Delay Function for Signalized Intersections in Traffic Assignment Models

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Abstract: The consideration of delay at signalized intersections improves the accuracy of equilibrium flows obtained from traffic assignment models. This delay depends not only on physical specifications of the intersection, intersection signal timing, and traffic volume and its composition but on drivers' behavior and specific traffic culture in each country. This paper proposes a delay function for traffic assignment models, which considers the special drivers' behavior in Iran. Unlike the existing models such as the *Highway Capacity Manual* model, the proposed delay function has modest data requirements on intersection characteristics, and this ensures the easy use of this function in a real traffic assignment model. To evaluate the proposed function in a real network, the traffic assignment model of the city of Mashhad, Iran is used. In two different scenarios, the equilibrium flows obtained when the proposed function is applied and those obtained when a simple uniform delay function is used are compared to the observed traffic flows. In a comparative sense, the results show the better performance of the proposed function in estimating the equilibrium flows.

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Introduction

The incorporation of signalized intersection delays in traffic assignment models improves the accuracy of the obtained equilibrium flows (Aashtiani and Iravani 1999; Jeihani et al. 2006). To simplify the traffic assignment problems, many studies have either neglected this delay or used unrealistic assumptions for it (Nielsen et al. 1998; Moridpour 2009). This is mainly due to the complicated procedures of computing the delay in the existing delay functions. In addition, to calculate the delay, they require extensive detailed information about the characteristics of the intersection and its approaches. However, in a real transportation network that is comprised of many signalized and unsignalized intersections, it is very time-consuming and labor intensive to collect, store, and update all this information in the traffic assignment model (Kurth et al. 1996; Horowitz 1997).

Another reason for neglecting the intersection delays in traffic assignment models is the lack of a delay function that can appropriately show the driving behavior in each country. The delay at intersections depends not only on factors such as the physical specifications of intersection, intersection signal timing, and traffic volume and its composition on intersection approaches but on drivers' behavior and the specific traffic culture in each country. Existing delay functions are each based on a related set of assumptions, and using those functions in a country where those assumptions are not valid may lead to poor results.

In this paper, a signal delay function for traffic assignment models is developed. This function has a simple structure ensuring it is easy to use. As opposed to existing delay functions such as the *Highway Capacity Manual* (HCM) model, the proposed delay function has modest data requirements on intersection characteristics. In addition, it is calibrated on the basis of special driving behavior in Iran, so it reflects the special driving behavior in Iran. There are some main differences in driving behavior at signalized intersections in Iran, including:

- Paying no attention to the right of way especially by left-turning drivers as they interfere with opposite through movements causing more delay for through movement vehicles and less delay for themselves;
- Disregarding the lane discipline that makes it difficult to use existing saturation flow rates for signalized intersections; and
- The presence of passengers waiting for taxis very close to intersections, which causes an increase in the overall delay at intersections.

This paper first briefly reviews existing delay functions and their applications in existing traffic assignment models. Then, the data used to develop the new delay function are discussed, followed by a section that presents the proposed function, and compares the model estimated delays to those estimated by the HCM model. The proposed function is then incorporated in a real network assignment model, and the obtained equilibrium flows are compared with the observed traffic flows. The conclusions and suggestions for future research are summarized in the final section of the paper.

Literature Review

There are many studies on intersection delay functions. This section reviews existing delay functions which are primarily de-

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veloped to determine the level of service (LOS) of signalized intersections. The delay functions which are currently used in traffic assignment models are also reviewed.

Existing Delay Functions

Delay at signalized intersections constitutes a considerable part of travel time in street networks, which depends on various factors. This delay can be presented by either "stopped delay" or "overall delay" (Olszewski 1993). Since overall delay is difficult to measure in field, the HCM proposes to multiply stopped delay by "1.3" to find overall delay. Regardless of how delay is presented, there are three basic components for signal delay (Quiroga and Bullock 1999): "uniform delay," "random delay," and "oversaturated delay." However, some existing models are not able to capture all these components.

The estimation models can be grouped into three categories depending on volume to capacity "V/Q" ratio (McShane and Roess 1990). The first category, "steady-state" models, comprises the models that consider traffic volume to be less than capacity. The most famous model in this category is the Webster model (Webster 1958) which is presented as Eq. (1)

$$D = C(1 - G/C)^2/[2(1 - V/S)] + (V/Q)^2/[2V(1 - V/Q)] - 0.65(Q/V^2)^{1/3}(V/Q)^{2+(G/C)} \tag{1}$$

where D=signal delay; C=cycle time; G=green time; V=traffic volume; S=saturation flow rate; and Q=capacity. The first term in this model is the uniform delay while the second term takes in to account the randomness of arrivals to an intersection by assuming that arrivals follow a Poisson distribution. The third term also is a correction factor reducing the delay by 5–15% (McShane and Roess 1990).

