2018 IEEE Intelligent Vehicles Symposium (IV)
Changshu, Suzhou, China, June 26-30, 2018

A dual traffic network coupled with improved delay models to estimate travel time in urban traffic systems

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***Abstract*—Travel time estimation plays a core role in intelligent traffic systems, as people or smart vehicles can choose a better travel route in advance, while local authorities can make urban traffic planning based on it. The paper proposes a dual traffic network topology coupled with improved delay models to estimate travel time in urban traffic system. The structure of the system is demonstrated by the dual traffic network (DTN) topology. It hires nodes to represent joint points of links and intersections; it also has two kinds of edges – links and turning cases of intersections. The BPR model is improved by concerning the influence of pedestrians and the lane width, and the HCM model is improved by adding travel time at intersections and considering three different turning cases to match with the DTN topology. The proposed methodology is evaluated by a comparison and an experiment in Changzhou, China. The error is greatly reduced, even though the degree of saturation exceeds 0.72. This proposed estimation methodology can improve the estimation accuracy significantly, especially in high degree of saturation cases.**

***Abstract*—Urban traffic, Travel time estimation, Dual traffic network, Improved BRP model, Improved HCM model**

I. Introduction

Advanced Traveler Information Systems (ATIS) research has become popular in these years, as people can use the provided information to make their route choices in advance, while local authorities can make urban traffic planning based on it [1]-[2]. The most significant parameter of ATIS is travel time, which can be estimated by the link delay and intersection delay, while topology also plays an important part in this system [3-5]. In addition, with the repaid progress of urbanization, residential areas are opened and become a part of a city's traffic system, which makes urban traffic more complicated [6]. The paper proposes a dual traffic network topology coupled with delay models to improve the accuracy of travel time estimation in the urban traffic system.

A well-organized topology is essential for travel time estimation. Angelini et al. [7] proposed the fundamental road network topology, where links were represented as edges and intersections were represented as nodes. Furthermore, Russo and Vitetta [8] reduced the number of different possible solutions to a network design problem. The universality and peculiarity of the urban street network topology were discussed in detail [9]. A dual approach was developed by Porta, Crucitti and Latora [10], they in turn represented intersections as edges while links as nodes.

The travel time estimation is the core of urban traffic network, which includes the link delay and the intersection delay [3-4]. Researchers have put forward numerous models for these two delays.

The Bureau of Public Roads (BPR) model conducted a regression analysis on American roads. Recent studies were mainly improved from this original BPR model [11]. Irawan [12] revised and implemented the BPR model in Indonesia, improving its accuracy when the saturation is low. A macroscopic Bureau of Public Roads model was used in area-wide traffic management and control [13].

One typical model for intersection delay estimation was developed by Webster [14] in Road Research Lab in U.K., with the consideration of signalized intersections and the ratio of effective green time for the cycle time. Based on Webster's intersection delay model, official researchers in U.S. developed Highway Capacity Manual (HCM) models for estimating delay of an intersection. It retained the first term the same as the Webster's model. Meanwhile, considered random arrivals [15]. The delay produced at intersections is still attractive to many researchers. Dion, Rakha and Kang [16] studied diverse situations at intersections, comparing the delay of under-saturated and over-saturated cases. For further studies, Qiao et al. [17] introduced fuzzy logic into intersection delay estimation, and the game theory was introduced to study the specific behaviors at intersections by Zohdy and Rakha [18].

Although researchers have already proposed many methods to estimate travel time in urban traffic network, few of them consider the influence of pedestrians, lane width on links and turning cases – going straight, turning left, turning right in their work. Thus, this paper proposed a new methodology to estimate the travel time in urban traffic network. The panorama of traffic is demonstrated by the dual traffic network (DTN) topology. Furthermore, BPR model is improved by concerning the influence of pedestrian and lane width, and HCM model is also improved by adding travel time at intersections and considering three different turning cases to match with the DTN topology.

The rest of the paper is organized as follows. Section 2 is an exposition of the DTN topology and how the BPR model and the HCM model are improved. In section 3, a typical urban area is selected to operate experiments, comparing the proposed methodology with the original ones and analyzing results. Conclusions and recommendations are drawn in Section 4.

