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A New Delay Parameter for Variable Traffic Flows at Signalized Intersections

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Abstract

Estimation of delay at signalized intersections is a complex process and depends on a number of parameters, among which the degree of saturation (x = v/c) is the most important. This paper presents a new methodology for estimating delay parameter k, and proposes an analytical delay model for signalized intersections that considers the variation in traffic flow. Unlike the existing delay models in the literature, the delay parameter k is not a fixed value and is expressed as a function of the degree of saturation. The proposed model is applicable to the entire range of expected operation including highly oversaturated traffic conditions. A comparative study of the proposed model against the existing models was performed to verify the improvements by the proposed model. Later, the TRAF-NETSIM (Traffic Network Simulation) microscopic simulation model was used in the calibration and verification of the new delay model for oversaturated conditions. The simulation was conducted in 3 consecutive time periods to reflect fluctuation in traffic demand. The relationship between the simulated and proposed delay model results were analyzed for 48 different scenarios.

Key words: Delay estimation, simulation, signalized intersections, delay parameter, degree of saturation, variable demand.

Introduction

Background and literature review

The quality of service (QOS) at an intersection is measured by a number of criteria, such as delay, capacity, speed, number of stops, queue lengths and degree of saturation, among which delay is the most important because it shows the direct measure of lost travel time and fuel consumption. Three types of analytical delay models (i.e. stochastic steady-state, deterministic and time dependent) with different assumptions have been developed in the past for predicting average delay experienced by vehicles at signalized intersections. Stochastic steady-state delay models assume that arrivals are random and departure headways are uniform (Newell, 1956; Webster, 1958; Miller, 1968). They are only applicable to undersaturated conditions, that is, demand is less than capacity, and predict infinite delay when arrival flow approaches capacity. However, when demand exceeds capacity oversaturated conditions exist and continuous overflow delay occurs.

Deterministic delay models can estimate continuous overflow delay, but they do not completely deal with the effect of randomness when arrival flows are close to capacity, and also fail when the degree of saturation is between 1.0 and 1.1.

As pointed out by Hurdle (1984), both types of delay model are utterly incompatible when the degree of saturation is equal to 1.0. Time-dependent delay models, therefore, are used to fill the gap between these 2 models and also to give more realistic results in the estimation of delay at signalized intersections. They are derived as a mix of steady-state and deterministic models using the coordinate transformation techniques described by Kimber and Hollis (1979). Thus, this type of model predicts delay for both undersaturated and oversaturated conditions without having any discontinuity at the degree of saturation 1.0. Various time-dependent delay models have been introduced within different mathematical forms to estimate delays for various traffic conditions at signalized intersections (Catling, 1977; Kimber and Hollis, 1978, 1979; Robertson 1979; Akcelik, 1980, 1988; ITE 1995; TRB, 1997, 2000). Among them, the most commonly used delay models are defined in the 1981 Australian Capacity Guide (Akçelik, 1980), the 1985 Canadian Capacity Guide for Signalized Intersections (ITE, 1995), and the 1997 and 2000 versions of the Highway Capacity Manual (TRB, 1998, 2000).

Burrow (1989) and Akcelik (1990) presented generalized delay expressions for existing time-dependent delay models due to their similar forms. In general, they include a uniform delay term and an overflow or an incremental delay term given by Eq. (1).

$$d = d_u + d_0 \quad (1)$$

in which d is average total delay (seconds), d_u is uniform delay (seconds) and d_o is overflow delay (seconds).

Unlike other models, the HCM 2000 delay model includes a uniform delay progression adjustment factor, which accounts for effects of signal progression. Moreover, it has an additional delay term called initial queue delay, which accounts for delay to all vehicles in the analysis period due to the initial queue at the start of the analysis period.

Delay parameter K

The amount of delay and the level of queue on an approach are based on arrival and service characteristics at a signalized intersection. The delay parameter k is used to describe arrival and service characteristics in delay models. The analytical equations developed for estimating this parameter are obtained using queuing analysis methods or simulation techniques. Estimating k with queuing analysis methods necessitates a knowledge of the arrival pattern, the service facility and the queue discipline.