The second category models estimate "oversaturation delay" considering the occasions when traffic volume in an intersection approach is more than the capacity of that approach. In these occasions, the queue, which is built up during the red phase, cannot be discharged in the following green time and has to wait for another red phase. The most famous model in this category is the Hurdle model (Hurdle 1984). He defined the uniform delay as one-half of the red interval, and the average overflow delay in a given cycle time as a function of queue lengths at the start and the end of cycle time.

The third group of delay functions is called "combined models." The performance of these models that are a combination of models in the first and second categories is more realistic. When V/Q is well below 1.0, these models follow the steady-state models, say the Webster model. At V/Q values close to 1.0, the combined models do not follow steady-state models that suggest an infinite queue/delay. When V/Q ratio is well greater than 1.00, combined models approach the oversaturation models. The representative model in this category is the HCM model whose record of functions is mentioned by Daniel et al. (1996). This model was originally developed to determine the intersection LOS. The delay functions proposed by the alternative versions of the HCM have similar frameworks, though their results have sometimes a minor difference (Braun and Ivan 1996). In the 2000 edition, the following model is proposed to estimate delay for each lane group [Transportation Research Board (TRB) 2000]:

$$D = D_1(PF) + D_2 + D_3 \tag{2}$$

where D_1=uniform delay; PF=progression adjustment factor, which takes in to account the effect of coordination between signals; D_2=incremental delay to account for the effect of random and oversaturation queues; and D_3=initial queue delay caused by the queue that is not discharged in the previous cycle. These components are presented in Eqs. (3)–(5)

$$D_1 = 0.5C(1 - G/C)^2/1 - [\min(1,X)G/C] \tag{3}$$

$$D_2 = 900T\{(X - 1) + [(X - 1)^2 + 8KIX/(QT)]^{0.5}\} \tag{4}$$

$$D_3 = 1,800Q_B(1 + U)T_1/(QT) \tag{5}$$

where X=degree of saturation; V/Q ratio; T=duration of analysis (h); K=incremental delay factor that depends on controller settings; I=upstream filtering/metering adjustment factor; Q_B=initial queue at the start of period T (vehicle); U=delay parameter; and T_1=duration of unmet demand in T (h). The Australian model proposed by Akcelik (1981) and the model used in TRANSYT program (McShane and Roess 1990) are also examples of the models in this group.

Although the third group models are the premier generation of the models, their main drawback is their complicated procedures to estimate delay. This complexity leads to either neglecting signal delay or simplifying that in traffic assignment models, though it is important to incorporate a precise delay estimate in traffic assignment models.

Delay Functions in Traffic Assignment Models

Traffic assignment procedures determine the distribution of traffic flows in different links of a transportation network by determining the effects of traffic flows on travel times through using travel time functions. After introducing Wardrop's principles (Wardrop 1952), i.e., user equilibrium and system optimization, Beckmann et al. (1956) showed that if travel time functions are separable and nondecreasing then traffic assignment problem can be formulated as a convex mathematical programming model that can be solved through several mathematical methods (Sheffi 1985; Patriksson 1994). In all these methods, consistent with Beckman's assumptions, travel time function for each link is a function of traffic volume on that link, and signal delay function for each intersection approach (if any signal delay function is used at all) is a function of traffic volume on that approach. Also, the first derivative of these functions with respect to the traffic volume is positive.

Some traffic assignment models simplified link travel time as a summation of free-flow travel time and congestion delay, without considering any delay at signalized intersections (Nielsen et al. 1998). However, since signalized intersection delays have a considerable effect on total travel time and hence on the passengers' route choices (Nielsen et al. 1998), it is important to use accurate delay estimates to calculate user equilibrium traffic flows in traffic assignment models.

Horowitz (1997) compared the performance of the delay functions mentioned by the HCM 1985 and the HCM 1994 in the traffic assignment model of a network that contained 552 signalized intersections, 925 unsignalized intersections, and 1,967 links. They prepared an extensive data set including the required information to calculate the delay through the HCM method. The traffic flows were obtained through an all-or-nothing assignment procedure. Both delay functions were shown to result in almost same delays on nearly all approaches. However, the additional phasing options and the superior de facto left lane check in the HCM 1994 led to lower delay values on some approaches. The study did not compare the estimated equilibrium traffic flows with

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Table 1. PCEs for Different Types of Vehicles

Vehicle type	Car	Taxi and passenger-carrying car	Van	Motorcycle and bicycle	Public bus	Nonpublic bus	Heavy truck
PCE	1.0	2.0	1.0	0.5	5.0	2.5	2.5

Note: Source: Mashhad comprehensive transportation studies (Aashtiani et al. 1996).

the observed flows. However, it was mentioned that the implementation of the HCM 1994 delay function requires fewer adjustments in traffic assignments. This delay function provides an opportunity to define a greater range of traffic conditions and phasing options.

