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Discussion on Influencing Factors of Free-flow Travel Time in Road Traffic Impedance Function

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Abstract

Road traffic impedance is an important part of traffic assignment and has a direct impact on the urban transportation planning, especially on the optimization of urban road network. The BPR function has been the classical traffic impedance since 1960s, which pays more attention on the link level. This paper aims to construct an improved BPR function based on the influencing factors of road traffic impedance, such as the density of intersections, the density of bus stops, non-motor vehicles and saturation. These factors can reflect the difference between road and link. The real data collection from different roads in Dalian are used to calculate the road traffic impedance function by the SPSS software. The results show that the density of intersections, the density of bus stops and saturation have positive effects on unit travel time in Dalian roads. These results not only point out the necessary of influencing factors, but also validates the correctness of the proposed impedance function. In summary, this function has a simple structure and high flexibility so that it is expected to be transplanted to other cities.

Keywords: Road traffic impedance; traffic assignment; urban transportation planning; improved BPR function

1. Introduction:

The road traffic impedance is the key factor of travellers' route choices. These route choices establish the traffic assignment of road network. Therefore, the impedance function is related to the traveller's individual interest and the effective usage of whole road network system. In a word, the road traffic impedance is one important target of traffic assignment of the traditional four step model. It shows the relationship between the travel time and traffic saturation, and between the delay and the density of intersections.

As the road traffic impedance concept, it is the research on road sections travel time, traffic load, the intersection delay and intersection load (Shao, 2004). It is composed of road sections impedance and nodes

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impedance. In order to study on road sections impedance, Bureau of Public Roads (BPR, 1964) do traffic surveys on a large number of road sections. They obtain the BPR function through regression analysis, which is a significant model from then on. In order to improve the accuracy of the BPR function, following researchers such as Spiess (1990), Davidson (1993) dedicate to the unremitting exploration and correction. About node impedance, Webster et al in Transport and Road Research Laboratory (TRRL) present an intersection delay model based on the queuing theory as early as 1958. This model contains the normal phase delay at the fixed mean of the vehicle arrival rate, and the additional delay at the random fluctuations of the vehicle arrival rate. The Webster model has played a significant role in promoting the intersection delay. But the Webster model's two disadvantages make it difficult to use in road traffic impedance function. One is that the limitations of saturation makes the model cannot be used in congestion. The other is that the model form is too complex to be applied to the traffic assignment model. Due to these disadvantages, the node impedance has been ignored in the existing urban road traffic assignment (Shao, 2004).

Our researchers have studied on the road traffic impedance since 1990s and gotten some results, which all pay more attention on road sections traffic impedance. Yang and Qian (1994) construct the road sections impedance function model according to the different kinds of urban roads and get the methods of calibrating parameters. Pei and Gai (2003) analyses and studies the problems of standard car and the selection of road sections capacity. Then he constructs the road sections impedance function model considering road pricing impact. Fu, Liu and Feng (2003) present the relation between average speeds of vehicles observed by time and distance on traffic network. A parameterized validation approach for the BPR function from volume delay function is applied to real situation. Wang, Zhou and Lv (2004) consider comprehensive factors of time, cost, traffic flow, toll stations and urban nodes. Based on the generalized rate, the road sections impedance function model is produced. Meng and Li (2005) analyse the characteristics of the highway and trunk road of big cities, and then get the corresponding form of impedance functions. Wang, Huan and Lu (2006) derive the relationship between traffic and travel time of the road sections, compare the difference between the BPR function and the derivation, and derive the fitting curve. Si and Sun (2006) discuss the travellers' traffic choice behaviours, based on the detailed study of different traffic volume and different traffic conditions of road sections impedance in 2006. They explore the impedance function of different transportation modes. Han and Yuan (2008) define the road sections impedance function according to different links and transportation modes in multi-user and multi-mode mixed traffic assignment model.