In steady-state delay models for an M/G/1 queuing system, the Pollaczek-Khintchine coefficient k given in Eq. (2) represents the arrival and service characteristics at an intersection.

$$k = \frac{1}{2}\left[1 + \left(\frac{\sigma_s}{\tau_s}\right)^2\right] \quad (2)$$

where σ_s and τ_s are the standard deviation and the mean of the service (departure) headway distribution, respectively.

Kimber et al. (1986) modified k to account for the effect of the non-randomness in arrival pattern in the following form:

$$k = \frac{1}{2}\left[\left(\frac{\sigma_a}{\tau_a}\right)^2 + \left(\frac{\sigma_s}{\tau_s}\right)^2\right] \quad (3)$$

in which σ_a andτ_a are the standard deviation and the mean of the arrival headway distribution, respectively.

The authors applied computer simulation techniques to estimate k in Eq. (3) using a single service first-in-first-out queuing process. They obtained arrival and service times from the lognormal distribution, and, for a separate case, from the negative exponential distribution. They also performed equivalent analytical calculations for Erlang 2 and hyper-exponential arrivals.

Kimber and Daly (1986) reported that the value of (σ_a/τ_a) varies between 0.75 and 1.25 for different traffic flows. Although they proved that (σ_a/τ_a) changes with traffic conditions, most well-known delay models in the literature have adopted a fixed value of delay parameter k. For random arrivals and departures at unsignalized intersections, $(\sigma_a/\tau_a) = (\sigma_s/\tau_s) = 1.0$, and, therefore, $k = 1.0$. On the other hand, for random arrivals and uniform departures at fixed time signalized intersections, $(\sigma_a/\tau_a) = 1$ and $(\sigma_s/\tau_s) = 0$, resulting in $k = 0.5$.

Akcelik and Rouphail (1993, 1994) developed an expression for k as a function of capacity per cycle. Using a steady-state delay model, 2 delay parameters of k and x_0 were derived from the simulation for random and platoon arrivals. Later, a coordinate transformation technique was employed to incorporate both delay parameters in time-dependent delay models. In these studies, k incorporates the ratio of variance-to-mean arrivals per cycle (I_u) at the upstream approach. For random arrivals I_u equals 1.0 and the delay parameter k is given by:

$$k = 1.22\,(s\,g)^{-0.22} \quad (4)$$

where sg is capacity per cycle (s is saturation flow in vehicles per second and g is green time in seconds).

The above expression is only applied when the degree of saturation is greater than 0.5, and the value of k in Eq. (4) ranges from 1.0 to 0.5 for capacity per cycle (sg) values in the range of 3 to 60 vehicles per cycle. The same authors also developed a delay parameter k for platooned arrivals. In their expression, the delay parameter k is not only a function of capacity per cycle but is also a function of the magnitude of the platooning and the cycle-to-cycle variation in the arriving stream.

Tarko et al. (1994) presented the following model to describe k exploiting the difference between the upstream and downstream intersection capacities. The essence of the theory in the model is that random overflow delay approaches zero when the capacity is less than or equal to the capacity at the downstream intersection. After a calibration procedure, the delay parameter k is expressed as

$$k = 0.408\left\{1 - e^{-0.5\left[(sg)_u - (sg)_d\right]}\right\} \quad (5)$$

in which $(sg)_u$ is upstream capacity in vehicles per cycle and $(sg)_d$ is downstream capacity in vehicles per cycle. The calibrated delay parameter is valid for $(sg)_u > (sg)_d$ and x > $(\text{sg})_d/100$; otherwise, it becomes zero.

