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Research Article

Analysis of Urban Rail Express and Local Lines Parking Scheme Based on Elastic Demand

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With the rapid economic development and the continuous expansion of the city scale, the construction of urban rail transit has also been greatly developed. The parking scheme in urban rail transit, as one of its core components, has also received more and more extensive attention. Therefore, in order to effectively solve the parking problem of express trains and local trains in urban rail transit, this paper constructs a two-level parking planning model for express trains and local trains in urban rail transit based on the demand elasticity of passenger flow. The model constructed by the upper level stops mainly aims at maximizing the operational benefit, with the lower limit of the train stops as the constraint; the routes of the lower level stops are designed to minimize the total travel time and limit the continuity and feasibility of the passenger path. Finally, the method proposed in this paper is verified by an example, which shows the usability and effectiveness of the model and proves that the high-speed local mobile parking scheme is more suitable for the passenger flow with special spatial distribution. It provides a certain reference value for the optimization of urban rail transit express and slow line parking scheme.

1. Introduction

In the process of planning the construction of urban rail transit parking stations, it is necessary to comprehensively consider the operation mode of combining express and local trains [1–3], as a transportation mode that meets the diverse needs of passengers. The scientific and reasonable train stop modes and operating frequencies can effectively improve the service quality of urban rail transit and greatly reduce the enterprise operating costs of transportation companies, and maximizing the operation of urban rail transit is of great significance [4–6]. In addition, many large cities at home and abroad, such as the subways in New York and Moscow, and the light rail in Boston, all use unique train stop solutions during peak operations. The research on the train stop plan is relatively early [7], and the research content was relatively rich in the 1970s. Wang et al. comprehensively analyzed and summarized important parking methods and proposed an operation effect evaluation plan that is different from the operation of the parking mode. There are relatively few studies on train parking plans in China [8]. Domestically, it is concentrated on passenger trains. Deng Lianbo et al. analyzed the train parking station in detail, chose the transfer with customers to set the game relationship, and took the user's balanced passenger flow distribution mode as the lower plan to build a two-tier plan model that optimized the passenger train parking method.

In view of the current domestic research on the combination of urban rail transit express and local trains, effective results have been achieved, but there is a lack of comprehensive analysis and research content considering changes in train operating costs. Through the analysis of examples, it can be seen that, after fully considering the internal relationship between the stop setting and passenger flow transfer options, combining the flexible changes of passenger flow and the choice of train passenger travel routes, the stop optimization plan meeting on the combination of express train and local train on rail transit is determined through the construction of a mathematical planning model.

2. Correlation Models

Stopping at each station is based on the train operation plan of stopping at each station following the train operational

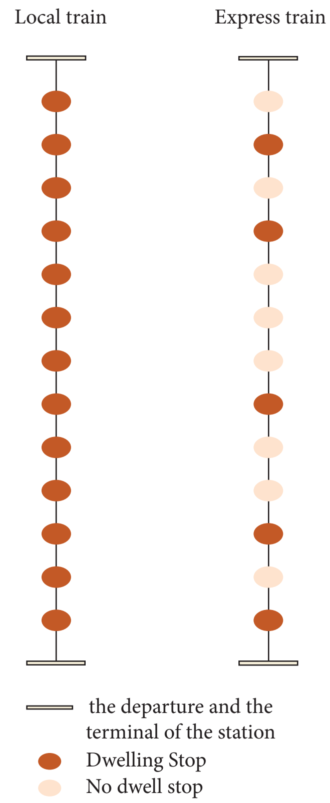

Figure 1: Schematic diagram of the express and local train operation organization model.

plan of off line through train. The low-speed operation mode can well solve the imbalance in the spatial distribution of passenger flow. It is suitable for urban rail transit lines with staircase-shaped or "convex"-shaped changes in cross-sectional passenger flow, especially for the lines where passengers in some stations are concentrated, passengers in other stations are more balanced, and the proportion of long-distance tourists is larger [9]. The schematic diagram of the express and local running organization mode is shown in Figure 1.

