waiting time of passengers at the station and the energy consumption of train operation. The fuzzy multi-objective optimization algorithm was used to solve the model to obtain the optimal one-direction URT-to-railway connection timetable. Various studies have been performed on URT–railway intermodal transport, and Table 2 presents a comparison of the research topics, methods, and considerations. However, there exist deficiencies and even gaps regarding several aspects:

1) In a transfer hub, operators should pay more attention to the dynamic demand of transfer passenger flow. The operator should adjust the connection schedule according to the demand–capacity matching degree reasonably and accurately.
2) In most of the aforementioned studies, only the waiting time of passengers was considered; the matching relationship between the capacity and transfer demand was ignored.
3) The transfers and connections are directly restricted by the train capacity and platform carrying capacity. However, in most of the aforementioned studies, the limitations of the train capacity and platform carrying capacity were not explicitly considered.

The key to resolve the connection problem between URT and railway is to optimize the connection scheme of URT at railway stations to adjust the transportation capacity and to develop a periodic timetable based on the number of arriving railway passengers. There is abundant experience for optimizing the URT operation plan. The operation plan is optimized by adjusting the timetables [22]–[24], the route scheme [25], and the skip-stop operation [26], [27]. According to these studies, adjustment means and timetable experience in the train operation plan provide some reference value for this work. Additionally, in almost all the aforementioned studies and URT–bus studies [9]–[12], the objective was to reduce passenger waiting (transfer) time. Therefore, in the present study, the minimum passenger waiting time at the transfer station was one of the optimization goals. Some studies focused on optimization of timetable for the connection in one kind of railway transit network. For example, Kang *et al.* [28], [29] quantitatively analyzed the relationship between the transfer connection time and the waiting time of passengers and established optimization models for the first and last URT train transfer respectively to increase the number of passengers that could successfully transfer. According to the accurate OD demand of railway, Niu *et al.* [30] proposed a systematic schedule synchronization approach involving two interconnected lines for transferring passengers from one rail line to another. However, in these studies, the period to be optimized was generally fixed, i.e., the peak period of transfer demand or the beginning and end periods of operation. For the connection between URT and railway, the period to be optimized is not fixed; it is determined by the demand–capacity relationship. For example, Wu *et al.* [31] and Wang *et al.* [32] proposed timetable synchronization optimization methods for optimizing the passenger transfer waiting time according to the time-dependent demand and train capacity. For a bus system, Wu *et al.* [33] examined the multi-objective re-synchronization of the timetable. According to the sensitive passenger flow demand and uneven headways, NSGA-II (Non-dominated Sorting Genetic Algorithm II) is used to optimize the bus connection time at the interchange station. The matching of URT–railway transfer is related to the operation plans and the number of passengers. There is no fixed peak period for passenger transfer. Therefore, this work proposes an optimization period determination method based on the matching of URT–railway supply and demand relationships, which can accurately identify the time range that should be adjusted according to the fluctuation of railway arriving passengers.

In summary, (1) few studies have been performed on the transfers and connections between URT and railway. Most of them focused on the level of planning and design. Research on the supply–demand relationship between URT and railway still needs to be solved urgently. (2) Numerous studies have been performed on the optimization of URT operation plans. In most of them, the internal passengers of the URT network or the transfer with a bus system were considered. The optimization goals were generally to minimize the transfer time of passengers and improve the success rate of transfers. A few studies have been performed on the optimization of the connection between a train and a railway. The transfer demand between these two modes is becoming increasingly significant; thus, in the present study, the impact of a large railway passenger flow on URT was considered, and the transfers and connections were optimized by adjusting the operation organization of the URT. This research makes a significant contribution to the optimization of passenger multimodal transport.

The main objectives of the present study are as follows:

1) According to an analysis of the fluctuation of the railway arriving passenger flow, the relationship between the URT timetable and the railway arriving passengers is investigated, and a method for calculating the effective evacuation capacity of URT trains is proposed. According to the dynamic passenger flow demand, the time period of mismatch between the URT and railway capacity is determined.
2) Considering the reserved capacity for subsequent sections in the URT line and the impact of a large passenger flow on other stations, the passenger flow control strategy [34]–[37] is used as an auxiliary means in the URT station.
3) A multi-objective nonlinear integer programming model considering the capacity convergence and platform safety constraints is established. It is mainly based on optimizing the train connection plan and supplementing the adjustment of the passenger flow control. It is necessary to ensure the rapid evacuation of passengers and the reserve capacity of subsequent sections.
4) A solution method for the URT connection timetable based on a genetic algorithm (GA) is designed, and a case study is examined to prove the effectiveness of the model and algorithm.

III. CHARACTERISTICS OF FLUCTUATION OF RAILWAY PASSENGER FLOW

Usually, the passenger flow arrives at a railway station via URT with a normal distribution. The process is slow, and the passenger flow is relatively uniform. However, the distribution of the flow of arriving railway passengers is uneven, exhibiting significant fluctuations within a day. This is because the arrival time of railway trains is non-uniformly distributed throughout the day, with peak periods, and the passenger transfer to URT is concentrated in a period after the railway train arrives. When a railway train arrives, the passenger flow leads to a sharp increase in the number of passengers in a short period. Owing to the different times and numbers of train arrivals, the high-speed railway stations in different cities have different peak periods of passenger flow. However, the peak time of URT is obvious and fixed (usually in the morning and evening). When the arrival peak period of a railway station coincides with the peak period of URT, the passengers may not be able to board, owing to the limited remaining space in the carriages. Moreover, the operating department may apply passenger inflow control at URT stations to reserve capacity for subsequent sections. If the two periods do not coincide, for example, when a large passenger flow coincides with the non-peak period of URT, the arriving railway passengers cannot evacuate quickly and are stranded on the URT platform. The following is an example of the operation data of Hongqiao High-Speed Railway Station on March 1, 2017.

In Fig. 2, the abscissa indicates the operation time of each day, and the ordinate indicates the number of trains arriving at Hongqiao High-Speed Railway Station in that hour.

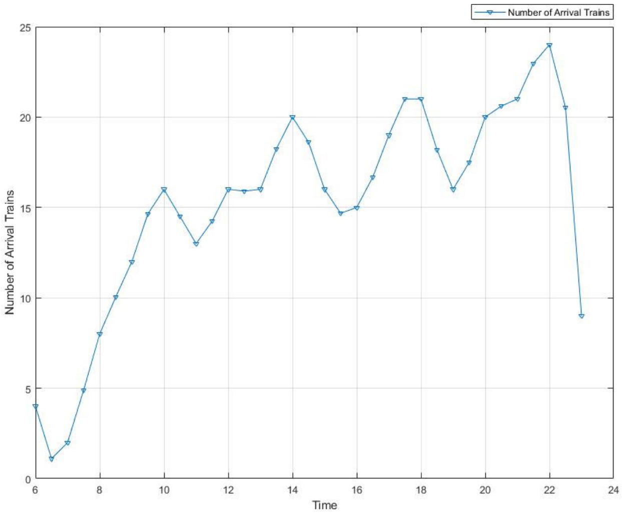

FIGURE 2. Arrival of trains at Hongqiao high-speed railway station.

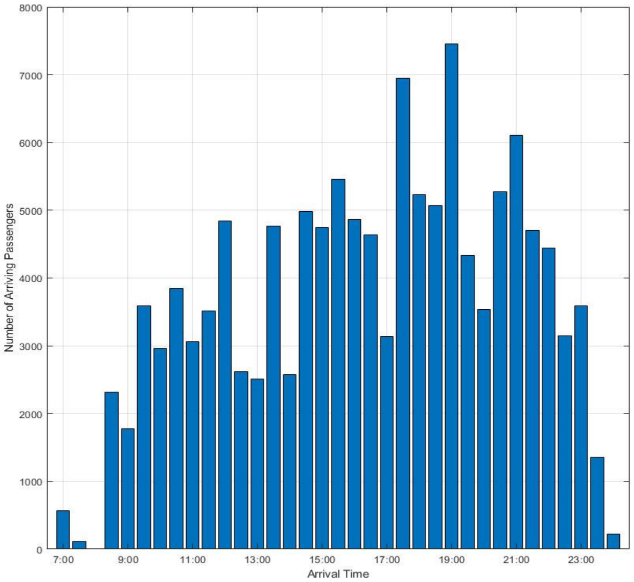

FIGURE 3. Arrival of passengers at Hongqiao high speed railway station.