In the estimation of k, empirical approaches were developed as an alternative to queuing analysis methods if there is no information about the queuing characteristics. They are employed to estimate k through the calibration by fitting the random delay to the simulated or observed delay in the field. Based on an empirical approach, Daniel (1995) presented a model to express the delay parameter k at signalized intersections for the 3 signal controller types. The author calibrated k by setting an estimate of the measured incremental delay to the time-dependent model and solving for k,which was expressed as a function of degree of saturation, and an exponential equation given as

$$k = e^{\beta_0} x^{\beta_1} \quad (6)$$

where β_0 and β_1 are regression coefficients and x is degree of saturation.

The results show that k for pre-timed control has the highest values, ranging between 0.39 and 0.02 for the degree of saturation varying from 0.5 to 1.0. Furthermore, k for semi-actuated and fully actuated control ranges from 0.197 to 0.005 and from 0.313 to 0.016, respectively.

The HCM and the Canadian delay models use a fixed value of 0.5 for k based on a queuing model with random arrivals and fixed service time. The Australian delay model, on the other hand, takes k as 1.5 to be compensated by x_0 as described before.

However, it is questionable to use a constant value for k instead of a varying value in the estimation of delay as traffic conditions vary during the day. The fluctuation in arrival flows should be taken into account to get more realistic estimations. Therefore, this study presents a different form of k as a function of the degree of saturation using the simulation model TRAF-NETSIM as proposed by Akgungor (1998), and Akgungor and Bullen (1999).

Research approach and methodology

Because traffic flow is a stochastic process, traffic conditions on any approach always fluctuate in time. To account for the effect of fluctuations, studies with different methodologies for variable demands were performed by Akcelik (1993, 1997) and Ceder et al. (1988, 1989). Akcelik (1993) considered different delay definitions using the peak flow factor (PFF) concept. Later, in 1997, he extended the use of the peak flow factor concept to multiple flow periods.

The model presented in the present study attempts to estimate delay at signalized intersections for variable demand conditions, which were reflected by the degree of saturation. As mentioned before, if there is no information about queue characteristics at a signalized intersection, an empirical approach is used to estimate the delay parameter k. The overflow delay that represents the additional delay consists of continuous and random overflow delays defined by Eq. (7) and illustrated in Figure 1. The former occurs only when the degree of saturation is greater than 1.0, while the latter may occur at all degrees of saturation.

$$d_o = d_{co} + d_{ro} \quad (7)$$

where d_{co} is continuous and d_{ro} is random overflow delays (seconds) respectively. The continuous overflow delay is defined as follows:

$$d_{co} = \frac{T}{2}(x - 1) \quad (8)$$

in which T is the time period for the analysis (hours) and x is the degree of saturation.

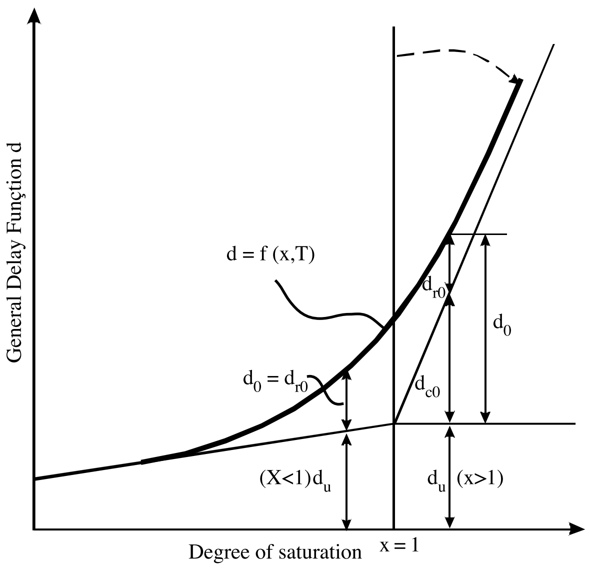

Figure 1. A general delay function for delay components (Akcelik, 1980).