3. Optimized Model of Express and Local Train Stopping

3.1. Model Assumptions.

(1) There are only two types of trains: express and local trains. Among them, local trains park at each stop, and an express train stops at interstops, and the number of express stops at each stop is not zero.

(2) Suppose there is an express train between two stations, and the passengers only choose the express train. If the passenger's departure station and terminal station are not express stations, please select each station. If there is an express station between the departure station and the terminal station, you can transfer between express trains.

(3) The technical parameters of express trains and local trains are the same and are not affected by the parking plan.

(4) The travel time difference of express trains mainly comes from the influence of stops. That is to say, the start-stop time and the stop time that occur when the train enters and exits the station' accelerates and decelerates and stops, respectively.

(5) Train overtaking only occurs at stations, and each station has overtaking conditions.

(6) Capability evaluation of the line [9].

3.2. The Definition of Constants and Variables. The definition of the constant is as follows:

(1) n is the number of stations on the urban rail transit line

(2) $l_{i,j}$ is the distance between the i-th station and the j-th station

(3) $\rho_{i,j}$ is the passenger flow between station i and station j

(4) $t_{i,j}$ is the pure operating time of the interval from station i to station j

(5) h_{s1} is the stop time of the train at the s-th station

(6) h_{s2} is the additional time and minutes for the start and stop of the train at the s-th station

(7) T is the length of the optimized time period

(8) c_1 is the fixed cost for the vehicle

(9) c_2 is the running cost per kilometer of the train

(10) c_3 is the cost of each stop of the train

(11) N is the number of vehicle bases required by the route

(12) m is the total number of departures of the route

(13) T_1 is the turnaround time for local trains

(14) T_2 is the turnaround time for express train

0–1 decision variables are introduced to describe the problem. The definition of decision variables is as follows:

(1) $x_i = 0$ means that the train does not stop at the i-th station. The train stops at i-th stop. $x_i = 1$, where $i = 1, 2, \cdots, n$; x_i is the stop attribute of the i-th station.

(2) m_1 is the number of departures of the local trains in the optimized time period.

(3) m_2 is the number of departures of the express train in the optimized time period.

3.3. Passenger Choice Behavior Analysis. The selection behavior of passengers between express and local travel is similar to the selection behavior of vehicles. The passengers selection is based on their interest in travel time and the comparison of the total departure time of various moving routes (express and local). Here the transportation options can be referred to choose the problem. The mobile impedance and concept is the degree to which various travel routes reflect the charm of passengers. The smaller the resistance of travel, the more attractive the travel route is to

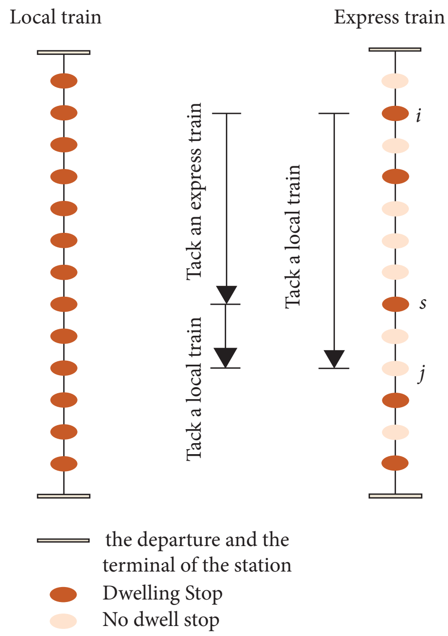

Figure 2: Schematic diagram of the route selection of passengers in the ij interval.

passengers, and passengers have a tendency to choose such a route to travel [10].

