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Comparative Study on the Vehicle Model of Demand-Responsive Feeder Bus

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Abstract: Demand-responsive feeder bus is a new operation mode of public transport, which is guided by passenger demand and provides door-to-door customized travel services. The number of passengers that need to be served at the same time on a bus, which is often decided by vehicle model, is a key parameter that determines the level of bus service. An analytical model of demand-responsive feeder bus was built to analyze the different bus models under certain passenger flow. Given a certain passenger flow, the required number of vehicles, passenger travel time and the vehicle travelled miles are compared and analyzed with different bus models. The numerical analysis shows that larger bus is more economic in vehicle travelled miles while passengers will experience longer travel time. The result may provide a reference for the public transport agencies deciding which model of vehicle to deploy that better balances the user cost and operating cost.

1. Introduction

In recent years, urban rail transit such as metro and light rail has been continuously developing and improving. Rail transit stations, however, usually may not be conveniently located for all passengers and the gap between the rail station and the passengers' final destinations exist, which is the so call "first/last mile" problem. Feeder buses are an important transportation mode for rail transit to deal with the problem, and their operation mode is mainly based on fixed-route transit (FRT), providing fixed-point and fixed-route bus services, thereby forming economies of scale. However, in comparison, it still lacks convenience and flexibility[1], and can only partially solve the shuttle problem of the "first/last mile". Demand-responsive transit (DRT) is a new type of public transportation operating mode that provides customized door-to-door bus services for passengers. It does not have fixed routes, stops, and timetables, but formulates scheduling plans and vehicle routing plans based on the demand of passengers[2]. It can provide door-to-door travel services for passengers, and also has the intensification advantages of public transportation, with great development prospects.

Recent studies on DRT feeder bus mainly focus on the vehicle routing problem. Many algorithms are proposed such as column generation algorithm[3], neighborhood search algorithm[4], adaptive genetic algorithm[5], and collaborative ant colony algorithm[6].The number of passengers that need to be served at the same time on a demand-responsive transit bus is also a key parameter that determines the level of bus service[7]. Since demand-responsive transit requires individual service for each passenger, if the number of passengers is too large, the total time required for service will be too long, leading to a decrease in the passenger experience. If the number of passengers is too small, the intensification of the transit system will be too poor, leading to a decrease in economic efficiency. Therefore, when planning demand-responsive transit, appropriate vehicle models should be selected, and the number of vehicles should be further determined based on the passenger capacity and passenger flow. In this paper, by establishing an analytical model of demand-responsive feeder buses, the number of vehicles required for different vehicle model choices and corresponding passenger travel time under certain passenger flow conditions is quantitatively compared. The vehicle travelled miles are also calculated as an index referring to energy consumption and operator cost. The model can provide a reference for public transportation planning.

2. Demand-Responsive Feeder Bus Modelling

2.1. Assumptions of DRT

As shown in Figure 1, the service area of the demand-responsive feeder bus is a rectangular zone with a length of L and a width of W, located on the right side of the rail station and at a distance of r from the rail station. The demand-responsive feeder bus operates between the rail station and the service area. Internal trips within the service area are not considered, only external trips passing through the rail station are considered. The demand density for travel per unit of time is ρ, which is uniformly distributed in time and space. The demand for travel from the service area to the rail station is equal to the demand for travel from the rail station to the service area, both of which are 0.5ρ. The average operating speed of the feeder bus is vb, the average dwelling time at a point is ts, the capacity of a vehicle is n0, and the number of vehicles in the fleet is Nb.

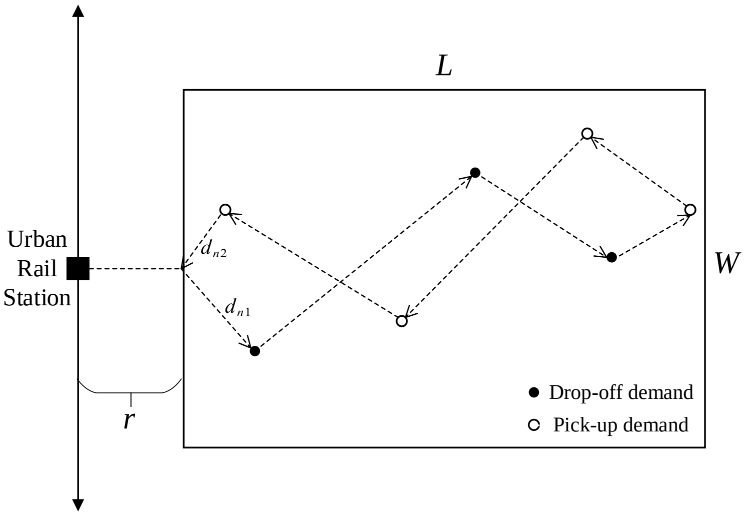

Figure1: Service area and DRT service policy

The feeder bus uses the rail station as a parking lot and adopts a "pick-up and drop-off separation" mode to shuttle back and forth. After loading n0 passengers who have arrived at the rail station, the feeder bus heads towards the service area, first visiting the nearest drop-off point, and then always selecting the nearest drop-off point as the next destination for each subsequent visit. After visiting n0 drop-off points one by one, the vehicle will head to the nearest pick-up point, then follow the strategy of selecting the nearest demand point as the next destination and visit n0 pick-up points one by one before returning to the rail station.