Referring to Eqs. (1) and (7), for undersaturated conditions, continuous overflow delay becomes zero and thus the simulated delay equals the sum of the uniform and random overflow delays. An estimate of random overflow delay holds true only if the simulated delay is greater than the estimate of uniform delay. If the simulated delay is less than uniform delay, the random overflow delay is zero accordingly. On the other hand, for oversaturated conditions, the random overflow delay is determined from the difference between the simulated delay and the sum of the uniform delay and the continuous overflow delay terms.

The value of k for undersaturated or oversaturated conditions is obtained by substituting the simulated random overflow delay into Eq. (9), which demonstrates a simple form of the Canadian delay model. The random overflow delay is, therefore, the core term in modeling the delay parameter k.

$$d = \frac{C(1-\frac{g}{C})^2}{2\left(1-x\frac{g}{C}\right)} \text{ or } 0.5(C-g)+ 900T\left[(x-1)+\sqrt{(x-1)^2+\frac{8kx}{cT}}\right] \tag{9}$$

in which C is cycle time (seconds), g is green time (seconds), x is degree of saturation indicating the ratio of arrival flow (or demand) to capacity (i.e. v/c) and g/C is green ratio, T is the duration of the analysis period (hours), k is the delay parameter and c is capacity.

Experimental setup and model development of k

The simulated intersection in this study consisted of one lane for every approach. The E-W links were considered major approaches while the N-S links were considered minor approaches. The link length of the intersection was set to 3000 ft (914 m) for each approach. However, queue spillback occurred when the degree of saturation was between 1.3 and 1.5. The intersection was considered a micro node in order to take into account the effects of spillback on total delay. Turning traffic and pedestrian traffic were excluded from the simulation to eliminate mixed effects, and only through traffic was considered in the analysis.

Entry link volumes varied from 60 to 900 veh/h for the minor approaches and from 100 to 1500 veh/h for the major approaches. Thus, the degree of saturation ranged between 0.1 and 1.5 for both major and minor approaches. The percentages of trucks and carpools for all links were arbitrarily taken as 5% and 0%, respectively.

In this experiment, the duration of each simulation run was 15 min. Ten simulation runs with different random seed numbers, which NETSIM uses to generate varying driver and vehicle characteristics, were performed for each entry link volume. The random seed number did not change with respect to the degree of saturation during each run, taking a different value for each run to obtain identical traffic movements.

When the degree of saturation x was less than 0.5 and greater than 1.0, the variation in k values was so great that supplementary simulation runs were performed to obtain a significant amount of data. Thus, a total of 182 simulation runs were carried out to develop a delay model suitable for variable demand conditions. A total number of 728 data points were obtained from the simulations. However, 94 of the total data points were excluded since the simulated delay was either less than the uniform delay or the sum of the uniform delay and the continuous overflow delay.

The simulation results showed that the variation in the calculated k values for low and high degrees of saturation was large, and, therefore, in modeling k a lower boundary limit of 0.0 and an upper boundary limit of 1.5 were applied to minimize the effect of large k values. Although no specific information on minimum and maximum boundary values of k was found in the literature, the Australian delay model takes k as 1.5 to be compensated by x_0 as mentioned earlier. Kimber and Daly (1986) found a maximum k value of 1.5 at one site while observing queue lengths at different sites.

Using the simulation results, the analytical form of the delay parameter k ranging between 0.488 and 1.5 was obtained through best-fit techniques as a second degree of parabolic function given in Eq. (10). Here, the proposed model is applicable for all degrees of saturation and at variable demand conditions.

$$k = 0.8x^2 - 1.4x + 1.1 \tag{10}$$

Comparison of the proposed delay model against the existing delay models

The performance of the delay model developed in this research was evaluated by comparing with the HCM 2000, the Australian, the Canadian delay models, and a deterministic delay model defined by Eq. (8). Here, only the overflow delay component was considered since the prescribed delay models have a similar expression for the uniform delay. For comparison and validation, the progress adjustment factor (PF), the incremental delay calibration factor (k) and the upstream filtering adjustment factor (I) in the HCM 2000 delay model were taken as 1.0, 0.5 and 1.0, respectively. The initial queue (i.e. d_3) was taken as zero since it was assumed that there exists no initial queue at the start of analysis period.