The above researches mainly discuss the link impedance function, on behalf of BPR function. If the BPR function is used in the urban road discontinuous traffic flow, some amendments might be needed (Zheng, Du and Sun, 2007). It is because that the BPR function is applicable to highway continuous traffic flows. In order to explore the urban road traffic impedance function, the difference between road and link is the key part of this research. The influencing factors on urban road may improve the BPR function to our country. Therefore, the amendment to the BPR function is the significant step for practice. The rest of this paper is structured as follows. Section 2 explores the influencing factors on road traffic impedance, based on the urban road qualities. And the data collection is the fundamental for following discussion. Section 3 proposes the traffic impedance model at the actual conditions of our country. It improves the BPR function through influencing factors inclusion. Section 4 analyses the model and results, explores the factors' effects and derives Dalian road impedance function. The final section provides a summary of the research.

2. Influencing Factors and Data Collection

2.1. Influencing factors

Traffic impedance is the integration of travel distance, travel time, travel cost, comfort, travel safety and other factors on road sections or links. So, the rigid and accurate road traffic impedance should include all the factors. However, it is difficult to establish such a scientific, strict, comprehensive, explanative and widely useful model. On the basis of a large number of theoretical analysis and engineering practice, researchers agree that the travel time is the primary factor (Shao, 2004). On the one hand, almost all other factors affecting the road traffic impedance is closely related to travel time in the urban transportation. There is the same trend with the travel time. On the other hand, the travel time is easier to measure and construct the model than other factors. Even if other factors are needed to take into account, they can be converted into travel time. Therefore, the travel time is often cited as the main indicators of measuring road traffic impedance, which is the research target of road sections traffic impedance and nodes traffic impedance.

In the exploration of link traffic impedance, discussions are mainly constructed between travel time and saturation. Less influencing factors exist in road sections and highway. Meanwhile, in the urban road, speed limit, the number of lanes and the density of signalized intersections are the physical attributes of road. These are designed by road designer, which can directly affect the travel time (Muhammad, 2010). The density of bus-stops not only affects the speed of the bus and dwell time, but also influences the speed of other vehicles (Zhang, Chen and Huang, 2004). The vehicle speed will result in different travel time. Our urban transportation is characterized by mixed traffic. That means there is coexistence of a variety of motorized and non-motor vehicle. The number of non-motor vehicles affected the vehicle speed, which results in increasing travel time. In summary, the influencing factors include the speed limit, the number of lanes, the density of intersections, the density of bus stops, saturation and the number of non-motor vehicles in the urban roads.

2.2. Data collection

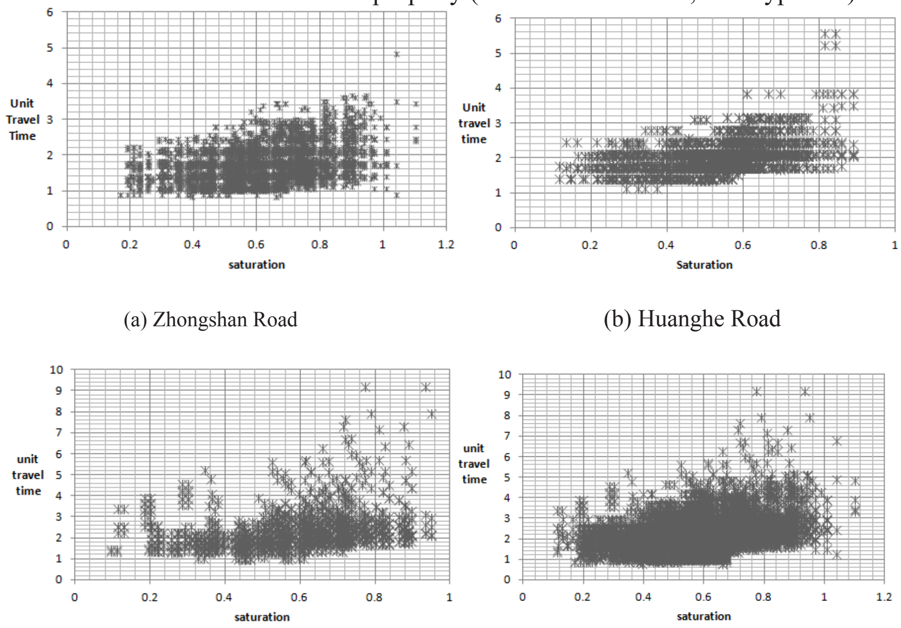
In order to get the representative data and provide a comprehensive situation of Dalian road network, several roads data including Zhongshan road, Huanghe road, Donglian road and side roads at the center of Dalian were collected between April and May in 2011. The actual road information includes the number of lanes, length of investigation, the number of intersections, traffic volume, design traffic volume and speed etc. Dalian has its own special topography, especial mountain roads. Few people choose the non-motor vehicle travel. So, there is no collection of non-motor vehicle traffic data. From the point of road property, Donglian road is urban express road, and Zhongshan road and Huanghe Road is urban trunk road. This survey is based on video acquisition. Then people and application software account the number of motor. The video capture devices are erected at two observation points in a fixed distance. In order to ensure the accuracy of travel time, these devices are adjusted to the same time. The details are shown in Table 1.

