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Estimation of Stopped Delay to Control Delay Conversion Factor and Development of Delay Model for Non-lane Based Heterogeneous Traffic

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Abstract

Delay is the most commonly used service measure for establishing the Level of Service (LOS) of a signalized intersection. Through this study, an attempt has been made to estimate the stopped delay to control delay conversion factor for Indian traffic condition. Racelogic VBOX GPS speed data recorder has been used for collecting the vehicle trajectories. From the study, the stopped delay to control delay conversion factor is obtained as 1.19 for Indian traffic condition. This factor accounts for the acceleration and deceleration of the vehicles while traversing the intersection. The existing analytical delay models are developed to cater the needs of traffic conditions in Western countries. The Indian traffic is characterized by the presence of heterogeneous vehicle classes and presence of loose lane discipline. The direct applicability of the delay models to the Indian traffic condition is questionable. Hence, an effort has been made to evaluate the applicability of various delay models to the Indian traffic condition. Based on the results obtained, a control delay model for non-lane based heterogeneous traffic has been proposed.

Keywords: Stopped delay, control delay, VBOX, delay model, heterogeneous traffic, signalized intersection

1. Introduction

The operational efficiency of any traffic facility is described qualitatively by means of Level of Service (LOS). The various service measure used for describing the LOS includes delay, number of stops, queue length etc. Among the quantitative factors, delay is the most commonly used service measure for establishing the LOS of a signalized intersection (Dion et al., 2004). It is considered as a surrogate measure of driver's discomfort, frustration and fuel consumption (HCM 2010). Delay is not only used for

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the design purpose (signal design) but also for evaluation (as a service measure). Stopped delay is defined as "the time that a vehicle spends for stopping on the approach of the intersection". The vehicle arrival and departure pattern have a significant influence on the stopped delay. Many researchers stated that stopped delay does not represent the total effectiveness of the intersection (Ko et al., 2008). Control delay is defined as the delay caused by traffic control devices. In other words, it is "the difference between the travel time when a vehicle is affected by a traffic control and the travel time of the same vehicle traversing on the intersection without impedance at the desired free flow speed". It includes stopped delay, time-in-queue delay and the acceleration and deceleration delay (Olszewski, 1993; Reilly and Gardner, 1977). As sophisticated devices are required to measure the components of control delay from the field, the control delay values are estimated based on the field measured stopped delays. For this purpose, the Highway Capacity Manual 2010 (HCM 2010) uses a stopped delay to control delay conversion factor of 1.3.

The Indian traffic is characterized by the presence of heterogeneous vehicle type and presence of loose lane discipline (Tiwari et al., 2011). The direct applicability of the above value may be questionable because of the difference in the static and dynamic characteristics of the various vehicle types plying on the Indian roads and the difference in driver behavior. Also, previous studies carried out in different countries reported different relationship between stopped delay and control delay. The attempts resulted in significantly different relationships due to numerous reasons such as driver and traffic behavior and some site-specific reasons (Mousa, 2002; Quiroga and Bullock, 1999). Hence, through this study, an attempt has been made to estimate the stopped delay to control delay conversion factor for Indian traffic condition.

Even though it is possible to measure the delay from the field, it is a tedious process. Hence it is always convenient to have a predictive model for the estimation of delay. There are a number of widely used delay models to determine the delay at a signalized intersection. The classic examples are Webster's delay model, Robertson's delay model, Australian HCM delay model, Canadian HCM delay model, Reilly's delay model, and United States HCM delay model. But all these analytical delay models are developed to cater the needs of traffic conditions in Western countries. Through their study on heterogeneous traffic, Prasanna Kumar and Dhinakaran (2012) found that a good correlation cannot be obtained between the field observed delays and the delay models developed for homogeneous traffic. Hoque and Imran (2007) modified the Webster's delay model for catering the needs of heterogeneous traffic in Bangladesh. The uniform and random delay term were retained and modification was done to the adjustment term. A study by Hadiuzzaman (2008) on non-lane based traffic found that the uniform and incremental delay term in HCM delay model should be decreased by 20% and 85% respectively, to better reflect the field condition. In addition, they proposed an intercept term in the HCM model.

The previous studies on delay models for heterogeneous traffic indicates that the direct applicability of the existing delay models to the non-lane based heterogeneous traffic condition can cause erroneous results. Hence, an attempt has been made to investigate the applicability of these delay models to the non-lane based heterogeneous traffic condition prevailing in India. The major contribution of the present study lies in the estimation of the stopped delay to control delay conversion factor for Indian traffic and to propose a delay model addressing the heterogeneous traffic condition.