Aashtiani and Iravani (1999) investigated the effect of signal delay on the performance of traffic assignment models. The transportation network of the city of Tehran, Iran was selected as a case study, which was modeled in the Equilibre Multimodal, Multimodal Equilibrium (EMME/2) traffic assignment software. They used a simple delay function which was based on the first term of Webster's model and compared the linear correlation (R^2) between the observed traffic flows and the estimated equilibrium traffic flows with and without considering the delay function. Although the model did not consider the incremental delay, their analysis showed that using the delay function leads to an improvement in R^2 from 0.69 (when no delay was considered) to 0.75.

Haider and Spurr (2006) developed a full-scale assignment model for the greater montreal area using geographic information systems (GIS). To develop their traffic assignment model, they simplified intersection delays by assuming a penalty of 30 s for left turns, 12 s for right turns, and 3 s for through movements. They used linear correlation between the observed flows and the estimated flows (R^2) and the percent root-mean-squared error (%RMSE) to assess the performance of the traffic assignment model in three successive hours of morning peak (6 a.m.–7 a.m., 7 a.m.–8 a.m., and 8 a.m.–9 a.m.). The R^2 values varied from 0.82 to 0.87 and the %RMSE values were all about 36%. However, taking constant values for the movement delays is very simplistic assumption, which ignores the effect of traffic volumes on intersection delay. This simplification would result in poor outcomes in high levels of traffic volume.

Data

To develop a delay estimation model for a signalized intersection, four types of data are required: traffic volume, delay, signal timing for each intersection movement, and the intersection geometry. The required data were collected from four intersections in Tehran, Iran. These were the Ivanak-Farahzadi, Shariati-Dowlat, Mojahedine Islam-Iran, and Resalat-Asnaashari intersections. The Ivanak-Farahzadi intersection was a T-intersection while others were four-leg intersections. To eliminate the effect of any specific configuration in the intersection geometries and to ensure that the data set represents all signalized intersections in the street network, these intersections were of those with a typical geometry that is mostly used in the street network. There was no auxiliary lane for either left or right turns at these intersections, the intersection approaches had zero slopes, and the approaches were not offset in relation to each other. Due to difficulties in data collection at the Resalat-Asnaashari intersection, only one approach of this intersection was considered for data collection. Right turns at this intersection were not allowed but some drivers still turned right. At the Mojahedine Islam-Iran intersection, turnings from Mojahedine Islam Street to Iran Street were not allowed.

Classified traffic volumes of different movements at all the intersection approaches were collected in 5-min intervals from 7 a.m. to 10 a.m. over five consecutive weekdays of October 2002 (Mazloumi 2003). Total traffic volume in terms of passenger car (PC) units was then calculated based on the PC equivalences (PCEs) presented in Table 1. These values were suggested in the Mashhad comprehensive transportation studies (Aashtiani et al. 1996) on the basis of the special traffic conditions and the traffic performance of each vehicle type in Iran. The logic behind these values is presented in the following discussions.

The PCE value for PCs was considered to be 1.0. Taxis have more interference effect on traffic flows compared to normal PCs. They are allowed to pick up passengers while they have some passengers on board. They frequently stop to pick up/drop off passengers. Due to this behavior, a higher PCE of 2.0 was considered for them. In addition, some private PCs carry passengers like taxis. Since these vehicles cannot be easily distinguished (by their colors or number plates) Aashtiani et al. (1996) assumed they constitute 25% of all PCs and have a PCE value of 2.0. Vans are operating like normal PCs, so a unit value of PCE was considered for them. Public transport buses stop more often compared to other types of buses in a traffic network, so a higher value of PCE was considered for them. Using these values ensures consistency between the delay function models of signalized intersections and the link travel time functions used in the traffic assignment models of Iranian cities. Note that these values were used in developing the link travel time functions of different road types (Aashtiani et al. 1996).

To collect the delay values in different movements of each intersection, the path of some individual vehicles was tracked. To do so, the number plates and passing times of a sample of cars, which passed predefined points located in different entrances/exits of each intersection, were recorded. Because the surveyors were not able to record the number plate of all cars, they were asked to only consider the cars with a specific color (e.g., white). Collecting the delay values was performed manually using several teams of surveyors. Each team comprised at least two trained persons. When a car approached the predefined point, one person loudly read the number plate (or its last three digits), and the other person recorded that along with the car passing time.