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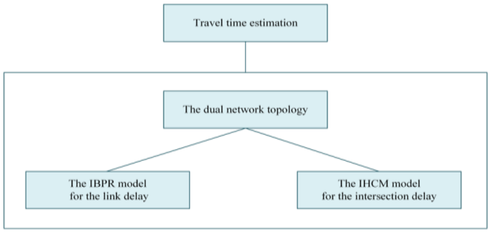
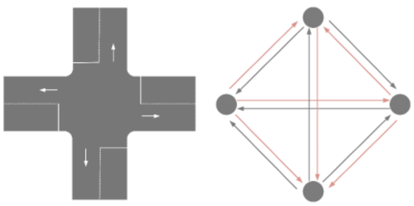


Figure 1. The structure of the estimation methodology



(a) (b)

Figure 2. The dual intersection

II. Methodology Formulation

This section mainly presents the proposed travel time estimation methodology (Fig. 1). First, to support the analysis of structure of the urban traffic system, a DTN topology is developed. It provides a foundation on how to make a complex urban traffic system into a simple network topology. Then, the IBPR model for links delay estimation and the IHCM model for intersection delay estimation are described in detail, by considering the influence of pedestrians, the influence of lane width and turning cases. After the methodology is formulated, the IBPR model and the IHCM model is evaluated, by analyzing their performance with original BPR and HCM models. In the end, some other methodologies are included, comparing the proposed estimation methodology with them.

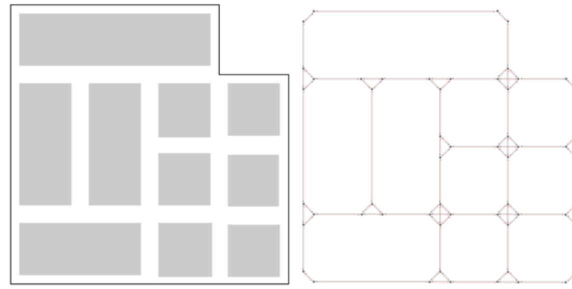
Based on the DTN topology, it can be found that when a vehicle travels across a route, the comprehensive delay can be calculated as following.

$$D(i,j) = \quad D_l(i,j) + \quad D_i(i,j) \tag{1}$$

where D represents comprehensive delay of the route, D_l denotes the links delay, and D_i reveals the intersection delay.

A. Dual Traffic Network Topology

The network topology is widely-used in network analysis in many aspects, including urban traffic network, social network, citation network, complex network, etc. [7, 10]. In the previous fundamental traffic network topology, intersections are represented as nodes which are difficult to be qualified [19-20]. Therefore, we propose a dual. Intersection topology for intersections to estimate three different options case by case – going straight, turning left and turning right in Fig. 2(b).



(a) (b)

Figure 3. The dual traffic network (DTN)

Nevertheless, proposed topology is not individually used, but it is embedded into and takes the place of nodes in fundamental traffic network topology. This hybrid topology terms as the dual traffic network (DTN) topology. More specifically, in this dual traffic network topology, nodes represent only joint points of links and intersections, while there are two kinds of edges – links and turning cases at intersections (Fig. 3).

B. IBPR model for the link delay

In order to quantify the delay of links, the Bureau of Public Roads in U.S. announced a BPR model by the regression analysis of a large amount of field data, especially the quantity of the traffic flow and the free flow delay [11].

$$D_l = D_{l0}(1+\alpha x^{\beta}) \tag{2}$$

where $x = q/c$ is termed as the degree of saturation, which represents the ratio of the quantity of traffic flow q to the capacity c, α, β represent delay parameters for the link and the recommended values are $\alpha = 0.15$ and $\beta = 4$ by the Bureau of Public Roads.

However, it is not an easy work of gathering field data from people, so the estimation of D_{l0} becomes important and useful. Therefore, we develop the improve BPR (IBPR) model by considering using the length of the link and the limited speed of the link as following.

$$D_{l0} = \frac{L}{V_m} \tag{3}$$

where L represents the length of the link, V_m represents the maximum speed of the link.

In ideal cases, the maximum speed should be the same as the limited speed of the link as showed below.

$$V_m = V_l \tag{4}$$

where V_l represents the limited speed of the link.