2. Literature Review

2.1 Previous studies on control delay conversion factor

From 1985 onwards, the average delay incurred by the vehicles at the signalized intersection is used as the measure of intersection performance. Delay reflects the inconvenience caused to the road users by the traffic signal. Stopped delay and control delay are the commonly used delay measures. Stopped delay indicates the time for which the vehicle is stationary at an intersection approach whereas control delay indicates the "difference between the travel time when a vehicle is affected by a traffic control and the travel time of the same vehicle traversing on the intersection without impedance at the desired free flow speed". From 1997 onwards, control delay is used as the service measure at signalized intersection. HCM recommended a multiplicative factor of 1.3 to obtain control delay from stopped delay. The relation between stopped delay and control delay is of interest because, although stopped delay is easy to measure from the field, the control delay better reflects the disutility caused to the road user.

Attempts have been made from 1990's to measure control delay from the field. Ground-based time-lapse photography (Buehler et al., 1976), aerial time-lapse photography (Benekohal, 1991), video-graphic technique (Benekohal, 1992), and path tracing (Mousa, 2002; Olszewski, 1993) are some of them. These methods are time-consuming, laborious and costly. In the case of path tracing method, the screen lines are pre-specified and the observers trace the trajectories of the vehicles. The precision of this method depends on the number of screen lines (Ko et al., 2008).

Through their study, Reilly and Gardner (1977) found out that there exists a linear relationship between the stopped delay and the control delay. Stopped delay was found to be 76 percent of control delay. Many researchers further examined the relationship between stopped delay and control delay. Olszewski (1993) after studying the trajectory of vehicles found that delay ratio is a function of red time and acceleration-deceleration delay for uniform delay component, whereas for overflow delay component it depends on cycle time and degree of saturation. Data from three intersection approaches in Singapore form the basis of the study. Teply (1989) found out that the delay ratio cannot be constant.

Quiroga and Bullock (1999) used GPS receivers to track the vehicle trajectory. The study was conducted at two arterials in Florida. They found out a linear relation between the stopped delay and control delay at signalized intersection and the model is given by

$$stopped\ delay = 0.959\ control\ delay - 19.3 \tag{1}$$

Through a path tracing method using 12 screen lines, Mousa (2002) attempted to find out the various components of control delay. For measuring the stopped delay, the author assumed a speed difference threshold of 1- 1.5 m/s as the stopping criteria. The developed model is given by

$$stopped\ delay = 0.58\ control\ delay - 2.31 \tag{2}$$

According to Quiroga and Bullock (1999), the constant term in the model represents the minimum deceleration and acceleration delay that need to occur before any stopped delay. The higher constant value in Quiroga and Bullock model compared to that of the Mousa model is due to the absence of non-stopped vehicles. Using the GPS speed data, Ko et al. (2008) tried to measure the various components of control delay. Both the speed profiles and acceleration profiles of the vehicles are used for capturing the control delay components. Akgungor and Korkmaz (2016) attempted to model the relationship between stopped delay and control delay using differential evolution algorithm. Using two wheeler and three wheeler probe vehicles, Saw et al. (2018) analysed the delay variability at signalized intersections under mixed traffic conditions.

2.2 Delay models

Based on the underlying assumptions, analytical models are classified into deterministic queuing model, shock wave delay model, steady-state stochastic model and time-dependent model (Dion et al., 2004). Using deterministic queuing theory, Webster developed the delay model. The model assumes random arrival and uniform departure headways (Webster, 1958). Later, time-dependent models were developed which assume constant arrival rate and capacity. Also, the model assumes that the queue length at the beginning of the arrival period is zero and increase linearly to the end of the analysis period. A much-used version of this time-dependent model is Akcelik's delay model or Australian delay model (Akcelik, 1988). Whitney (reported in Hurdle 1984) developed an algorithm in FORTRAN for determining the random delay. Robertson approximated the algorithm into an equation and developed the Roberston's delay model. Reilly (1977) compared the field delay and predicted delays at various saturated intersection approaches and found that Akcelik's delay model is overestimating the overflow delay when the volume to capacity ratio approaches one and recommended a modified version of Akcelik's model which is often called '1/2 of Australian model'. Canadian capacity delay models were made by modifying the Australian delay model (Teply, 1991; Teply et al., 2008). The United States HCM delay model proposed in 1985 went through major revisions in 1994, 2000 and 2010 (HCM 2000, HCM 2010). The Webster's delay model is given by

$$d = \frac{C}{2}\frac{\left(1-\frac{g}{C}\right)^2}{\left(1-\frac{v}{s}\right)} + \frac{\left(\frac{v}{c}\right)^2}{2v\left(1-\frac{v}{c}\right)} - 0.65\left(\frac{C}{v^2}\right)^{\left(1/3\right)}\left(\frac{v}{c}\right)^{\left(2+5\frac{g}{C}\right)} \tag{3}$$

where, d is average delay (sec/veh), g is effective green time (sec), C is cycle time (sec), v is arrival flow (veh/hour), s is saturation flow (veh/hour), c is capacity (veh/hour).

