Research on Operation Cost in Urban Transportation System Based on Stopping Distance and Vehicle Density

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***Abstract*—The route spacing, stopping distance and vehicle density of transportation network are all important variables that affect the operation cost and automobile exhaust emission of urban transportation system. This paper will consider the relationship between the operating cost of the traffic system and the emission of automobile exhaust. We try to explore how the stopping distance and vehicle density affect the operating costs and exhaust emissions of the automobile in an ideal traffic network and discuss about the possibility that the cost change will be controlled within a certain range when the stopping distance is increased or reduced by 100 meters in a certain range under certain vehicle density, as well as the highest change in automobile exhaust emissions.**

***Index Terms*—exhaust emission; stopping distance; operation cost; transportation network**

I. INTRODUCTION

In a comprehensive traffic survey of Beijing, the survey shows that a bus trip takes 42.6 minutes in the bus, while the time taken outside the bus takes 23.6 minutes (including 15 minutes' walk to the bus stop, 8.6 minutes' waiting for the bus and transfer). Corresponding travel time for different modes of travel are shown in figure 1. [1,2] Therefore, how to optimize roads and parking spaces, reduce user travel costs and reduce operation costs in urban transportation system is worth studying and is of practical significance.

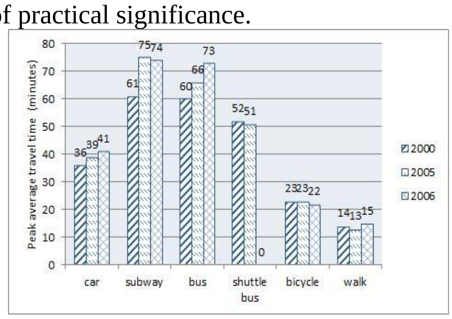

Figure 1. Average time of different transportation.

Stopping distance refers to the distance between any two adjacent points among the spots of bus stations and traffic lights. The operation cost of the urban transportation system is diversified in composition. Table 1 shows the main elements of the composition of operating costs.

Table 1. Composition of operation costs [3-6].

Terms	Personal	Social
Cost categories	Actual payment; Unseen costs	Pollution; Traffic accident; Traffic jam cost; City development
Cost constitution	Cost for vehicles, gas, pass, parking; Time cost	Noise, air pollution, global warming; Health, production; administration; Other costs; City development

The operation cost and vehicle exhaust volume of urban transportation system is closely related to the speed of the vehicle, which is restricted by the stopping distance and the vehicle density that measures the size of the city and the automobile ownership. This paper will discuss how to choose the appropriate stopping distance and control the appropriate vehicle density, so that the operation cost and exhaust emissions of urban traffic will be controlled within some acceptable range or at the minimum. And we will focus on how to select the effective values of stopping distance and vehicle density, so that the total cost of transportation system will be controlled within a certain range when exhaust emissions are limited to a certain value.

II. ESTABLISHMENT OF OPERATION COST AND EXHAUST EMISSION MODEL OF URBAN TRANSPORTATION SYSTEM

A. *Relationship between Automobile Speed, Stopping Distance and Vehicle Density*

ν is used to indicate the vehicle velocity (km/h), S is used to indicate the stopping distance (km) and ρ is used to indicate the vehicle density (automobile/km).

In all kinds of traffic engineering documents, the relationship between traffic flow (vehicles passing through a road section within a unit time), speed ν and traffic density ρ are all basic assumptions:

$$Q = v * \rho$$

From this, we can see that when the bearing capacity of a road is limited, that is, when the traffic flow Q is fixed, the vehicle velocity ν is inversely proportional to the traffic density ρ. When the vehicle density is 100~150 vehicles/km, and the speed is between 50 and 70 km/h, the flow rate is the greatest.

The larger the parking distance s is, the larger the vehicle velocity ν will be. Based on the simple consideration, we assume that the vehicle velocity is in direct proportion to the parking distance. In this way, we get a simple model of the relationship between vehicle velocity, stopping distance and vehicle density, which is as follows:

$$v = k\frac{s}{\rho} \tag{1}$$

k is the ratio coefficient.

B. *Establishment of Operation Cost and Exhaust Emission Model of Urban Transportation System*

We consider a simplified urban area where the network structure of the urban road is simple rectangular, as shown in figure 2:

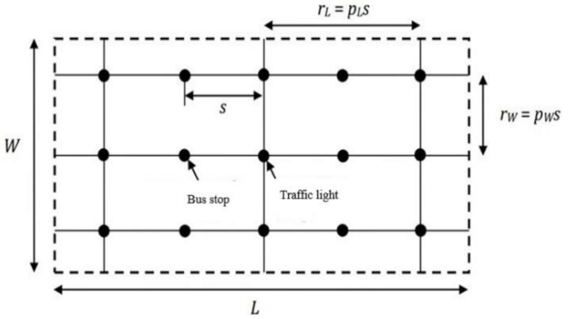

Figure 2. Network structure of urban road.