2.2. Modelling DRT

Every vehicle would allocate n0 passengers, therefore the headway of the bus can be formulated as:

$$h = \frac{2n_0}{\rho LW} \tag{1}$$

According to the Reference[8], a demand-responsive vehicle will travel the following total distance to serve n0 passengers:

$$D = \varphi\sqrt{LWn_0} \tag{2}$$

Among it, the value of φ is relevant to the shape of the service area and road network

A vehicle will go through the distance of S and the time of C in a circulation of departing the rail station, finishing the drop-off service and pick-up service sequentially and returning to the rail station.

$$S = 2r + 2D = 2r + 2\varphi\sqrt{LWn_0} \tag{3}$$

$$C = \frac{S}{v_b} + 2n_0 t_s = 2\left(\frac{r + \varphi\sqrt{LWn_0}}{v_b} + n_0 t_s\right) \tag{4}$$

The relationship between circulation time, headway and the number of vehicles is formulated as:

$$h = \frac{C}{N_b} \tag{5}$$

With the eqs. (1), (4), under a certain vehicle model(n0) and certain passenger demand ρ, the minimum number of vehicles should satisfy the formula:

$$N_b = \frac{\rho LWr}{v_b n_0} + \frac{\varphi\rho(LW)^{1.5}}{v_b\sqrt{n_0}} + \rho LWt_s \tag{6}$$

Further, calculate the average passenger travel time with the minimum number of vehicles. The travel time includes waiting time and riding time. The average waiting time is often represented by half of the headway.

$$T_{wt} = \frac{h}{2} = \frac{n_0}{\rho LW} \tag{7}$$

As for the riding time, the ith passenger to be dropped-off will has a riding time of:

$$t_{i,1} = \frac{r + \frac{i}{n_0}D}{v_b} + (i-1)t_s = \frac{r}{v_b} - t_s + \left(\frac{\varphi\sqrt{LW}}{\sqrt{n_0}v_b} - t_s\right)i \tag{8}$$

So, for the n0 passengers to be dropped-off in a vehicle, their average riding time is:

$$T_{rd,1}=\frac{1}{n_0}\sum_{i=1}^{n_0}t_{i,1}=\frac{r}{v_b}-t_s+\frac{(1+n_0)}{2}\left(\frac{\varphi\sqrt{LW}}{\sqrt{n_0}v_b}-t_s\right) \tag{9}$$

The ith passenger to be picked-up will has a riding time of:

$$t_{i,2}=\frac{r+\frac{n_0-i}{n_0}D}{v_b}+(n_0-i-1)t_s \tag{10}$$

Let j=n0-i, the formula will has the similar expression as the eqs.(8), and therefore the average riding time for the n0 passengers to be picked-up in a vehicle can be written like the eqs. (9):

$$T_{rd,2}=\frac{1}{n_0}\sum_{j=1}^{n_0}t_{j,2}=\frac{r}{v_b}-t_s+\frac{(1+n_0)}{2}\left(\frac{\varphi\sqrt{LW}}{\sqrt{n_0}v_b}-t_s\right) \tag{11}$$

The total picked-up demand and dropped-off demand are equal, so the average riding time of all passengers is:

$$T_{rd}=\frac{T_{rd,1}+T_{rd,2}}{2}=\frac{r}{v_b}-t_s+\frac{(1+n_0)}{2}\left(\frac{\varphi\sqrt{LW}}{\sqrt{n_0}v_b}-t_s\right) \tag{12}$$

Waiting time and riding time should have different time values. According to Reference[9], a weight of 2:1 is chosen between them, and the average travel time for passengers is obtained as:

$$T=2T_{wt}+T_{rd} \tag{13}$$

2.3. Numerical Analysis

This article chooses three typical models of vehicle commonly used in DRT, namely, small minivans (n0=5); large minivans (n0=10); and mini buses (n0=15). Different models are assumed to have the same speed. In real cities, the grid-like road network is the most common structure. Therefore, according to Reference[10], φ is set to 0.64. Other parameters example are shown in Table 1.

Table 1: Parameter values in numerical example

Notation and symbol	Value	Unit
Length of service area L	2	km
Width of service area W	1.5	km
Distance between r	1	km
Operating speed of vehicles Vb	20	km/h
Dwelling time ts	30	s
Travel demand density ρ	10~50	passengers/km2/h

According to eqs.(6)，the minimum required number of vehicles under different travel demand densities when deploying different vehicle models is obtained. The results rounded up to the nearest integer are shown in Figure 2. When using the same vehicle, the higher the travel demand, the higher the number of vehicles required. At the same level of travel demand, the larger the vehicle, the fewer vehicles are required.

