Urban Road Traffic Impedance Function
——Dalian City Case Study*

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Abstract: The typical U.S. Bureau of Public Roads (BPR) volume-delay function is modified to construct the more suitable model to China's road traffic situation. Factors influencing road traffic impedance, such as the number of lanes, speed limit, intersection density, bus stop density, saturation and congestion are considered. On the basis of actual data collected from different main roads in Dalian city, traffic impedance functions for different road types (expressway, trunk road, secondary trunk road and slip road) are calculated using SPSS software. The results analysis of the traditional and improved BPR volume-delay functions is compared to certify the useful improved BPR volume-delay function. To apply road traffic impedance to the traditional four-step model, we calculate the daily conversion coefficients. These reflect the relationship between hourly traffic impedance and daily impedance function and suggest the suitable usage of daily conversion coefficients in further research.

Key words: traffic engineering; urban transportation planning; improved BPR volume-delay function; daily conversion coefficient; road traffic impedance; traffic assignment

1 Introduction

Road traffic impedance is a key factor in travelers' route choices. These route choices in turn govern traffic assignment across the road network. Therefore, the road traffic impedance function is of interest to both the individual traveler, and those who seek effective use of whole road network. International research has previously looked at how road traffic impedance influences travelers' route choices and its value in obtaining exact traffic assignment and reasonable urban road traffic. In 1964, the US Bureau of Public Roads (BPR) conducted traffic surveys on a large number of road sections to study road traffic impedance. They used regression analysis on the data collection to obtain the BPR volume-delay function[1], and it has since become a widely used model. The BPR volume-delay function is primarily focused on road sections or highways, not urban roads. This means it has some drawbacks. Researchers such as Speiss[2] and Davvideon[3] have conducted research to improve the BPR volume-delay function. Spiess et al[2] develop two aspects of the BPR volume-delay function. One is the high β, which lowers accuracy. The otheris lower saturation, which has little effect on travel time. Davvideon[3] uses queuing models to improve traffic impedance analysis. When road traffic volume reaches road capacity, travel time is infinite.

The research described tries to improve road traffic impedance on the basis of the relationships among travel time, travel distance and traffic, and is based on the conditions in a given region, such as a road section. There is less research around how network nodes, such as road intersections, affect travel time. These have a significant influence on the accuracy of road traffic impedance in a general road network. As early as 1958, Webster et al. present an intersection delay model based on queuing theory in Transport and Road Research Laboratory (TRRL). This model represents normal phase delay as the fixed mean of the vehicle arrival rate, and additional delay as the random fluctuations in the vehicle arrival rate[4]. The Webster model plays a significant role in promoting interest in the intersection delay. However, the Webster model has two disadvantages that make it difficult to use in a road traffic impedance function. First, saturation limitations mean the model cannot be used in congestion. Second, the model structure is too

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complex to be applied to the traffic assignment model.

Chinese researchers have studied road traffic impedance since the 1990s and table 1 summarizes some of the results obtained.