The network of the urban transportation system is composed of two parallel lines, which are in consistent span r_L and r_W. We assume that $r_L = r_W$, the length L and width W of the span combination form the scale of the city. The distance between parking sites, namely the parking distance, is S, and the span is an integer multiple of the parking distance, that is, $r_L = p_L S$, $r_W = p_W S$. It is assumed that $p_W = p_L$. The distance between buses for each route is H. We also assume that passengers' travel starting points are evenly distributed throughout the city, that is, the travel demand density is the same at every point in the city. Each passenger arrives at the nearest parking site by walking. The travel ways of passengers include automobile (including private cars and taxis), bus and Bus Rapid Transit (BRT). Automobiles may not need to get to the parking site first before traveling, and we don't pay attention to these details. When the data is processed, the appropriate data can be selected. Chen et al. [7-9] compiled cost parameters from a large amount of American data, and Wang and Chen [10-16] also sorted out data on parameters of vehicle exhaust emissions (greenhouse gas carbon dioxide as the main object). We give parameters as shown in Tables 2 and 3 in combination with the actual situation in China.

Table 2. Urban Model Parameters.

Parameters	Description	Value
$L(km)$	Length of urban area	30
$W(km)$	Width of urban area	30
$\delta(pax/km^2-hr)$	Demand density	200
$v_a(km/hr)$	Passengers' walking velocity	5
$\mu(\$/hr)$	Passengers' time value	10

Table 3. Model parameters.

Parameters	Description	Bus	Car	BRT
$v(Km/h)$	Speed	--	--	40
$\tau(Sec)$	Wait delay time	30	0	30
p	Factor	2	1	2
$Tr(Sec)$	Transfer delay time	20	0	30
$H(Min)$	Bus time interval			
$c_1(\$/km-hr)$	Road cost	10	5	270
$c_V(\$/veh-km)$	Gas cost	0.6	0.5	0.66
$c_M(\$/veh-hr)$	Labor cost	65	50	85
$c_S(\$/st-hr)$	Construction cost	1	0	7
$E_1(g/km-hr)$	Tail gas cost	0	0	1100
$E_V(g/veh-hr)$	Operation gas cost	1500	1500	1500
$E_M(g/veh-hr)$	Traffic gas cost	2600	2600	2600
$E_S(g/st-hr)$	Infrastructure gas cost	0	0	1700

Looking for an analytic expression of operation cost and system gas emission expression of urban transportation system, we can estimate and compare the influence of the level of transportation system service and exhaust emissions on the environment. In the choice of traffic mode, we do two comparisons. The first is the comparison between bus and automobile, and the endogenous determinants are the stopping distance S and vehicle density ρ. The second is the comparison between the bus and BRT, and the endogenous determinants are the headway H and stopping distance S.

The total cost of the urban transportation system can be expressed as the sum of the passenger cost and the agency cost. The passenger cost is composed of the expected visit and waiting time cost and the expected trip time cost in the vehicle, which is multiplied by the total passenger demand $(D = \delta L^2)$ and the wage level (μ, namely Passengers' time value). The agency costs are composed of road infrastructure costs, fleet size and labor costs, fuel and maintenance costs, and site infrastructure costs. We have the total cost formula of the urban transportation system [17-19]:

$$\begin{aligned} C = &\left(\frac{(0.5r_L + 0.5r_w + s)}{2v_a} + H + Tr + (L+W)\left(\frac{1}{3v} + \frac{\tau}{3s}\right)\right)\mu D \\ &+ \frac{2LW}{ps}C_1 + \frac{4LW}{psH}C_V + \frac{4LW}{psH}\left(\frac{1}{v} + \frac{\tau}{s}\right)C_M + \frac{2LW}{ps^2}C_S \end{aligned} \tag{2}$$

Where, we can know Passenger cost = $\left((0.5r_L+0.5r_w+s)/2v_a+H+Tr+(L+W)(1/3v+\tau/3s)\right)\mu D$, road infrastructure cost = $2LWC_1/ps$, maintaining and fuel cost = $4LWC_V/psH$, sum of fleet size and labor cost = $4LWC_M(1/v+\tau/s)/psH$, stop infrastructure cost = $2LWC_S/ps^2$.

