Express/local train plan optimization for urban rail transit in condition of full-length and short-turn modes

LUO Qin¹ ², HOU Yufei³, LI Wei²³* and ZHANG Xiongfei¹ ²

¹College of Urban Traffic and Logistics, Shenzhen Technology University, Lantian Road 3002, Shenzhen, P.R.China
²Shenzhen Key Laboratory of Urban Rail Transit, Shenzhen University, Nanshan Ave 3688, Shenzhen, P.R.China
³Key Laboratory of Optoelectronic Devices and Systems of Ministry of Education and Guangdong Province, College of Optoelectronic Engineering, Shenzhen University, Nanshan Ave 3688, Shenzhen, P.R.China

*E-mail: aliweib1@126.com

Abstract. Operating the express/local train plan can meet the characteristics of imbalance of passenger volume temporal and spatial distribution, and satisfy the demands of long-distance commuters who want to travel fast. Although the program can improve the organizational operating efficiency and passenger service level, it will reduce the carrying capacity of system to some extent. Above all, based on analysing the factors of the express/local train plan and the composition of passenger travel time in detail, the 0-1 integer programming model of stop-schedule plan problem was established by minimizing the passenger travel time. And combined with a simulation case, the immune genetic algorithm was designed to study the effect of line capacity.

1. Introduction

With the continuous expansion of urban scale and the development of urban rail transit network, the round-trip passenger flow between the city centre and suburban grows gradually. As the central city has been saturated basically, more and more companies and residential buildings tend to transfer to the suburbs, which further promotes the swelling of the traffic flow. Therefore, cities need to use the express and local train operating mode to meet the demands for the commuting passenger. In this mode, how to ensure the service level of rail transit, and provide the foundation and safeguard for rail transport operating enterprises working better, is a significant project.

Following are some representative studies about the express/local train plan. Wang L et al.[1] studied the operational efficiency of the rail transit system, and proposed the optimal goal of the express/local train plan on the relationship between the stop scheme and the operational efficiency. Altazin E et al. [2] presented that stops on train lines can be skipped to minimize both the recovery time and the waiting time of passengers. Cheng J [3] considered both the total travel time of the passengers and operating costs to build up a multi-objective optimization model, and designed an algorithm to solve the problem. Hassannayebi E et al. [4] studied the optimal time table of express/local train and built up a model in order to reduce the passenger waiting time by using variance and penalty function Pan H C [5] focused on the analysis of the influence of the carrying capacity of express/slow train multi-operation, then discussed the relations between the proportion of...
express/slow train and the maximal capacity. Han Y et al. [6] established to determine the reasonable opening train number between two major cities, train passenger capacity, the train stations along the number of stops and parking opportunities mathematical model to make the total time delay to minimum and railway enterprises benefit the most. Liao J Q [7] respectively devised the operation scheme in condition of the single route and the full-length & short-run route aiming at the maximum travel saving time of all passengers. Gao Y et al. [8] aimed to find the relationship among energy consumption, travel time and timetables, and propose a bi-objective programming model to better understand the relationship between lowering energy consumption and reducing travel time.

In this paper, by analysing the different passenger trip time because of choosing different types of trains, we propose to reduce total travel time as the target, and accordingly, make a reasonable stop plan of the express train.

2. Analysis of Passenger Flow Characteristics and Effects

2.1. Passenger Flow Characteristics

The long-distance regional rail transit line is connected in series with urban areas, suburbs and satellite towns, and the intercity passenger flow is not only large, but also imbalanced in time direction. During the morning rush, the traffic flow moves from satellite towns or suburbs to the downtown, and at the evening peak, the situation is opposite. Meanwhile, with different levels of development along the rail transit, the boarding of stations is also inconsistent, and overall, it shows the disproportion of the section flow. Consequently, two types of the fluctuating passenger flow have demands for regional express rails. On the one hand, Commuter flow prefers to take the through train from downtown area to the suburban. On the other hand, short-distance passengers want to achieve that any two stations can be reached directly.

