Modeling on Coordinated Passenger Flow Control for Multiple Stations in a Single Line of Urban Rail Transit

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Abstract. This paper studies the problem of morning peak passenger congestion in urban rail transit system. Taking multiple stations of a single line as the research object, taking the attributes of train stop and station traffic limit as decision variables, and taking the maximum number of passengers in the urban rail transit system and the minimum proportion variance of each station as the objective function, taking multiple stations of a single line as the research object. A multi-station coordinated passenger flow control model of urban rail transit was constructed and solved by genetic algorithm. In the end, the downward direction of morning peak of Changchun metro line 1 is taken as a case to verify the effectiveness of the model and algorithm.

1. Introduction
Urban rail transit, with its characteristics of high traffic volume, efficiency and efficiency, has gradually formed a long-term stable passenger demand. The passenger flow of urban rail transit has the characteristics of time concentration and huge flow, which leads to the problem of station passenger flow congestion and area section passenger flow overload. At present, the maximum capacity of the line cannot meet the rapid growth of passenger demand. Based on the operation experience, the time and number of people are determined to limit the flow, control the excessive passenger demand in the large area outside the station, and reduce the passenger density in the station of a single station. The reasonable distribution of passenger flow in the station, however, does not improve the satisfaction of passenger demand in the station.

The current research background is that there is an urgent need for multi-station coordinated passenger flow control, and the research on methods to alleviate station congestion and train congestion during rush hours has a long-term development prospect.

2. Analysis of single-line and multi-station coordinated passenger flow control
The single-line multi-station system of urban rail transit is a dynamic system composed of lines, stations, trains and passengers, the passenger flow reflects the size of demand, the line coverage area and station location determine the service scope of urban rail transit. The train departure interval and operation schedule determine the service frequency and service time of urban rail transit system.
Interactive relationship between single-line multi-station elements: The station is connected by the line, the train runs on the line, and stops at each station. During the stop, the station interacts with the passenger on and off, and the passenger changes dynamically between different states. The train starts at a certain interval, runs on the line according to the fixed time standard and stops at each station. According to the travel purpose, passengers select the departure station, the arrival station, the departure station, the waiting station, the boarding time of the train, the running time of the train, and the arrival station, and complete a complete journey. Passenger arrivals and waits take place in the station, passengers take a ride in the train, and the process of getting on and off the train interacts with the train and the station.

The multi-station coordinated passenger flow control method of urban rail transit is the multi-station coordinated station restricted flow organization and the adjustment of train operation scheme. The first method is to manage the passenger flow demand along the route from the perspective of synergistically controlling the crowded station of passenger flow and the inbound demand of its upstream station, and to formulate a multi-station coordinated station restriction organization strategy, including the restriction time and limit flow at each station. The second method is to adjust the passenger load distribution of the train within the allowable range of the line capacity through the way of non-stop stops, rearrange the capacity in the crowded station, and adapt to the unbalanced passenger flow demand along the route, so that the proportion of each station on board is balanced. At the same time, two methods are used for multi-station coordinated passenger flow control to solve the problem of urban rail transit congestion.

3. Establishment of passenger flow cooperative control model

3.1 Model Assumption
Single stand together more passenger flow in urban rail transit control model on the assumption:(1) This paper only studies the direction of passenger congestion. (2) In the process of train operation, the problem of bottom turnover is not considered. (3) Simplify the travel process of passengers in and out of the station. The passenger's travel activities in the urban rail transit system include the process of station off-limit, station waiting, getting on and off the train, taking a bus and station being stuck. In this paper, the process of getting in and out of the station is simplified.

3.2 Decision Variables and Objective Functions
Two types of decision variables in the model: Station limit \( q_{s,r}^i \), represents that during the period before the arrival of train \( r \), the entrance of station \( s \) is limited to the number of passengers who cannot enter the station. Train stop attribute \( h_{s,r}^j \), the 0-1 variable representing whether the train \( r \) stops at station \( s \).

There are two types of model objective functions, the maximum number of people on the line \( (Z_1) \) and the minimum variance for each station \( (Z_2) \). The operation target of urban rail transit single line multi-station transportation system is to transport more passengers and provide better service.

\[
\max M(Z) = \max\{M_1(Z), M_2(Z), \ldots, M_J(Z)\}
\]

In the formula, \( \max\{Z_1\} \) is the upper threshold of \( Z_1 \), \( \min\{Z_1\} \) is the lower threshold of \( Z_1 \), \( \max\{Z_2\} \) is the upper threshold of \( Z_2 \), \( \max\{Z_2\} \) is the lower threshold of \( Z_2 \).