The performance study was carried out for traffic conditions with a cycle length of 90 s, an effective green time of 30 s, a saturation flow rate of 1500 vph, and a capacity of 500 vph. The degree of saturation was chosen between 0.1 and 1.5, so that the demand varied from 50 to 750 vph. Four analyses time periods were used in the comparison of models: 15, 30, 45 and 60 min.

The estimated overflow delays and percent differences only for the first analysis period are given in Table 1 and plotted in Figure 2.

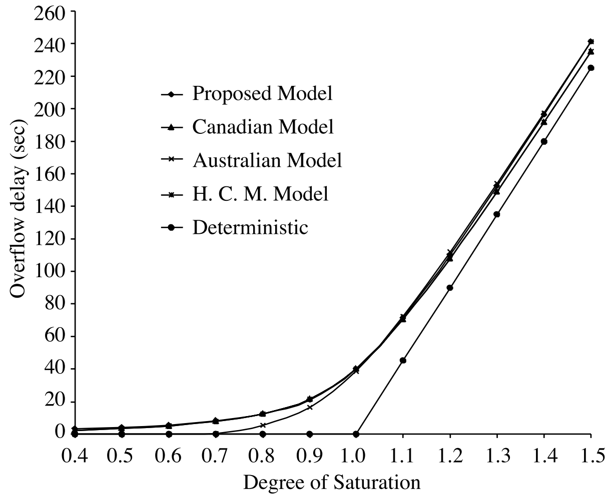

Figure 2. Comparison of overflow delays for the analysis time period of 0.25 h.

As shown in the figure, the proposed model generally estimated overflow delays very close to that estimated by the Canadian and the HCM 2000 delay models for both undersaturated and oversaturated conditions. It differed from the Australian delay model for the undersaturated conditions, producing slightly higher overflow delays for x values below 0.7.

When the degree of saturation is 1.0, all delay models except for the deterministic one estimated the overflow delay around 40 s. For x between 1.1 and 1.5, the proposed model estimated overflow delays lower than the Australian model but higher than the Canadian and the HCM 2000 models did. The evaluation of overflow delays for the remaining analyses periods showed similar outcomes.

Validation of the proposed delay model for variable demand and oversaturated conditions

In order to verify and test the performance of the proposed model, an experimental study was performed using the TRAF-NETSIM simulation program for a number of scenarios designed to cover variable demand and oversaturated conditions. For this purpose, an intersection with 4 legs was constructed using ITRAF (Interactive traffic network data editor for the integrated traffic simulation system). The intersection consisted of one lane on each approach with the major approaches having the actual flow variations over time. A mean startup lost time of 2.0 s, a free flow speed of 30 mph (approximately 48 km/h), a mean discharge headway of 2.0 s per vehicle and a lane width of 12 feet (approxi-

Table 1. Comparison of estimated overflow delays produced by proposed and existing delay models (analysis time period T = 0.25 h).

x	Proposed Delay Model Estimates	Australian Delay Model Estimates	PD	Canadian and HCM 2000 Delay Model Estimates	PD	Deterministic Delay model Estimates	PD
0.1	0.77	0.00	-	0.40	48.05	0.00	-
0.2	1.53	0.00	-	0.90	41.18	0.00	-
0.3	2.30	0.00	-	1.54	33.04	0.00	-
0.4	3.17	0.00	-	2.38	24.92	0.00	-
0.5	4.24	0.00	-	3.54	16.51	0.00	-
0.6	5.74	0.00	-	5.25	8.54	0.00	-
0.7	8.11	0.32	96.05	7.93	2.22	0.00	-
0.8	12.45	5.54	55.50	12.63	-1.45	0.00	-
0.9	21.42	16.51	22.92	21.82	-1.87	0.00	-
1.0	40.25	38.75	3.73	40.25	0.00	0.00	-
1.1	71.37	72.44	-1.50	70.34	1.44	45.00	36.95
1.2	110.18	112.07	-1.72	108.00	1.98	90.00	18.32
1.3	152.46	154.19	-1.13	149.12	2.19	135.00	11.45
1.4	196.36	197.45	-0.56	191.82	2.31	180.00	8.33
1.5	241.12	241.29	-0.07	235.33	2.40	225.00	6.69