Besides, this original BPR (OBPR) model does not consider the influence of pedestrians, which has a dramatic effect in the urban traffic network. Therefore, real maximum speed of the link V_m should be smaller than the limited speed

V_l, with the consideration of the influence of pedestrians' density and width of the link, as adjustment factors.

$$V_m = \lambda_p \lambda_w V_l \tag{5}$$

where λ_p represents the adjustment factor of pedestrians, λ_w represents the adjustment factor of width of the link.

In terms of the influence of pedestrians, when pedestrians go across links, they will impede the movement of vehicles, which may decrease the performance of links and then have a negative impact on the speed of vehicles. As actions of going across links are stochastic, it forms a complex behavior process. However, we can simply attain this value by the ratio of the standard density of population to the practical density of population [21].

$$\lambda_p = \begin{cases} 1.0, P \le P_s \\ \dfrac{P_s}{P}, P > P_s \end{cases} \tag{6}$$

where P_s represents the standard density of population in the selected region, P represents the real density of population in the selected region. The definition of the density of population varies in different regions at different time, for example, all workers are included into consideration in the business districts at peak time.

Width of the lane also has a phenomenal influence on the performance of the link. In urban planning, the standard width for one lane is 3.5 m. When the practical width for the link is smaller than this threshold 3.5 m, the maximum speed of the link will decrease; When the practical width exceeds the threshold value, the performance of links will improve, but still be limited by the ability of vehicles themselves [22].

$$\lambda_w = \begin{cases} 0.5(W-1.5), W \le 3.5m \\ -0.05W^2 + 0.63W - 0.54, W > 3.5m \end{cases} \tag{7}$$

where W represents the width of a lane.

Consequently, the IBPR model, considering the influence of pedestrians and width of the link, is shown below.

$$D_l = \frac{L}{\lambda_p \lambda_w V_l}(1 + \alpha x^{\beta}) \tag{8}$$

C. IHCM model for the intersection delay

HCM model was developed by American Transportation Research Board in his Highway Capacity Manual (HCM), which is a well-known formula for calculating intersection delay. The HCM model is still improving by the official researchers, and now it has three versions: 1985 version, 2000 version and the latest 2010 version (Transportation Research Board 2010). However, those versions did not consider the travel delay of an intersection, so the IHCM is composed of the HCM model and travelling delay on intersections.

$$D_i = D_{i-s} + D_{i-t} \tag{9}$$

where D_i represents the total delay at the intersection, D_{i-s} represents the delay of signal control at the intersection and D_{i-t} represents the delay of travel time at the intersection.

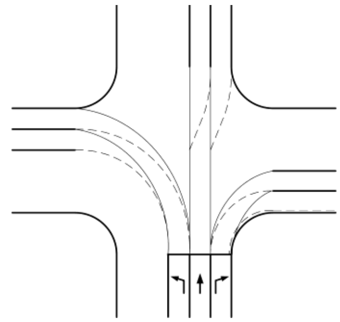


Figure 4. Turning cases at an intersection

In fact, HCM model is improved from Webster formula, and it remains the first term, uniform delay, the same as Webster's. The original HCM model refers to the latest 2010 version, which contains three terms – uniform delay, incremental delay and initial queue delay. The delay of signal control is completely the same as the HCM delay model, which consists of two parts – the first term as uniform delay and the second term as incremental delay. Uniform delay can calculate the delay for the vehicle stochastic arrival, and it concerns about the quantity of vehicle volume, the signal period, especially the effective green period. Increment delay accounts for the delay caused by the cycle-to-cycle basis, which can be used even the quantity exceeds the capacity. However, the used delay of signal control is derived based on the assumption of no initial queue.

$$D_{i-s} = \frac{C(1-u)^2}{2(1-u\min(1,x))} + 900T[(x-1) + \sqrt{(x-1)^2 + \frac{8kIx}{CT}}] \tag{10}$$

where $u = g/s$ is the ratio of the period of effective green light g to the period of signal light s, T represents the period of sampling, k represents the adjustment factor for the actuated control, it's 0.5 for nearly saturated area, I represents filter factor, which is 1 for separate intersections. The other parameters are as defined previously

However, the OHCM model does not include delay for traveling on intersections and consider the turning differences. Matching with the dual traffic network topology, there are three options at intersections – going straight, turning left, turning right. For empirical analysis, the travel delay is, turning right<going straight<turning left.

