Study On Train Routing Plan Of Y-Line Of Urban Rail Transit Considering Passenger Travel Purpose

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Abstract. Through the questionnaire survey on the passengers of the case line, the travel purpose of the passengers is divided into three categories: leisure, commuting and business. Based on the analysis of the rules of passenger's choice of route, the model of passenger's choice of route and the model of route planning are established, and the parameters of logic model are calibrated according to the results of questionnaire survey, and the generalized cost of passenger's travel is obtained by considering the degree of train congestion. The validity of passenger flow distribution model and routing planning model is verified by solving the case line model.

1. Introduction
With the development of urban rail transit in China, some new lines end at the middle station of the existing rail transit line, or the extension line from the middle station of the existing rail transit line. Thus, the existing rail transit line and the new line or extension line form a "Y" shape line, which is called a "Y" shape line. How to analyze the passenger flow of Y-line, understand the demand of passenger flow and reasonably organize the train routing of Y-line, make the train operation and passenger flow demand more match, and provide efficient and high-quality transportation service is an important content that needs to be studied at present.

Zhang, Liu, etc. considered the heterogeneity of passengers in their study[1-2], Zhao studied the factors affecting the choice of passenger routes[3], Yan divided passengers into commuter and non-commuter passenger flows[4], and Liu considered the direct preference of passengers in the study[5].

There are few researches on passenger classification in the existing researches, most of them are based on single line. In the existing studies, passenger travel choice behavior, passenger flow distribution and train routing are considered separately, and passenger flow distribution is only carried out under the condition of established routing, which fails to consider passenger flow choice behavior and train routing formulation in a unified way. Therefore, this paper unifies passenger classification, route selection preference and train routing to get the optimal train routing plan under specific classification.
2. Problem description

2.1. Train routing plan of Y-line

The train routing plan is a plan that specifies the train operation interval and departure pairs. A reasonable train routing plan can meet the needs of passengers, reduce the operating costs of the operating enterprises, and achieve a win-win situation between the operating enterprises and passengers. To make a reasonable train routing plan, first of all, it is necessary to sort out the passenger demand, secondly, it is necessary to understand the basic situation of the line, such as the location of turn back station, station type, etc., finally, it is necessary to formulate the corresponding solution model and get the optimal routing results.

The train routing form of Y-type line is the combination and expansion of the basic train routing form of urban rail transit. According to the operation section of train routing and the main branch line of Y-type line, the train routing of Y-type line can be divided into three categories: independent operation, direct operation and mixed operation. As shown in Figure 1.

| Table 1. Typical train route plan of Y type line |
|-----------------------------------------------|
| Independent operating | Direct operating routes | Mixed routing mode |
| all direct operating | partial direct operating |

2.2. Passenger's demand for route selection

Urban rail transit should not only meet the needs of passengers, but also ensure the service quality and efficiency. Generally speaking, there are at least two train routes on the Y-type line, and there may be multiple routes between the OD of passengers. Different passengers will have different preferences when choosing the route. Different passengers have different preferences for waiting time when they take subway, and passengers who need short travel time will be sensitive to waiting time. The degree of congestion in the car is one of the most direct physiological manifestations of passengers' travel comfort. The degree of congestion in the car is expressed as the full load rate of the section, for the train, it is expressed as the full load rate of the train or the density of passengers, and the degree of congestion directly affects passengers’ feeling. For Y-type line, if the line adopts the traditional independent operation routing, all passengers from the main line to the branch line need to transfer, that would greatly increase the travel time cost of passengers.

When the conditions of facilities and equipment are determined, in order to make the train routing serve the passengers better and save the cost of operation enterprises, it is necessary to deeply understand the characteristics of line passenger flow and the choice of passengers when they travel, and establish the Logit model of passenger flow distribution with the actual passenger selection characteristics of the route, and lay the foundation for the development of the train routing. This paper will elaborate on this problem in the next chapter.

3. Path selection

In order to explore the passenger's demand and path selection preferences, the passenger route selection Logit model of Y-line is established and parameter-calibrated. This paper investigates the passengers of Guangzhou Metro Line 3.

3.1. Passenger flow survey

In order to understand the passenger flow structure of Guangzhou Metro Line 3, a total of 300 questionnaires were issued and 271 valid questionnaires were collected.
3.1.1. Passenger property
According to the results of the questionnaire, the gender, age and income ratio of passengers are as follows.