PD: Percent difference.

mately 3.66 m) were used as input values for both minor and major approaches. The link lengths of the minor and the major approaches were chosen as 3000 ft (approximately 914 m) and 4000 ft (approximately 1219 m), respectively. The intersection was operated at a common cycle length of 90 s. The ratio between the minor and major approach green times was set to 30/50 (s/s).

The 60-min simulation period was subdivided into 3 time periods to reflect the demand variation in the traffic flow. The first period was an initial time period and had a fixed duration of 5 min with a constant degree of saturation 0.7 for all cases. During this period, the intersection was initialized without transferring a queue to the second period. The second period, which was the actual analysis period, had 1 of 4 oversaturated traffic conditions with the degree of saturation ranging between 1.1 and 1.4, and 6 analyses time periods varying from 5 to 30 min. The third or the last period was the dissipation period and the traffic flow had the degrees of saturation of 0.5 and 0.7. The duration of this period changed with respect to the duration of second period, depending on the time necessary to dissipate the oversaturation queue that had built up over the second period.

The combination of these values yielded a total of 48 scenarios, listed in Table 2, for the validation study. In order to account for random traffic arrivals and obtain good average delay estimates, each scenario was replicated by changing the random seed numbers (10 in total), which yielded different event sequences and different delay estimates. For these 10 replications, 20 data points were acquired for 2 major approaches during each scenario. As a result, this study incorporated a total of 480 TRAF-NETSIM runs and 960 data points for the 48 scenarios.

Table 2. The list of simulation scenarios used in the validation experiment.

Time Periods	Degree of Saturation	Simulation Time	Number of Setups
Initialization Period	0.7	5	1 x 1 = 1
Analysis Period	1.1, 1.2, 1.3 and 1.4	5, 10, 15, 20, 25 and 30	4 x 6 = 24
Dissipation Period	0.7 and 0.5	Varying time duration	2 x 1 = 2

Discussion of Validation Results

The evaluation of the validation results revealed that, as shown in Figures 3-5, delays estimated by the proposed model were in close agreement with the other models and in similar approximation to those simulated by the TRAF-NETSIM. From Figures 3 and 4, the delays slightly diverge from the trend line at around 300 s/veh where the degree of saturation is about 1.4 and the analysis time period is over 20 min. At such traffic conditions, the queue developed on the link is assumed to be longer than the length of the link.

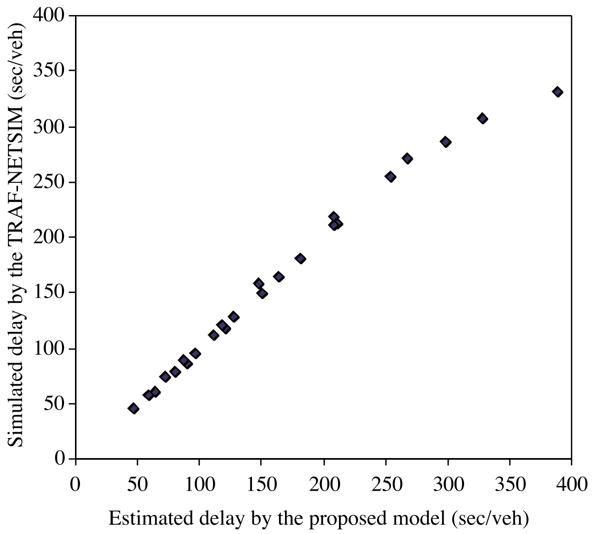

Figure 3. Comparison of total delay estimates by the proposed delay model and total delay simulations by the TRAF-NETSIM for the 0.7-o/s-0.5 traffic conditions.