The predefined points at entrances were located well away from the intersection to prevent travel time being affected by the signal queue. At intersection exits, this distance was shorter, but vehicles still traveled at free-flow speed at those points. By matching the vehicle number plates recorded in different entrances/exits of each intersection, the travel time of each vehicle was calculated. To calculate vehicle delay times, free-flow travel time of each intersection movement was then reduced from travel times recoded in that movement. The free-flow travel times were calculated on the basis of the free-flow speeds of 60, 50, and 40 km/h for arterial roads type 1, arterial roads type 2, and collector streets (Aashtiani et al. 1996). Overall, 12,847 delay observations were collected comprising left turns, right turns, and

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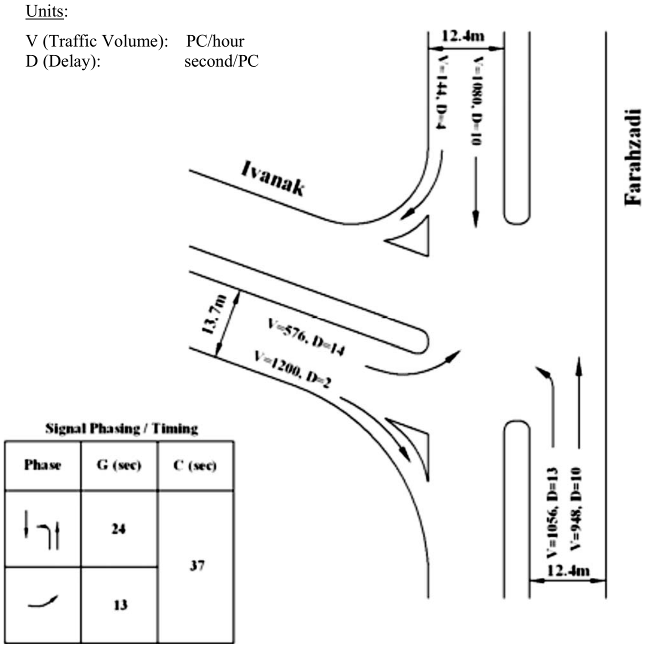

Fig. 1. Summary of collected data at the Ivanak-Farahzadi intersection

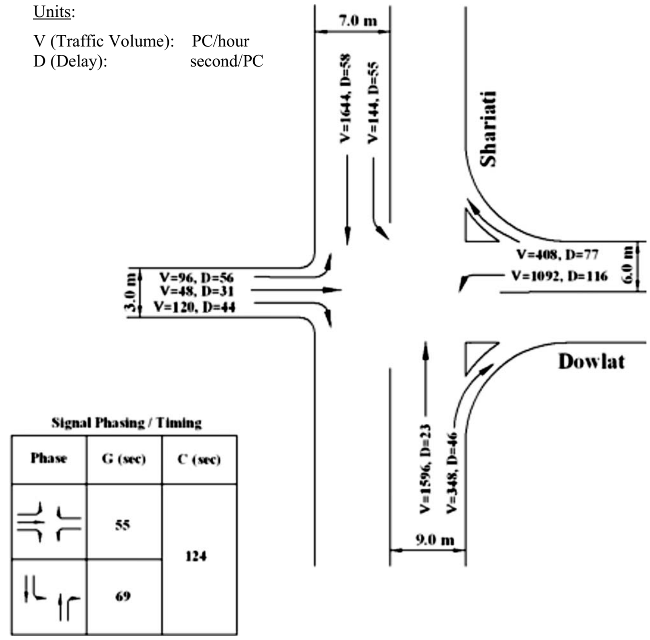

Fig. 2. Summary of collected data at the Shariati-Dowlat intersection

through movements. The average delay in each movement in different 5-min time intervals was then computed considering the delay of vehicles arriving within each 5-min interval. Then, using a weighting average on the movement delays of each approach (with the weights equal to the traffic volumes of those movements in different 5-min intervals), delay values were obtained for each intersection approach.

The traffic signals at the intersections were pretimed, and their green times and the cycle times were constant over the period of data collection. At Ivanak-Farahzadi and Shariati-Dowlat, the left turns interfered with their cophase opposite through movements. The signals at the other two intersections provided protected movements for left turns. For each intersection, the times when the signals turned to green/red were recorded manually. Furthermore, the geometries of the intersection approaches were surveyed.

Figs. 1–4 show a summary of the collected data at the four intersections. In these figures, the average hourly traffic flow (PC/h), the average delay at different considered movements (s/PC), and the width (m) of each surveyed approach are presented. These figures also show the phasing and timing of the intersection signals.

Fig. 5 shows the variation of delay in relation to the V/Q in different intersections. Accordingly, the Ivanak-Farahzadi intersection operated well below the capacity, and traffic volume at the Resalat-Asnaashari intersection was near the capacity. The V/Q at the other two intersections also varied from low to high. The ranging of the V/Q from low to high values ensures the model ability to well estimate low and high delay values.

Delay Function Development

This section develops a function to estimate total approach delay taking into account the traffic conditions in Iran, which is supposed to be used in traffic assignment models. To ensure the easy use of the function in traffic assignment models, the general form shown in Eq. (6) is used to estimate the delay (Mazloumi 2008)

$$D=(C-G)^2/\{2C[1-V/(W\times S)]\}+a(V/Q)^b+e \qquad (6)$$

where D=average approach delay (s/PC); C=cycle length (s); G=green time (s); V=total traffic volume on the approach (PC/h); S=saturation flow rate for 1-m width of the approach (S=600 PC/h green/1-m width); W=approach width (m); Q=approach capacity; $Q=WSG/C$ (PC/h); and a, b, and e=model parameters.

