Research on Passenger Flow Control Model of Urban Rail Transit Network

Xue Su, Yiping Li
Wuhan Railway Vocational College of Technology, Wuhan, Hubei 430205, China
20070106@wru.edu.cn

Abstract. The current urban rail transit faces the pressure of effective transportation management brought about by the large passenger flow. Through this research, it is proposed to construct a coordinated control model for urban rail transit passenger flow and optimize the urban rail transit operation organization. Using the Mixed Logit model to construct the urban rail transit network passenger flow collaborative control optimization model can accurately describe the distribution of the urban rail transit network passenger flow online, which is especially applicable to the network topology change scenario brought by the new line introduction. Empirical evidence shows the correctness and effectiveness of the model.

1. Introduction
With the expansion of the urban population, the operating mileage of urban rail lines is increasing, and the demand for passenger flows is also increasing rapidly. Urban rail transit organizations are facing tremendous pressure in the case of large passenger flows. It has become common for many rail transit organizations in central cities to limit passenger crowding and the efficiency of its passenger transportation directly affects the operating efficiency of the entire city. In order to improve the transportation capacity of the urban rail transit network, it is particularly important to optimize its operating organization on the whole, thus solving the traffic problem caused by large passenger flows[1].

In order to better manage and operate urban rail transit, experts in related fields at home and abroad have conducted a lot of research on the control of passenger flow in recent years. In terms of passenger flow distribution, Wu Xiangyun[2] built a passenger flow distribution model for urban rail transit networks based on the principle of equilibrium allocation. Liu Jianfeng[3] established a passenger flow distribution model of urban rail transit network based on Logit model, also he[4] built a random user equilibrium model for passenger flow distribution based on Probit model. Lin Zhan[5] et al. proposed a method of network distribution based on an improved logit passenger flow distribution model. Yan Yan[6] proposed an urban rail transit route selection model based on the NL (nest logit) model. The research is to construct a generalized cost function of urban rail transit routes based on the passenger's route selection behavior, then solve the effective route set therein, and finally establish a passenger flow distribution model. The classical Logit distribution model has become the mainstream of current research and applications due to its fast solution speed and convenient application. In the control of passenger flow, Zhao Peng established a line passenger flow coordination control model with the objective function of maximum passenger turnover and minimum passenger delay. Yao Xiangming[7] constructed a line-level passenger flow inbound collaborative control model and a network-level passenger flow inbound collaborative control model from the aspect of network.

Since the classic Logit model is not accurate enough, this paper studies the mixed-logit model
based on discrete selection theory\cite{8}\cite{9} to characterize the passenger flow distribution model in urban rail transit network. Based on the interpretation of passenger behavior, we attempt to reveal the heterogeneity of the passenger's choice of travel path, so that the model can adapt to the urban rail transit network topology change scenario. Then based on the passenger flow distribution model described by Mixed-Logit, a passenger flow collaborative control model at the level of urban rail transit network is constructed.

2. Construction of Passenger Flow Collaborative Control Model

The passenger flow between stations in the entire network can be obtained through the passenger presence information of the automatic ticket sales system (AFC system). When assigning passenger flow in urban rail transit, the passenger flow between OD pairs is based on a certain route selection principle and allocation method, which is in accordance with the process of actually distributing to various sections on the road network. Passengers' choice of travel route conforms to some random distribution law. The passenger flow allocation amount on each effective path can be obtained by obtaining the selection probability of the effective paths between the ODs.

2.1. Effective Route Selection Model

In the urban rail transit network, the route that passengers may consider choosing to travel can be called the effective route. The determination of the effective route for passenger travel can be divided into two stages: generating a valid route set and route selection. The effective route set can be generated by the breadth-first graph search algorithm proposed in the literature to obtain the effective path set between OD point pairs a-b, which is recorded as $K_{mn}^\alpha$. The heterogeneity of passengers is obvious in route selection. This study was based on the Mixed Logit model.

The basic theory of the Mixed Logit model is the utility maximization theory, and the utility value $U_{nk}$ consists of two parts: a certain term $V_{nk}$ and a random term $\varepsilon_{nk}$. The joint density function of the random vector $\varepsilon_{nk} = (\varepsilon_{n1}, \ldots, \varepsilon_{nk})$ is $f(\varepsilon)$.