Therefore, the data points of the last 2 scenarios (i.e. T = 30 min, 0.7-1.4-0.5 and 0.7-1.4-0.7) were trimmed from the overall setup and the final scatter diagram is included in Figure 5.

As expected, the delays simulated by the TRAF-NETSIM varied between replications of the same scenario. For each scenario, the average values of the replications were used in the comparison of the simulated delays with the simulation model and the estimated delays with proposed and existing models (see Table 3)

One interesting outcome of this study is that the changes in the degree of saturation during the last time period (the dissipation period) had no significant effect on the average maximum delays as long as these latter conditions were undersaturated.

The regression analysis results were very encouraging because the constant coefficient is not substantially different from the null, with the regression results for the intercept and no intercept cases almost the same for the delay model. For both situations, the regression equation was forced through zero because the delay by the proposed model should be zero when simulation generates zero delay. Moreover, the other case was considered in the regression analysis of the model since it presents the actual magnitude

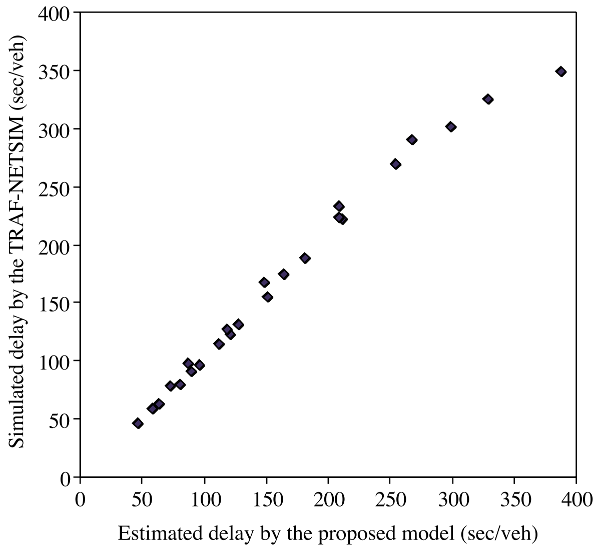

Figure 4. Comparison of total delay estimates by the proposed delay model and total delay simulations by the TRAF-NETSIM for the 0.7-o/s-0.7 traffic conditions.

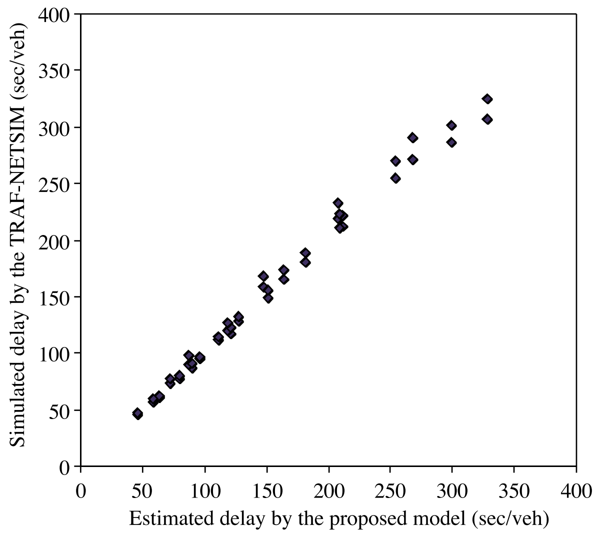

Figure 5. Comparison of total delay estimates by proposed delay model and total delay simulations by the TRAF-NETSIM with trimmed data.

Table 3. Comparison of total delays produced the proposed delay model and existing models and the TRAF-NETSIM simulations for the 0.7–o/s–0.5 and 0.7–o/s–0.7 traffic conditions.