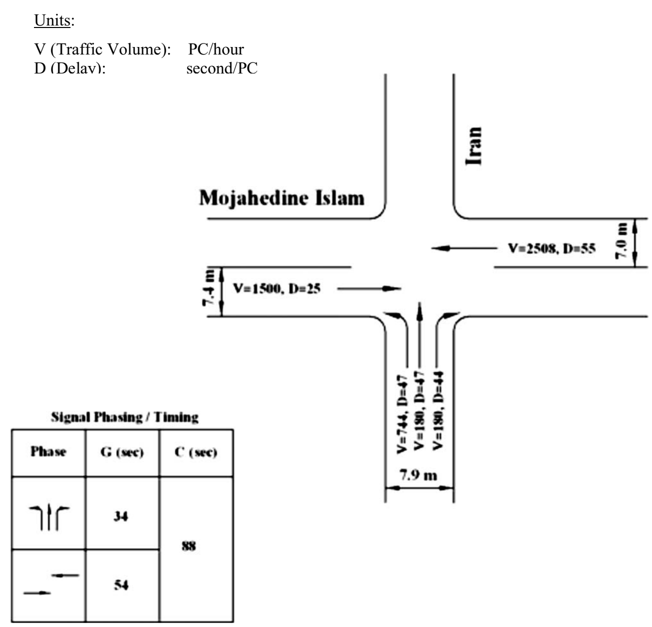

Fig. 3. Summary of collected data at the Mojahedine Islam-Iran intersection

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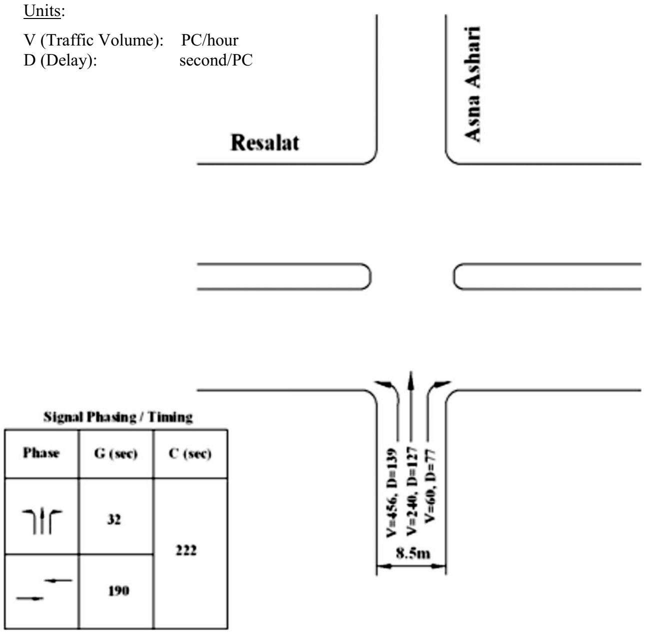

Fig. 4. Summary of collected data at the Resalat-Asnaashari intersection

The first term of the model is the generally accepted form of the uniform delay and is inspired from Webster's model (Webster 1958). Total delay is expected to increase with V/Q as a result of incremental delay. To account this delay, the second term is added to the function. In Iran, traffic flow at intersections is often delayed by the passengers waiting for a taxi, or vehicles that pick up/drop off passengers. The final constant term takes into account the effect of other factors on intersection delay. Since the model parameters will be calibrated on the basis of the collected data, they will reflect the driving circumstances in Iran. Most importantly, this model is a separable function since considering a pretimed signal for each approach, i.e., fixed green and cycle times, the delay of each approach only depends on the traffic volume of that approach. It is also a nondecreasing function as its first derivative is nonnegative. Therefore, according to Beckmann et al. (1956), traffic assignment problem is capable of being transformed to a convex optimization problem.

Table 2. Results of Nonlinear Regression Analysis

Parameter	Coefficient value	t-statistic
a	36.9	9.8
b	2.8	4.9
e	7.8	3.0

The value of 600 (PC/h green/1-m width) for saturation flow rate was obtained previously in the Mashhad comprehensive transportation studies (Aashtiani et al. 1996). The saturation flow rate for each intersection depends on many factors like lane width, the presence of bus stop, the approach slope, etc. (Cuddon 1993). This diversity of factors necessitates the collection of an extensive data set, which is time-consuming and labor-intensive. The fixed value used in this paper ensures the easy use of the model in traffic assignment models. The reason why the street width is used instead of the number of lanes is that due to driving behavior in Iran, the number of lanes does not necessarily show the number of cars being accommodated across the street width.