According to the data, the average number of trains arriving per hour was >15. At 13:00–15:00, 17:00–19:00, and 19:00–22:00, there are significant fluctuations in the number of high-speed railway trains arriving. In this stage, the crest corresponds to approximately 24 trains, and the trough corresponds to approximately 13 trains.

As shown in Fig. 3, the trend of the flow of the arriving railway passengers throughout the day is consistent with the trend of the train arrivals but is not exactly the same. This is related to the rated capacity and occupancy rate of the trains when they arrive at the station. The passenger flow peaks at 14:00–16:00, 18:00–19:00, and 21:00–23:00. Within the period of 10:00–22:00, the passenger flow for trains can increase by 10000 in 1 h, and there are approximately 5000 passengers transferring to URT. The fluctuation of this large passenger flow significantly affects the URT system. If the passengers encounter the peak period at the railway station, the URT cannot evacuate the passengers quickly and safely, resulting in stranded passengers. Therefore, it must be determined whether it is necessary to adjust the URT–train connection plan to match the suddenly increased passenger flow demand.

IV. METHOD OF DETERMINING ADJUSTMENT TIME RANGE

According to the characteristics of the fluctuation of the large passenger flow of the railway station, this work proposes a method for determining the adjustment period of the URT connection plan within 1 d. The purpose is to ensure that the URT establishes a link to the large passenger flow of the railway hub in terms of time.

A. DETERMINE EFFECTIVE EVACUATION CAPACITY OF URT TRAINS

The capacity of URT is the key to satisfy the demand of passengers arriving at the station. In this study, the effective evacuation capacity of the URT is defined as the number of passengers that each train can evacuate during the dwell time. It is determined by the minimum value between the residual capacity of the train and the number of people who can board the train during the dwell time. In Fig. 4, the residual capacity of the train in Example A is lower, the number of passengers in the train reaches the maximum capacity in in a short time (< dwell time), which leads to passengers stranded on the platform. In the Example A, the effective evacuation capacity of this URT train is the maximum number of people that can occupy the remaining space of the carriage. In Example B, the train has a large residual capacity, but the doors of the train open in dwell time. At this time, the number of passengers that board successfully when the doors open is smaller than residual capacity of the train. In this situation, the effective evacuation capacity of the train is the number of passengers on board in the dwell time.

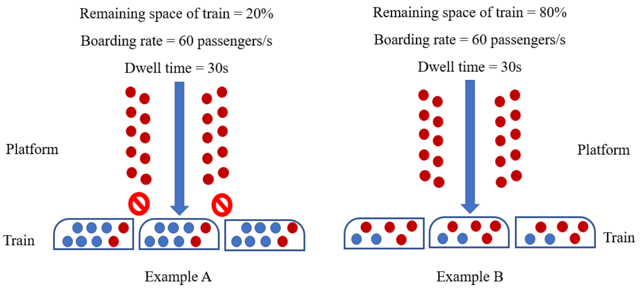

FIGURE 4. Example diagram of the effective evacuation capacity of trains.

According to [38], the speed of passengers boarding the train in front of the doors of a URT train in Beijing is [0.66, 2.27] (person/s), which is affected by the number of passengers in the train. The URT train types and passenger flow characteristics are similar between Shanghai and Beijing. In this study, it is assumed that the average passenger boarding speed at each door $\omega_i^d \omega_i^d$ is 1.5 people/s. There

TABLE 3. Notation related to (1)–(3).

Notations	Definition
$d \in \{x, y\}$	Train running direction: x and y correspond to up and down, respectively
$N_{i,j}^{d}$	Effective evacuation capacity of the j^{th} train in direction d of Line i after the train arrives at the station in the research period
C_{i}^{d}	Rated capacity of each train in direction d of Line i
α_{max}	Maximum load factor of the train
$\alpha_{i,j}^{d}$	Load factor of the j^{th} train in direction d of Line i before arriving at the station
$D_{i,j}^{d}$	Number of passengers getting off at the station for the j^{th} train in direction d of Line i
K_{i}^{d}	Passenger boarding rate of the URT train in direction d of Line i at the station
$t_{dwell^{i,j}}^{d}$	Station dwell time of the j^{th} train in direction d of Line i
τ_{i}^{d}	Additional time of opening and closing doors in the station dwell time for each train in direction d of Line i
L_{i}^{d}	Number of doors on each side of each train in direction d of Line i
ω_{i}^{d}	Average passenger boarding rate at each door of the URT train in direction d of Line i

are eight carriages, each with five doors. Thus, the boarding rate is assumed to be 60 people/s. d represents the operation direction of the train: $\{\text{up } (x), \text{ down } (y)\}$.

$$N_{i,j}^{d} = min\left\{C_{i}^{d}\left(\alpha_{max} - \alpha_{i,j}^{d}\right) + D_{i,j}^{d}, K_{i}^{d}\left(t_{dwell^{i,j}}^{d} - \tau_{i}^{d}\right)\right\} \tag{1}$$

$$K_{i}^{d} = L_{i}^{d} \times \omega_{i}^{d} \tag{2}$$

The residual capacity of the train is the product of the residual load factor $\left(\alpha_{max} - \alpha_{i,j}^{d}\right)$ after the train arrives at the station, the rated capacity C_{i}^{d} of the train, and the number of people getting off the train $D_{i,j}^{d}$. The number of people who can board during the dwell time is obtained by multiplying the boarding time $\left(t_{dwell^{i,j}}^{d} - \tau_{i}^{d}\right)$ by the passenger boarding rate K_{i}^{d}. Therefore, this paper proposes that the effective evacuation capacity $N_{i,j}^{d}$ of the j^{th} train in a certain direction of Line i after arriving at the station is determined by the residual capacity of the train and the number of passengers that can board the train during the dwell time. The dwell time $t_{dwell^{i,j}}^{d}$ is a decision variable that determines the effective evacuation capacity of the URT train.

When a station of URT Line i is the starting station, the load factor before the train arrives at the station is 0, and the number of people leaving the station from the up or down direction of Line i is 0:

$$\begin{cases} \alpha_{i,j}^{d} = 0 \\ D_{i,j}^{d} = 0 \end{cases} . \tag{3}$$

The notation used in (1)-(3) is presented in Table 3.

B. TRANSPORTATION CAPACITY MATCHING DEGREE

To select the period of adjustment in a day, this paper proposes the concept of the transportation capacity matching degree. This value is used to judge whether the passenger flow can be evacuated safely and quickly and whether the transportation capacity of URT can be used efficiently. On one hand, when passengers transfer to URT after the railway train arrives, the transportation capacity of the URT should be considered to satisfy the passenger flow demand. On the other hand, the number of trains used should be minimized to fully utilize the transportation capacity while ensuring the station safety and the efficiency of passenger evacuation. The transportation capacity matching degree is an intuitive description for the quality of the connection of transportation capacity. P is calculated using the number of passengers transferring from railway to URT and the effective evacuation capacity of URT, as follows (4)–(7).

$$P = \frac{F_r}{U_r} \times k_r \tag{4}$$

$$F_r = \sum_{a=1}^{g} F_r^{a} \tag{5}$$

$$U_r = \sum_{i}^{n} \sum_{j=1}^{m} \left\{N_{i,j}^{d} \cdot \left(1 - \mu_{i}^{d}\right)\right\} \tag{6}$$

To simplify the calculation, suppose that in a certain period, the dwell time in a certain direction of Line i is a fixed value $t_{dwell^{i}}^{d}$. The effective evacuation capacity of Line i in 1 h is obtained by combining (6) and (1):

$$U_r = \frac{3600}{I_i^d} \times \left\{min\left(C_{i}^{d}\left(\alpha_{max} - \alpha_{i}^{d}\right) + \sum_{j=1}^{m} D_{i,j}^{d}, K_{i}^{d}\left(t_{dwell^{i}}^{d} - \tau_{i}^{d}\right)\right)\right\}\left(1 - \mu_{i}^{d}\right), \tag{7}$$

where k_r is the transfer coefficient, which represents the proportion of passengers arriving at the railway station who transfer to URT. The theoretical value is between 0 and 1. k_r is determined by the network size of URT. When the URT structure is a single line or backbone frame network, it is relatively unattractive to passengers, and k_r is relatively small. However, with the continuous expansion of the network, the attractiveness of URT to passengers increases exponentially, and k_r increases. According to [1]–[5], in China, k_r is 0.4–0.6.