Analysis Time Period (min)	Proposed Delay Model Estimates	Australian Delay Model Estimates	Canadian and HCM 2000 Delay Model Estimates	TRAF-NETSIM simulations for the 0.7-O/S-0.5 traffic condition	TRAF-NETSIM simulations for the 0.7-O/S-0.7 traffic condition
Degree of saturation = 1.1					
5	46.66	46.67	46.22	45.71	46.68
10	64.26	64.28	63.68	60.68	62.14
15	80.54	80.57	79.88	77.54	79.72
20	96.35	96.38	95.63	94.34	96.83
25	112.10	112.13	111.33	111.21	114.24
30	127.50	127.54	126.70	128.05	131.53
Degree of saturation = 1.2					
5	59.28	59.78	58.30	56.48	58.9
10	90.64	91.24	89.47	86.29	90.19
15	121.01	121.66	119.74	117.25	122.61
20	151.17	151.86	149.85	148.58	155.17
25	181.60	182.31	180.24	179.87	187.95
30	211.61	212.33	210.22	211.44	221.15
Degree of saturation = 1.3					
5	73.14	73.66	71.60	73.39	77.42
10	119.15	119.75	117.40	120.08	126.23
15	164.23	164.86	162.39	164.63	173.57
20	209.19	209.85	207.31	210.15	222.81
25	254.64	255.31	252.73	254.08	268.93
30	299.52	300.20	297.59	286.04	300.98
Degree of saturation = 1.4					
5	87.64	87.93	85.51	88.95	97.49
10	148.58	148.90	146.24	157.99	167.39
15	208.52	208.85	206.09	218.12	232.26
20	268.37	268.71	265.90	271.18	290.29
25	328.91	329.26	326.41	307.13	324.89
30	388.71	389.06	386.19	330.80	348.74

of the differences between them without affecting the originality of the data. The linear regression analysis with and without intercept produced coefficients of determination (R^2) of 98.06% and 97.95%, respectively, before trimming the data. R^2 was increased to 99% for both cases after trimming the data.

Conclusions and Recommendations

Using a new methodology, a new analytical delay model for signalized intersections considering the variation in traffic flow was successfully developed in this study. Unlike the existing delay models, which use a constant value of k, the proposed delay model employed a varying k as a function of degree of saturation in order to better describe the variation in traffic flow. A comparative study was performed for degrees of saturation ranging from 0.1 to 1.5. The comparison results indicated that the proposed model can be used as a reliable tool for delay estimations at signalized intersection for varying time periods as an alternative model.

In the validation of the proposed model, the TRAF-NETSIM microscopic simulation model was applied for oversaturated conditions. The results obtained from the simulations and the proposed model were used in the linear regression analysis with and without intercept and it was demonstrated that a close relationship existed between them ($R^2 = 0.99$ for both cases). Based on the results presented in this study, the following conclusions can be drawn:

1. Use of a varying k value is more appropriate than use of a constant k value for variable demand conditions because arrival flows change or fluctuate in a specific time period.
2. Defining the delay parameter k as a function of the degree of saturation improves the model estimation of delay since the degree of saturation in the delay parameter model reflects fluctuation in demand.
3. The variation in the degree of saturation during the dissipation period does not have a significant effect on the average maximum delay as long as the traffic conditions during this period are undersaturated.
4. Finally, the results of this study indicate that the time-dependent delay model developed in this research produces good estimates of delays at signalized intersections under variable demand conditions.

In the research presented herein, the delay model was developed for fixed time traffic signals, and further studies should be conducted for vehicle-actuated signal controls. In this study, the percentages of trucks and carpools were taken as 5% and 0% respectively, but they can be selected according to local traffic conditions. In the case of Turkey, for example, they are more likely to be higher percentages, and thus an increase in average delay time is expected without any inconsistency in the proposed method. The developed delay model was verified only for oversaturated conditions, and not for undersaturated conditions. Finally, future research associated with more field data could better specify the performance of the delay model developed in this research.

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