Figure 1. Passenger flow structure

3.1.2. Path selection
In order to explore the relationship between personal attributes of passengers and travel path selection, the following scenarios and questions are set in the questionnaire.

“If you travel during the morning rush hour and the basic travel time to your destination is 28 minutes, which route will you choose?
(1) Waiting for 5 minutes, no transfer, total travel time 36 minutes.(2) Wait 3 minutes, transfer 2 minutes, total travel time 33 minutes.(3) Transfer 0-8 minutes, total travel time 29-38 minutes.”

The results are as follows.

Figure 2. Path selection for passengers with different attributes
3.2. Parameter calibration

3.2.1. Chi-square test

In order to verify whether there is correlation between passenger attributes and path selection, chi square test is carried out on the result of passenger selection.

| Properties        | Parameters     | Value | df | Sig. |
|-------------------|----------------|-------|----|------|
| Gender            | Pearson Chi-Square | .106  | 1  | .744 |
|                   | LR             | .106  | 1  | .745 |
| Age               | Pearson Chi-Square | 4.087a | 4  | .394 |
|                   | LR             | 4.064 | 4  | .397 |
| Income            | Pearson Chi-Square | 14.264 | 3  | .003 |
|                   | LR             | 13.320 | 3  | .004 |
| Travel purpose    | Pearson Chi-Square | 55.233 | 5  | .043 |
|                   | LR             | 59.168 | 5  | .041 |

Table 2 shows that the passenger's travel purpose and income are highly correlated with the passenger's route selection behavior. Since the number of passenger samples at some income levels is small in this survey, in this paper, the passengers are classified according to the travel purpose with a relatively significant relationship with the passenger travel path.

3.2.2. Parameter calibration

Compared with the road network, the common line operation section of each route has less independent influence on different paths, so different travel paths can be regarded as mutually independent.

Logit model has many forms of utility function, but the most classical and widely used is the linear form of utility function. The formula is as follows:

\[
V^{t,k} = \sum_{i}^{N} \theta_i X_i
\]  

(1)

\(X_i\) refers to the i-th factor that affects the passenger path selection. Each factor is independent and distributed. \(\theta_i\) is the coefficient of relevant factors. The specific value is calibrated according to the questionnaire survey. According to the above survey results, this paper constructs the utility function of passenger travel path selection as follows:

\[
V^{t,k}_{lm} = \theta_{1}^{t,k} t_{lm,r}^{k} + \theta_{2}^{t,k} t_{lm,rd}^{k} + \theta_{3}^{t,k} t_{lm,hd}^{k} + \epsilon_{lm}^{k}
\]  

(2)

\(V^{t,k}_{lm}\) ——The utility value of the t-th passenger to the k-th path between \(lm\),

\(t_{lm,r}^{k}\) ——The travel time of the k-th path, including the running time and stop time of the train;

\(t_{lm,rd}^{k}\) ——Arrival waiting time of the k-th path.

\(t_{lm,hd}^{k}\) ——Waiting time for transfer of the k-th path.

\(\theta_{1}^{t,k}, \theta_{2}^{t,k}, \theta_{3}^{t,k}\) ——The coefficients of the above three influencing factors are respectively calibrated according to the questionnaire data.

\(t = 1, 2, 3\) ——represent the purpose of passenger travel for commuting, leisure and business.

\(\epsilon_{lm}^{k}\) ——The random utility term of the k-th path obeys Gumble distribution.

This paper introduces another concept in economic theory marginal utility. In this paper, the marginal utility of passenger transfer time and waiting time is calculated based on the travel time of
passengers. The waiting time and transfer time of passengers in travel are all transformed into the travel time of passengers. Thus, the generalized travel time cost of passengers is obtained. The calculation formula of generalized travel time is as follows.

\[ C_{lm}^{i,j,k} = t_{lm}^{i,k} + MRS_{km}^{i,j,k} + MRS_{hd}^{i,j,k} \]

\[ MRS_{hd}^{i,j} = \frac{\theta_i}{\theta_j} \]

In this paper, SPSS software is used for regression analysis of passenger questionnaire data, and the results of model estimation and parameter calibration are as follows.