To calibrate the above model, the values of W, G, C, D, and V are available from the data collection. A total of 312 data points are obtained after aggregating the data into 5-min intervals based on which the model parameters are calibrated. The nonlinear regression technique is used to calibrate the model parameters. Table 2 presents the parameter values, and their respective t-statistics. All the parameters are significant at 95% confidence level.

The model goodness of fit (R^2) is 0.71, which shows that almost three quarter of the variability in the data are captured by the model. Fig. 6 shows the model estimated delays versus observed delays at the different intersections. The model performance de-

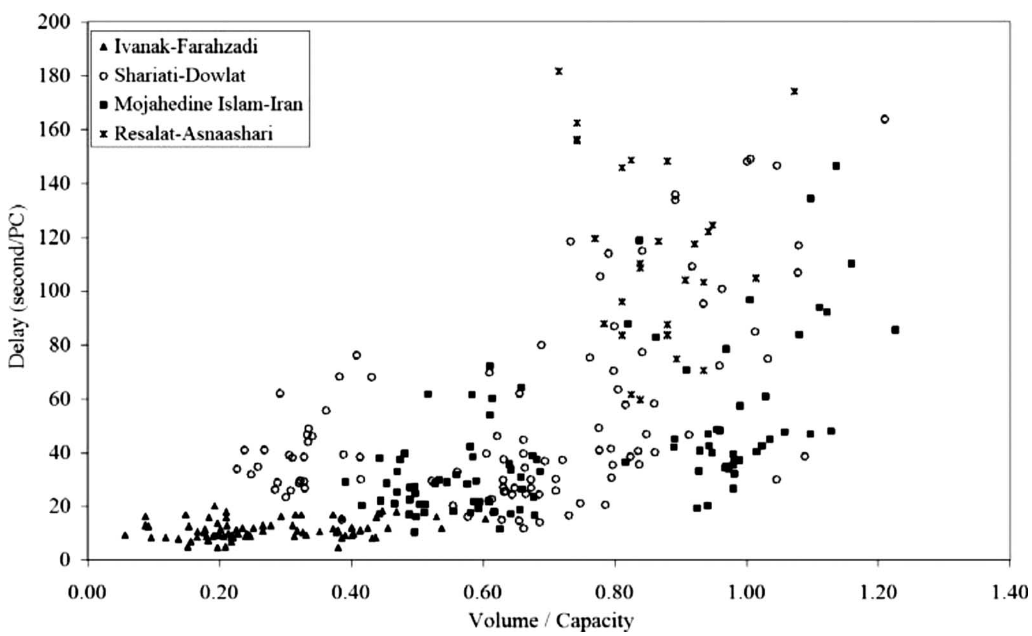

Fig. 5. Variation of delay in relation to volume/capacity ratio in the different intersections

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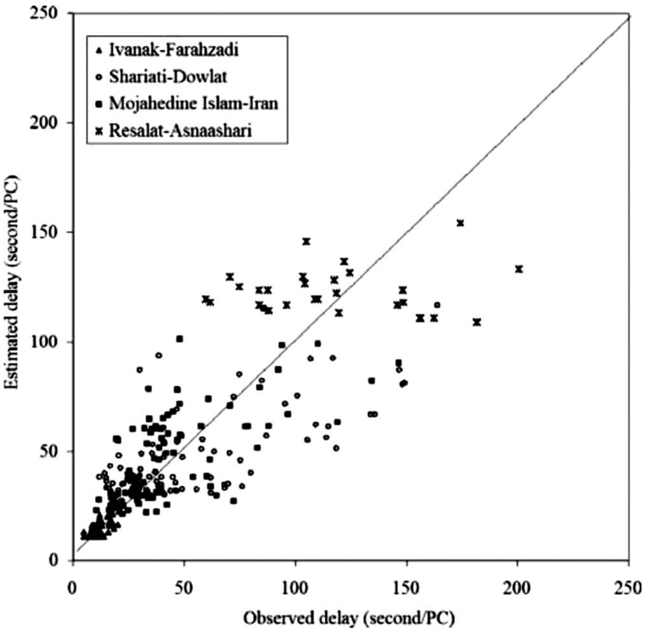

Fig. 6. Estimated delays versus observed delays

Table 3. Average Observed and Estimated Approach Delays in the Different Intersections

Intersection	Average observed (s/PC)[a]	Average estimated (s/PC)[a]	Average error (s/PC)[a]
Ivanak-Farahzadi	11	14	3
Shariati-Dowlat	52	46	−6
Mojahedine Islam-Iran	42	46	4
Resalat-Asnaashari	124	123	−1
All intersections	45	45	0

[a]Average in different 5-min intervals over a 3-h interval.

teriorates in heavy congestion, i.e., in the Resalat-Asnaashari intersection where V/Q is high. In low traffic intersections, however, the performance is satisfactory.

Table 3 compares the intersection average estimated and observed delays. As seen, the model estimated delay values are reasonably close to the average observed delays. This means the model can provide precise estimations of signal delays in static traffic assignment models, where the average delay is of interests.