As shown in Figure 2, assuming a set of vehicles K: $\{k \mid k = e, l\}$, e represents transfers between express trains, and l represents stops at each station. The travel impedance is represented by $f(\rho_{i,j,e}, x)$ and $f(\rho_{i,j,e}, x)$, respectively. Generally speaking, with the increase of passenger flow, the traffic impedance of the transportation mode will also increase. Mobility impedance functions is represented by commonly used functions $f(\rho_{i,j,l}, x), f(\rho_{i,j,e}, x)$:

$$f\left(\rho_{i,j,k}, x\right) = \alpha \cdot \left(\rho_{i,j,k}\right)^{\beta} - V_{i,j,k}(x), \quad i, j \in N, k - \{e, l\}, \tag{1}$$

where $\rho_{i,j,k}$ is the number of passengers who choose the k-th movement mode from station i to station j of the urban rail transit line. $V_{i,j,k}(x)$ is the observation utility value of traffic mode k in i-j interval; $\alpha\beta$ are the parameters to be determined.

Time is the most concerned issue in passenger travel. Because this issue has no choice between means of transport, it ignores the impact of passenger flow on the impedance function and chooses the total travel time to reflect the observed utility value [11].

The choice between passengers follows the following rules. First, the impedance function of the two moving paths $f(\rho_{i,j,e}, x) f(\rho_{i,j,l}, x)$ is calculated and the two are compared. The transfer of low-speed trains is more attractive than just ordinary trains. Passengers choose express train transfers with a certain probability. P_0 is the passenger flow $\rho_{i,j}$ between station i and station j; that is, the number of passengers who take the express train between station i and station s (get on the train from station i and get off from the station). ρ_{i} is the flow of passengers who locally stop at each station between station s and station j (get on the train from station s and get off from the station). Figure 3 shows the specific process of the passenger's selection action [12].

4. Upper-Level Stops Scheme

4.1. Related Definition. The train runs on a single row, but it is assumed that the flow of passengers is evenly distributed; as for the capacity of the train, all passengers on the platform can get on the train, and there will be no passenger detention. The set of stations $S = \{1, 2, \cdots, n\}$ includes starting station, terminal station, and intermediate station. The train set $L = \{\mathrm{A}, \mathrm{B}\}$ 0-1 is a variable decided by policy x_{As}. When a train stops at station s, it is 1; otherwise, it is 0. When the train x_{Bs} stops at station s, it is 1. Otherwise, it is 0.

4.2. Objective Function. The operating unit first pursues the highest profit as follows:

$$\begin{aligned}
&\text{maxincome} = \text{operating income} - \text{operating cost},\\
&\text{Operating income} = \sum_{o,d} q_{od} p_{od},\\
&p_{od} = D\left(T_{od}\right) = p'_{od} \exp\left(\theta\left(T'_{od} - T_{od}\right)\right),\\
&\text{Operating cost} = C \times (NA + NB) \times L,\\
&NA = \frac{TA}{\left(I_1 + I_2\right)},\\
&NB = \frac{TB}{\left(I_1 + I_2\right)},\\
&TA = \sum_i e_i + \sum_s x_{As} h_s,\\
&TB = \sum_i e_i + \sum_s x_{Bs} h_s.
\end{aligned} \tag{2}$$

Among them, q_{od} indicates the fare of the urban rail in the interval od; od indicates the passenger flow between two stations, p_{od} indicates the flexibility of time; D() indicates the elastic function within the time of passenger flow; T'_{od} indicates the travel time of the passengers in the interval od, and p'_{od} and T'_{od} indicate the base number of passenger flow and the travel time of passengers under the standard stop plan [13]; θ represents the time elasticity coefficient; C represents the consumption cost of trains in the unit; N is the base number of trains required; and L is the length of train crossing. The base number of train A is NA, and the operating period is TA; the base number of train B is NB, and the operating period is TB. I_1 is the interval time for the departure between train A and B; I_2 means the departure interval between train B and A. e_i represents the operating hours and minutes of interval i; $h_s$represents the parking duration of station s. The highest value of operating revenue can be expressed as