From table 1, we can see that the same road type has the consistent attributes (the same number of lanes, the same speed limit). Based on the actual data collection, the number of lanes and speed limit are constant variables in Huanghe road and Zhongshan road. In Donglian road, the number of lanes and speed limit has a linear relationship. And this research survey only involves three main roads in Dalian city. From the point of math, the number of lanes and speed limit are linear correlation. Both influencing factors also exist in road sections. Therefore, the following mainly discusses the density of bus stops, density of intersections and saturation.

Table 1 Collection of Observed Data

Road Type		Density of intersections number/km	Speed limit km/h	Density of bus stops number/km	Number of lanes number
Dong lian road	Zhonghua road -Fenghua road	4	60	3	3
	Songjiang road -Tianhe road	2	80	3	4
	Zhonghua road -Qianshan road	1	80	5	4
Huang he road	Wutong road -Xishan street	1	60	2	3
	Shenyang road -Yinghua street	2	60	3	3
	Ruyi street -Dongbei road	3	60	4	3
	Youzheng street - Gaizhou street	4	60	2	3
Zhong shan road	Jiansha street -Xingyu street	3	60	4	3
	Shuxiang street -Lingshui road	2	60	2	3
	Taiyuan street -Dongbei road	4	60	4	3

In order to observe the relationship between unit travel time and other factors correctly, the graphs of different influencing factors are shown in figure 1-3. This survey is based on the video acquisition in a fixed location. Therefore, the same road owns the identical road property (the number of lanes, road type etc.).



(a) Zhongshan Road (b) Huanghe Road

(c) Donglian Road (d) the whole data

Fig.1 Saturation Rates- Unit Travel Time Scatter

It can be seen from the figure 1 that the unit travel time increases with the increment of the saturation. When the saturation is between 0 and 0.4, the unit travel time increased gently. While the saturation reaches around 0.6, the unit travel time raises quickly. These are proved the correct choice of exponential saturation model. So β value should be greater than 1 and the parameters of saturation is greater than 0. Zhongshan road and Huanghe road have the similar scatter. Meanwhile, in figure 1, the unit travel time in Donglian Road is higher than other two roads. When the saturation researches 0.5, unit travel time is over 5. Even in lower saturation, the unit travel time is higher than 3. These validate the traffic congestion existing. With the increment of saturation, the unit travel time increases. When the saturation reaches some certain level, the traffic congestion has happened. Although the traffic volume increases slowly, the unit travel time appears the exponential increases. Due to the increment of unit travel time, people will decrease the number of travel, or transfer to other roads. This will lead to the decrement of traffic and saturation. The travel time is also declined with the reduction of saturation. But the travel time is much higher than non-congestion at the same level of saturation.