Along with the consideration of rapid evacuation of the railway passenger flow, the impact of large passenger flows on other stations should also be reduced. It is considered that to reserve the transportation capacity for the subsequent URT operation section, a reasonable and effective passenger inflow control strategy must be adopted to reduce the impact of a single station flow on other stations, particularly in special lines such as Y-type and loop lines. In general, URT takes passenger flow control measures according to the real-time passenger flow if it is faced with a sudden large passenger flow caused by emergencies, large-scale activities, or severe weather or the regular large passenger flow in the morning/evening peak. In previous studies [36], [37], the

TABLE 4. Notation related to transportation capacity matching degree.

Notations	Definition
F_r	Sum of arriving passengers for all railway trains in a certain period
U_r	Sum of effective evacuation capacities of all URT trains passing through the station in a certain period
F_r^a	Number of arriving passengers for railway train a in a certain period
k_r	Proportion of arriving railway passengers transferring to URT
I_i^d	Departure interval in direction d of Line i
$t_{dwell^i}^d$	Station dwell time of the train in direction d of Line i
α_i^d	Hourly load factor of the train in direction d of Line i before the train arrives at the station
μ_i^d	Passenger flow control intensity for direction d of Line i at the station
g	Number of trains arriving at the station during the research period
n	Number of URT lines connected to the railway at the station
m_i	Number of trains passing through the station on URT line i during the research period

TABLE 5. Transportation capacity matching degree ***P***.

	Very good	Good	Even	Poor	Very poor
P	0.86–0.90	0.91–0.95 or 0.70–0.85	0.96–1.00 or 0.54–0.69	1.01–1.10 or 0.38–0.53	>1.10 or 0–0.37

formulation of the passenger flow control strategy usually included three parts: stations, durations, and intensity. In the present study, the intensity μ_i^d of the passenger flow control had to be determined for transfer station in mismatch period. This value is the ratio between the limited passenger flow (the passenger flow demand that cannot be satisfied under the control condition) and the actual passenger flow demand of the station per unit time. In the actual operation, the number and speed of passengers entering the station are often limited by the means of temporary closing of the station or setting the current limited fence, adjusting the number of gates, etc. In the present study, this value is used as the input parameter. The determination process of the value is not the focus of this work.

In Equation (7), the dwell time $t_{dwell^i}^d$ and interval I_i^d are decision variables that determine the effective evacuation capacity of URT trains. All the other parameters are input parameters. The notation used in (4)–(7) is presented in Table 4.

C. EVALUATION CRITERION

In this study, the transportation capacity matching degree P is used to express the matching relationship between the demand of arriving railway passengers and the URT effective evacuation capacity, which reflects the transportation coordination of the two transportation modes. According to [39], the range and level classification of P is presented in Table 5.

According to (4), if $P \leq 0.53$, the effective evacuation capacity of URT is significantly larger than the number of railway-to-URT passengers. There are two reasons for this situation: a) passengers are unwilling to choose URT for transfer given their personal preferences; b) in the early morning or late night, few passengers arrive at the railway station. In the former case, the convenience, travel time, and distance from the URT station to the destination significantly affect the choice of the transportation mode [40]. If the coverage of the URT network in the city is too sparse, few areas can be reached by transferring from railway to URT, and passengers will be unwilling to choose URT. With regard to the latter case, in the early morning and late night, few trains arrive at the railway station typically, and the demand for passengers to transfer to URT is relatively small. Both these situations result in the wastage of transportation resources. When $P \in [0.54, 0.85]$, the capacity of URT is slightly excessive. Possibly, there are few arriving railway passengers and it is the transition period to the peak period or the end of operation. If $P \geq 1$, the effective evacuation capacity of URT cannot satisfy the transfer demand of railway passengers, and the coordination of the connection is destroyed. Generally, when a railway train arrives at non-rush hours, the URT can satisfy the needs of transfer passengers without adjusting its own operation plan. However, when the number of arriving passengers increases significantly, it is difficult to satisfy the needs of evacuation and transfer with the original plan. Therefore, it is necessary to adjust the URT operation plan to satisfy the increasing demand of the railway-to-URT passengers.

According to [39], the most economical and reasonable situation is $P \in [0.86, 0.90]$. In this case, the effective evacuation capacity of URT is slightly greater than the transfer demand of the flow of arriving railway passengers. The passengers feel that the environment of the carriage is relatively comfortable. Additionally, the URT provides transport capacity for a small number of non-railway passengers. In general, operator can not only provide a good service level but also avoid wastage of resources and achieve win–win benefits. Therefore, in this study, it is stipulated that capacity adjustment is needed when the transportation capacity matching degree of the research period is >0.90.

D. EXAMPLE

Hongqiao Hub, which is the busiest railway hub in China, was selected for analysis. Shanghai Metro Lines 2 and 10 connect here, as shown in Fig. 5. According to the passenger flow data for the railway and URT obtained from March 1, 2017, 268 high-speed railway trains arrived from 06:30 to 23:59. Nearly 130000 passengers arrived by high-speed rail every day in 2017. Calculating P for this day reveals that 17:12–17:21 was an extremely busy period. Thus, 17:12–17:21 as an example, six trains arrived in 9 min. In <10 min, the number of passengers was $F_r = 3032$. The

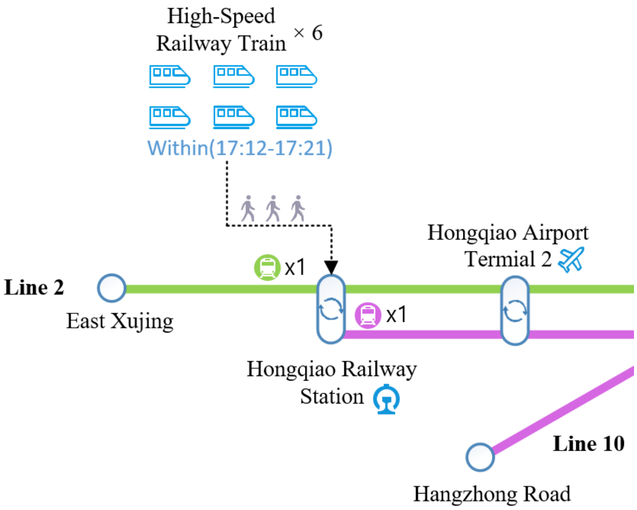

FIGURE 5. Local topology of Hongqiao Hub.

TABLE 6. Number of arrival trains and passengers in the period 17:12–17:21.

Train number	G7585	G44	G462	G7142	G127	G1638
Arrival time	17:12	17:14	17:15	17:18	17:20	17:21
Number of arriving passengers	449	559	395	647	473	509

train numbers, arrival times, and numbers of passengers are presented in Table 6.

To distinguish the names of the URT station and the railway station in Hongqiao, we present the following definitions: Hongqiao Railway Station (URT station), Hongqiao High Speed Railway Station or Hongqiao Station (railway station for intercity passenger), and Hongqiao Hub (URT & railway).