Tab. 1 Summary of Chinese research on traffic impedance function

References	Improved methods	Theory basis	Results
YANG Pei-kun et al, 1994[5]	Proposes three road section traffic impedance models based on different kinds of urban road.	Traffic theory	Based on the project, obtains satisfactory results in Wuxi City
PEI Yu-long et al, 2003[6]	Considers the influence of tolls on travel time for a road section. The toll influences are divided into toll course and toll amount.	Queuing theory and Traffic theory	Research onmodel formation and analysis, according to the toll influences on travel time of road section.
FU Bai-bai et al, 2003[7]	Based on the relationship between time and distance for data observed in a traffic network, a parameterized validation approach for the BPR is applied to a real situation.	Braess' paradox	Using road sections from cities in Winnipeg, Canada to calibrate, the results suit with the observed data.
WANG Yuan-qing et al, 2004[8]	Considers the influence of time, toll, traffic flow, and the effect of tollbooths and city nodes on the road traffic impedance function.	Queuing theory and traffic theory	Using the calibration of OD survey data in Tangshan City, the proposed model better reflects traffic distribution as compared with the BPR volume-delay function.
MENG Xiang-hai et al, 2005[9]	The road traffic impedance function is formulated with consideration of the average delay of vehicles passing any type of intersectionon expressways and main roads.	Traffic theory	Based on actual data collection on roads in Beijing City, proposes the models of the expressway and the main-road in urban.
WANG Shu-sheng et al, 2006[10]	Deductes the relationship between link flow and travel time on road section and gets road traffic impedance	Traffic theory	The proposed model can replace the BPR volume-delay function.
SI Bing-feng et al, 2008[11]	Uses the travel demand model to build a road traffic impedance function for a mixed urban network. Includes factors such as travel speed, average passengers, and road capacity.	Traffic theory	The BPR volume-delay function is not suitable for our urban mixed network, and should be improved.
CHEN Dong-dong et al, 2010[12]	Examines road traffic impedance and traffic assignment with continuous flow and interval flow.	Traffic theory	On the basis of real-time traffic data collection in traffic information systems, the proposed model has high accuracy and applicability.

The research summarized in table 1 improves different aspects of the BPR volume-delay function, suggesting that modified BPR volume-delay function is highly valuable. It also shows that the BPR volume-delay function is applicable to highways with continuous traffic flows. If it is used in urban roads with discontinuous traffic flow, amendments might be needed[13]. A key part of exploring the urban road traffic impedance function is the difference between roads and links. It is important to apply road traffic impedance function in traffic assignment. Therefore, meaningful correction of BPR volume-delay function has a strong practical significance.

The remainder of this paper is structured as follows. Section 2 focuses on the essential difference between urban roads and highways. The improved road traffic impedance function is constructed with our real data, considering road property, intersection delay in the road section impedance and road congestion in the urban. Section 3 presents the improved BPR volume-delay function calibration and then obtains a road traffic impedance function for different road types. The results are summarized and analyzed. Finally, section 4 presents the daily conversion coefficients that enable the function to be applied to travel demand forecasting.

2 Model formation

Road traffic impedance is composed of road section traffic impedance and node traffic impedance. The Webster model can obtain node impedance with high precision, but it needs a huge amount of calculation to obtain road traffic impedance function. Therefore, researches always ignore node traffic impedance in traffic assignment theory of urban roads, and using travel time to obtain BPR volume-delay function[14]. The BPR volume-delay function is the most important travel time estimation model. However, it was established under congestion-free highway conditions, making it unsuitable for use in China without adjusting for signal controls and non-motor vehicles. The monotonically increasing relationship between saturation and travel time does not match real life in major Chinese cities, which have traffic congestion. When serious road congestion exists, travel time increases as saturation decreases. As traffic congestion gradually increases, saturation will gradually increase and travel time will decrease[15]. To overcome these shortcomings and fully consider the factors influencing road traffic impedance, the improved road traffic impedance function, called the improved BPR volume-delay function in this paper, is described below. It considers both node impedance and serious traffic congestion.

$$t = \alpha_0 + \alpha_1 x_1 + \alpha_2 x_2 + \alpha_3 x_3 + \alpha_4 x_4 + \cdots + \alpha_n z^{\beta} = t_0 + \alpha_n z^{\beta} = t_0(1 + \alpha z^{\beta}), \quad (1)$$

$$z = \begin{cases} Q/C, & z \in [0,1], \quad Q/C \leqslant 1.0, \\ (2C - Q)/C, & z \in (1,2), \quad Q/C > 1.0, \end{cases} \quad (2)$$

where, t is travel time along the road; t_0 is free-flow travel time along the road; $x_1, x_2, x_3, \ldots, x_n$ are the influencing factors, including bus stop density and intersection density in Dalian city. Other influencing factors, such as the number of non-motor vehicles, the speed limit, and the number of lanes can be added; Q is traffic volume (per hour); C is designed traffic capacity (per hour); z is saturation; α, α_1, α_2, ..., α_n, β are the coefficients of each influence factor; α, β are the estimated parameter values.