2.2. Travel Time Cost

Although operating express/local train makes the total trip time of passengers who take local train to be prolonged because of overtaking, it saves the time of those who take express train.

2.3. Carrying Capacity

Express and local train scheme will reduce the capacity of lines. In the traditional pattern, the line capacity is only related to the minimum headway \( I \), and its calculating method is

\[
n_r = \frac{3600}{I}
\]

(1)

However, the carrying capacity of express/local train take the deduction coefficient method for calculation and analysis. The deduction coefficient of the express train refers to the number of the local cars deducted from the parallel operation chart because of drawing an express train, and the formula is

\[
e_d = 1 + \left( \frac{t_d}{I} \right) - k
\]

(2)

where, \( t_d \) is the difference of travel time of express/local train, and \( k \) means the times which are crossed of slow trains [9].

3. Optimization Model and Algorithm

3.1. Problem Description

Operating express/local train combination plan is mainly for long-distance passengers, it can not only shorten the travel time of those who take the express train, but also increase their time benefit. At the same time, this plan also needs to consider the problem that crossed by the express train will increase the waiting time and stop yielding time of people taking local trains at the stations. Based on the above analysis, this paper studies the express train stop scheme of express/local train combination plan in condition of the full-length & short-run route. As well, we make use of the time benefit of passengers and traffic capacity as the key index to evaluate the superiority of the plan.
3.2. Model Assumption
The model selects the morning peak as the optimization period to study. It uses the mixed-routing mode, and the long train routing operates both of local and express trains, while the short train routing only operates local trains. Two kinds of trains own the same technical parameters. Regardless of the circulation of rolling stock, the model only discusses the one-way situation. Every station can support trains to turn back. Passengers arriving can all be considered to obey normal distribution, because people are generally reluctant to transfer other trains, the model define when the passenger's travel starting point and the final station are slow stations, the passengers only wait for the slow, when the passenger's starting point and the end of the station is only a slow station, the passengers only wait for the slow, besides, when the passenger's starting point and the end of the station are fast stations, the passengers can either choose express or slow trains. The last assumption is that every station can support overtaking.

3.3. Modeling
Passenger travel time t includes waiting time \( t_w \) and running time \( t_r \). In which, because of arriving time of passengers obey normal distribution, their average waiting time is half of the interval.

\[
t = t_w + t_r
\]

According to the different nature of OD, the total passenger travel time is divided into four categories, and model parameters are listed in Table1.

| Parameters (unit) | Explanation |
|------------------|-------------|
| \( f_1 \) | The operating frequency of the slow train of the long routing |
| \( f_2 \) | The operating frequency of the express train of the long routing |
| \( f_3 \) | The operating frequency of the slow train of the short routing |
| \( q_{y-m}^{v-l} \) (person) | The number of passengers waiting to the \( m^{th} \) train which is the slow train of the long routing from the \( j^{th} \) station to the \( f^{th} \) station |
| \( q_{y-m}^{v-x} \) (person) | The number of passengers waiting to the \( m^{th} \) train which is the express train of the long routing from the \( j^{th} \) station to the \( f^{th} \) station |
| \( q_{y-m}^{s-l} \) (person) | The number of passengers waiting to the \( m^{th} \) train which is the slow train of the short routing from the \( j^{th} \) station to the \( f^{th} \) station |
| \( T \) (min) | The length of the optimized period |
| \( h_i \) | The increased delay time because the slow train is crossed by the express train at preceding stations |
| \( x_k \) | Boolean variable. When the slow train is crossed by the express train at the \( k^{th} \) station, the value is one, otherwise, the value is zero. |
| \( t_y \) (min) | The interval running time of trains |
| \( t_s \) (min) | The train stopping time |
| \( h_u \) | The increased stopping time because the slow train is crossed by the express train at this station |
| \( x_w \) | Boolean variable. When the slow train is crossed by the express train at the \( w^{th} \) station, the value is one, otherwise, the value is zero. |
| \( c_1/c_2/c_3 \) | Boolean variable. When passengers take the slow train of the long routing, the value of \( c_1 \) is one, others is zero, when passengers take the express train of the long routing, the value of \( c_2 \) is one, others is zero, and when passengers take the slow train of the short routing, the value of \( c_3 \) is one, others is zero. |
| \( t_3^{(l)} \) (min) | The travel time of passengers who choose to take slow trains |
\begin{align*}
t_3^{(c)} \text{ (min)} & \quad \text{The travel time of passengers who choose to take express trains} \\
q_{i \rightarrow m} \text{ (person)} & \quad \text{The number of passengers waiting to the } m^{th} \text{ train} \\
\eta_{\text{max}} & \quad \text{Maximum section load factor} \\
a & \quad \text{Passenger capacity of the train}
\end{align*}