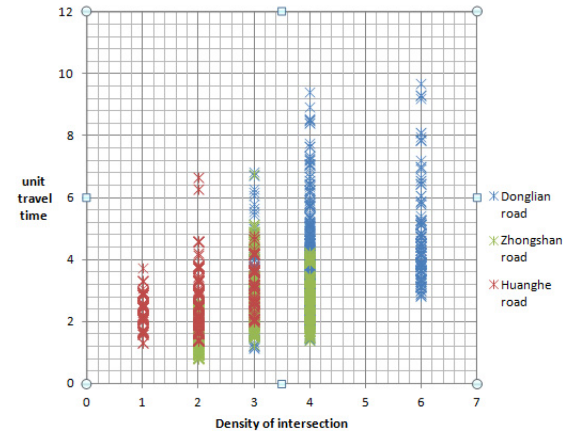


Fig.2 Density of Intersections - Unit Travel Time Scatter

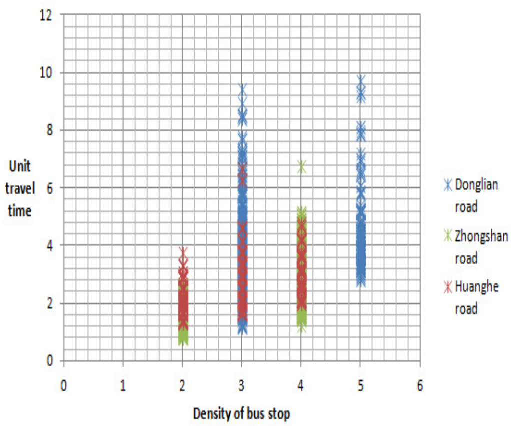


Fig.3 Density of Bus Stops- Unit Travel Time Scatter

It can be obtained from figure 2-figure 3 that at the same level of the density of intersections and the density of bus stops, the unit travel time is not identical but has a range. With their growths, the unit travel time will increase. It points out that unit travel time of Zhongshan road and Huanghe road more centralized than Donglian road. The congestion may exist in Donglian road, because of the higher unit travel time than Zhongshan road and Huanghe road.

3. Proposed Model

Based on the differences between roads and road sections, the road traffic impedance should include the impact of density of bus-stops, density of intersections and saturation in Dalian city. In order to follow the classic BPR function, the revised impedance function model is created as:

$$\begin{aligned} t &= \alpha_0 + \alpha_1 x_1 + \alpha_2 x_2 + \alpha_3 x_3 + \alpha_4 x_4 + \ldots + \alpha_n \left(\frac{Q}{C}\right)^{\beta} \\ &= t_0 + \alpha_n \left(\frac{Q}{C}\right)^{\beta} \\ &= t_0 \left[1 + \alpha \left(\frac{Q}{C}\right)^{\beta}\right] \end{aligned} \tag{1}$$

The parameters are defined as:

t: travel time across the road;
t_0: free-flow travel time across the road;
x_1, x_2, x_3...: influencing factors include the density of bus stops and the density of intersections in Dalian city, can add other influencing factors, such as the number of non-motor vehicles, the speed limit, the number of lanes et al;
Q: traffic volume (per hour);
C: design traffic capacity (per hour);
$\alpha_0, \alpha_1, \alpha_2, \alpha_3, \alpha_4, \ldots \alpha_n, \beta$: coefficient of each influence factor.
α : estimated values of parameters.

Although this model structure is complex, containing index form of non-linear parameters. It can be solved by statistical software or simple programming. This model has the advantages of the BPR function. Firstly, when the traffic flow rate increases, the travel time should not be reduced, this reflects the reality. This means that travel time is a monotonically increasing function of link flow. Secondly, the model allows a certain degree of overload. When the assigned traffic flow is higher than the capacity, the model should feedback the travel time. In addition, this model not only reflects the consideration of physical properties, such as the density of the signalized intersections, but also the impact of the bus stops. Despite the different road types will lead to the different relationship among density, speed and flow (Dai, Zhao, Zhang and Zhou, 2007). This model considers these parameters only in one model, rather than the different traffic impedance of rank roads. All of these mean this model has good adaptability and transferability.