Based on the Mixed Logit model theory, in order to reflect the differences in the selection process of passengers, this paper constructs a route selection model, which assumes that the characteristic variable parameters are random variables. For passenger n, the k-th path from the starting point r to the ending point s has a random utility of:

$$f_n^\alpha(k | K_{mn}^\alpha) = \int L_{nk}^\alpha(\beta) f(\beta) d\beta$$  \hspace{1cm} (1)

where $f_n^\alpha$ denotes the probability that pedestrian n selects route k from the set of valid routes; $\beta = [\beta_1, \beta_2, \ldots, \beta_I]$ the parameters to be estimated, each parameter is subject to a probability distribution; $f(\beta)$ is a joint distribution density function; $X_i^\alpha = [X_{ik1}, \ldots, X_{ikn}]$ is the characteristic variable of route k; I is the number of characteristic variables. The influencing factors considered in this article are as follows:

1. The boarding time $X_{ik1}$ is the boarding time of the k-th route between OD and r-s, including the waiting time of passengers at the starting platform, train running time and platform stopping time;

$$X_{ik1} = \sum_{(i,j)} TC_{i,j} \ast \delta_{i,j,k}^\alpha$$  \hspace{1cm} (2)

where $\delta_{i,j,k}^\alpha$ is parameter 0-1, which means that if the interval segment (i, j) belongs to the k-th route between OD and r-s, the value is 1, otherwise it is 0.

2. The transfer time $X_{ik2}$ is the transfer time of the k-th route between OD and r-s;
\[
X_{2k}^{rs} = \sum_{(i,j)} TH_{i,j} \delta_{i,j,k}^{rs}
\]  

(3)

Among them, \( \delta_{i,j,k}^{rs} \) is parameter 0-1, which indicates that if the interval segment \((i, j)\) belongs to the \(k\)-th route between OD and \(r-s\), the value is 1; otherwise, it is 0.

2.2. Passenger Flow Distribution Process

The preparatory work for using the route distribution method to improve the urban rail transit network has been detailed. The next is to allocate the passenger flow to all OD points. The specific method steps are as follows:

- Using graph-based traversal algorithm to find the effective route set \(K_{rs}^{nm}\) for OD point and \(r-s\);
- Applying formula (1) to calculate the selection ratio \(f_{nk}^{rs}\) of OD points to each effective route between \(r-s\);
- Applying the following formula to assign network passenger flow to the route:

\[
rsrs
\begin{align*}
rs
rs
rs
rs
rs
\end{align*}
\]

(4)

\(rs\) is the passenger numbers of OD points and \(r-s\), and \(p_{rs}^{nk}\) is the passenger flow allocation amount on the effective route of OD points and \(r-s\). Change the OD points and repeat the above steps.

2.3. Construction of Passenger Flow Collaborative Control Model

Assuming the passenger flow demand \(P_{ij}(t_i)\) of the station \(v_i\) during the time period \(t_i\), each OD flow starting from the station is allocated in turn under the constraints of capacity constraints. Taking the OD pair \((v_i, v_j)\) as an example, the passenger flow in each section on the \(k\)-th route is:

\[
q_{ij}^{v_i,v_j}(t_i) = P_{v_i}(t_i) \cdot f_{ik}^{v_i,v_j}
\]

(5)

Among them, \(f_{ik}^{v_i,v_j}\) is the proportion of passenger flow allocated on the \(k\)-th route.

The objective function of the multi-station coordinated passenger flow control optimization model of the urban rail transit network based on the operation chart is to maximize the passenger turnover rate.

3. Passenger Flow Control of Wuhan Metro Network

3.1. Case Information

We take Wuhan metro network as the subject of the study, select the morning peak hours (07:00-09:30) on September 04, 2018 (Tuesday) for analysis of network passenger flow control.

The construction of the virtual line of the Wuhan subway network allows passengers to transfer at most twice. There are a total of 152 virtual lines composed of 4 actual lines and a total of 7,429 virtual trips.

- Line 1 uses the Dajiao road to run cyclically. There are 238 pairs of passenger trains running throughout the day. Among them, 103 trains run from 7:00 am to 9:30 am in the morning rush hour.
- Line 2 adopts both entire and partial trip to run cyclically and runs 226 pairs of passenger trains throughout the day, 99 trains in the morning rush hour, and the shortest departure interval is 2'49".
- Passenger flow allocation parameters include transfer time conversion coefficients, transfer times conversion coefficients in the generalized cost model, route cost expansion factor \(H\) in the effective route algorithm, route cost threshold \(f_{max}\) and parameters in the traffic distribution model. The values of the above parameters refer to [4] [16]. The values of each parameter are shown in Table 1 below:
Table 1. Values of related parameters

| Parameter | $\varphi$ | $\beta$ | $H$ | $f_{\text{max(min)}}$ | $\theta$ |
|-----------|-----------|---------|-----|----------------|--------|
| Value     | 1.86      | 4       | 0.15| 12              | 19.6   |

Through statistical processing of the AFC credit card data on November 01, 2018, 1.3 million rides are completed throughout the day and 317,000 passenger rides during the morning peak. The time period OD passenger flow data obtained from the AFC credit card data is the passenger flow of the subway. In order to reflect the effect of flow control, it is assumed that the passenger flow demand is twice the completed passenger flow.