The improved BPR volume-delay function has the advantages of the BPR volume-delay function, such as a simple structure and easy calculation. In the case of traffic congestion, using $(2C\text{-}Q)/C$[15] will calculate saturation, which increases as travel time grows. In addition, the model considers node impedance, which reflects the influence of bus stop density, intersection density, number of lanes and speed limit on road traffic impedance and improves road travel time accuracy at free flow.

3 Data collection and analysis

To obtain representative data and provide a comprehensive view of the Dalian road network, data for several roads including Zhongshan road, Huanghe road, Dongliian road, and side roads at the center of Dalian city were collected between April and May, 2011. Variables recorded include the number of lanes, the number of intersections, length under investigation, traffic volume, designed traffic volume, and speed. SPSS 17.0 is used to calibrate the road traffic impedance function with the above model and data collection. Existing research has discussed aspects of the "study of road traffic impedance based on the BPR function", such as data structure, data analysis, the relationships among unit travel time, speed limit, intersection density, bus stop density, number of lanes and saturation, calibrating the road traffic impedance function with SPSS17.0 and the significance of influencing factors[16]. When the β value is defined, the model transfonns to multiple linear model with t-value). Based on influencing factor estimates, the road traffic impedance of different road types in Dalian City can be obtained as follows.

Urban express road: $t = 1.029(1 + 1.448z^{1.435})$, (3)

$$z = \begin{cases} Q/C, & z \in [0,1], \; Q/C \leqslant 1.0, \\ (2C - Q)/C, & z \in (1,2), \; Q/C > 1.0; \end{cases} \quad (4)$$

Trunk road: $t = t_0\left[1 + 0.905\left(\frac{Q}{C}\right)^{3.497}\right]$, (5)

Secondary Trunk Road:

$$t = t_0\left[1 + 0.726\left(\frac{Q}{C}\right)^{5.897}\right], \quad (6)$$

Slip road: $t = t_0\left[1 + 0.596\left(\frac{Q}{C}\right)^{1.457}\right]$. (7)

Figure 1 shows a comparison of the traditional and improved BPR volume-delay functions based on the data collection and parameter values. The graphs plot unit travel time against saturation rates. The red curve is the proposed road traffic impedance function (improved BPR volume-delay function), and the green curve is the traditional BPR volume-delay function. In the traditional BPR volume-delay function, free-flow travel time along the road is based on the improved BPR volume-delay function. Therefore, figure 1 does not take into account the difference in free-flow travel time along the road. Expressways should take congestion into account, as average speeds of less than or equal to 20 km/h are seen as a serious road congestion. The formula $(2C - Q)/C$ can be