When the effective evacuation capacity of URT in Hongqiao Railway Station is calculated, because this station is the starting station in the up direction of Line 10 and the second station in the up direction of Line 2, transportation capacity should be reserved for the subsequent stations. Thus, it is preferable that a large number of passengers do not board the train at the front station. Otherwise, the passengers in the subsequent stations may be unable to board. Passenger inflow control is often adopted at the front station by limiting the speed of passengers entering the station. Thus, sufficient transportation capacity can be reserved for the subsequent sections in Line 2 and Line 10. It is assumed that $\mu_2^x = 53\%$, $\mu_{10}^x = 46\%$, $t_{dwell2}^x = 20\text{s}$, and the time needed by the arriving railway passengers to walk to the URT platform is 10 min. According to the operation data of Shanghai Metro for March 1, 2017, the effective evacuation capacity of URT within the period 17:22–17:31 was calculated using (1)–(7), and U_r was 1515. Assuming that 60% of the passengers arriving at the railway station transfer to URT, the transportation capacity matching degree in this period is $P = 120.08\%$. Considering the condition that the transportation level of the subsequent stations of Lines 2 and 10 is not affected, the URT capacity of Hongqiao Railway Station does not match the transportation demand. Therefore, it should be adjusted.

V. METHODOLOGY

The standard of capacity coordination between the demand of arriving railway passengers and the URT capacity indicates that the capacity should be used fully. According to the judgment criteria presented in Section IV.C., the connection scheme of URT under the condition of an insufficient effective evacuation capacity ($P > 0.9$) was examined. The constraints of capacity connection and platform safety are considered, and the station dwell time and departure interval are taken as decision variables. Considering cost savings, the first target is the optimal transportation capacity matching degree, and the second target is the minimum waiting time of passengers. According to these two goals, a multi-objective coordination optimization model is established.

In this model, the connection scheme of URT trains is adjusted to optimize the transportation connection between the capacity and the demand. The two parameters adjusted are the dwell time of trains at the station and the train departure interval.

The following assumptions are made.

(1) The background of a large passenger flow of the railway; when the transportation capacity matching degree P is greater than 0.90 in a certain period, the operation plan of the URT must be adjusted. For a period with $P < 0.86$, no further study is required.

(2) The departure interval of trains in the same direction of the same line is uniform within a certain period.

(3) "First come first served," i.e., passengers board the train in sequence.

(4) Passengers must wait for others to get off the train before boarding.

(5) After leaving the railway station, the passengers arrive at the URT platform in a random order and follow a uniform distribution. (The fluctuation of the passenger walking speeds is ignored, and the average travel time of the passengers is determined according to their average travel speed.)

(6) The train marshalling and capacity of trains on the same line are fixed; that is, the trains have the same passenger carrying capacity. When the number of passengers reaches the maximum capacity of the train, the remaining passengers cannot board the train and must wait in line for the next train.

(7) The time granularity for adjustment is 1 h. The time range of the adjustment plan some periods within a day.

(8) In the model, the passengers become stranded at the platform no more than once in each queue.

A. SETS AND PARAMETERS

1) ARRIVAL AND DEPARTURE TIMES OF URT TRAIN

The departure time of the j^{th} train of Line i at transfer station in direction d during the research period can be calculated using the following formula:

$$S^d_{i,j} = t^d_{i,0} + (j-1)I^d_i \quad j > 1. \tag{8}$$

The arrival time of the j^{th} train of Line i at the transfer station in direction d during the research period can be calculated using the following formula:

$$A^d_{i,j} = S^d_{i,j} - t^d_{dwell^i}. \tag{9}$$

Here, $t^d_{i,0}$ represents the departure time of the first train in direction d of Line i at the transfer station ,I^d_i represents the departure interval of the train in direction d of Line i (s), $S^d_{i,j}$ represents the departure time of the j^{th} train in direction d of Line i at the transfer station, $A^d_{i,j}$ represents the arrival time of the j^{th} train in direction d of Line i at the transfer station, and $t^d_{dwell^i}$ represents the dwell time of the train in direction d of Line i at the transfer station.

2) NUMBER OF ARRIVING RAILWAY PASSENGERS TRANSFERRING TO URT

The number of arriving railway passengers who transfer to URT during the research period is calculated using the following formula:

$$F_r \times k_r = \left(\sum_{a=1}^{g} F^a_r\right) \times k_r, \tag{10}$$

where F^a_r represents the number of railway passengers arriving from train a in the research period, and k_r represents the proportion of arriving passengers transferring to URT.

3) AVERAGE ARRIVAL RATE OF TRANSFER PASSENGERS

The number of passengers arriving at the upward or downward platform of Line i per second during the research period is given as

$$\lambda^d_i = \frac{F_r \times k_r \times k^d_i}{T_r} \times \left(1 - \mu^d_i\right), \tag{11}$$

where T_r represents the study duration, and k^d_i represents the proportion of passengers who select direction d of line i in URT transfer.

In the time range (t_1, t_2), the average arrival rate of railway passengers entering the URT platform is λ^d_i. In this period, the number of people who transfer to direction d of Line i from the railway station is given as

$$U^{id}_{(t_1,t_2)} = \lambda^d_i \times (t_2 - t_1). \tag{12}$$

4) NUMBER OF PASSENGERS WAITING AT PLATFORM

Before the arrival of each train, the passengers waiting on the platform include the passengers transferred from railway, non-railway passengers, and stranded passengers in the platform. In this study, we consider not only the large passenger flow of the railway but also the effects of other passengers on the platform safety and transport capacity. It is assumed that the average arrival rate of non-railway passengers is v^d_i. In the time range (t_1, t_2), the number of non-railway passengers who take the train on Line i in direction d is given as

$$Q^{id}_{(t_1,t_2)} = v^d_i \times \left(1 - \mu^d_i\right) \times (t_2 - t_1). \tag{13}$$

The number of passengers waiting at the up or down platform before the departure of the j^{th} train on Line i is given as

$$W^d_{ij} = \begin{cases} U^{id}_{\left(t^d_{i,0}, S^d_{i,j}\right)} + Q^{id}_{\left(t^d_{i,0}, S^d_{i,j}\right)} + R^d_{i,0}, & j=1 \\ U^{id}_{\left(S^d_{i,j-1}, S^d_{i,j}\right)} + Q^{id}_{\left(S^d_{i,j-1}, S^d_{i,j}\right)} + R^d_{i,j-1}, & j=2,3\cdots \end{cases} \tag{14}$$

where $W^d_{i,j}$ represents the number of passengers waiting for the up or down platform before the departure of the j^{th} train on Line i, $R^d_{i,0}$ represents the initial number of passengers waiting for the train on the d direction platform of Line i at the beginning of the study period, and $R^d_{i,j}$ represents the number of people stranded on the d direction platform before the $(j-1)^{\text{th}}$ train leaves the station on Line i.

Whether there is detention depends on whether the transport capacity of the train can satisfy the demand of the passenger flow. When the passenger flow demand exceeds the effective evacuation capacity of the train, passenger retention occurs, resulting in an undesirable waiting environment and security risks. The number of passengers stranded on the d direction platform of Line i after the departure of the j^{th} train is given as

$$R^d_{i,j} = max\left\{W^d_{i,j} - N^d_{i,j}, 0\right\}. \tag{15}$$

5) WAITING TIME OF PASSENGERS

On the d direction platform of line i, from the departure time of the $(j-1)^{\text{th}}$ train to the departure time of the j^{th} train, the passenger waiting time on the platform before the departure of the j^{th} train is given as

$$T^d_{i,j} = \int_0^{I^d_i} \left(\lambda^d_i + v^d_i\right) dt + R^d_{i,j} \cdot I^d_i. \tag{16}$$

B. MODELING

The decision variables are the departure interval I^d_i and dwell time $t^d_{dwell^i}$ of URT Line i. The other parameters are input parameters. The model is described by (19)–(25).