4. Results Analysis

According to the above model and data collection, SPSS 17.0 is used to calibrate the road traffic impedance function. The influencing factors: the density of intersections, the density of bus stops and saturation are chosen to analyze the model. The parameters are calculated, and then the results are shown in Table 2. The nonlinear model cannot show the t-value of coefficients. When the β value is defined, the model transforms to multiple linear model with t-value.

Table 2 Result of the Improved Model

Road Name	Constant	Density of intersections	Density of bus stop	Saturation	β	r^2
Zhongshan Road	0.470 (15.948)	0.351 (10.715)	0.084 (2.515)	1.434 (20.245)	3.497	0.525
Huanghe Road	0.909 (28.986)	-0.500 (-18.243)	0.851 (33.734)	1.749 (14.798)	5.879	0.403
Donglian Road	1.313 (8.370)	0.598 (8.180)	-0.266 (-2.933)	2.563 (10.601)	3.626	0.248
All	0.530 (18.279)	0.291 (24.399)	0.362 (25.026)	0.484 (8.213)	4.713	0.476

T-stats are in parentheses.

According to the above results, the road traffic impedance function turns out to be:

Donglian Road: $t = 2.822 \times \left\{ 1 + 0.908 \times (\frac{Q}{C})^{3.626} \right\}$ (2)

Zhongshan Road: $t = 1.585 \times \left\{ 1 + 0.905 \times (\frac{Q}{C})^{3.497} \right\}$ (3)

Huanghe Road: $t = 2.408 \times \left\{ 1 + 0.726 \times (\frac{Q}{C})^{5.897} \right\}$ (4)

All Road: $t = 2.352 \times \left\{ 1 + 0.206 \times (\frac{Q}{C})^{4.713} \right\}$ (5)

These results suggest that:

- All significant coefficients show that the model can be applied to different road types. These mean that roads are not necessary to research hierarchically in advance. This certificates that the different road properties are taken into account in the model. Although the goodness of fit of some roads is low, the actual data collection may cause that. Therefore, the model has good transplant. It can be used in different roads of different cities.
- The correlation coefficients are great in different roads and whole data. In real data collection, the correlation coefficient of different roads is 0.248-0.525. It means that the influencing factors listed in the model can explain 24.8%-52.5% of unit travel time changes. Dalian's correlation coefficient is 0.476.
- In Zhongshan road and all roads function, all coefficients are positive significant. This means that the increase of intersections, bus stops and saturation will grow the travel time. In all roads, 1% growth in density of intersections will increase 0.291% unit travel time. So does the bus-stops and saturation. However, the coefficients of the density of intersections in Huanghe road and the density of bus stops in Donglian road are negative. These may inflect that the Huanghe road has better planned intersections, which will decrease unit travel time. Meanwhile, the congestion in Donglian road may cause the negative influencing factors on unit travel time.
- Based on the standard road traffic impedance function, the coefficients of α is 0.2-0.9 and β is 3.3-5.9. All suggest the correct choice of the exponential form of saturation.
- The free-flow unit travel time is large based on the actual data collection (1.585-2.822). These mean that the vehicle speed is no quicker than 40km/h, too smaller than the speed limit of different road types. This situation certifies that Dalian roads have minor congestion anywhere.

5. Conclusion

This paper focuses on our urban traffic characteristics. The influencing factors of traffic impedance on different road types are taken into account. The road traffic impedance function is constructed, which can reflect each type road characteristics. The calibration methods of the relevant parameters in the model are given. The transportation networks equilibrium theory can provide a basis guideline to our practical application in urban transportation planning and management. This model is also flexible to be applied to other cities. The data collection only based on fixed roads is inadequate. If some roads are surveyed on time, human, material and financial resources will be enormous. If motor is chosen as research object instead of road. Then real-time data collection can be applied in high technology of information collection. So, it is easy to construct the road traffic impedance of city. This will be the main future research directions. All researches are based on data collection. It will be very helpful that the relevant departments can cooperate to get the more data. In the future research, the real time vehicle data will be collected so that the disaggregated model can be constructed.

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