Table 3. Result Model fitting

| Travel purpose | -2Likelihood | Sig. | Cox and Snell R² | Nagelkerke R² |
|----------------|--------------|------|-----------------|---------------|
| Commuting      | 73.453       | 0.021| 0.467           | 0.54          |
| Entertainment  | 80.274       | 0.027| 0.408           | 0.489         |
| Business       | 75.895       | 0.038| 0.386           | 0.447         |

From table 3, it can be seen that the significance level of model fitting is 0.038, which is less than the hypothesis level of 0.05, so it can be seen that the parameters of the model are not all zero, the model hypothesis factors and dependent variables have strong significance, and the overall fitting results are credible.

Table 4. Estimation of parameters

| B        | Sig.  | B        | Sig.  | B        | Sig.  |
|----------|-------|----------|-------|----------|-------|
| \( \theta_1^1 \) | -1.805| 0.013    | \( \theta_1^2 \) | -2.017| 0.008    | \( \theta_1^3 \) | -3.327| 0.019    |
| \( \theta_2^1 \) | -2.742| 0.021    | \( \theta_2^2 \) | -2.042| 0.043    | \( \theta_2^3 \) | -3.531| 0.027    |
| \( \theta_3^1 \) | -2.243| 0.042    | \( \theta_3^2 \) | -2.847| 0.021    | \( \theta_3^3 \) | -3.494| 0.009    |

According to the formula (3), the marginal substitution rate of each variable for travel time is as follows.

Table 5. Marginal rate of substitution

| marginal substitution rate | MRS_{jd}^{2,1} | MRS_{hd}^{3,1} | MRS_{jd}^{2,2} | MRS_{hd}^{2,3} | MRS_{jd}^{2,3} | MRS_{hd}^{3,3} |
|---------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| value                     | 1.52            | 1.24            | 1.01            | 1.41            | 1.13            | 1.12            |

4. Routing model

4.1. Basic assumptions
1) Taking hours as the unit, this paper mainly considers the train routing plan in peak hours;
2) The train stops at each station, and the train formation in each routing is the same;
3) Assuming that the parking capacity of the depot and the station storage line is sufficient, the number of trains that can be used is unlimited;
4) the routing plan of up and down trains is the same, and the trains depart in pairs;
5) passengers are evenly distributed on the train;
6) only the internal passenger flow of a single line is considered, and the transfer between other lines and the research line is not considered.

4.2. Basic assumptions
In order to establish the train routing model of Y-line, the parameters set in this paper are shown in table 6.
Table 6. Parameters

| Symbol | Meaning |
|--------|---------|
| $V$    | Station set, $v_i$ means different stations, $n$ is the total number of stations on the line |
| $E$    | Interval set, $e_i$ represents the $i$-th interval, $m$ is the total number of intervals |
| $R$    | Set of all routes, $r_i$ represents the $i$-th route, $N_r$ is the total number of routes |
| $E_{ri}$ | Set of intervals included in the $i$-th train routing |
| $V_{ri}$ | Set of stations included in the $i$-th train routing |
| $E_{lm}^k$ | Set of intervals contained in the $k$-th path between $l$ and $m$ |
| $V_{lm}^k$ | Set of stations contained in the $k$-th path between $l$ and $m$ |
| $T$    | Time frame for preparing train routing plan, in hours |
| $\alpha$ | Unit purchase cost of train, unit: yuan / (train × minute) |
| $\beta$ | Unit running cost of train, yuan / (train × km) |
| $l_{e_i}$ | Mileage of interval $e_i$, KM |
| $l_{r_i}$ | Mileage of route $r_i$, KM |
| $t_{\text{inj}}$ | Reentry time of turn back station, minutes |
| $t_{ei}$ | Running time of interval $e_i$, minutes |
| $t_{vi}$ | Stop time at station $i$, minutes |
| $a_{jd}$ | Arrival waiting time coefficient |
| $a_{td}$ | Transfer time coefficient |
| $\lambda$ | Unit time cost of passengers, yuan / minute |
| $q_{lm}$ | Passenger flow between $l$ and $m$, in units of people |
| $p_{lm}^{t,k}$ | The probability of selecting the $k$-th route for the T-class passengers between $l$ and $m$ |
| $p_{lm}^{r}$ | Passenger flow proportion of class T passengers between $l$ and $m$ |
| $Q_{zi}$ | Rated seats of train |
| $Q_{zb}$ | Standard passenger capacity of train |
| $\delta_{e_i}^{x}$ | 0-1 variable, 1 when $x$ contains $V$, otherwise 0 |
| $N_{r \text{min}}$ | Minimum total number of train routing on the line |
| $N_{r \text{max}}$ | Maximum total number of train routing on the line |
| $n_{e_i \text{min}}$ | The lower limit of the number of routes containing interval $e_i$ |
| $n_{e_i \text{max}}$ | The upper limit of the number of routes containing interval $e_i$ |
| $h_{e_i \text{min}}$ | Lower limit of train departure interval in section $e_i$, min |
| $h_{e_i \text{max}}$ | Upper limit of train departure interval in section $e_i$, min |
| $\eta$ | Capacity rate |
| $\xi$ | Weight of enterprise operation cost |
| $A, B$ | Penalty coefficient due to congestion |
| $\rho, \gamma$ | Penalty coefficient due to congestion |
| $x_i$ | Passenger flow of section $e_i$ |
Objective function
Objective function includes operating enterprise cost and passenger cost.