In contrast to the HCM model, which has a complicated procedure to calculate the delay, the proposed model has a simple structure enabling its easy use in traffic assignment models. To show that the underlying assumptions of the HCM model are not valid in Iran, intersection estimated delays are compared with the observed delays in Fig. 7. The saturation degree used to calculate the HCM estimated delays is obtained following the HCM procedure. Accordingly, the HCM model overestimates the total intersection delay for the intersections with conflicting left turns (Ivanak-Farahzadi and Shariati-Dowlat). The HCM model assumes that left-turning vehicles wait until they find a gap in the opposite through movement flow, which results in an increase in their delay. However, left turners in Iran do not wait until through movements pass the intersection. Interfering with the opposite through movements, the left turners force them to stop. In other words, the right-of-way rules are almost ignored by this group of Iranian drivers who want to minimize their travel times. This issue highlights that the traffic assignment models in Iran need a model to estimate the delay at signalized intersections that is based on the specific driving culture in Iran.

Application of the Delay Function in a Traffic Assignment Model

To evaluate the performance of the proposed delay function in a traffic assignment model, the information of a real transportation system is required. In this research, the transportation system of Mashhad, Iran in 1994 (Aashtiani et al. 1996) is used as a case

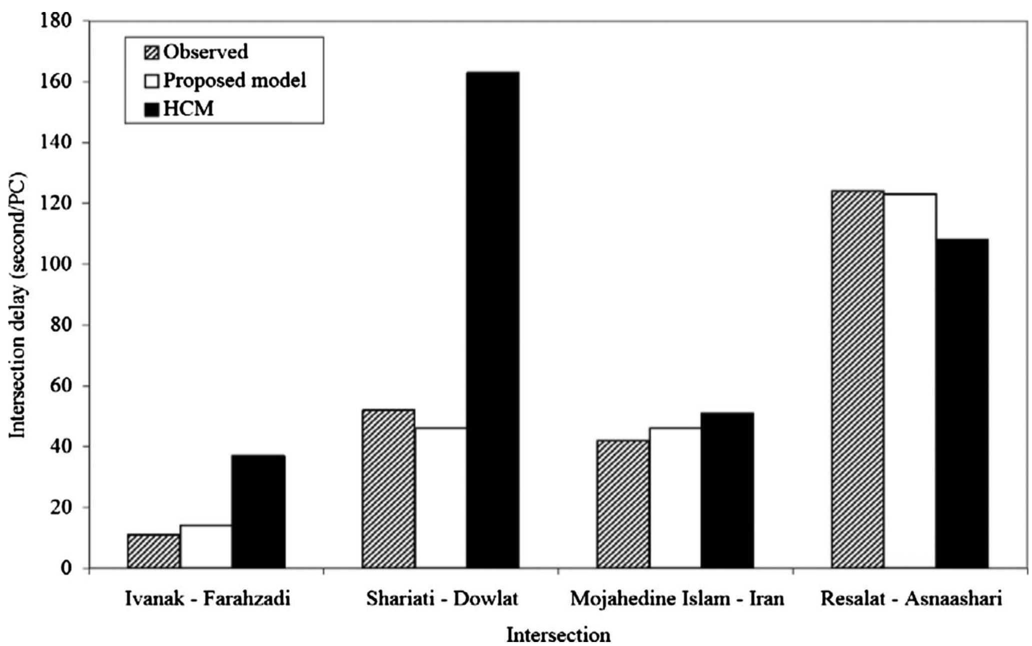

Fig. 7. Comparison of the observed delays with those obtained from the different models

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Table 4. Performance of the Different Delay Functions in Estimating Traffic Flows

Considered function	R^2	RMSE (PC/h)	MAE (PC/h)	MARE (%)
Uniform	0.532	880	537	44
Proposed	0.850	370	267	30

study. Mashhad with a population of almost 2 million covered an area of 288 km^2 in 1994. The city was divided into 163 traffic zones including 141 internal and 22 external zones. To obtain the demand information and the number of trips between traffic zones, origin-destination surveys for the study area were carried out in 1994. The 163×163 origin-destination demand matrices were then obtained for different vehicle types and different time intervals.

The supply infrastructure included street network and public transport system. In 1994, the street network included 690 nodes including 50 signalized intersections and 640 unsignalized intersections. The information of signal phasing/timing at signalized intersections was recorded. There were 1,036 links with defined performance types of access roads, arterial roads type 2, arterial roads type 1, and freeways. The Mashhad public transport system also included 746 buses operating in 117 bus routes. All the information of bus network including bus routes, bus stop locations, and the number of buses operating over each route were collected.