3.3 Model Constraints
3.3.1 Traffic and Passenger Entry Restrictions

The number of passengers inside the station is determined by the demand of the station and the traffic limit outside the entrance. During the peak hours of the arrival time when the passenger flow demand is high, the passenger who has the incoming demand shall be limited to the flow, so as to reduce the number of people gathering on the platform and avoid the safety risk of the excessive crowding on the platform. Passengers enter the station to wait in the station capacity range. Restrictions on the flow and passengers entering the station are shown in equation (2)- (5):

\[ q_{s,r}^O = q_{s,r}^{ar} \times (t_{s,r}^a - t_{s,r-1}^{dp}) \]  
\[ q_{s,r}^E = q_{s,r}^O - q_{s,r}^L \]  
\[ q_{s,r}^R \leq Q_s^E \]  
\[ q_s^L = \sum_{r=1}^{R} q_{s,r} \]  

The constraint (2) calculate the passenger demand for entering the station outside the entrance of the station, and multiply the passenger arrival rate and the calculated interval time. In the formula, \( q_{s,r}^O \) represents the number of passengers waiting outside the entrance of station \( s \) during the time period before the arrival of train \( r \). \( q_{s,r}^{ar} \) represents passenger arrival rate outside entrance of station \( s \) (person/minute), \( t_{s,r}^a \) is the arrival time of train \( r \) at station \( s \), \( t_{s,r-1}^{dp} \) is the departure time of train \( r-1 \) at station \( s \).

The constraint (3) measures affecting the number of passengers who cannot enter the station is used to indicate the number of passengers who enter the station using the difference between the passenger demand outside the station and the limited flow.

The constraint (4) requires that the number of inbound passengers of each station shall not exceed the threshold of the number of inbound passengers of the station.

The constraint (5) statistics of the total restricted traffic volume of each station, and the sum of all the restricted passengers in the statistical period.

3.3.2 Passenger Loading and Unloading Constraints

Passengers wait and get on and off at the station platform. The number of passengers on the platform is limited by the remaining capacity of the train. If the number of passengers on the platform does not exceed the remaining capacity of the train, all passengers on the platform will get on the train. Otherwise, some passengers who exceed the train’s remaining capacity will be stuck on the platform and have to wait for at least one more train. The number of people who get off the train during the stop is calculated according to the alight rate. Constraints such as type (6) - (12):

\[ q_{s,r}^b = \begin{cases} q_{s,r}^p \times h_{s,r}, & q_{s,r}^p \leq q_{s,r}^a \times (Q_{s,r}^{ar} + q_{s,r}^a) \\ (q_{s,r}^a + q_{s,r}^a) \times h_{s,r}, & q_{s,r}^a > q_{s,r}^a \times (Q_{s,r}^{ar} + q_{s,r}^a) \\ \end{cases} \]  
\[ q_{s,r}^d = \begin{cases} q_{s,r}^p, & q_{s,r}^p \leq q_{s,r}^a \times \eta_{s,r}^d, h_{s,r} = 0 \\ 0, & h_{s,r} = 1 \text{ and } q_{s,r}^p \leq q_{s,r}^a \times \eta_{s,r}^d \\ q_{s,r}^a - q_{s,r}^a - q_{s,r}^a, & h_{s,r} = 1 \text{ and } q_{s,r}^p > q_{s,r}^a \times \eta_{s,r}^d \\ \end{cases} \]  
\[ q_s^b = \sum_{r=1}^{R} q_{s,r}^b \]  
\[ q_s^a = q_s^{in} \times \eta_{s}^{dl} \times h_{s,r} \]  
\[ q_{s,r}^{ar} = Q_{s,r}^{ar} - q_s^{in} \]  
\[ q_s^b \leq q_{s,r}^{ar} + q_s^a \]  
\[ q_s^{in} = q_{s-1,r}^{in} - q_{s-1,r}^a + q_{s-1,r}^b \]
The constraint (6) the relationship between the residual capacity of the train and the number of people waiting on the platform is treated according to the situation. Constraint (7) records the change in the number of passengers who have not boarded the bus in constraint (6), which is represented by the variable of the number of passengers remaining. Constraint (8) calculates the total number of people getting on the train at each station. These three constraints express and record the number of passengers in the whole process from entering the urban rail transit system to getting on the train and leaving the station. In constraint (9) during the train stop, the number of passengers who get off the train is calculated according to a certain proportion of the number of passengers in the train. In constraint (10), the residual capacity is obtained by subtracting the total number of passengers allowed by the train when the train arrives at the station. Constraint (11) is required that during the train stop, the number of passengers on board shall not exceed the sum of the remaining capacity of the train and the number of people off the train. Constraint (12) denotes the change in the number of passengers inside the train before and after the stop, which is calculated from the number of passengers arriving at the last station minus the number of people getting off at the last station plus the number of people getting on at the last station. These constraints record the change in the number of passengers on the platform and in the train during the train stop.