In terms of the turning distance, for the following analysis, it starts from the stopping line. If a vehicle goes straight, the distance is just right the length of this intersection. If a vehicle turns right, it should take a few distances with a small radius. If a vehicle turns left, the radius of that travel is obvious longer than others (Figure 4).

$$S = \begin{cases} S_i \\ \dfrac{\pi R}{2} \\ S_{i0} + \dfrac{\pi R_0}{2} \end{cases} \tag{11}$$

where S is the turning distance, S_i, S_{i0} represent straight distances, and R, R_0 are the turn radii of turning process.

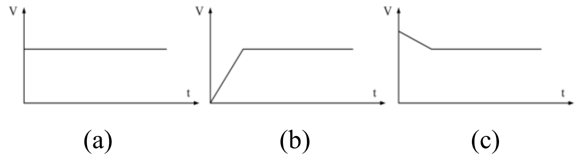


Figure 5. IBPR and IHCM models analysis

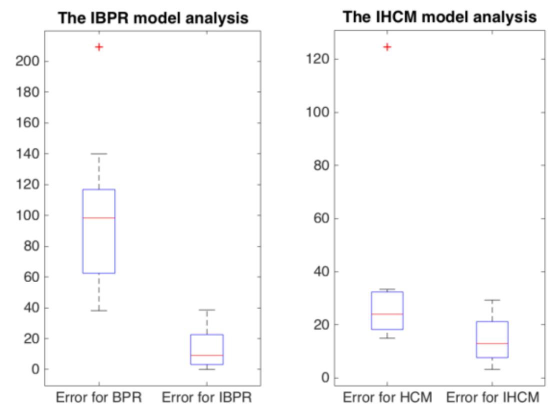


Figure 6. IBPR and IHCM models analysis

In each turning case, vehicles may have different travelling modes. People cannot drive too fast, as turning needs to overcome the centrifugal force. Therefore, there should be a normal speed for turning is between 20-30km/h. In mode a, if the speed of a vehicle is right within the specified speed period, it can go across an intersection with a constant speed. In mode b, if a vehicle meets a red signal and stops, it should restart and achieve to the normal speed for turning. There is also a case that is when the length of the turning is too short, so the vehicle can pass the intersection with acceleration stage. In mode c, the situation is completely opposite to mode b, a vehicle has a higher speed and needs to slow it down for turning (Figure 5).

$$D_{i-t}=\begin{cases}\sqrt{\dfrac{2S}{a}}, S\le S_0\\ \dfrac{V_s}{a}+\dfrac{S-S_0}{V_s}, S>S_0\end{cases} \tag{12}$$

where S represents the distance of turning, V_s represents the average turning speed, a is the acceleration of the vehicle to reach V_s.

Thus, the delay for intersection can be obtained as following.

$$D_i=\begin{cases}\dfrac{C(1-u)^2}{2(1-u\min(1,x))}+900T[(x-1)+\sqrt{(x-1)^2+\dfrac{8klx}{cT}}]+\sqrt{\dfrac{2S}{a}}, S\le S_0\\ \dfrac{C(1-u)^2}{2(1-u\min(1,x))}+900T[(x-1)+\sqrt{(x-1)^2+\dfrac{8klx}{cT}}]+\dfrac{V_s}{a}+\dfrac{S-S_0}{V_s}, S>S_0\end{cases} \tag{13}$$

III. Model Evaluation

A. Evaluation for improved delay models

In order to evaluate the improved delay models, a link and an intersection are elaborately analyzed. The studied link is on Changshu road, which is about 1.2 km, and the studied intersection is the intersection of Changwu Road and Changhong road. Data is obtained from Chen [23], local governments public documents and the area's panoramic map.