Agency costs = road infrastructure cost + maintaining and fuel cost + fleet size + labor cost + stop infrastructure cost.

The most typical measure of automobile exhaust emission is that the greenhouse gas carbon dioxide is the representative and the main object. It can be simply considered that, in case of a large amount of carbon dioxide emissions, it means that the exhaust gas of automobiles is not well treated, and other harmful gases, such as nitrogen oxides and fine particles, will also emit more. It can be considered that the emission of carbon dioxide is directly proportional to the emission of other harmful gases. In this way, we use carbon dioxide emissions as a measure of automobile exhaust emissions. As a result, as the total cost of the transportation system, we can imitate the total gas emission formula as follows [20]:

$$E=\frac{2LW}{ps}E_1+\frac{4LW}{psH}E_V+\frac{4LW}{psH}\left(\frac{1}{v}+\frac{\tau}{s}\right)E_M+\frac{2LW}{ps^2}E_S \tag{3}$$

C. Cost Model and Gas Emission Model of Bus and Automobile

Buses and automobiles run directly on competing roads. The speed of running affects the operation cost and exhaust emissions of vehicles. The driving speed of the automobile is mainly determined by the stopping distance and the vehicle density. Therefore, we apply the above formula (1) to the formulas (2) and (3) and put the corresponding parameter values of Tables 2 and 3 into the formulas (2) and (3). The headway H of bus is 5min. the stopping distance H and delay time of transfer Tr are meaningless for automobiles, so H = 0 and Tr = 0. The following formula is obtained:

$$C_{Bus}=5.4\times10^5 s+\frac{7200\rho+321960}{s}+\frac{280.8\rho+12600}{s^2}+1.6\times10^5 \tag{4}$$

$$C_{Car}=3.6\times10^5 s+\frac{7200\rho+30600}{s}+\frac{432\rho}{s^2} \tag{5}$$

$$E_{Bus}=\frac{3.24\times10^6}{s}+\frac{11232\rho+46800}{s^2} \tag{6}$$

$$E_{Car}=\frac{6.48\times10^6}{s}+\frac{22464\rho}{s^2} \tag{7}$$

Where, C_{Bus} is buses' operating costs, C_{Car} is cars' operating costs , E_{Bus} is buses' off-gas discharge, E_{Car} is cars' off-gas discharge ($1/H$ refers to number of vehicles setting out per hour. As for cars, $1/H$ for (H = 0) means number of cars setting out per hour.)

Cost and gas emission models of the bus and BRT:

BRT is a new type of vehicle with the exclusive right of way. That is, it does not share the lane with other vehicles, but the city specializes in its exclusive driveway, so the vehicle density has no effect on it. So we directly assign the velocity v a value. It is set as $v_{Bus}=30$, and using the parameters in Tables 2 and 3, we get the specific formula of cost and gas emission for bus and BRT:

$$C'_{Bus}=5.4\times10^5 s+1.8\times10^6 H+\frac{30900}{s}+\frac{4980}{sH}+\frac{900}{s^2}+\frac{975}{s^2H}+1.21\times10^6 \tag{8}$$

$$C'_{BRT}=5.4\times10^5 s+1.8\times10^6 H+\frac{5.43\times10^5}{s}+\frac{5013}{sH}+\frac{6300}{s^2}+\frac{1275}{s^2H}+9.15\times10^5 \tag{9}$$

$$E'_{Bus}=\frac{2.856\times10^6}{sH}+\frac{39000}{s^2H} \tag{10}$$

$$E'_{Car}=\frac{9.9\times10^5}{s}+\frac{2.817\times10^6}{s}+\frac{39000}{s^2H}+\frac{1.53\times10^6}{s^2} \tag{11}$$

Where C'_{Bus} is buses' operating costs, C'_{BRT} is BRTs' operating costs , E'_{Bus} is buses' off-gas discharge, E'_{BRT} is BRTs' off-gas discharge.