Objective Function :

$$\begin{cases} \min Y = \left|P - P_{optimal}\right| = \left|\frac{F_r}{U_r} \times k_r - P_{optimal}\right| & (17) \\ \min Z = \sum_{i}^{n} \sum_{j=1}^{m} T_{i,j}^{d} & (18) \end{cases}$$

Here, U_r is calculated using (7), and T_{ij}^{d} is calculated using (16). The decision variables I_i^d and $t_{dwell^i}^{d}$ affect the values of Y and Z. The following formulas give the model limitations:

$$\text{s. t.} \quad W_{i,j}^{d} \le E_i^d \forall i, \quad \forall j, d \in \{x, y\} \tag{19}$$

$$I_{min} \le I_i^d \le I_{max} \quad \forall i, d \in x, y \tag{20}$$

$$t_{dwell}^{min} \le t_{dwell^i}^{d} \le t_{dwell}^{max} \quad \forall i, d \in x, y \tag{21}$$

$$T_E - I_i^d \le A_{i,l}^{d} \le T_E \quad \forall i, d \in x, y \tag{22}$$

$$I_i^d, t_{dwell^i}^{d} \in N^* \qquad \forall i, d \in x, y, \tag{23}$$

where E_i^d represents the passenger capacity limit of the up or down platform of Line i; $I_{i,O}^{d}$ represents the departure interval of the up or down direction of Line i before the adjustment; I_{min} and I_{max} represent the minimum and maximum departure intervals of the train, respectively; t_{dwell}^{min} and t_{dwell}^{max} represent the minimum and maximum station dwell times, respectively; $A_{i,l}^{d}$ represents the arrival time of the last train in the research period; and $\{T_S, T_E\}$ represents the period in which the train operation plan must be adjusted.

Equation (17) indicates the best transportation capacity matching degree between the effective evacuation capacity of all trains passing through the transfer station and the flow of arriving railway passengers during the study period. According to Section IV.C., the optimal transportation capacity matching degree is 0.9. Equation (18) gives the shortest total waiting time for transfer passengers in the study period. Equation (19) gives the constraint of platform safety; the number of people waiting at the platform cannot exceed the platform capacity limit. Generally, the platform capacities for the up and down directions at the same station are equal. Equation (20) gives the basic constraint of the train departure interval, where I_{min} mainly depends on the technical conditions of the line. The departure interval must be larger than the minimum tracking interval. To ensure the line service level, the departure interval must be smaller than the maximum departure interval. At peak hours, I_{max} is determined by the passenger flow demand, and at non-peak hours, I_{max} is determined by the service level. Equation (21) gives the constraint of the dwell time. Equation (22) gives the arrival-time constraint of the last train. Equation (23) gives the integer constraint of the decision variable. The train departure interval and dwell time are both integers (units: seconds).

C. SOLUTION ALGORITHM

In this model, the constraints are linear, and the two objective functions are nonlinear; thus, it is a multi-objective nonlinear integer programming model. Y is obtained by the game of the values of I_i^d and $t_{dwell^i}^{d}$. We need not increase or decrease I_i^d and $t_{dwell^i}^{d}$ blindly to improve or reduce the URT capacity; rather, the values should be matched with the passenger flow demand. Therefore, the difficulty in solving the model is how to synergistically adjust the two decision variables to obtain the optimal effective evacuation capacity and transportation capacity matching degree. The set of feasible solutions composed of I_i^d and $t_{dwell^i}^{d}$ is relatively large, and many constraints are added to the model to limit the range of the solution set. It is difficult to obtain the optimal solution quickly and accurately if the enumeration method or traditional transportation organization method is used to solve this model; thus, a heuristic algorithm is chosen to solve the model. The GA is a mature and widely used heuristic algorithm. It is an efficient random search and optimization method based on the theory of biological evolution. Its main characteristics are the group search strategy and information exchange between individuals in the population. The search does not depend on gradient information. It has good global convergence, a high calculation efficiency, and high robustness [41]. According to the GA, the specific algorithm design is as follows:

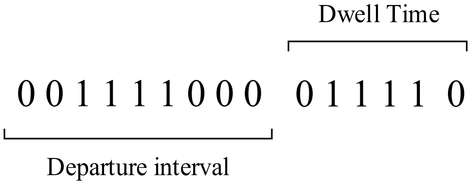

FIGURE 6. **Individual chromosome structure.**

1) CODING METHOD

In a GA, binary symbol strings are often used to represent individuals in a population. Variables are represented by a binary code symbol of length k. According to constraints (20) and (21), the departure interval of the train must exceed the minimum departure interval, and the dwell time should not be >40 s. It is assumed that the minimum departure interval is 120 s and the maximum departure interval is 420 s. Then, the number of bits of the binary code is set as $k = 15$, and the chromosome is divided into two parts: the train departure interval and the dwell time. According to the ranges of the decision variables, the variables correspond to 9- and 6-bit binary codes, respectively. Assuming that the interval of the up-direction train of line i is 120 s and the dwell time is 30 s, the chromosome structure is shown in Fig. 6.

2) FITNESS FUNCTION

Fitness is used to measure the quality of individuals in a population (degree of conformity) and is usually expressed in the form of numerical values. In general, a lower (or higher) fitness value indicates a higher-quality solution and a higher probability of the individual to be selected. Therefore, the selection of the fitness function, which directly affects the convergence speed of the genetic algorithm and whether the optimal solution is obtained, is significant. In the foregoing model, the effect of constraints (20)–(23) is to limit the range of the solution set. For restriction (19), in reality, there

TABLE 7. Transportation capacity matching degree for each hour.

Period	06:00–07:00	07:00–08:00	08:00–09:00	09:00–10:00	10:00–11:00	11:00–12:00	12:00–13:00	13:00–14:00	14:00–15:00
Number of arriving railway passengers	347	335	4093	6559	6907	7676	5806	7345	9721
Effective evacuation capacity of URT	2150	2968	3825	5408	6455	7432	6039	6643	7286
Transportation capacity matching degree	0.113	0.079	0.749	0.849	0.749	0.723	0.673	0.774	0.934
Period	15:00–16:00	16:00–17:00	17:00–18:00	18:00–19:00	19:00–20:00	20:00–21:00	21:00–22:00	22:00–23:00	23:00–24:00
Number of arriving railway passengers	10313	7765	12173	15061	8517	11359	8705	7565	1579
Effective evacuation capacity of URT	8327	5507	8346	6660	6783	7093	9081	7799	2473
Transportation capacity matching degree	0.867	0.987	1.021	1.583	0.879	1.121	0.671	0.679	0.447

Data source: China Railway Shanghai Bureau Group Co., Ltd. (collected on March 1, 2017).

must be a situation where the passenger demand exceeds the platform capacity. There will be a situation in which passengers cannot enter the station and queue outside the station. To reduce the likelihood of this situation, measures are taken, e.g., the heredity of individuals of inferior populations is minimized in the calculation process. In the construction of the fitness function, the penalty function is added to reduce the probability that the individual inherits to the next generation. The fitness-function value Y' is the sum of the objective-function value Y and Z and the penalty-function value:

$$Y' = \varphi \cdot Y + \delta \cdot \frac{Z}{F_r \times k_r} + \frac{\beta}{m \cdot n}\left(\sum_{i}^{n} \sum_{j=1}^{m_i} \sum_{d} R_{i,j}^{d}\right), \qquad (24)$$

where φ and μ are weight coefficients, and β is a penalty coefficient.

In (24), Y is determined using (17), and it represents the gap between the transportation capacity matching degree and the optimal value. Z is determined using (18) and represents the average waiting time of passengers. $R_{i,j}^{d}$ is determined using (15) and represents the number of passengers left after the train leaves. In summary, it is better for Y, Z, and $R_{i,j}^{d}$, as well as the fitness-function value Y', to be closer to 0.