A practical method in determining the equilibrium flows in transportation networks is the Frank-Wolfe method (Sheffi 1985) which is applied in many traffic assignment software packages. In this study, the EMME/2 traffic assignment software is used, which uses the Frank-Wolfe method. Here, the general function used in estimating each link travel time is expressed as follows:

$$T = T(X) + D(X) \tag{7}$$

where $T(X)$=BPR travel time function (Bureau of Public Roads 1964) calibrated for each road performance type to estimate the link travel time (Aashtiani et al. 1996) and $D(X)$=delay at the downstream signalized intersection. Note that both $T(X)$ and $D(X)$ are separable and nondecreasing functions, so T will be separable and nondecreasing, which satisfies the assumptions of Beckmann et al. (1956).

To evaluate the accuracy of the traffic assignment results, one approach is to compare the equilibrium traffic flows obtained from traffic assignment with the observed traffic flows in the transportation network. The observed traffic flows were collected manually in 119 links of Mashhad transportation network for a morning peak hour (Aashtiani et al. 1996). The counted traffic flows were then converted to PC equivalent flows on the basis of the values presented in Table 1.

Two different scenarios are considered, each with a different delay function used in the traffic assignment model. In each scenario, a comparison is made between the obtained traffic flows and observed ones. The first scenario only uses the uniform delay, the first term in the HCM model, to estimate the delay at signalized intersections. This function has a simple structure without any parameter, so there is no need to data collection to calibrate the function. Using the uniform delay function resulted in a reasonable accuracy in obtaining equilibrium traffic flows (Moridpour 2009). To simplify the computation and to avoid an extensive data collection, saturation flow rate is assumed to be S=600 (PC/h green/1-m width) for all signalized intersections. The second scenario considers the delay function developed in this study in the traffic assignment model.

The linear correlation (R^2) between the observed PC equivalent flows and the estimated flows in the two scenarios are presented in Table 4. The values closer to 1.0 indicate the better performance of the model. The obtained traffic flows are also compared to the observed traffic flows in each link under different scenarios. The RMSE, mean absolute error (MAE), and mean absolute relative error (MARE) are chosen to determine the absolute and relative errors. The application of the proposed model results in the R^2 equaling to 0.85 that is considerably higher than that when only the uniform delay is used (0.53). Other error measures also improve when the developed model is used. The results presented in Table 4 show that the application of the developed model leads to a higher accuracy level compared to that when the uniform delay is used.

Table 5 presents the accuracy of the obtained equilibrium traffic flows in different road types. In comparison to the uniform delay, the proposed delay function has an inconsiderable effect on the accuracy of the equilibrium traffic flows in access roads, as traffic flows at access road intersections are usually well below the capacity of intersections, and the incremental delay has a minor effect on total signal delay. Therefore, the consideration of the other two terms in the proposed delay function has minor effects on the traffic flow of access roads. The application of the proposed delay function substantially improves the accuracy of the estimated traffic flows in arterial roads type 2. This is very important as the portion of this type of roads is usually higher compared to other road types in a network. In the case of arterial roads type 1, using the developed model relatively improves the results.

Conclusions

Considering signalized intersection delays improves the reliability of traffic assignment models by increasing the accuracy of the obtained equilibrium flows. The delay at signalized intersections

Table 5. Performance of the Delay Functions in Estimating Traffic Flows in Different Road Types

Considered function	Road type	R^2	RMSE (PC/h)	MAE (PC/h)	MARE (%)
Uniform	Access	0.698	197	140	47
	Arterial type 2	0.396	1,023	678	44
	Arterial type 1	0.918	288	202	41
Proposed	Access	0.700	198	141	48
	Arterial type 2	0.783	417	314	18
	Arterial type 1	0.926	195	147	40

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depends on various factors such as intersection geometry, signal timing, and traffic volume and its composition as well as drivers' behavior and specific traffic culture in each country.

This paper shows how the existing assumptions in delay function models can be modified to be suitable for specific traffic culture in Iran. Based on the data collected from four signalized intersections in Iran, a model is proposed to estimate the delay at signalized intersections in traffic assignment models. The results presented in this paper showed that the proposed model performs better at intersections with conflicting left turns. The fundamental assumptions in the HCM model are not valid in Iran as left-turning vehicles do not wait until the opposite through movement pass through the intersection.

The simple structure of the model and its modest data requirements, compared to the existing models like the HCM model, make it easy to use this function in a real network assignment model. The performance of the proposed model, which is essentially developed for traffic assignment models, is examined in the traffic assignment model of Mashhad, Iran. The uniform delay and the proposed models are compared. The results suggest that the application of the model considerably improves the equilibrium traffic flows.

The paper clearly highlights that a different delay model reflecting the special circumstances of each country must be developed. The procedure explained in this paper can be applied in other Asian cities to develop models that specifically show the driving culture and traffic condition in those cities. To develop such models, it is suggested to use PCE and saturation flow rate values suitable for conditions in those cities. Also, the data used for the model development was collected from four intersections. Expanding the data set covering data from a higher number of intersections can be a promising future direction for this research.

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