The oversaturation delay proposed by Robertson is given by

$$OD = \frac{15\,T}{c}\left\{(x-v) + \sqrt{(x-v)^2 + \frac{240\,v}{T}}\right\} \tag{4}$$

where, T is the analysis period (minutes), OD is the oversaturation delay (sec), and all other variables are previously defined.

The oversaturation delay proposed by Akcelik is given by

$$OD = \frac{T}{4}\left\{(x-1) + \sqrt{(x-1)^2 + m\frac{(x-x_o)}{cT}}\right\} \tag{1}$$

where,

$$x_o = 0.67 + \frac{sg}{600}$$

T is the analysis period (minutes), m is the parameter that accounts for arrival type (m = 6 for random arrival and 12 for platoon arrival), s is saturation flow (veh/sec) and all other variables are previously defined.

The oversaturation delay proposed by Reilly is given by

$$OD = 450\,T\left\{(x-1) + \sqrt{(x-1)^2 + m\frac{(x-x_o)}{cT}}\right\} \tag{6}$$

where,

$$x_o = 0.67 + \frac{Cc}{2160000}$$

T is the analysis period (hours), OD is the oversaturation delay (sec), and all other variables are previously defined.

The HCM 2010 delay model is given by

$$d = d_1 PF + d_2 + d_3 \tag{7}$$

where, d is the average control delay (sec/veh), d_1 is the average uniform delay per vehicle, d_2 is the average incremental delay per vehicle, d_3 is the additional delay per vehicle due to pre-existing queue, and PF is the adjustment factor accounting for the quality of progression in coordinated systems.

$$d_1 = 0.50\,C\frac{\left(1-\frac{g}{C}\right)^2}{\left(1-\frac{g}{C}min\,(x,1)\right)} \tag{8}$$

$$d_2 = 900T\left[(x-1) + \sqrt{(x-1)^2 + \frac{8\mathrm{kI}x}{cT}}\right] \tag{9}$$

where, I is the adjustment factor for upstream filtering/metering, k is the adjustment factor for the signal control system and all other variables are previously defined.

$$d_3 = \begin{cases} 0, if\ no\ pre-existing\ queue \\ \dfrac{1800Q_b(1+u)t}{cT}, else \end{cases} \tag{10}$$

where,

$$t = min\left\{T, \frac{Q_b}{c[1-min\,(1,x)]}\right\} \tag{11}$$

and

$$u = \begin{cases} 0, if\ t < T \\ 1 - \dfrac{cT}{Q_b[1 - min(1, x)]}, else \end{cases} \tag{12}$$

Q_b is the initial queue at the start of T (veh), t is the duration of unmet demand in T (hours) and u is the delay parameter.

The comprehensive review of the existing literature suggests that a lot of attention has been given on delay models at signalized intersection from 1920 onwards. However, these studies were mainly carried out in developed countries where the traffic is homogeneous. Hence, these models might not be able to accurately estimate the delay under heterogeneous traffic conditions at signalized intersections. The direct application of these models to the mixed traffic condition may lead to erroneous results.

3. Methodology

Delay at signalized intersections were measured by means of Racelogic VBOX speed recorder and video graphic technique. Probe vehicle fitted with the VBOX is allowed to run repeatedly through the study corridor. Figure 1 shows the distance-time plot and speed-time diagram, illustrating the various delay measure. It shows the trajectory of an unimpeded vehicle (moving at free-flow speed) and that of an impeded vehicle (delayed due to the control device).

t_1 is the time when the vehicle starts decelerating, L_1 is the position of the vehicle at time t_1, the time interval t_2 to t_3 is the duration for which the vehicle is actually stopped, from t_3 the vehicle starts accelerating, t_4 is the time at which the vehicle crosses the stop line, t_5 is the time at which the vehicle re-accelerated back to the free flow speed and the acceleration ends, L_5 is the position of the vehicle at time t_5. Approach delay is "the horizontal (time) difference between the hypothetical extension of the approaching velocity slope and the departure slope after full acceleration is achieved". Control delay is the delay caused by the control device. The difference between the time taken by the impeded vehicles (due to control device) to cross the intersection and to that of the unimpeded vehicle gives the control delay. Also, the control delay is the summation of deceleration delay, stopped delay and acceleration delay. From Figure 1 stopped delay d_s can be obtained by

$$d_s = t_3 - t_2 \tag{13}$$

and the control delay d_c can be obtained by

$$d_c = t_5 - t_1 - \frac{(L_5 - L_1)}{V_f} \tag{14}$$

where V_f is the free-flow speed.