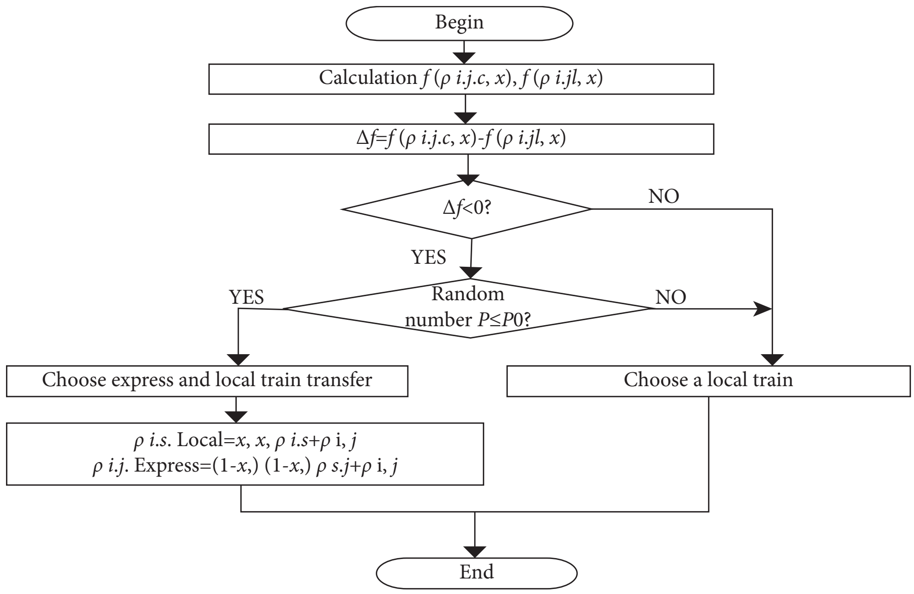

Figure 3: Passenger choice behavior analysis process.

$$\text{maxincome} = \sum_{o,d} q_{od}(T_{od}) - C\frac{(2\sum_i e_i + \sum_s x_{As}h_s + \sum_s x_{Bs}h_s)}{(I_1 + I_2)} L. \tag{3}$$

4.3. Constraint Condition.

(1) Passengers between the two stations will be sent. The train will definitely stop at the station.

$$x_{As} + x_{Bs} \geq 1, s \in [1, n]. \tag{4}$$

(2) All trains depart from the stop and return to the fleet after completing their transportation tasks. In other words, all trains stop at the departure station.

$$x_{A1} = x_{An} = x_{B1} = x_{Bn} = 1. \tag{5}$$

(3) The number of transfer stations is less than 1; that is to say, the number of stops for the two types of trains is less than 1.

$$\sum_{2}^{n-1} x_{As}x_{Bs} \geq 1. \tag{6}$$

(4) Tracking interval time limit: In order not to move during operation, the departure time interval of all stations is not less than the tracking interval time.

$$I_1 + \sum_{1}^{i} (x_{As} - x_{Bs})h_s \geq I_{\min}, i \in [1, n],$$
$$I_2 + \sum_{1}^{i} (x_{Bs} - x_{As})h_s \geq I_{\min}, i \in [1, n]. \tag{7}$$

5. Route Selection Model For Lower Level Passengers

5.1. Objective Function. The criteria for passengers to choose a route generally include cost, time consumption, degree of congestion, and transfer consumption. There are many documents that define various types of consumption using generalized travel expenses. For passengers by urban rail transit, there is basically no difference in the fares of different riding plans in a certain interval [14]. Due to the characteristics of urban rail transit, congestion only occurs in cars and stations. There will be no traffic jams while on a journey. The cost of transfer is determined by the design of the station, and the time spent for travel is the most directly determined influencing factor based on the stop.