1) When the passenger travel OD belongs to the following four cases, the passenger can only choose the slow trains of the long route, and the time is as formula (4):

- The starting point \( i \) \((i=1, 2, 3, \ldots, n)\) is a slow station of the long route, the final station \( j \) is any type of station.
- The starting point \( i \) is an express station of the long route, the final station \( j \) is a slow station of long and short route.
- The starting point \( i \) is a slow station of the short route, the final station \( j \) is an express or express station of long route.
- The starting point \( i \) is an express station of the short route, the final station \( j \) is a slow station of long route.

\[
t_1 = \sum_{m=1}^{l_i} q_{i \rightarrow m}^{e-i} \cdot \left( \frac{T}{2f_1} + \sum_{k=1}^{j_i} h_k x_k + t_j + \sum_{w=1}^{l_i} (t_s + x_w h_w) \right)
\]  

(4)

2) When the passenger travel OD belongs to the following two cases, the passenger can choose the slow or express trains of the long route, and the time is as formula (5).

- The starting point \( i \) is an express station of the long route, the final station \( j \) is an express station of long and short route.
- The starting point \( i \) is an express station of the short route, the final station \( j \) is an express station of the long route.

3) When the starting point \( i \) and the final station \( j \) are both the express station of the short route, the passenger can choose the slow or express trains of any type of station, and the time is as formula (6).

\[
t_2 = \left( \sum_{m=1}^{l_i} q_{i \rightarrow m}^{e-i} + \sum_{m=1}^{l_j} q_{i \rightarrow m}^{e-j} \right) \cdot \left( \frac{T}{2(c_1 f_1 + c_2 f_2)} + \sum_{k=1}^{l_i} c_k h_k x_k + t_j + \sum_{w=1}^{l_i} (t_s + c_1 x_w h_w) \right)
\]

(5)

\[
t_3^{(l)} = \left( \sum_{m=1}^{l_i} q_{i \rightarrow m}^{e-i} \right) \cdot \left( \frac{T}{2f_1} + t_j + \sum_{w=1}^{l_i} t_s \right)
\]

\[
t_3^{(e)} = \left( \sum_{m=1}^{l_j} q_{i \rightarrow m}^{e-j} \right) \cdot \left( \frac{T}{2f_2} + t_j + \sum_{w=1}^{l_j} t_s \right)
\]

(6)

\[
t_4 = \left( \sum_{m=1}^{l_i} q_{i \rightarrow m}^{e-i} + \sum_{m=1}^{l_j} q_{i \rightarrow m}^{e-j} \right) \cdot \left( \frac{T}{2(c_1 f_1 + c_2 f_2)} + \sum_{k=1}^{l_i} c_k h_k x_k + t_j + \sum_{w=1}^{l_i} (t_s + c_1 x_w h_w) \right)
\]

(7)

4) When the passenger travel OD belongs to the following two cases, the passenger can only choose the slow trains of the long or short route, and the time is as formula (7):

- The starting point \( i \) is a slow station of the short route, the final station \( j \) is the express or local station of short route.
- The starting point \( i \) is an express station of the short route, the final station \( j \) is the local station of short route.