Regression analysis is used to establish the relation between stopped delay and control delay. For developing the delay model for non-lane based heterogeneous traffic condition, the delay estimates obtained from some of the existing delay models are compared with the field measured control delay values. The delay models considered include Webster's delay model, Robertson's delay model, Australian HCM delay model, Canadian HCM delay model, Reilly's delay model, and United States HCM delay model. The most suitable model was selected based on statistical performance measures and calibrated to cater the needs of Indian traffic condition.

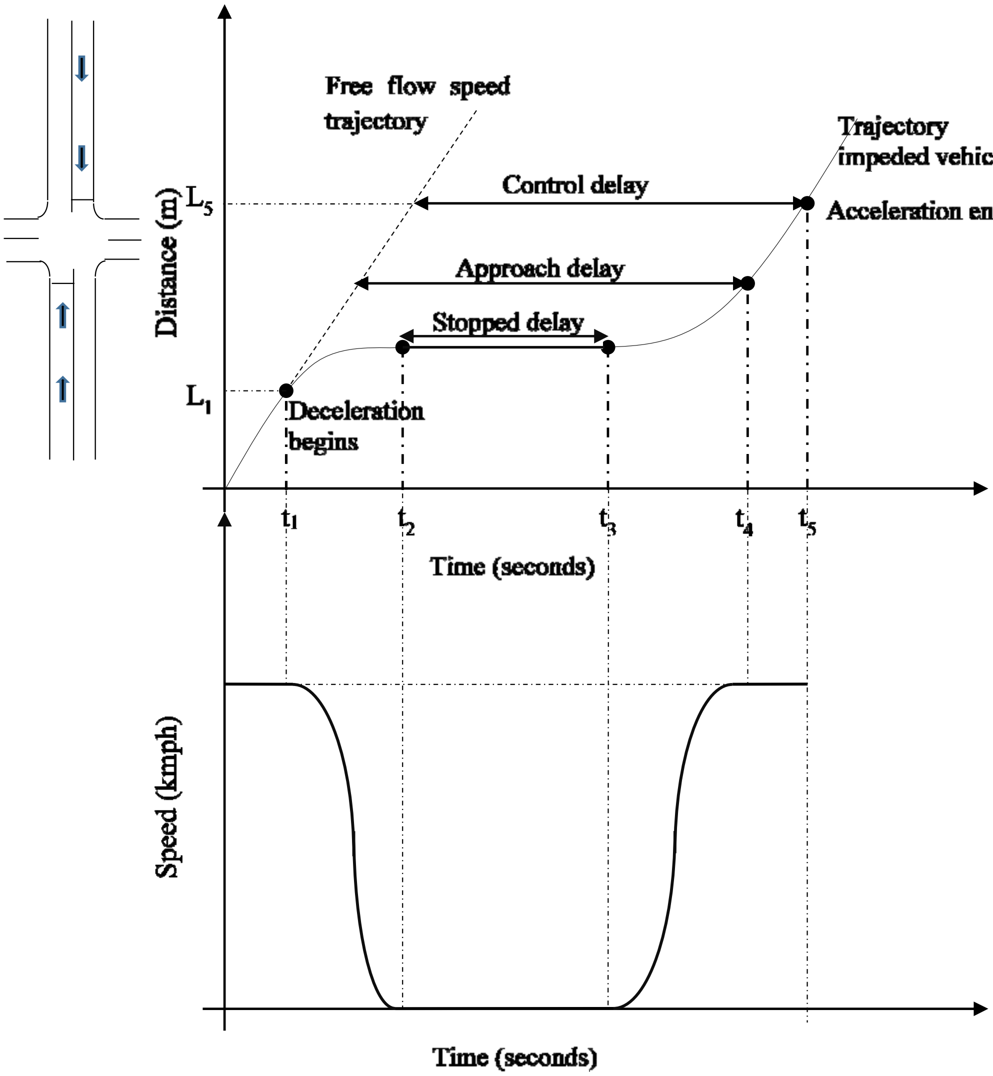


Figure 1: Distance-time and speed-time diagram of a stopped vehicle at the signalized intersection.