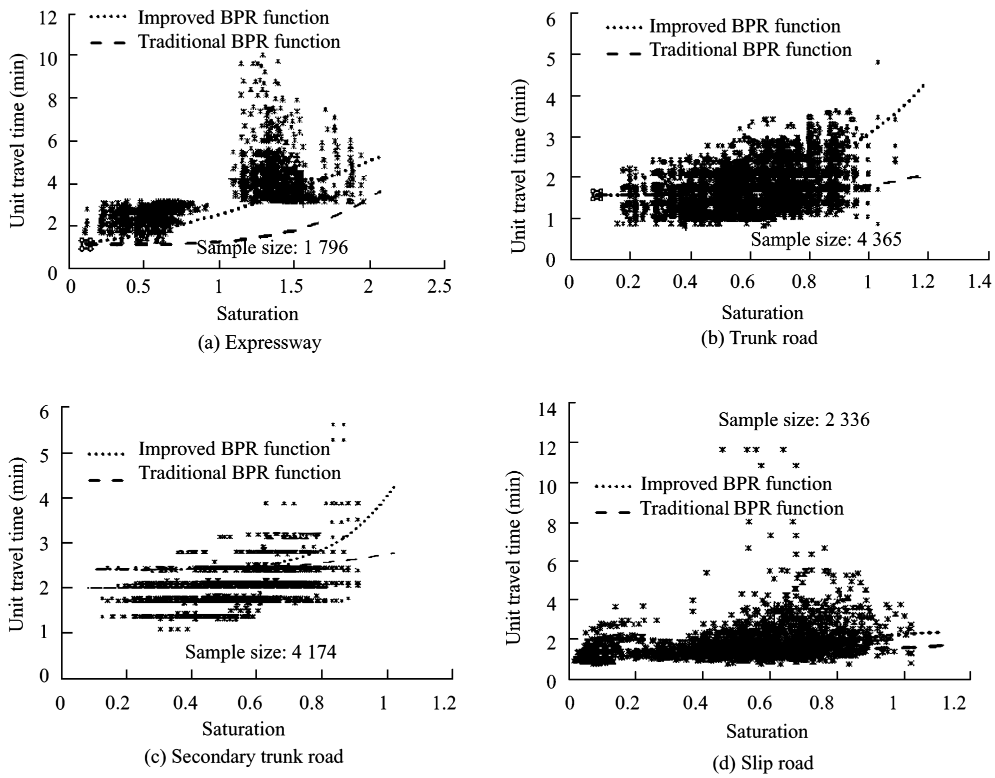

Fig. 1 Graphs showing saturation rates against unit travel time

used to take traffic congestion into account for saturation.

The graphs in figure 1 demonstrate that the proposed model parameter values (such as $\alpha = 0.905$, $\beta = 3.497$ in trunk road) perform better than the traditional BPR volume-delay function ($\alpha = 0.15$, $\beta = 4$) in Dalian city. The unit travel time of the proposed model is larger than the traditional BPR volume-delay function. This indicates that road traffic impedance on urban roads is larger than on highways or road sections. These differences are clear when saturation reaches 0.6. All above conclusions show the importance of considering speed limit, intersection density, bus stop density, number of lanes and saturation in the road traffic impedance function. On expressways, trunk roads and secondary trunk roads, free-flow travel time along the road increases as the road level decreases. Free-flow travel time along the road appears larger in relatively higher densities of signal groups and bus stops. On slip roads, unit travel time is lower than on trunk roads and secondary trunk roads. This indicates that signal groups and bus stop density on trunk roads and secondary trunk roads should be planned to maximize travel convenience.

The secondary trunk road has the largest free-flow travel time of all road types, which reflects the importance of taking speed limits, intersection density, bus stop density, number of lanes and saturation into consideration. These are improvements infree-flow travel time estimates over the traditional BPR model. On expressways, traffic congestion considerations in the proposed model are more suitable than in the traditional BPR volume-delay function for existing traffic congestion in urban. However, according to actual data and the $(2C - Q)/C$ standard, saturation appears segmented. How to choose a standard for travel congestion should be examined in further research.

4 Daily conversion coefficient in road traffic impedance

In the four-step travel demand model, traffic distribution requires a daily traffic volume, whereas road traffic impedance is built up using hourly traffic volumes. This means that the proposed model (improved BPR volume-delay function), which uses hourly traffic volume, is not suitable for use in a four-step travel demand model and must be modified to use daily traffic volume. This is a weighted average of hourly traffic volume. The daily average travel time is a weighted average of unit travel time and 1day (24 hours) of traffic volume. The formula is derived as follows:

$$t_{ai} = t_{a0}(1 + \alpha z_a^{\beta}), \tag{8}$$

$$\overline{t_a} = \sum_{i=1}^{24} t_{ai} \times z_a \times \frac{C_a}{Q_a}, \tag{9}$$

$$\overline{t_a} = t_{a0} \sum_{i=1}^{24} \eta_{ai}\left[1 + \alpha \left(\frac{Q_a}{C_a}\eta_{ai}\right)^{\beta}\right] =$$