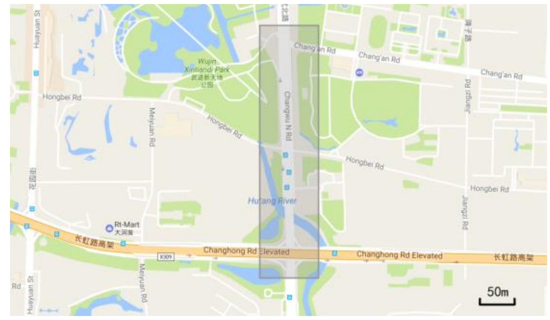


Figure 7. The case study area in Changzhou, China. Shaded area shows the studies routes. Map data Google 2017

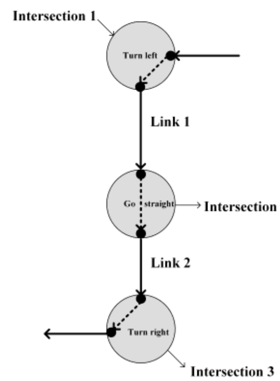


Figure 8. The dual traffic network topology of the selected route

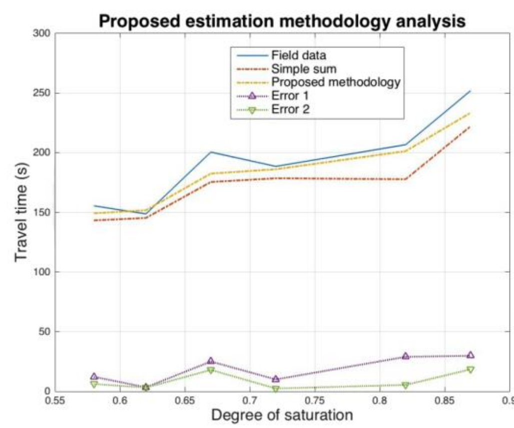


Figure 9. Proposed estimation ethodology analysis

Errors between original models and field data, as well as errors of the improved models and field data are individually calculated and showed in box diagrams in Fig. 6.

It can be seen in Fig. 6, improved delay models are well performed than the original ones. Obviously, the IBPR model has a much smaller error, especially, the average error of the IBPR model is nearly approaching to zero. The similar situation can be found in IHCM model, the average errors decreased dramatically and the smallest error is approximately zero.

B. Comparison

The comparison in Table 1 focuses on the indexes that different models considered, including topology analysis, travel time, link delay, intersection delay, the influence of

TABLE I. COMPARISON BETWEEN DIFFERENT METHODOLOGIES

Methodology	Topology analysis	Estimation of travel time	Estimation of the link delay	Estimation of the intersection delay	Influence of pedestrian	Influence of lane width	Influence of turning cases
The proposed methodology	√	√	√	√	√	√	√
Neuro network model	√	√	√	×	×	×	×
Pedestrian intersection model	×	×	√	√	×	×	×
OBPR model	×	√	×	×	×	×	×
OHCM model	×	×	√	×	×	×	×

TABLE II. IBPR SELECTED DATA

L (m)	V_l (m)	q (number/h)	V (m)	t (s)	λp	λw	BPR (s)	IBPR (s)
1.20	60.00	800.00	38.00	113.68	0.85	0.75	72.47	113.68
1.20	60.00	840.00	37.00	116.76	0.85	0.75	72.57	113.84
1.20	60.00	1050.00	34.00	127.06	0.70	0.75	73.40	139.81
1.20	60.00	1180.00	24.00	180.00	0.70	0.75	74.23	141.40
1.20	60.00	1200.00	27.00	160.00	0.55	0.75	74.39	180.33
1.20	60.00	1290.00	24.00	180.00	0.55	0.75	75.19	182.28
1.20	60.00	1336.00	23.00	187.83	0.55	0.75	75.67	183.44
1.20	60.00	1380.00	23.00	187.83	0.55	0.75	76.18	184.67
1.20	60.00	1540.00	15.00	288.00	0.40	0.75	78.48	261.59