3.2. Analysis of results

3.2.1. Distribute Network Passenger Flow

According to the passenger flow allocation method of urban passenger transportation network, the network passenger flow is allocated. First find the shortest route between each OD point pair, then find the effective route between each OD point pair according to the definition of the effective route, and calculate the passenger's selection probability $f_{i,j}^{k}$ of each effective route through the Mixed Logit model, and finally allocate the passenger flow in the network period to a valid route. For the OD point pair r-s in the network, the effective route from point r to point s is the same as the effective route from point s to point r. Due to the design of Wuhan subway lines, lines 1, 2, 3, and 4 all intersect in pairs, that is, each line has transfer stations with other lines for transfers, so the maximum number of transfer is limited to two.

After finding the effective routes of all OD point pairs on the road network and the selection probability of each effective route, the network passenger flow is allocated to the effective route to obtain the passenger flow of the period from station i to station j on the running liner.

3.2.2. Analysis of Flow Control Results

The passenger flow demand from 7:00 to 9:30 in the morning peak is 633,226 people. The result of the model is obtained by software, and the maximum turnover of the objective function was 8,117,794 person-km. A total of 575,288 passenger transports are completed along the route, and the number of passenger limitation is 57861. When the last trains in the morning peak of each line passes the stations, there are 77 people still unable to board the train, that is, waiting at the platform. During the morning rush hour, the average travel distance per person on the subway is 14.1 kilometers. The passenger flow coordination control is performed on the basis of all stations on the entire road. In order to better implement the passenger flow control scheme, the passenger flow control schemes for each line station are given below respectively.

The total flow control rate of the stations of Wuhan Metro Line 2 during the entire morning rush hour is shown in Figure 1.

After the above analysis, the details of flow control number as well as rate of the flow control station of Line 2 throughout the morning peak are shown in Table 2.

Based on the analysis of Table 2, the traffic control rate of Zhongnan Road during the early morning peak is shown above. By gathering statistics on passenger flow demand of the early morning peak of Zhongnan Road, the passenger flow demand is low with 4278 people. So we can find out that the reason for the high flow control rate is that there are a large number of passengers from Line 2 in the direction of Guanggu Square, which makes the platform capacity of Zhongnan Road and the capacity of trains and passenger trains close to saturation, resulting in the phenomenon of small passenger flow demand but high flow control rate.

Hongshan Square is also an interchange station. The reason for this phenomenon is the same as that of Zhongnan Road Station. There are a large number of passenger transfers to the direction of Guanggu Square, which makes the platform capacity and passenger train capacity close to saturation.
Figure 1. Overall flow control rate of each station of Wuhan Metro Line 2

Table 2. The overall flow control condition of stations of Line 2

| Line number | Running direction | Station name         | Passenger flow demand | Total flow control number | Flow control rate% |
|-------------|-------------------|----------------------|------------------------|----------------------------|-------------------|
| Line 2      | Jinyintan towards Guanggu Square | Jiyu Bridge          | 12084                  | 2109                       | 17.5              |
|             |                   | Crab Cape            | 11296                  | 3180                       | 28.2              |
|             |                   | Little Turtle Mountain | 8186                  | 3414                       | 41.7              |
|             |                   | Hongshan Square     | 5602                   | 2885                       | 51.5              |
|             |                   | Zhongnan Road        | 3432                   | 2012                       | 58.6              |
|             |                   | Baotong Temple       | 3924                   | 2569                       | 65.6              |
|             |                   | Jiedaokou            | 8674                   | 3544                       | 40.9              |
|             |                   | Guangbutun           | 8250                   | 2422                       | 29.4              |
|             | Guanggu Square towards Jinyintan | Huquan          | 25670                  | 3907                       | 15.2              |

4. Conclusions and Prospects
This article manages the passenger flow demand from the perspective of passenger flow control and allocates passenger flow by distributing network passenger flow to the effective route for the process of allocation. Considering the difference in preferences of effective route selection caused by the differences among passengers, a route selection model is constructed, and a passenger flow control model is constructed based on this. The following conclusions can be drawn:

1) Using the Mixed Logit model to calculate the probabilities of passengers choosing effective routes between each OD point pair, the passenger flow on each effective route can be obtained more accurately.

2) Based on the route selection model described in the article and the objective of maximizing
passenger turnover, a passenger flow control model for urban rail transit is constructed. The calculation of flow control rate can be used as a reference for passenger flow control decisions.

(3) The software is used to obtain the result of the flow control model, and the optimization results are consistent with the actual situation. The correctness and effectiveness of the flow control model are verified by analyzing the data of Wuhan Metro Line 2.

The passenger flow control model in this paper is relatively complicated, with a large amount of processing data. In the passenger flow allocation, a simpler allocation method is used. The change of the generalized route cost caused by the flow change is not considered. The model does not consider limiting the number of passengers waiting for trains. Because the model has a large number of subscripts, the model is difficult to solve. When the scale of the road network is larger, the difficulty will increase sharply. In future research, we will continue to optimize the model, so as to effectively and accurately solve the problem of larger-scale road network and do further research in this field.

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