$$t_{a0}\left[1 + \alpha \frac{Q_a}{\left(\sum_{i=1}^{24} \eta_{ai}^{\beta+1}\right)^{\frac{-1}{\beta}} C_a}\right]^{\beta}, \tag{10}$$

$$\eta_{ai} = z_a \times \frac{C_a}{Q_a}, \tag{11}$$

$$z_a = \begin{cases} q_{ai}/C_a, & z \in [0,1],\ q_{ai}/C_a \leqslant 1.0, \\ (2C_a - q_{ai})/C_a, & z \in (1,2),\ q_{ai}/C_a > 1.0, \end{cases} \tag{12}$$

$$Q_a = \sum_{i=1}^{24} z_a \times C_a, \tag{13}$$

where, t_{ai} is travel time along road a in hour i of one day (24 hours); t_{a0} is free-flow travel time along road a; C_a is designed traffic capacity (per hour) of road a (per hour); Q_a is traffic volume of road a (per day); $\overline{t_a}$ is average daily travel time on road a; q_{ai} is road traffic on road a in hour i of one day (24 hours); z_a is saturation of road a.

The equation shows that η_{ai} is an hourly coefficient, $\left(\sum_{i=1}^{24} \eta_{ai}^{\beta+1}\right)^{\frac{-1}{\beta}}$ is the daily conversion coefficient. When hourly traffic volume does not change by hour, the daily conversion coefficient is 24. When hourly traffic volume varies significantly across the day, the daily conversion coefficient is low. Daily conversion traffic volume is the combination of the daily conversion coefficient and 24 hours of traffic volume. Based on road types, using the daily conversion coefficient and 24 hours of traffic volume, we can derive the daily BPR volume-delay function.

The daily conversion coefficient of different road types in Dalian city ranges between 12 and 20 (such as 19.300 in expressway). The results show that the daily conversion coefficient both in expressways and trunk roads is nearly 20, indicating that they undertake the majority of traffic in urban transportation. Expressways and trunk road shave similar hourly traffic throughout the day. The daily conversion coefficient of secondary trunk roads is a little smaller, showing that it has inconsistent traffic throughout the day. When expressways and trunk roads are not congested, fewer travelers choose secondary trunk roads. The daily conversion coefficient for slip roads is smaller than expressways and trunk roads, but larger than secondary trunk roads. This implies that travelers have reduced choices when using slip roads, due to them being the only alternative to reach a destination. Slip roads will take some traffic when expressways and trunk roads are congested.

Expressway:

$$t = t_0 \times \left[1 + 1.448 \times \left(\frac{\sum_{i=1}^{24} z_a}{19.300}\right)^{1.435}\right], \tag{14}$$

$$z_a = \begin{cases} q_{ai}/C_a, & z \in [0,1],\ q_{ai}/C_a \leqslant 1.0, \\ (2C_a - q_{ai})/C_a, & z \in (1,2),\ q_{ai}/C_a > 1.0; \end{cases} \tag{15}$$

Trunk road:

$$t = t_0\left[1 + 0.905\left(\frac{Q_a}{19.994C_a}\right)^{3.497}\right]; \tag{16}$$

Secondary Trunk Road:

$$t = t_0\left[1 + 0.726\left(\frac{Q_a}{12.830C_a}\right)^{5.897}\right]; \tag{17}$$

Slip road:

$$t = t_0\left[1 + 0.596\left(\frac{Q_a}{16.797C_a}\right)^{1.457}\right]. \tag{18}$$

5 Conclusions

This paper improves the BPR volume-delay function on the basis of research on the road impedance function, and the relationship between travel speed and traffic volume. Such a model considers bus stop density, intersection density, road attribution and traffic congestion. Using Dalian city as a case study, a road impedance function is calculated according to road type (expressway, trunk road, secondary trunk road and slip road) using data collected in the city. Based on the results, as compared to the standard BPR volume-delay function, the proposed model better reflects the road traffic impedance function in Dalian city.