III. Solution and Analysis of Operation Cost and Exhaust Emission Models of Urban Transportation System

A. Solution of Cost Model and Gas Emission Model of Buses and Automobiles

Now, we discuss the nature of the specific cost formulas (4) and (5) for buses and cars. Obviously, for the functions $c_{bus}(s,\rho)$ and $c_{car}(s,\rho)$, when s is fixed, they are both the monotone increasing functions of the independent variable ρ. That is, the bigger ρ is, the bigger $C_{bus}(s,\rho)$ and $C_{car}(s,\rho)$ will be. But for the independent variable s, the function has a monotonous increase or a monotonous decline. We use the Matlab software to solve the problem and draw the related graphics of the functions. The results are as follows in Figures 3, 4 and 5:

When ρ = 50, 100 and 150, the formula $C_{bus}(s,\rho)$ gets the minimum when $s=1.16, 1.42$ *and* 1.65, and the values of $\min C_{bus}(s,\rho)$ are respectively are $1.3941\times10^6, 1.6807\times10^6$ and 1.9208×10^6, and the monotonicity of the function $C_{bus}(s,\rho)$ on the independent variable s is as follows: (the abscissa refers to s, and the ordinate refers to $C_{bus}(s,\rho)$).

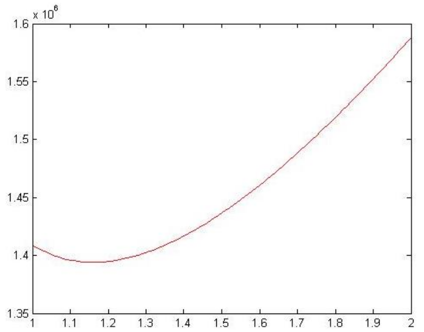

Figure 3. Monotonicity of the function $C_{bus}(s,50)$.

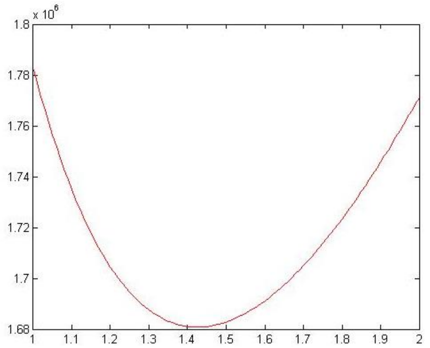

Figure 4. Monotonicity of the function $C_{bus}(s,100)$.

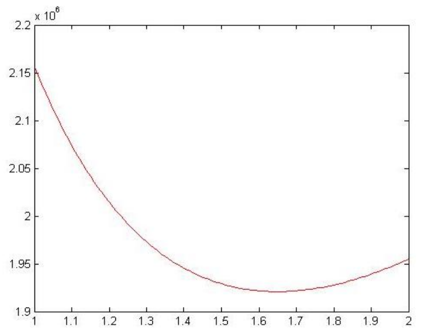

Figure 5. Monotonicity of the function $C_{bus}(s,150)$.

In particular, we calculate some values with the typical function $C_{bus}(s,100)$, as follows in Table 4:

Table 4. Some values of the function $C_{BUS}(s,100)$.

s	**1.1**	**1.2**	**1.3**	**1.4**
$C_{bus}(\times 10^6)$	1.7349	1.7046	1.6876	1.6810
s	**1.5**	**1.6**	**1.7**	**1.8**
$C_{bus}(\times 10^6)$	1.6827	1.6911	1.7050	1.7234

In the same way, for the cost function of the car $C_{car}(s,\rho)$, the Matlab software is used to solve the problem. We get the extreme points in three cases, as follows in Table 5:

Table 5. The cost function of a car $C_{CAR}(s,\rho)$.

ρ	**50**	**100**	**150**
s	1.1	1.5	1.8
$C_{car}(\times 10^6)$	0.7689	1.0596	1.2850

From the above three cases of ρ and several monotonous graphs and Table 5, we can see that with the change in the value of ρ, the points of the functions $C_{Bus}(s,\rho)$ and $C_{Car}(s,\rho)$ about the minimum value of s are also changed accordingly. As ρ gradually increases, the value of the point at the minimum value increases. That is to say, for the practical significance, when the vehicle density is bigger, the bus parking space should be correspondingly larger, so as to ensure that the operation cost of the bus system is reduced correspondingly, which enlightens us that in the urban road construction, the roads with larger population density and larger vehicle density should be constructed at larger distances between the bus stations or the traffic lights, so as to reduce the operation cost of the transportation system.

For the specific emission formulas of bus and car (6) and (7), when vehicle density ρ is given, it can be proved that they are monotonic decreasing functions about s . The following figure takes the bus as an example, and when ρ = 100, the function diagram of $E_{Bus}(s,100)$ was drawn by MATLAB in Figure 6 below:

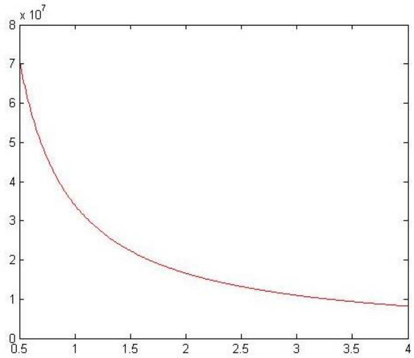

Figure 6. Gas emission function of $E_{bus}(s,100)$.