3) CONTROL PARAMETERS

The selection of control parameters affects the speed and accuracy of the GA, including the population size and genetic operators. The population size affects the convergence of the GA, and the number of control parameters is generally 20–100. Better adaptability of the chromosomes yields a higher probability of survival and inheritance. Crossover is the operation of exchanging one or more genes on the parent chromosome to generate new individuals. The crossover probability is generally 0.4–0.99. Mutation is a random change introduced of an individual. Under certain conditions, one or several genes on a chromosome are randomly changed. The probability of variation is generally 0.0001–0.1. Generation gap measures the proportion of each generation that is selected to change. The gap is generally default 1.

4) ALGORITHM TERMINATION RULE

A maximum genetic threshold *MAXGEN* is provided. The algorithm iteration stops when it reaches *MAXGEN*.

VI. CASE STUDY

A. SCENARIO

The Shanghai Hongqiao Hub is taken as an example to validate the model and solution method. The passenger flow data were obtained in 2017, when only Lines 2 and 10 were operated. The local network structure of the URT is shown in Fig. 5. To simplify, the data for Line 2 are used for verification. According to the actual data, there were very few passengers who went to East Xujing via the down direction of Line 2. Thus, in the model, only the supply–demand matching relationship of the up direction of Line 2 is studied. Using the method in Section IV, combined with the data for the arriving railway passengers, URT departure intervals, and URT dwell times, as well as the URT passenger data for each hour of the day, the transportation capacity matching degree for each hour was calculated, as shown in Table 7.

A comparison revealed that [14:00–15:00], [16:00–17:00], [17:00–18:00], [18:00–19:00], and [20:00–21:00] were the periods with poor capacity matching, which are marked with red font in Table 7. The values for these periods were higher

TABLE 8. Model parameters.

Variables	Definitions	Value
C_2^x	Rated capacity of each train in direction d of Line i	2480
L_2^x	Number of doors on each side of each train in the up direction of Line 2	40
ω_2^x	Average passenger boarding rate of each door of the URT train in the up direction of Line 2 at the platform	1.5
α_{max}	Maximum load factor of the train	120%
μ_2^x	Passenger flow control intensity of the up direction of Line 2 at the station	60%
E_2^x	Passenger capacity limit of the platform	1000
$t^x_{dwell^{2,0}}$	Station dwell time of the initial scheme of the train in the up direction of Line 2 at the station	30
$I^x_{2,0}$	Departure interval of the initial plan of the train in the up direction of Line 2 at the station	440
I_{min} , I_{max}	Minimum and maximum departure intervals	120, 420
t^{min}_{dwell} , t^{max}_{dwell}	Minimum and maximum station dwell times	20, 60
τ_2^x	Operation time of opening and closing the door when the train stops in the up direction of Line 2	5
k_r	Proportion of arriving railway passengers transferring to URT	70
v_2^x	Arrival speed of non-railway passengers in the up direction of Line 2	0.15
φ	Weight coefficient φ	0.5
δ	Weight coefficient δ	0.0015
β	Penalty coefficient β	0.001

TABLE 9. Inbound and outbound passenger flow data.

Passenger type	Parameters	Value
Railway passenger	Number of railway arrivals	15061
	Time needed by the arriving railway passengers to walk to the URT platform	10 min
Passenger of URT (up direction of Line 2)	Proportion of inbound passengers for Lines 2 and 10	7:3
	Load factor of section in front of station	10%
	Number of outbound passengers	268
	Initial passenger volume of platform	0

Data source: Shanghai Metro Operation Co., Ltd. (collected on March 1, 2017).

than the optimal value of 0.9. The period with the worst value, i.e., [18:00–19:00], was taken as an optimization case. The detailed model parameter settings are presented in Table 8. The flow of railway passengers arriving at the station and data for the URT passengers in this period are presented in Table 9.

The simulation was conducted in Visual Studio 2013, on a personal computer with an Intel Core i5-8700 central processing unit. Through multiple rounds of tests, the parameter values were set as follows, with an excellent genetic iteration effect: population size = 50, generation gap = 1.0, crossover probability = 0.8, compilation probability = 0.1, $MAXGEN = 200$.

Given that the units of measurement of the target function values Y and Z, and the penalty-function value in the fitness function are inconsistent, they should be normalized before the comprehensive fitness value is calculated. The weight coefficients φ and δ and the penalty coefficient β are the amplification coefficients used to homogenize the heterogeneity index. According to multiple tests, φ was set as 0.5, δ was set as 0.0015, and β was set as 0.001.

B. RESULTS AND ANALYSIS

If the enumeration method is used, there are 12000 feasible solutions in the case of only one direction of one line. In the case of multiple lines, there are more feasible solutions. The algorithm proposed herein can significantly accelerate the solution process and improve the accuracy. Taking the actual operation plan of Shanghai Metro Line 2 as the initial scheme, the departure interval in the evening peak [17:00–20:30] was 7 min and 20 s, and the dwell time at Hongqiao Railway Station was 30 s. This scheme was used as the initial scheme for the iterative calculation.

There were 50 solutions in each generation, and the solution with the smallest fitness value was the optimal solution of this generation. 30 independent calculations were performed with identical GA parameters. These calculations reached convergence after 180–200 iterations. Each calculation took approximately 3–5 min. The best of the 30 calculations was selected as the analysis case. The process converged approximately after the 190th generation and a better solution was obtained. The variations of the average fitness and optimal

TABLE 10. **Optimal and initial solutions.**

Scheme	Coding	Departure interval I_2^x	Dwell time t^x_{dwell2}	Fitness value Y'
Initial scheme	110111000011110	440 s	30 s	2.326
…	…	…	…	…
Random solution in the 34th generation	110001110100011	398 s	35 s	1.786
…	…	…	…	…
Optimal solution in the 34th generation	010110001111001	177 s	57 s	0.423
…	…	…	…	…
Optimal solution in the 160th generation	100110110111010	310 s	58 s	0.276
Optimal scheme	101100011101000	355 s	40 s	0.273