This paper considers the difference of hourly traffic and daily traffic in improved BPR volume-delay function. Daily conversion coefficients for road traffic impedance provide a basic guideline to applying our model in urban transportation planning and management. This model is also flexible enough to be applied to other cities. Real-time data collection based only on individual roads is inadequate, and lacks the depth of multifaceted collection from different roads. Departmental coordination to obtain further data will help to improve this model. Further data should be collected so that future research can construct a disaggregated model.

References

[1] Bureau of Public Roads. Traffic Assignment Manual [M]. Washington, D. C.: U. S. Department of Commerce, 1964.

[2] SPIESS H. Conical Volume-Delay Functions [J]. Transportation Science, 1990, 24 (2): 153 - 158.

[3] DAVIDSON K B. The Theoretical Basis of a Flow-travel Time Relationship for Use in Transportation Planning [J]. Australian Road Research, 1978, 8 (1): 32 - 35.

[4] WEBSTER F V. Traffic Signal Settings [M]. Wokingham, UK: Transport and Road Research Laboratory, 1958: 1 - 44.

[5] YANG Pei-kun, QIAN Lin-bo. Research on Link Travel Time Functions for Traffic Assignment [J]. Journal of Tongji University, 1994, 22 (1): 27 - 32. (in Chinese)

[6] PEI Yu-long, GAI Chun-ying. Study of the Link Performance Function of Highway Segments Considering Toll Influences [J]. China Journal of Highway and Transport, 2003, 16 (1): 91 - 94. (in Chinese)

[7] FU Bai-bai, LIU Fa-sheng, FENG En-min. Traffic Network Costs Analysis and Validation [J]. Journal of Transportation Systems Engineering and Information Technology, 2003, 3 (4): 53 - 57. (in Chinese)

[8] WANG Yuan-qing, ZHOU Wei, LÜ Lian-en. Theory and Application Study of the Road Traffic Impedance Function [J]. Journal of Highway and Transportation Research and Development, 2004, 21 (9): 82 - 85. (in Chinese)

[9] MENG Xiang-hai, LI Shi-lian. Study on the Impedance Functions of Urban Express Way and Main-road [J]. Journal of Highway and Transportation Research and Development, 2005, 5 (4): 31 - 34. (in Chinese)

[10] WANG Shu-sheng, HUANG Wei, LU Zhen-bo. Deduction of Link Performance Function and Its Regression Analysis [J]. Journal of Highway and Transportation Research and Development, 2006, 23 (4): 107 - 110. (in Chinese)

[11] SI Bing-feng, SUN Zhuang-zhi. Mixed Traffic Network Flow Split Model Based on Stochastic User Equilibrium [J]. China Journal of Highway and Transport, 2006, 19 (1): 93 - 98. (in Chinese)

[12] CHEN Dong-dong, YANG Chao. Impedance Functions of Urban Transportation Networks for Traffic Assignment [J]. Traffic & Transportation, 2010, 26 (S2): 17 - 20. (in Chinese)

[13] ZHENG Yuan, DU Yu-chuan, SUN Li-jun. Considerations on Problems in the BPR Function [J]. Traffic and Transportation, 2007, 23 (S1): 24 - 26. (in Chinese)

[14] SHAO Chun-fu. Traffic Planning [M]. China Railway Publishing House, 2004: 171 - 185. (in Chinese)

[15] WANG Su-xin, WANG Lei-zhen, GAO Li, et al. Improvement Study on BPR Link Performance Function [J]. Journal of Wuhan University of Technology: Transportation Science & Engineering Edition, 2009, 33 (3): 446 - 449. (in Chinese)

[16] HE Nan, LIU Ning, ZHAO Sheng-chuan. A Study of Road Traffic Impedance Based on BPR Function [J]. Journal of Nanjing Institute of Technology: Natural Science Edition, 2013, 11 (1): 6 - 11. (in Chinese)

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