### 3.3.3 Train Operation Plan Constraints

The adjusted train operation plan includes big station stop and big and small intersection, big station stop plan changes station attribute, big and small intersection plan changes train operation section range.

Determine the section scope of the small intersection scheme, and analyze the distribution of crowded stations on the line, that is, the inflow, outflow and cross-sectional passenger flow data of all stations on the line. The priority sequence of each station is obtained, and the priority section of each station is chosen as the alternative section of the small crossing road. Check whether the station and line conditions of the small crossing train are satisfied, and determine the operating section of the small crossing road.

After the adjustment of the train operation plan, the train operation plan for the study period is composed of the large station stop plan, the small road plan and the general train plan. Uniformly assign values to variables $h_{s,r}$, as shown in equation (13).

$$h_{s,r} = \begin{cases} 
1 & \text{(the train } r \text{ stop at station } s) \\
0 & \text{(The train } r \text{ doesn’t stop at station } s) 
\end{cases}$$

### 3.3.4 Train Operation Time Constraint

Train operation and stop are expressed by four kinds of variables: arrival time, stopping time, departure time and interval running time. The trains leave at the departure station at a certain interval, and the trains running before and after meet the minimum tracking interval requirements. As shown in equation (14) - (16):

$$t_{s,r}^{dp} = t_{s,r}^a + t_{s,r}^{dp} \times h_{s,r}$$

$$t_{s,r}^a = t_{s-1,r}^{dp} + t_{s-1,r}^{ap}$$

$$t_{s,r}^{dp} - t_{s,r-1}^{dp} \geq I$$

In constraint (13), the train departure time is obtained by the arrival time of the train at the same station plus the stopping time; In constraint (14), the arrival time of a train at one station is obtained by the departure time of the previous station plus the running time between two stations. Constraint (15) requires that the departure time of two adjacent trains at the same station shall not be less than the minimum departure time. These three times constraints describe the time and space displacement of the train during the study period.

### 4. Model Algorithm
Genetic algorithm (GA) is a probabilistic optimization method that simulates biological evolution and genetic variation mechanism proposed in the 1960s, which is widely used in the fields of combinatorial optimization, function optimization, automatic control, production scheduling, image processing, machine learning, artificial life and data mining. The concepts of biological evolution process and genetic algorithm correspond to each other. The implementation of genetic algorithm includes five parts: coding the solution of optimization problem, construction and application of adaptive function, selection process, crossover process and mutation process.

The process of solving the single-line multi-station cooperative passenger flow control model based on genetic algorithm is as follows:

**Step 1:** System initialization. Initialize the parameters of genetic algorithm, including population numbers NP, Population maximal evolution algebra \( N_m \), Cross factor \( P_c \) and variation factor \( P_m \). The variable sets \( h^i = (h^i_1, ..., h^i_{l1}, ..., h^i_{l2}, ..., h^i_{l3}, ..., h^i_{lR}) \) of the multi-station coordinated passenger flow control system of urban rail transit are determined and initial generation according to constraint conditions \( G_i \). Set up the initial loop algebra \( i = 1 \).

**Step 2:** Design the test site set \( h = (h^1, h^2, ..., h^{N_P}) \), the calculation of the coordinated passenger flow control of single line and multiple stations is realized, and the variables of waiting number and boarding number of each station platform are constantly updated, and the fitness function value is calculated.

**Step 3:** Determine the variation range and circular algebra of fitness function, if the value change range of fitness function is less than a small value \( \varepsilon \) or larger than loop algebraic upper limit of \( N_m \) to end the algorithm. Otherwise enter step 4.

**Step 4:** The selection, crossover and mutation process of genetic algorithm are carried out. In the crossover operator, the crossover factor \( P_c = 0.8 \). In the mutation operator, the coefficient of variation \( P_m = 0.2 \). Update circular algebra, make \( i = i + 1 \) into step 2.