TABLE III. IHCM SELECTED DATA

Lane	q (number/h)	C (s)	u	x	c	D_{i-t} (s)	T (s)	OHCM (s)	IHCM (s)
East turn left 1	280	150	0.2	0.848	330	3	41	55.96	58.96
North left turn 2	248	150	0.23	0.653	380	3	44	60.05	63.05
North left turn 1	297	150	0.23	0.9	330	3	36	69.33	72.33
North straight 1	504	150	0.33	1.417	356	7	315.34	292.85	299.85
North straight 1	575	150	0.33	1.528	376	7	325.42	295.8	302.8
South left turn 1	254	150	0.23	0.5	508	3	27	50.95	53.95
South left turn 2	455	150	0.23	1.207	377	3	276.21	151.55	154.55
South straight 2	250	150	0.33	0.653	383	7	33	72.25	79.25
South straight 3	566	150	0.33	1.03	550	7	23	56.26	63.26

pedestrian, lane width, turning cases. From Table 1, the proposed methodology covers more indexes which means it concerns more aspects in travel time estimation. Neutro network [24] model can be used to conduct comprehensive analysis, but it does not consider the influence of pedestrian, lane width and turning cases and use the topology analysis. Pedestrian intersection model [21] concerns the influence of pedestrian, but it can only be used to analyze intersections. Individual BPR model [11] and HCM model [15] apparently can only be used to estimate delay of links or intersections.

C. Experiment and Results

The proposed estimation methodology above is applied in an urban traffic network of Changzhou, China. Changzhou, located at the at the south of Jialing river on the plain and coordinated at 37° 47'N, 119° 58'E, is part of the well-developed Yangtze Delta region of China. The selected region is a typical area for analysis, so the results can be extended to other cases.

Selected data is listed in Table 2 and 3. The field quantity, the ratio of the period of effective green light, and the period of sampling and the field travel time are obtained from Chen [23]. The length of links, the limitation of speed, the lane width, population density is provided by local government public documents. The average vehicle speed and acceleration at intersections are obtained from vehicle makers.

The studied route consists of two links and three intersections. In this experiment, the corresponding dual traffic network topology is built firstly in Fig. 8. Intersection 1 is the intersection of Changwu Road and Changan Road. Intersection 2 is the intersection of Changwu Road and Changhong Road, and Intersection 3 is the intersection of Changwu Road and Changhong Road. Link 1 is the link between the intersection1 and 2. Link 2 is the link between intersection 2 and 3.

Proposed estimation methodology analysis is shown in Fig. 9. Error 1 stands for the error between the field data and the simple sum of the results of BPR model and HCM model, while Error 2 represents the error between the field data and the proposed estimation methodology. Comparing with the result obtained from the simple sum, the proposed estimation improves the accuracy significantly in urban traffic network. The sample sum cannot well-estimate the travel time when the saturation exceeds approximately 0.72, but the proposed estimation methodology is improved in this case, keeping the estimation error near 0.

IV. CONCLUSION

The paper proposed a dual traffic network coupled with improved delay models to estimate travel time in the urban traffic system. Based on the travel time estimation obtained from this proposed estimation methodology, people can decide a better travel route in advance and local governments can make urban traffic optimization plans.

When residential areas open and become a part of a city's traffic system, it makes the urban traffic system more complicated. Although there are many existed models for estimating travel time, most of them only studied one aspect – the link delay or the intersection delay. To demonstrate urban traffic structure, a new DTN topology is developed by indicating the different turning cases – turning left, turning right and going straight. Meanwhile, the IBPR model for links delay and the IHCM model for intersections delay are improved from their prototypes. The IBPR model considers the influence of pedestrians, the influence of lane width, while the IHCM model includes the corresponding turning cases with the DTN topology and travel time at intersections.

Furthermore, the individual evaluation of the IBPR model and the IHCM model represents the improved models which have high accuracy. The proposed methodology includes comprehensive information than other researches, such as topology analysis, the influence of pedestrians, the influence of lane width and the influence of turning cases. Then, this methodology was applied to a district of Changzhou, China. The paper correspondingly develops a DTN topology and calculates the travel time. In the end, the results illustrate the proposed estimation methodology improve the estimation accuracy significantly, especially with a high degree of saturation beyond 0.72.

Even though the proposed methodology – a dual traffic network topology coupled with improved delay models – is developed based on Chinese urban traffic systems, it is not localized and can be easily implemented in other urban traffic systems. However, some aspects are not included into this methodology, such as the presence of on-street parking, the interference of non-motor vehicle, the unsignalised intersections etc.

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