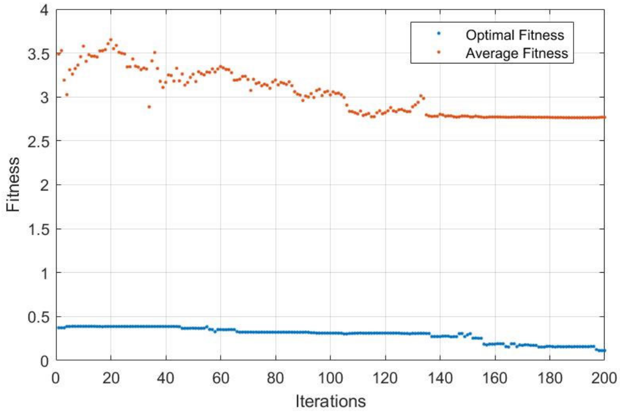

FIGURE 7. **Convergence process of the GA.**

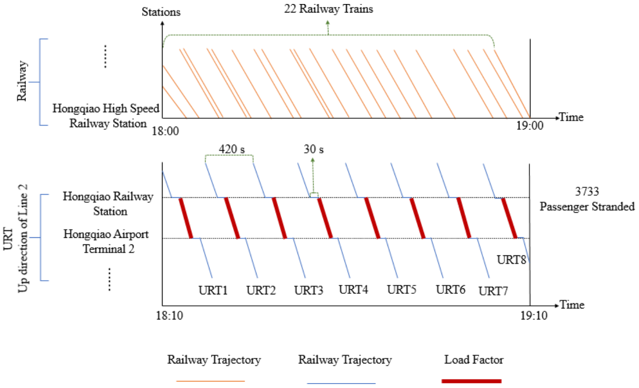

FIGURE 8. **Connection timetable before optimization.**

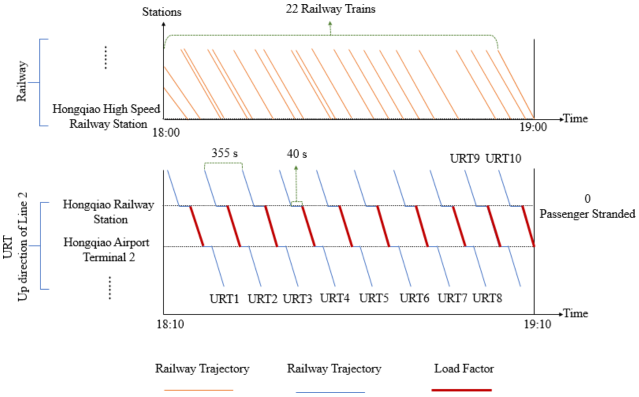

FIGURE 9. **Connection timetable after optimization.**

fitness for each generation are presented in Fig. 7. The abscissa indicates the iteration number, and the ordinate indicates the fitness value. The blue point represents the optimal fitness value of every iteration, and the orange point represents the average fitness value. In the first 140 generations, the rate of change was relatively high, and the fluctuations were relatively large. After 140 generations, the fitness value gradually became stable. The optimal solution was obtained at the 197th generation, which was 101100011101000. The corresponding decimal scheme is presented in Table 10. In the optimal plan, the interval of the up direction of Line 2 was 355 s, and the dwell time was 40 s. Compared with the fitness value of the optimal scheme, that of the initial scheme was nearly 90% lower. To verify the accuracy of the model, the solutions in several iterations were used to check the calculations (the fitness was compared). The optimal solution of one generation and non-optimal solutions were among these compared solutions.

Through optimization, the connection timetable of the up direction of Line 2 at Hongqiao Railway Station was obtained. For visual comparison, Figs. 8 and Figs.9 show the timetables of the URT–railway connection before and after optimization, respectively. The figures present comparisons of the timetables and load factors. To verify the accuracy and superiority of the model, key technical indicators of the initial scheme and the optimal scheme were compared, as shown in Table 11. For the initial scheme, the transportation capacity matching degree was >1, indicating that the capacity supply did not satisfy the passenger demand, resulting in a large number of passengers stranded. After the optimization, the increase in the dwell time and the reduction in the departure interval enhanced the transportation capacity. The capacity was slightly larger and satisfied the passenger demand. Additionally, the passenger waiting time and retention were reduced, and the evacuation safety was guaranteed. When the operation of two more trains and a dwell time of 10 s in the 18:00–19:00 period were added at Hongqiao Railway Station, the transportation capacity matching degree was reduced by

TABLE 11. Technical index comparison.

Scheme	Fitness value Y'	Transportation capacity matching degree Y	Average waiting time of passengers / s $Z/(F_r \times k_r)$	Number of passengers stranded R	Number of trains per hour
Initial Scheme	2.326	1.583	415	3733	8
Optimal scheme	0.273	0.923	177.5	0	10

41.7%, and the gap from the optimal fitness value (0.9) was reduced from 0.683 to 0.023. The average waiting time of passengers was reduced by 57.2%, and all the stranded passengers were evacuated. The matching degree of the transportation capacity and passenger demand was improved, and the passenger service level and enterprise operation efficiency were increased. Owing to the increased number of trains, the costs were higher, which may have reduced the load factor in some sections. However, Line 2 passed through the city center and multiple passenger terminals in Shanghai; thus, the capacity wastage may have been small at the peak hour.

VII. CONCLUSION

This work addresses the crucial issues of transfer between URT and railways in the context of the rapid development of China's railways. According to the fluctuation characteristics of railway passenger flows, a method for calculating the effective capacity of URT to evacuate passenger flows was proposed. Then, the transportation capacity matching degree was introduced, and a method was proposed for determining the adjustment period of the URT train connection scheme according to the railway operation plan and historical passenger flow data. The objective functions were designed to 1) optimize the matching between the demand of railway-to-URT passengers and the effective evacuation capacity of URT and 2) minimize the passenger waiting time. Considering the constraints of the connection capacity and the maximum capacity of the platform, the train dwell time and the departure interval were set as decision variables. In consideration of constraints of the connection capacity and the maximum capacity of the platform, reserve capacity for the subsequent sections is also considered. A nonlinear integer programming model of an URT train cooperatively connecting a large railway passenger flow was established, the train dwell time and the departure interval were set as decision variables. Then, a solution method based on a GA was proposed. Finally, the transfer between the two transport modes in the Shanghai Hongqiao Hub was analyzed as a case study. The period when the high-speed railway has a high density of passengers was selected for analysis. Here, the effective evacuation capacity of URT could not satisfy the fluctuating demand of the arriving passengers. For this period, an optimized train connection plan of URT was obtained via the GA. The optimal solution effectively alleviates the passenger flow congestion and evacuation at the transfer station and ensures the supply capacity of the subsequent sections of the line.

This method is applicable to the transfer between railway and URT. It is suitable for stations where URT accounts for a large proportion of the transfer sharing. For passengers, the method can improve the experience of an integrated travel chain. For the railway hub, it can help to ensure the safety and rapid evacuation of passengers and increase number of passengers that use public transportation. For the URT operation enterprises, it can help to improve the passenger service level and operation efficiency. Additionally, it provides auxiliary decision-making support for railway–URT connections. The proposed method is also applicable to the coordination between different rail transit systems. However, in coordination, which rail transit system should be adjusted first requires more discussion.

In this study, a method for URT cooperation with a large railway passenger flow was developed. The railway passenger flow and the non-railway passenger flow of the URT station are the main inputs. Owing to the limitation on the length of this article, the content regarding the capacity reserved for subsequent stations was simplified. The actual situation is far more complex; the considerations in this article are insufficient. In addition to a large railway passenger flow, many external factors should be considered, including the station layout, transfer characteristics, starting and ending stations, and transfer hedge between URT and the transfer station. These factors should be considered in future research.

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REFERENCES

[1] N. Tianwei, "Study on the evaluation and optimization scheme for passengers' transfer modes in railway transport hub," M.S. thesis, Dept. Transp. Eng., Beijing Jiaotong Univ., Beijing, China, 2015.

[2] W. Zixu, "Research on internal and external connection of railway passenger hub," M.S. thesis, Dept. Transp. Eng., Beijing Jiaotong Univ., Beijing, China, 2014.

[3] T. Xueyan, "Studying on the transfer mode choice behavior of arrival passengers in high-speed railway passenger transport hub," M.S. thesis, Transp. Eng., Chang'an Univ., Xi'an, China, 2017.

[4] X. Liang, "Research on transfer of railway and urt in integrated passenger transportation hub," M.S. thesis, Transp. Eng., Southwest Jiaotong Univ., Sichuan, China, 2009.

[5] Z. Xinming, "Study on forecasting of passenger flow sharing ratio in traffic hub based on Markov model," *Transp. Sci. Technol.*, no. 3, pp. 180–182, Jun. 2016.

[6] K. K. T. Lee and P. Schonfeld, "Optimal slack time for timed transfers at a transit terminal," *J. Adv. Transp.*, vol. 25, no. 3, pp. 281–308, Sep. 1991.

[7] Y. P. Wang and C. Q. Ma, "Study on the coordination between urban rail transit and bus," *Adv. Mater. Res.*, vols. 255–260, pp. 4085–4089, May 2011.

[8] W. Cheng, Y. Bie, Z. Liu, and Y. Jiang, "A transfer optimization method for urban passenger hub based on multiple objectives," *Recent Patents Comput. Sci.*, vol. 7, no. 2, pp. 110–118, Nov. 2014.

[9] J. Wei, K. Long, J. Gu, Q. Ju, and P. Zhu, "Optimizing bus line based on metro-bus integration," *Sustainability*, vol. 12, no. 4, p. 1493, Feb. 2020.

[10] L.-B. Deng, W. Gao, W.-L. Zhou, and T.-Z. Lai, "Optimal design of feeder-bus network related to urban rail line based on transfer system," *Procedia-Social Behav. Sci.*, vol. 96, pp. 2383–2394, Nov. 2013.