With the help of eclipse platform and JAVA language compilation, the solution of single-line multi-station collaborative passenger flow control model based on genetic algorithm is realized, and the interface of initial parameter setting and operation results are provided. The population size and circular algebra can be adjusted based on the demand of different solving efficiency.

5. Case study

5.1 Overview of a virtual Metro Line 1

There are 15 stations in the line 1. Station C is a transfer station for line 1 and line 2. In metro line 1, it is the most difficult to organize passenger flow in station C during peak hours.

5.2 Case Parameter Setting

In station A- station F section, each station during rush hour in line 1 is shown in the table 1.

| Table 1. Orders of passenger volume in stations in the morning peak hour |
|-----------------------------|-----------------------------|
| Station | Inbound(per) | Outbound(per) |
| A      | 652          | 1876          |
| B      | 2457         | 4478          |
| C      | 8319         | 11230         |
| D      | 9227         | 3435          |
| E      | 1764         | 2112          |
| F      | 735          | 563           |

The passenger arrival rate and disembarkation rate of each station in the segment are shown in table 2. The train is booked at 1,350.
Table 2. Passenger arrival rate and alighting rate in each station

| Station | A  | B  | C  | D  | E  | F  |
|---------|----|----|----|----|----|----|
| Passenger arrival rate | 24 | 42 | 188 | 153 | 62 | 46 |
| Get off rate | 1.5% | 4.6% | 16.2% | 5.2% | 64.6% | 76.2% |

5.3 Case Solution Results and Analysis

There are five train operating plans in the combination of train operating plans: I Station A - Station B - Station C - Station D - Station E - Station F; II. Station C - Station D - Station E - Station F (Small cross road scheme, Station C is the starting station); III Station A - Station C - Station D - Station E - Station F; IV Station A - Station B - Station D - Station E - Station F; V Station C - Station D - Station E - Station F (Large station parking scheme, Station C is a parking station after three stations in continuous fire stations).

Among the five schemes, scheme I covers all the stations on the section. Plan II is the small road plan, with an empty train to serve the passengers of Station C; Scheme III does not stop Station B, scheme IV does not stop at Station C, and scheme V does not stop at Station A and Station B. The latter three schemes reduce the occupation of line capacity of upstream station of liberation road station to different degrees.

Based on the existing station traffic restriction organization and the adjustment of the above train operation plan, a multi-station coordinated station traffic restriction plan was developed, and the time and flow limitation of each station were determined based on the proportion balance between the crowded station and the upstream station.

After the operation in the peak period, the optimal scheme of multi-station coordinated passenger flow control (scenario 2) would increase the number of people in the line system as a whole to 1266, compared with the original limiting scheme (scenario 1), as shown in table 3.

Table 3. Comparison of limited passenger volume before and after coordination control of passenger flow multi stations

| Statistic          | scenario 1: limited passenger volume before | scenario 2 limited passenger volume after |
|--------------------|---------------------------------------------|------------------------------------------|
| limited passenger  | 3212                                        | 4478                                     |

In scenario 2, the optimal scheme of multi station coordinated traffic control current limiting number than scenario 1 increased, because the scenario 2 with the optimization target, realize the proportion of each station on the crowded station passenger flow and its number of upstream station platforms in the coordinated control of limit excessive passenger demand to the station, the platform capabilities within the permitted threshold number of passengers affected degree is small, so the line on the total loss is not big.

For each station get on the car balance, adjust the train operation plan and multi station current-limiting organization coordination of station, after Station A, Station B, Station C limit flow increased in different degree, the increase of the limit of flow are controlled under 600 people, the Station C of limit flow rate decreased.

6. Conclusion

To train stop current limiting properties and station number of decision variables, and to get on the bus passengers in urban rail transit system and the proportion of each station on the objective function is minimum variance, build the urban rail transit single station passenger flow control model, more
choice for the passenger departure station, the train operation plan, current limiting and passenger train and passenger boarding, the train operation time constraints, choose the model solution method based on genetic algorithm searching for the optimal solution quickly.

Finally, taking the downward direction of morning peak of a virtual metro line as the case, the parameters were set and solved, and the combination of the adjusted train operation scheme and the station current-limit organization strategy coordinated by multiple stations were obtained. The solution results were analyzed to verify the effectiveness of the model and algorithm.

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