To minimize the total travel time, there are four aspects, including waiting, stopping, transferring, and intermediate time. Among them, the halfway time depends on the passenger's choice. So in the objective function, except the halfway time, the travel time is represented by waiting stations, stops, transfers, etc.

$$\min T_{od} = \sum_{o,d} p_{od} \cdot \left(u_o + \sum_{1}^{n} (y_{As}(od) + y_{Bs}(od))h_s + \sum_{1}^{n} (y_{As}(od) y_{Bs}(od))r_s \right). \tag{8}$$

Among them, u_o is the waiting time of passengers at station o. Consider that the average time for passengers arriving at the station and waiting time is equal to half of the departure interval. No matter whether the passenger is taking Train A or Train B, the longest waiting time is the departure interval of the same train. So $u_s = I_1 + \sum_1^i (x_{As} - x_{Bs})h_s + I_2 + \sum_1^i (x_{Bs} - x_{As})h_s$.

5.2. Restrictions.

(1) The riding route is continuously restricted. In other words, passengers have to take trains at all stations from the start to the end.

$$\sum_{1}^{n} y_{As}(od) + \sum_{1}^{n} y_{Bs}(od) \geq 1, s \in [0, d]\ o, d \in [1, n]. \quad (9)$$

(2) The feasibility of the ride route is limited. In other words, passengers can only choose trains that stop at the station.

$$\begin{aligned} y_{As}(od) &\leq x_{As}, s \in [o, d]\ o, d \in [1, n], \\ y_{Bs}(od) &\leq x_{Bs}, s \in [o, d]\ o, d \in [1, n]. \end{aligned} \quad (10)$$

(3) Restrictions on the transfer station, which means that the train must stop at transfer station twice.

$$y_{As}(od) y_{Bs}(od) \leq x_{As} x_{Bs}, s \in [o, d]\ o, d \in [1, n]. \quad (11)$$

(4) Restrictions on the directionality of the riding route. Passengers must be transported from the departure point to the destination via OD. The riding route is from O to D. No round-trip and repeated transportation occur. According to the following restrictions, passengers can only take one train or transfer at stations between O and D.

$$\begin{aligned} & y_{Ad}(od) y_{Ad}(od) + y_{Bo}(od) y_{Bd}(od) \\ & + \sum_{o}^{d} y_{As}(od) y_{Bs}(od) \leq 1 \quad o, d \in [1, n]. \end{aligned} \quad (12)$$

6. Stopping Model Solution

In view of the current research content on the parking problem of urban rail transit trains, a station parking plan programming model is constructed according to the elastic demand theory, and the membership function corresponding to the objective function is found to achieve the purpose of dimensionless processing of the objective function. Then, we use an improved elastic demand algorithm to solve the multiobjective planning model [15]. The specific steps of the elastic demand algorithm are as follows:

(1) Determine the initial group size N_0, crossover probability P_c, mutation probability P_m, and initial temperature t_0.

(2) Encoding and decoding: The optimization problem of urban rail transit station can adopt the binary code method. The dyeing length n is equal to the number of stations. 1 indicates that the train will stop at this station, and 0 indicates that the train does not stop at this station. The encoding form is as follows: 110101···101001.

(3) In order to form the first group, initialize the seed and generate a solution n_0 that can be executed randomly.

(4) Determination of the matching degree function: The optimization problem of urban rail transit parking scheme is a multifunctional optimization problem that takes into account the interests of passengers and the interests of enterprises. The objective functions of two different dimensions are processed dimensionlessly through elastic demand theory, the membership function obtained by each objective function after elastic demand is determined in this paper. Both values $u_1(x), u_2(x)$ are between 0 and 1; therefore, the sum of the two can be used as the fitness function, i.e., $f(x) = \lambda_1 u_1(x) + \lambda_2 u_2(x)$; here, λ_1, λ_2 is the weighting coefficient. The importance of the two objective functions is represented by the used expansion index and weighting coefficient.

