A Model Layout Region Optimization for Feeder Buses of Rail Transit

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Abstract

This paper analyses the characteristics of urban rail transit and conventional buses and then expands on the necessity of combining them. Based on previous studies, a method of laying region and route of urban rail transit feeder buses is proposed. According to the definition of marginal trip distance which is the boundary of choosing a direct bus or rail-feeder bus (transfer is considered here) to destination, the influence of service level on passenger’s choosing behavior is combined with the generalized trip cost in the indirect gravitation-regions of urban rail transit. On this basis, a model for layout region of feeder buses is constructed and an algorithm is proposed. Finally, a numerical example of the joining routine layout between urban rail transit and conventional buses in Baiyun District, Guangzhou City, China is presented to evaluate the model. The result shows that the model with high accuracy is easy to apply, and is the important basis for laying design of feeder buses.

1. Introduction

Urban rail transit with several advantages like high capacity, high speed and timely and efficient service is playing an important role in public transportation system in recent years. However, there are still a lot of limitations in rail transit system, such as high construction costs, high requirements for...
technology and environment, and low covering rate etc. From another point of view, the conventional public transit network can travel from streets to streets and provide door to door service. Therefore, it is necessary to combine both transit systems above to not only improve the efficiency and attractiveness of the whole public transportation system, but also make the access of residents more easily.

Urban rail transit feeder bus has been a research hotspot in the past several years. Salzbom constructed a mathematical model to calculate the feeder bus service frequency back in 1972. Lee and Schonfeld proposed an opportunity model in 1991 which considered delay time. Vuchic proposed an effective way to determine the structure of feeder bus network according to maximum passenger transport demands (Vukan R Vuchic, 2004). Martins and Pato summarized the number of lines and layout method of rail transit feeder bus, and proposed an optimization algorithm of line layout (Martins CL, Pato MV, 1998). In 2006, Kuan introduced a heuristic genetic algorithm to solve the N-P problem of bus network optimization (Kuan S N, Ong H L, Ng KM, 2006). In general, most of these studies focus on minimizing passenger waiting time and optimizing departure plan to solve feeder bus route layout and network optimization problems. There is a great significance to coordinate the operation of rail transit with feeder bus. But there are fewer studies about the layout of connecting region and lines, only Xue Xingjian proposed a model for layout region of feeder bus of rail transit. Based on the attraction area of rail transit, it discussed the process and idea of feeder bus layout for a new rail transit station. However, in these researches, it is found that there are some problems in parameter selection and calibration. In this study, the impact of service level on passenger transfer choice is considered. And a numerical example of the joining route layout between rail transit and conventional bus in Guangzhou-baiyun area is presented to demonstrate the improvements and modifications of the previous model. The results indicate that the model can provide desirable layout designs that meet the real-world conditions.

2. Definition of layout region for connecting line of rail station

The conventional rail-feeder bus system is using rail transit skeleton network as a center, rail transit and bus transfer junction stations as nodes that exhibits as a fishbone structure. In this system, when passengers choose transfer stations, they want the trip cost as small as possible. Therefore, their choice is the best layout combination of rail transit and conventional bus. The area where all the travelers choose a station is the layout region for connecting line of this station. The layout region of each rail station is overlapped. This is because passengers use rail travel in two directions, and at the same position, distinct directions correspond to different transfer stations so that they take different feeder lines.

3. Improved marginal trip distance

In The Study on the Urban Rail Transit Feeder Bus Routes Optimization, Xue Xingjian defined marginal trip distance as traveling by different traffic modes but with the same trip cost. This paper mainly studies the marginal trip distance between direct bus and rail-feeder bus (transfer is considered here). The conventional bus network is flexible, suitable for short trip and with high density. The rail transit is mainly responsible for medium and long distance transportation, and gradually embodies its superiority as the distance increases. When trip distance is shorter than the marginal distance, the trip cost of rail-feeder bus is greater than direct bus. Only when the travel distance is longer than the marginal trip distance, it has priority in attracting passenger flow. The relationship is shown in Fig. 1.

The marginal trip distance model of direct bus and rail-feeder bus (transfer is considered here) is,

\[ F_{t1} = F_{t2} \]  

where \( F_{t1} \) —— trip cost of conventional public transit; \( F_{t2} \) —— trip cost of feeder bus transit transfers to rail transit.
When trip distance is the marginal trip distance, the trip cost of rail-feeder bus equals direct bus.

In the above definition of marginal trip distance, trip cost, namely generalized trip cost is the major factor considered within. The trip cost includes time cost and money cost, where money cost is direct cost and time cost equals the total time spent on transferring and another traffic mode after transferring minus the total time without transferring. However, passengers who choose transfer manners not only consider generalized trip cost but also comfort level and time. The comfort level together with time and cost, formed the service level of transfer modes. And it is also one of the modern passenger requirements in transportation system. Therefore, this paper will discuss comfort level when calculating generalized trip cost.