4.3.1. Operating enterprise cost
Operating enterprise costs include train purchase cost $Z_1$ and train travel kilometers fee $Z_2$, as follows.

$$
\min Z_1 = 1.2 \alpha \sum_{i=1}^{N_i} \sum_{v_i \in V_i} \left( \sum_{j=1}^{N_j} \left( t_{ij} + t_{ji} \right) + 2t_{ij}^v \right) \delta_{ij} \gamma_{ij}
$$

(5)

$$
\min Z_2 = 2 \beta \sum_{i=1}^{N_i} \delta_{ij} \gamma_{ij}
$$

(6)

4.3.2. Passenger cost
The cost of passengers includes three parts: the time when passengers are on the train, the time when passengers are waiting for the train at the station and the time when they are waiting for transfer, which are indicated by $t_{im,c}^k$, $t_{im,jd}^k$, and $t_{im,hd}^k$, respectively.

$$
t_{im,c}^k = \sum_{v \in V_i} t_{iv} + \sum_{v \in V_i} t_{vi}
$$

(7)

$$
t_{im,jd}^k = \frac{a_{jd}}{f_{ij}} \quad \forall R_i \in y_k
$$

(8)

$$
t_{im,hd}^k = \sum_{v \in V_i} \left( a_{hd} T / f_{ij} \right)
$$

(9)

$$
s_{lm}^k = \begin{cases} 
0 & n_{lm}^k = 1 \\
1 & n_{lm}^k \geq 1 
\end{cases}
$$

(10)
When the number of passengers in the train is less than the number of rated seats, passenger feels most comfortable. When the number of passengers on the train is between the number of rated seats and standard capacity, passenger feels less comfortable. When the number of passengers on the train is between standard capacity and the maximum passengers number, passenger feels worst. Penalty coefficient is exponentially related to congestion.

\[ U_i = \begin{cases} 0 & x_i \leq Q_y \\ \left( \frac{x_i - Q_y}{Q_y} \right) \cdot A & Q_y \leq x_i < Q_u \\ \left( \frac{x_i - Q_u}{Q_u} \right) \cdot B & Q_u \leq x_i \end{cases} \]

Therefore, passenger travel costs is as follows.

\[ \min Z_3 = \lambda \sum_{i=1}^{d} \sum_{m=2}^{K} \sum_{k=1}^{K} q_{lm} \cdot p_{lm} \cdot p_{lm}^{t,k} \cdot \left[ (1 + U_i) r_{lm,c} + \frac{a_{nt} T}{f_{nt}} + s_{nt} \sum_{n} \left( \frac{a_{nt} T}{f_{nt}} \right) \right] \]

4.4. Restrictions

(1) There is a limit to the number of routes each station and intervals belongs to.

\[ n_{min} \leq \sum_{i=1}^{N} \delta_{i}^{e} \leq n_{max}, \forall e_{j} \in E \]

(2) Total number of routes.

\[ N_{r_{min}} \leq \sum_{i=1}^{N} \delta_{i} \leq N_{r_{max}} \]