In summary, we establish the following objective function to achieve the minimization of the total passenger travel time.

\[
\min Z = \min \left( \sum_{i=1}^{n} \sum_{j=1}^{n} t_i + t_2 + t_3 + t_4 \right)
\]

(8)

s.t. \( q_{i \rightarrow m} \leq \eta_{\text{max}} \cdot a \)
\[ f_d \geq 1 \quad (d=1, 2, 3) \]

3.4. Solution Algorithm

The evolutionary algorithm, which is represented by genetic algorithm, is an iterative search algorithm which imitates the biological evolution mechanism. It uses the crossover and mutation operator to realize the information interaction and local search between individuals in the group, and provides optimization opportunities for each individual. By survival of the fittest competition selection mechanism, genetic algorithm guides the population to a better direction of evolution. In this paper, we do the objective function is to solve the minimization problem. Thus, we structure a fitness function as formula (9), and the greater the fitness value, the better the individual.

\[ F(x) = m - Z(x) \]  

(9)

where, \( m \) is the total travel time of passengers in the traditional pattern.

Based on the general genetic algorithm, immune genetic algorithm is added the inoculation operator and makes the antibody mutate by utilizing the population information[10]. In addition, it is added the detection operator in order to lead a better evolutionary direction and improve the efficiency of algorithm. And it is also added balance operator to coordinate the concentration between the better individuals and the worse ones. The solution flow chart is shown in figure 1.

![Figure 1. The flow of solving algorithm.](image)

4. Case Analysis

4.1. Line Profile

Taking a regional express rail as an example, this paper analyses and examines the optimization problem on express/local train stopping schedule under the circumstance of the full-length & short-run route. There are 26 stations and the 7th to 20th stations belong to the short routing section. Based on the flow data of this case, when the short route is from the 7th to the 20th stations and the proportion of the long and short route is 1:1, the demand of passenger flow can be satisfied furthest.

4.2. Solution

We design the immune genetic algorithm to solve model. The algorithm parameter values are shown in table 2. From the case, the departure times during optimized period are 20 pair per hour, and in this situation, we calculate the travel time by changing the proportion of the express/local train which changes from 19:1 to 1:19, and when the proportion is 5:15, in which there are 5 express trains, the objective function value takes the minimum, that is, the passenger travel time is the shortest. At this point, the best express train stop program is shown in table 3, in which the number 1 represents that express trains stop at the station, and the number 0 means that express trains do no stop at the station. And by computation, in this plan, the express train overtake at the 7th and the 19th station.

| Parameters       | Value | Parameters       | Value | Parameters       | Value |
|------------------|-------|------------------|-------|------------------|-------|
| Population       | 50    | Crossover probability | 0.9   | Inoculation probability | 0.8   |
| Iterations       | 100   | Mutant probability | 0.05  | The number of vaccine in vaccine base | 8     |
Table 3. The Best Express Train Stop Program.

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 |
|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| 1 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 1 |

4.3. Capacity Analysis
It has an impact on carrying capacity to operate the express/local train. According to the foregoing case, when the minimum headway is 120 s and the ratio of express and local train is 1:3; the capacity depresses from 30 to 25 pairs/h.

4.4. Time Benefit Analysis
Different from the general trains, passengers who take the direct trains save the travel time, while the time of some passengers travel by slow trains is increased. In this case, the passenger travel time of general trains is 38 688 413 min, while in combination mode, the time saves 545 985 min. Comparing with the total travel time before and after the plan, we can find that in the specific passenger flow conditions, although the traffic capacity is reduced, the time benefit is still obvious.

5. Conclusion
This paper sets up a model, based on express and local train operating plan, aiming for minimize travel time of passengers, and by analysing different time composition of the full-length and short-run route. Case analysis results confirm the validity of this model. However, the combined operating mode will make the carrying capacity reduce, in the actual operation; it can obtain the relatively large capacity to change the proportion of express and local train.

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