(5) Selecting operation: Roulette is adopted for the link of selection, where the fitness $f(x_i)$ has the probability $P(x_i) = f(x_i)/\sum i = 1nf(x_i)$ of the individual x_i being selected. It is not combined with the most adaptable individuals in the group and is copied directly to the next generation.

The plan model of the two-story building lacks mature and effective solutions, but there is uniqueness in the problem of the two-story building plan of the urban rail station plan. In addition to corporate characteristics, urban rail operating companies also have requirements for public services. Therefore, when formulating a transportation plan, in addition to considering the benefits, the interests of passengers must also be maximized. Moreover, the goals of the upper and lower level are integrated and consistent. Based on the above characteristics, we designed a solution that separately integrates the objective function and constraint conditions of the two-layer model, and finally obtained a multipurpose 0–1 nonlinear planning model.

The integrated model is

$$\begin{aligned} \max Z_1 &= \sum_{o,d} q_{od} D(T_{od}) \\ &\quad - C\left(2\sum_i e_i + \sum_s x_{As} h_s + \sum_s x_{Bs} h_s\right) / (I_1 + I_2) L, \\ \max Z_2 &= \sum_{o,d} p_{od}, \\ &\quad \cdot \left(u_o + \sum_{1}^{n} (y_{As}(od) + y_{Bs}(od)) h_s + \sum_{1}^{n} (y_{As}(od) y_{Bs}(od)) r_s\right). \end{aligned} \quad (13)$$

Z_1 includes two aspects, i.e., to maximize ticket revenue and to minimize train costs. The former is correlated with fare and number of passengers; if the fare is fixed, it will be proportional to the number of passengers. The passenger flow elasticity function determines the ratio of the number of passengers to the travel time. This requirement shortens travel time. It is consistent with the optimization direction of Z_2 Therefore, the processing of multiple targets is emphasized on the more comprehensive Z_1, and the weighting coefficient method is adopted, the two of which are, respectively, multiplied by the weighting coefficient, weighted and combined.

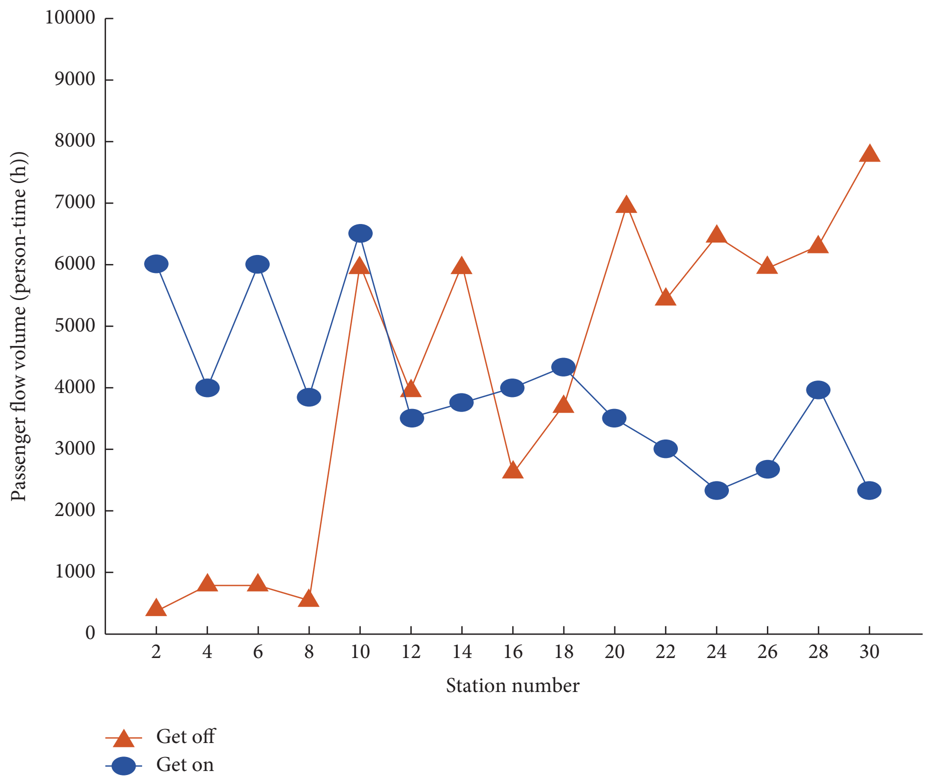

FIGURE 4: Passenger flow on and off at each station on a certain line.