(3) Routing length.

\[ \sum_{j=1}^{n} \delta_{i}^{e} \geq w, \forall r_{i} \in R \]

(4) Section passenger flow and section capacity determine service frequency.

\[ f_{r_{min}} \leq f_{i} \leq f_{r_{max}}, r_{i} \in R \]

(5) Passengers must be transported by train.

\[ \sum_{k \in K} q_{lm}^{k} = q_{lm} \]

(6) Interval between trains

\[ h_{r_{min}} \leq T / \sum_{i=1}^{N} \delta_{i}^{e} \cdot f_{i} \leq h_{r_{max}}, \forall e_{j} \in E \]

(7) The number of passengers on the train shall not exceed the full load rate of the interval.

\[ \sum_{i \in \mathcal{V}, r_{i} \in a} \sum_{k \in K} q_{lm}^{k} \left( r_{i}, e_{j} \right) \leq \eta, \forall e_{j} \in E \]
4.5. **Multi objective function to single objective function**

In this paper, $\xi$ is defined as the weight of enterprise operation cost, and $1 - \xi$ as the weight of passenger travel cost.

$$
\min Z_i = \xi (Z_i + Z_j) + (1 - \xi)Z_i
$$

(20)

5. **Solving algorithm**

Enumeration is a classical algorithm to solve the problem under certain conditions. By enumerating and calculating the target value of all the cases that meet the set limit conditions, the optimal solution can be obtained. In this paper, enumeration method is used to solve the model.

6. **Case analysis**

6.1. **Case description and parameter value**

The following figure shows the urban rail transit lines of a city, which has totally 29 sections.

![Figure 3. Case line](image)

Table 7. Station spacing and interval running time

| No. | Stopping time | Running time (s) | Length (km) | No. | Stopping time | Running time (s) | Length (km) |
|-----|---------------|------------------|-------------|-----|---------------|------------------|-------------|
| 1   | 45            | 135              | 3.9         | 16  | 25            | 95               | 1.4         |
| 2   | 25            | 155              | 6.2         | 17  | 45            | 135              | 3.4         |
| 3   | 45            | 135              | 3.0         | 18  | 30            | 150              | 0.833       |
| 4   | 30            | 150              | 2.2         | 19  | 30            | 150              | 2.3         |
| 5   | 30            | 90               | 1.9         | 20  | 35            | 205              | 6.3         |
| 6   | 35            | 85               | 2.6         | 21  | 40            | 260              | 5.5         |
| 7   | 40            | 140              | 2.1         | 22  | 30            | 150              | 2.5         |
| 8   | 30            | 90               | 1.2         | 23  | 30            | 150              | 3.6         |
| 9   | 30            | 90               | 1.5         | 24  | 45            | 75               | 1.2         |
| 10  | 45            | 195              | 1.3         | 25  | 45            | 145              | 1.3         |
| 11  | 45            | 75               | 1.2         | 26  | 35            | 90               | 0.843       |
| 12  | 35            | 85               | 0.972       | 27  | 30            | 85               | 0.89        |
| 13  | 30            | 150              | 1.2         | 28  | 35            | 80               | 1.6         |
| 14  | 35            | 85               | 1.9         | 29  | 40            | 145              | 2.4         |
| 15  | 40            | 80               | 1.3         | 30  | 45            |                  |             |
### Table 8. Model parameter setting

| Parameters | Value | Parameters | Value |
|-----------|-------|-----------|-------|
| $z_{i,o}$, $z_{i,d}$ | 135s | $\xi$ | 0.2 |
| $\alpha$ | 4 yuan/train-min | $\eta$ | 120% |
| $\beta$ | 60 yuan/train-min | $N_{r_{min}}$ | 2 |
| $T$ | 1 hour | $N_{r_{max}}$ | 3 |
| $a_{jd}$, $a_{hd}$ | 0.5 | $h_{e_{f_{min}}}$ | 105 s |
| $\lambda$ | 0.8 yuan/min | $h_{e_{f_{max}}}$ | 15 mins |
| $Q_{si}$ | 192 per train | $Q_{bi}$ | 1350 per train |
| $\rho$ | 0.01 | $\gamma$ | 0.02 |
| A | 1 | B | 2 |

### 6.2. Results

The algorithm in Chapter 5 is used to get the optimal train routing plan, the result shows that the best routing plan that contains two routings.