Most urban bus fare is the same through the whole journey nowadays, while rail transit fare is consist of start-price and distance-price. Established trip cost model of conventional public transit by considering the value of passengers distribution time and trip time and corresponding comfort index is shown below.

$$ F_{T_1} = T_w E \alpha + \frac{D}{v_f} E \beta + a + C_i $$  \hspace{1cm} (2)

Trip cost model of feeder bus transferring to rail transit is:

$$ F_{T_2} = (T_w + T_r + T_d) E \alpha + \left( \frac{\lambda D}{v_f} + \frac{(1-\lambda)D}{v_r} \right) E \beta + a + b + [(1-\lambda)D - s] \delta + C_2 $$  \hspace{1cm} (3)

where,

- $E$ —— unit time value, yuan/h;
- $E = 6z$, $z$ denotes monthly income of passengers, the unit is thousand yuan;
- $T_w$ —— passengers’ distribution time;
- $T_r$ —— passengers transfer walking time;
- $T_d$ —— passengers transfer waiting time;
- $D$ —— passengers travel distance;
- $v_f$ —— operational speed of conventional public transit;
- $v_r$ —— operational speed of urban rail transit;
- $\alpha$ —— time value factor of walking and waiting, this paper assumes $\alpha = 1$;
- $\beta$ —— time value factor of riding, this paper assumes $\beta = 0.5$;
- $a$ —— bus fare;
- $b$ —— start-price of urban rail transit;
- $\lambda$ ——the ratio of travel distance and total travel distance of conventional public transit, namely the
travel distance of conventional public transit is $\lambda D$ and the travel distance of subway is $(1-\lambda)D$ in the process of rail transit transferring to feeder bus transit;

- $\delta$ —— unit km fare of urban rail transit;
- $s$ —— start-distance of urban rail transit;
- $C_1$ —— passengers direct-comfort level of conventional public transit;
- $C_2$ —— passengers direct-comfort level of feeder bus transit transferring to rail transit.

Simultaneously, the result by substituting formula 2 and formula 3 into formula 1 is:

$$T_w E\alpha + \frac{D}{v} E\beta + a + C_1 = (T_w + T_v + T_d) E\alpha + \left(\frac{\lambda D}{v_f} + \frac{(1-\lambda)D}{v_r}\right) E\beta + a + b + [(1-\lambda)D - s] \delta + C_2$$

(4)

By simplification, the solution is:

$$D = \frac{2[(T_v + T_d)E + b + C_2 - C_1 - s\delta]}{(1-\lambda)(\frac{E}{v_f} - \frac{E}{v_r} - 2\delta)}$$

(5)

Equation (5) is the formula of improved marginal trip distance.

4. Layout region model

4.1. Objective

The objective of layout region model for feeder bus of rail transit is to minimize passenger travel time. As shown in Fig. 2, for the sake of simplicity, only two destinations are considered here including the starting point (O) and finishing point (D) on the line. Suppose passengers from different feeder stations spend the same distributed time and transfer time. Hence, the objective is to minimize riding time including feeder bus time and rail time.

Fig. 2. Schematic diagram of bus feeder underground subway
Assume $t_A, t_B$ and $t_C$ are the minimum riding times for passengers to transfer at station A, B and C respectively. If they satisfy the conditions in Equation (6), passengers will choose to transfer at station B, that is, feeder bus connects station B.

$$t_B \leq t_A, t_B \leq t_C$$  \hspace{1cm} (6)

### 4.2. Model construction

Based on previous analysis, layout region model for feeder bus of rail transit is constructed. A passenger at point $P_i$ wants to take the metro from station $j$ to destination $G_k$. The travel time is the shortest time of all paths from station $j$. $A$ is the collection of all rail station sites, then:

$$\min t_j = t_{p, R_j} + t_{p, R_k}, j \in A$$  \hspace{1cm} (7)

$$t_{p, R_j} = \frac{l_{p, R_j}}{v_j}$$  \hspace{1cm} (8)

$$t_{p, R_k} = \frac{l_{p, R_k}}{v_r}$$  \hspace{1cm} (9)

$$l_{p, R_j} = c l_{ij}$$  \hspace{1cm} (10)

$$ST_j = l_{p, R_j} + l_{p, R_k} \geq \frac{2[(T_v + T_d)E + b + C_2 - C_1 - s \delta_k]}{(1 - \lambda)(E/v_j - E/v_r - 2 \delta)}$$  \hspace{1cm} (11)

where, $t_{p, R_j}$ — riding feeder bus time;

$t_{p, R_k}$ — riding urban rail transit time;

$l_{p, R_j}$ — riding feeder bus distance in km;

$l_{p, R_k}$ — riding urban rail transit distance in km;

$l_{p, R_j}$ — the shortest distance from point $i$ to station $j$, in km;

$c$ — non-linear coefficient;

$\delta_k$ — destination, $k = 1, 2$, that is, origin-destination OD.