[11] Q. Fang, Z. Li, Z. Wang, J. Wu, H. Yu, and M. Leng, "Research on planning and model design of micro-cycle bus line based on metro station connection," *J. Manage. Sci. Eng. Res.*, vol. 2, no. 1, pp. 9–15, 2019.

[12] P. DiJoseph and S. I.-J. Chien, "Optimizing sustainable feeder bus operation considering realistic networks and heterogeneous demand," *J. Adv. Transp.*, vol. 47, no. 5, pp. 483–497, Aug. 2013.

[13] J. G. Jin, K. M. Teo, and A. R. Odoni, "Optimizing bus bridging services in response to disruptions of urban transit rail networks," *Transp. Sci.*, vol. 50, no. 3, pp. 790–804, Aug. 2016.

[14] W. Gu, J. Yu, Y. Ji, Y. Zheng, and H. M. Zhang, "Plan-based flexible bus bridging operation strategy," *Transp. Res. C, Emerg. Technol.*, vol. 91, pp. 209–229, Jun. 2018.

[15] L. Kang, X. Zhu, H. Sun, J. Wu, Z. Gao, and B. Hu, "Last train timetabling optimization and bus bridging service management in urban railway transit networks," *Omega*, vol. 84, pp. 31–44, Apr. 2019.

[16] Z. Lv, D. He, H. F. Jia, and C. B. Li, "Research on the layout of the integrative urban rail transit line station," *Appl. Mech. Mater.*, vols. 409–410, pp. 1222–1229, Sep. 2013.

[17] X. Chen and Y. Chang, "The study of evacuation passenger service level of shanghai-nanjing high-speed railway stations," *Procedia-Social Behav. Sci.*, vol. 96, pp. 265–269, Nov. 2013.

[18] S. Chen, Y. Leng, B. Mao, and S. Liu, "Integrated weight-based multi-criteria evaluation on transfer in large transport terminals: A case study of the Beijing south railway station," *Transp. Res. A, Policy Pract.*, vol. 66, pp. 13–26, Aug. 2014.

[19] Z. Chuan-Ling, Y. Chong-Ming, and Y. De-Ming, "Evaluation of connection model of intercity railway and suburban rail transit based on rough-set," *J. Transp. Syst. Eng. Inf. Technol.*, vol. 11, no. 2, pp. 130–135, Apr. 2011.

[20] P. Liu, "A modal for operation coordination among regional rail transit, urban metro and bus," *Appl. Mech. Mater.*, vols. 178–181, pp. 1970–1973, May 2012.

[21] W. Li, Q. Peng, C. Wen, and X. Xu, "Comprehensive optimization of a metro timetable considering passenger waiting time and energy efficiency," *IEEE Access*, vol. 7, pp. 160144–160167, 2019.

[22] L. Sijie, X. Ruihua, and Y. Rudong, "Optimizing urban rail transit network operation plans based on transport capacity coordination," *J. Southeast Univ., Natural Sci. Ed.*, vol. 47, no. 5, pp. 1048–1054, Sep. 2017.

[23] E. Barrena, D. Canca, L. C. Coelho, and G. Laporte, "Single-line rail rapid transit timetabling under dynamic passenger demand," *Transp. Res. B, Methodol.*, vol. 70, pp. 134–150, Dec. 2014.

[24] H. Niu and X. Zhou, "Optimizing urban rail timetable under time-dependent demand and oversaturated conditions," *Transp. Res. C, Emerg. Technol.*, vol. 36, pp. 212–230, Nov. 2013.

[25] L. Deng, Q. Zeng, W. Gao, and S. Bin, "Optimization of train plan for urban rail transit in the multi-routing mode," *J. Mod. Transp.*, vol. 19, no. 4, pp. 233–239, Dec. 2011.

[26] P. Shang, R. Li, Z. Liu, L. Yang, and Y. Wang, "Equity-oriented skip-stopping schedule optimization in an oversaturated urban rail transit network," *Transp. Res. C, Emerg. Technol.*, vol. 89, pp. 321–343, Apr. 2018.

[27] A. Yang, J. Huang, B. Wang, and Y. Chen, "Train scheduling for minimizing the total travel time with a skip-stop operation in urban rail transit," *IEEE Access*, vol. 7, pp. 81956–81968, 2019.

[28] L. Kang and X. Zhu, "A simulated annealing algorithm for first train transfer problem in urban railway networks," *Appl. Math. Model.*, vol. 40, no. 1, pp. 419–435, Jan. 2016.

[29] L. Kang, J. Wu, H. Sun, X. Zhu, and Z. Gao, "A case study on the coordination of last trains for the beijing subway network," *Transp. Res. B, Methodol.*, vol. 72, pp. 112–127, Feb. 2015.

[30] H. Niu, X. Tian, and X. Zhou, "Demand-driven train schedule synchronization for high-speed rail lines," *IEEE Trans. Intell. Transp. Syst.*, vol. 16, no. 5, pp. 2642–2652, Oct. 2015.

[31] J. Wu, M. Liu, H. Sun, T. Li, Z. Gao, and D. Z. W. Wang, "Equity-based timetable synchronization optimization in urban subway network," *Transp. Res. C, Emerg. Technol.*, vol. 51, pp. 1–18, Feb. 2015.

[32] Y. Wang, D. Li, and Z. Cao, "Integrated timetable synchronization optimization with capacity constraint under time-dependent demand for a rail transit network," *Comput. Ind. Eng.*, vol. 142, Apr. 2020, Art. no. 106374.

[33] Y. Wu, H. Yang, J. Tang, and Y. Yu, "Multi-objective re-synchronizing of bus timetable: Model, complexity and solution," *Transp. Res. C, Emerg. Technol.*, vol. 67, pp. 149–168, Jun. 2016.

[34] Z. Jiang, W. Fan, W. Liu, B. Zhu, and J. Gu, "Reinforcement learning approach for coordinated passenger inflow control of urban rail transit in peak hours," *Transp. Res. C, Emerg. Technol.*, vol. 88, pp. 1–16, Mar. 2018.

[35] J. Shi, L. Yang, J. Yang, F. Zhou, and Z. Gao, "Cooperative passenger flow control in an oversaturated metro network with operational risk thresholds," *Transp. Res. C, Emerg. Technol.*, vol. 107, pp. 301–336, Oct. 2019.

[36] F. Yuan, H. Sun, L. Kang, and J. Wu, "Passenger flow control strategies for urban rail transit networks," *Appl. Math. Model.*, vol. 82, pp. 168–188, Jun. 2020.

[37] X. Yao, P. Zhao, and K. Qiao, "Modeling on coordinated passenger inflow control for urban rail transit network," *J. Central South Univ., Sci. Technol.*, vol. 46, no. 1, pp. 342–350, Jan. 2015.

[38] C. Shou-Hua, Y. Zhen-Zhou, and Z. Dan, "Characteristics analysis and model establishment for passenger boarding time in urban rail transit," *J. China Railway Soc.*, vol. 31, no. 3, pp. 89–93, Jun. 2009.

[39] L. Yanhong, X. Haihong, and Z. Langya, "Research on the capacity match between passenger-dedicated lines junction centers and urban traffic," *Transp. Sci. Technol.*, vol. 3, pp. 76–79, Jun. 2006.

[40] D. He and L.-J. Xu, "Research on mechanism of traffic mode choices in urban railway passenger hub," in *Proc. Int. Conf. Manage. Service Sci.*, Wuhan, China, Sep. 2009, pp. 1–4.

[41] V. S. Summanwar, V. K. Jayaraman, B. D. Kulkarni, H. S. Kusumakar, K. Gupta, and J. Rajesh, "Solution of constrained optimization problems by multi-objective genetic algorithm," *Comput. Chem. Eng.*, vol. 26, no. 10, pp. 1481–1492, Oct. 2002.

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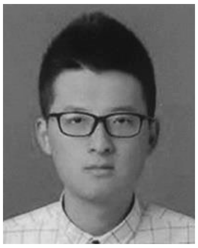

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