![Figure 4. Model result](image)

12 trains/hour 12 trains/hour

### 6.3. Comparison

#### 6.3.1. Compared with actual routing plan

According to the model solution result, we compared the results with actual routing plan as follows.

| Routing (Y) | Frequency (Y) | Purchase (Y) | Operating (Y) | Waiting (Y) | Transfer (Y) | In vehicle cost (Y) | Total cost (Y) |
|-------------|---------------|--------------|---------------|-------------|--------------|--------------------|----------------|
| Actual Routing | 1-30 | 14 | 3 745 | 58 620 | 113 345 | 18 278 | 605 261 | 197 268 |
| 4-17 | 7 | 3 745 | 58 620 | 113 345 | 18 278 | 605 261 | 197 268 |
| 11-25 | 7 | 3 745 | 58 620 | 113 345 | 18 278 | 605 261 | 197 268 |
| Solution result | 1-25 | 12 | 3 580 | 57 843 | 116 620 | 13 451 | 592 224 | 190 618 |
| 4-30 | 12 | 3 580 | 57 843 | 116 620 | 13 451 | 592 224 | 190 618 |
| Fluctuation range | 8 | -165 | -777 | 3 275 | -4 827 | -13 037 | -6 650 |
| Increase proportion | -14.3% | -4.41% | -1.33% | 2.89% | -26.41% | -2.15% | -3.37% |

The results of the above table show that the model in this paper can reduce the number of departure pairs, train purchase cost and running kilometres cost to meet the needs of passengers, so as to reduce the operation cost of enterprises. In addition, the solution of the model also reduces the travel cost of passengers, thus reducing the total cost by 3.37%.

#### 6.3.2. Sensitivity analysis of passenger flow structure

The chapter 3 of this paper shows that passengers with different travel purposes have different choices of travel routes. This section analyzes the results of the proportion of passengers with different travel purposes on the train routing.
The proportion of commuting, leisure and business office is 0.38, 0.35 and 0.27 respectively in the case line. But in this section, we study how the routing plan changes when passenger flow construction changes. We let passenger flow with commuting, leisure and business purpose as the main passenger flow separately, assuming that the proportion of passenger flow in the three cases is 6:2:2, 2:6:2 and 2:2:6 respectively, and get the optimal traffic results as follows.

Table 10. Optimal Routes with Different Passenger Flow Structures

| Main Passenger | Routing   | Frequency /hour | Purchase | Operating | In vehicle | Waiting | Transfer | Total cost |
|----------------|-----------|-----------------|----------|-----------|------------|---------|----------|------------|
| Commuting      | 1-30      | 16              | 4 045    | 60 620    | 575 261   | 98 278  | 113 345  | 201 109    |
|                | 4-17      | 8               |          |           |            |         |          |            |
|                | 11-25     | 8               |          |           |            |         |          |            |
| Leisure        | 1-30      | 20              | 3 830    | 59 562    | 591 508   | 94 537  | 13 424   | 190 607    |
|                | 4-25      | 10              |          |           |            |         |          |            |
| Business       | 1-25      | 12              | 3 580    | 57 843    | 592 224   | 116 620 | 67 452   | 193 598    |
|                | 4-30      | 12              |          |           |            |         |          |            |

It can be seen that when the main passenger travel purpose of the line is commuting, the optimal combination of routes is three routes, at which time the departure frequency is the largest and the passenger's travel time is the shortest; when the line is dominated by leisure passengers, the optimal route is two direct routes, at which time the line's travel time is the shortest; when the line is dominated by business passengers, the total departure pairs and the enterprise cost is the least.

7. Conclusion
In this paper, the optimal routing plan obtained by the model is compared with the actual routing plan. It is found that both the optimal routing plan and the actual routing plan of the model have direct routing, which is determined by the passenger flow characteristics of the line. At the same time, the total cost of the model results is 3.37% lower than the total cost of the actual routing plan, which verifies the effectiveness of the model results. In addition, this paper obtains the optimal results by changing the proportion of passengers with different travel purposes, and finds that the optimal results are also different, which verifies the effectiveness of the passenger flow distribution model.

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