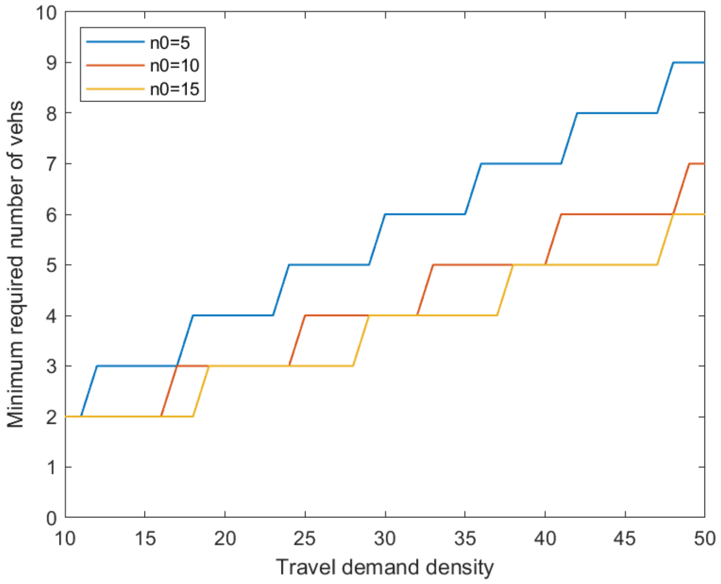

Figure 2: Vehicle requirement versus travel demand for different models

According to eqs. (13), the average travel time for passengers when the minimum number of vehicles is deployed at different travel demand densities is obtained, as shown in Figure 3. The average travel time for passengers decreases as the travel demand density increases. This is because according to eqs(7), the higher the travel demand, the more frequent the vehicle departs, and the waiting time for passengers decreases. Since each vehicle carries a fixed number of passengers, the in-vehicle riding time does not change with demand density.

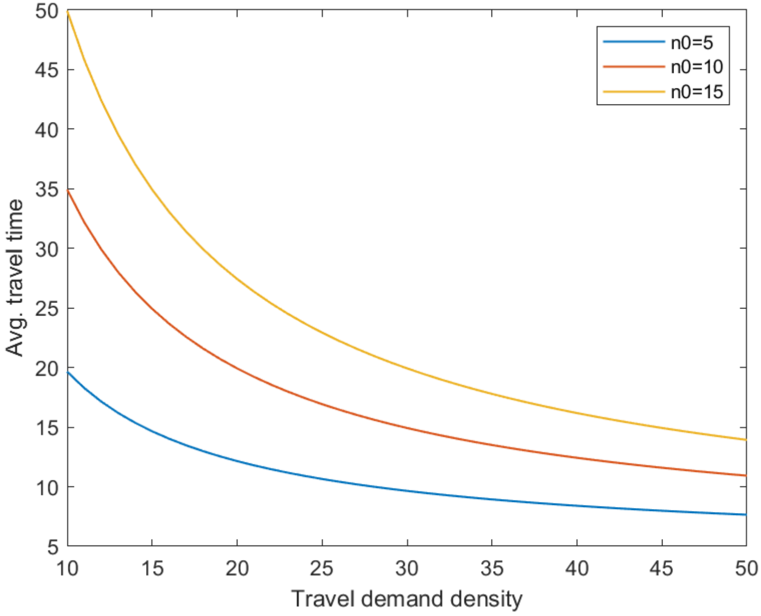

Figure 3: Avg. travel time versus travel demand in minimum vehicle requirment

From the above calculation results, under the same travel demand density, a smaller passenger capacity vehicle means that more vehicles need to be deployed, but the passenger travel time is lower. When using the same vehicle model, since the number of passengers carried by each vehicle is the same, the average riding time inside the vehicle is also the same. According to eqs.(9), the passenger riding time of the three vehicle models can be calculated and shown in Table 2, and the results show that larger vehicle models significantly increase passenger riding time inside the vehicle.

Table 2: The avg.riding time for passengers in different vehicle model

Capacity(n0)	Avg. riding time(min)
5	4.65
10	10.93
15	13.93

The vehicle runs a cycle and serves a total of 2n0 passengers. According to eqs.(3), the vehicle travelled miles(VMT) is used as the energy consumption index, and the per capita energy consumption of these passengers receiving bus services is S/2n0. The calculation results for different vehicle models are as Table 3. Larger car models result in longer passenger travel time, but also in exchange for smaller energy consumption.

Table 3: The per capita energy consumption for passenger in different vehicle model

Capacity(n0)	Per capita energy consumption (km)
5	0.67
10	0.45
15	0.36

3. Conclusion

This paper built an analytical model to compare the required number of vehicles when deploy different vehicle models in the demand-responsive feeder bus, and also compare the corresponding level of service and energy consumption level of the bus system. Quantitative analysis is carried out through a numerical example, and the results show that if vehicle with a larger passenger capacity is used, the number of vehicles invested can be reduced, and at the same time lower per capita energy consumption can be obtained, but the travel time of passengers will be longer; smaller vehicle will result in more vehicles input, energy consumption per capita, but travel time will be significantly reduced.

According to the model proposed in this paper, the public transport management department can easily calculate the vehicle investment, operating energy consumption and service level when choosing different models, so as to achieve a better balance among the three.

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