The distance of feeder bus transferring to rail transit must be longer than marginal travel distance to ensure that trip cost is smaller than the trip cost of transferring to conventional bus directly.

### 4.3. Algorithm

1. Initialization. According to the definition of primary and secondary attracting range, the whole area is divided into a 500 m by 500 m square for unit grid. Number each grid vertex as $n$ verities, $p_1, p_2, p_3, \ldots, p_n$. Assume $R_j$ represents the metro station $j$, and there are $m$ stations in total, numbered $R_1, R_2, R_3, \ldots, R_m$. $\delta_k$ is the trip destination as the origin and destination on the rail line. Take $S_j$ as layout region of station $j$. 


2. Set $i=1$, $k=1$.
3. Create a satisfactory function $F_j(p_j)$ for layout region of station $j$.
4. According to formula 7-10, calculate $t_1, t_2, t_3 \ldots t_m$.
5. Set $t_j = \min \{t_1, t_2, t_3 \ldots t_m\}$.
6. According to formula 11, if $t_j$ meets condition constraints, then return $F_j(p_j)=1$, otherwise set $F_j(p_j)=0$.
7. When $i=2$, execute the next step, or $k=k+1$, and go to Step 3.
8. When $i=n$, executed the next step, or $i=i+1$, and go to Step 3.
9. Find out all points which satisfy $F_j(p_j)=1$.

Fig. 3. Divide study area

Fig. 4. Schematic diagram of line
5. Example

A numerical example with respect to urban rail transit and bus in Baiyun District, Guangzhou is presented to verify the accuracy of proposed model and algorithm. Baiyun District operated two rail transit lines in 2010 including the northern extension of Metro Line 3 and the southern extension of Metro Line 3. Suppose a passenger near Yongtai Bus Station wants go to Guangzhou Railway Station which is on the metro line 2 and 5.

By field investigation and analysis and combining relevant data together, approximate values are given to parameters as:

- Operational speed of Guangzhou-baiyun conventional public transit is \( v_f = 0.25 \) km/min;
- Operational speed of Guangzhou Metro Line 2 is \( v_r = 0.58 \) km/min;

According to the ‘code for transport planning on urban road (GB 50220-95)’, the nonlinear coefficient of public transport route and the average nonlinear coefficient on the all network should not be more than 1.4. This example takes \( c = 1.2 \).

Guangzhou conventional bus fare is 2 yuan for the whole journey;

In Guangzhou, metro passengers will pay an initial 2 yuan within 4 kilometers and increase 1 yuan for every 4 kilometers after that. Fares will increase by 1 yuan for every 6 kilometers after travelling 12 kilometers, and 1 yuan for every 8 kilometers after 24 kilometers. Therefore, in this study \( b = 2 \) yuan, \( s = 4 \) km, \( \delta = 0.25 \) yuan/km;

Monthly income of a Guangzhou-baiyun resident is 4 thousand yuan;

Passengers distribution time equals 10 minutes.

Passengers may choose to transfer at Jiahe Wanggang or Huangbian. The data are shown in the table below.

The marginal trip distance is calculated as 12 kilometers. The trip distance of this example is more than 12 kilometers so that the trip cost of rail—feeder bus (has one transfer) is smaller. Rail-feeder bus (has one transfer) is more comfortable than direct bus and the quantization is \( C_1-C_2 = 1 \) yuan.

Jiahe Wanggang and Huangbian are all in the metro line 2 and can reach Guangzhou Railway Station directly. When passengers choose to transfer at Jiahe Wanggang, the travel time is 28 minutes compared with 29 minutes at Huangbian. So this region should feeder to Jiahe Wanggang.

The results are close to practical survey data. In fact, Guangzhou has established a feeder bus line between Yongtai Bus Station and Jiahe Wanggang, which demonstrates that the model result is reliable.

6. Conclusions

Urban rail transit feeder buses are necessary for the sustainable development of urban transit systems. Based on previous research results, especially Xue Xingjian’s study, this paper further improves the proposed layout region model. Besides calculating the marginal trip distance on the basis of generalized trip cost, the passenger comfort level is added. Additionally, the fare is valued according to the real world. The operational speed of conventional public transit and urban rail transit are recalculated as well. When residents’ travel distance is greater than the marginal trip distance, the generalized trip cost of taking metro transferring from feeder-bus is less than the direct bus.
Based on the idea of minimizing passenger travel time, this paper establishes a layout region model for feeder buses. A numerical example of the joining routine layout between urban rail transit and conventional buses in Guangzhou-baiyun is presented to demonstrate the improvements of previous model.

Due to the limitation of data, this paper did not consider the effect of OD distribution and the operation cost of feeder buses etc. Future studies are oriented to combine OD distributions to optimize bus network and improve the benefit of rail transit and feeder buses.

References