Because the function of the gas emission is monotonically decreasing, we cannot discuss the extreme value of the gas emission function at this time. But in case of each value of ρ , the gas emission from the bus and the car at different extreme points of the cost is determined. So, we might as well look at the car exhaust emission at the cost extremes. The cost extreme points and gas emissions under different values of ρ is sorted out as follows in Table 6:

Table 6. Cost extreme points and gas emissions.

Travel Mode	ρ	**50**	**100**	**150**
Bus	s	1.16	1.42	1.65
	$C_{Bus}(\times 10^6)$	1.394	1.680	1.920
	$E_{Bus}(\times 10^7)$	2.869	2.360	2.042
Automobile	s	1.1	1.5	1.8
	$C_{Car}(\times 10^6)$	0.768	1.059	1.285
	$E_{Car}(\times 10^7)$	5.983	4.419	3.704

It can be seen from the table that at different values of vehicle density ρ, the cost functions of bus and car are similar at the extreme points S, but the cost varies greatly. However, with the increase of vehicle density ρ and stopping distance S, the cost is narrowing. In fact, through careful analysis of the formulas (2), (4) and (5), we found that the operation cost of bus is much higher than that of the car, which is mainly because the travel time cost of the bus is much higher than that of the car, and cars are less than buses to consider the time of the headway H and the delay time for parking τ. Meanwhile, due to the vehicle speed $v = ks/\rho$, the speed of the car tends to be higher than that of the bus, that is, the travel time is shorter. Therefore, the cost of the bus operation is relatively high, which is mainly reflected in the longer travel time. In terms of vehicle emissions, the data in the table shows that, under different values of ρ, the exhaust emissions of the car are almost twice as much as that of the bus, and the operating cost is not half as much as that of the bus. If we take environmental-based considerations, in the worst case, we can sacrifice more than half of the cost to double the environmental benefits. That is, by choosing the bus as a means of transportation, much more travel time is sacrificed. In fact, it enlightens us that we should encourage everyone to take the bus more frequently, at the expense of some personal travel time for less car exhaust, so as to protect the environment. Therefore, from the aspect of environmental protection, the government has made great efforts to develop public transport, encourage bus travel and advocate fewer private cars, which is based on such theory.

B. Probability Analysis of the Typical Function Operation Cost Function of Bus

$$C_{Bus} = 540000s + \frac{7200\rho + 321960}{s} + \frac{280.8\rho + 12600}{s^2} + 160000 \tag{12}$$

It is established when the parameters of the model are determined by certain values. As the parameters change, the general operating cost function may transform into different expressions.

$$C = \left(\frac{\left(0.5r_L + 0.5r_w + s\right)}{2v_a} + H + Tr + \left(L + W\right)\left(\frac{1}{3v} + \frac{\tau}{3s}\right)\right)\mu D + \frac{2LW}{ps}C_1 + \frac{4LW}{psH}C_V + \frac{4LW}{psH}\left(\frac{1}{v} + \frac{\tau}{s}\right)C_M + \frac{2LW}{ps^2}C_S \tag{13}$$

There will be different forms of expression accordingly. In practical applications, it is very cumbersome to do a precise calculation of each parameter, which brings too much trouble to the urban planning and construction of some cities or some regions. Moreover, in fact, for the setting of some traffic light junctions, the planners should not only consider the operation cost and environmental impact caused by cars, but also consider the customs, convenience and health of local people [21-32], and the security [33-35] of vehicle systems.

IV. CONCLUSION

We mainly discuss how the choice of parking space and vehicle density affects the operating cost and exhaust emission of the urban transportation system. In the case of bad weather in China's cities, it is of practical significance to discuss which factors can improve the environmental protection and reduce the cost. We built a mathematical model of urban operation cost and vehicle exhaust emissions, and discussed the change of cost and exhaust emissions caused by the change of parking distance s and vehicle density ρ under different travel modes. It is concluded that as long as we sacrifice some personal time cost, we can take more buses and reduce the use of cars (including private cars and taxis), so we can reduce a number of vehicle exhaust emissions. Environmental protection requires the sacrifice of time, but if each person sacrifices a little time, the time multiplied by the great base number of China's population could reduce a large amount of vehicle exhaust.

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