TABLE 1: Values of relevant parameters of the model.

Parameter	Value
Research period length/(min)	60
Total number of departures/(time)	16 ~ 25
Fixed cost/(yuan/train)	8000
Operating variable cost/(yuan/km)	150
Stop cost/(yuan/time)	200
Return time of the first and last stations/(min)	3
Additional time/s for start and stop	30
Stop time/s	45
Maximum passenger capacity of train/(person/train)	2460

$$\min Z = -\gamma_1 Z_1 + \gamma_2 Z_2. \tag{14}$$

Among them, $\gamma_1 + \gamma_2 = 1$. The large number of OD points is the main factor for the large scale of the model. If the number of OD points can be reduced, the total number of decision variables and constraints can be effectively reduced. The integrated simplified model can be programmed and solved by the existing optimization software (such as LINGO 11.0).

7. Analysis and Results

The planned new urban rail transit line has a total length of 100 km, with 30 stations set up along the line. The average station interval is 1.89 kilometers, and the running time of all sections is 32.17 minutes. The train on this route consists of six cars, all of which belong to Train A (capacity of 280 people). The passenger status at each station along the line during the study period is shown in Figure 4. We can refer to Table 1 for the values of related parameters in the model.

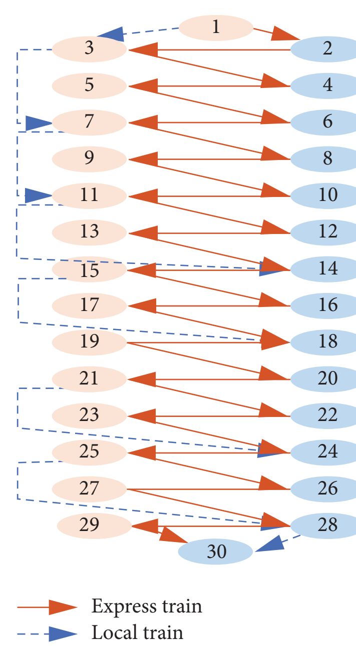

FIGURE 5: Schematic diagram of the optimal stop plan for express and local train trains.

From the calculation results, it can be seen that the comprehensive evaluation value of the two objective functions is the most appropriate when the total number of

Table 2: Comparison of travel time and operating cost before and after rapid operation.

Compare items	Before departure	After departure	Saving rate (%)
Total travel time of passengers/(h)	26940	24595	9.1
Enterprise operating cost/yuan	519440	485440	6.3

departures is 22 (16 times per station and 6 express trains) during 60 minutes. The corresponding parking plan that is most suitable for express trains is 1010001001101, and the schematic diagram of the parking plan is shown in Figure 5. When the total number of departures is 22, compare and analyze the total travel time of passengers before and after the local train and the operating cost of the enterprise by referring to Table 2.

8. Conclusions

The parking plan of express trains in this paper is done by choosing various ways in which urban rail transit passengers deeply study in choosing urban rail transit, taking into account the operation effect and service quality of the trains, optimizing the train transportation organization under the urban rail transit system, and achieving the effect of reducing operating costs and realizing urban rail. This paper aims to optimize the service quality of transportation system. In addition, the travel speeds of different types of trains caused by special stops are also different, which will cause new traffic organization problems. Therefore, timely and effective access to train stop information service systems will be the focus of future research.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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