4. Data Collection

The study area for the estimation of stopped delay to control delay conversion factor includes three corridors, which covers fifteen signalized intersections within a roadway length of approximately 25 km. The traffic flow on these corridors is highly heterogeneous. Some intersections included in the study are having very good flow characteristics with wide approaches, flared geometry at the stop-line, well-maintained footpaths, and exclusive left-turn lanes. Whereas, traffic flow at some of the intersections are influenced by the pavement conditions, roadside activities and parking. The probe vehicle was fitted with Racelogic VBOX SL3 10 Hz differential GPS speed data recorder. Table 1 gives the details of the study corridors. Figure 2 shows the study corridors. The spacing between the intersections varied between different corridors. On an average, the distance between the consecutive intersections varies between 0.5 km to

1 km. The probe vehicle used in the study was a medium sized car. The driver was requested to drive at their desired speed through the corridors. Approximately thirty runs were made on all the corridors during peak hours and off-peak hours.

Table 1: Details of the Study Corridor

Name of Corridor (Corridor Identity)	Length of Stretch (km)	No. of 3-legged Intersections	No. of 4-legged Intersections
Madam Cama Road (A)	1.5	2	3
LBS Road (B)	11.5	11	6
SV Road (C)	12.1	6	4

Considering the need for a Highway Capacity Manual for India, CSIR-CRRI in coordination with the prominent academic institutes in the country has taken up a project named “Development of Indian Highway Capacity Manual (Indo-HCM)”. The data collected for this project has been used for the present study. Video-graphic data of vehicle arrival and discharge at the stop-line has been collected at ten different isolated signalized intersections from various cities of the country. The details of the selected intersections are given in Table 2. The cycle time of the study intersections varied from 120 seconds to 302 seconds. Hence, the results from the present study provide a more general conclusion than the previous studies. Motorized two-wheelers, motorized three-wheelers, cars, Light Commercial Vehicles (LCVs), bus, and trucks are the vehicle types considered for the delay calculation. Data were collected during both morning and evening hours. For field measurement of saturation flow, the classified count of vehicles discharging at the stop line during the green time was noted at every five-second interval. The Passenger Car Unit (PCU) values recommended by Indian Highway Capacity Manual (Indo-HCM) has been used for converting the saturation flow in vehicles/hour to PCU/hour.

For field measurement of delay, the classified count of vehicles in the queue at every five-second interval during the red time was noted. Also, the number of vehicles discharging without stopping was noted for every cycle. The count of vehicles in the queue at every 5-second is multiplied by the sampling time interval (5 seconds). This gives the total delay in vehicle seconds on that particular approach. Approach delay is obtained by dividing the total delay by the approach volume. The stopped delay (sec/vehicle) is obtained by multiplying the approach delay with an empirical correction factor of 0.9. Using the above-mentioned PCU values, the stopped delay in sec/vehicle are converted to sec/PCU. To obtain the control delay (sec/PCU), the stopped delay is multiplied by control delay conversion factor of 1.19. The data obtained from 33 approaches forms the basis of the proposed delay model. The inventory details of the signalized intersection were also collected.

Corridor A

Corridor B Corridor C

Figure 2: Study corridors A to C.
Source: Google Maps
Note: The red line in the figures indicates the selected corridor.

Table 2: Details of Selected Intersections

Intersection	Type	Approach Width (m)	Cycle Time (sec)	Saturation Flow (PCU/hour)*
I1	4-legged	7.6 - 10.8	120	3120 - 5064
I2	4-legged	11.0 - 11.4	140	5144-5954
I3	4-legged	8.0 -14.8	302	5507-6175
I4	4-legged	10.5 - 11.3	180	5327-6427
I5	4-legged	10.0 - 10.4	100	4700-5783
I6	4-legged	7.5 – 9.0	100	3829-6296
I7	3-legged	9.7 - 13.6	105	3448-5044
I8	4-legged	7.0 - 9.1	155	4028-5989
I9	4-legged	7.5 – 9.0	125	2880-3194
I10	3-legged	8.0 - 11.0	102	3923-5766

**Indicates the range of saturation flow of all the approaches of an intersection*

5. Stopped Delay to Control Delay Conversion Factor

To estimate the stopped delay to control delay conversion factor, the data obtained from the Racelogic VBOX SL3 10 Hz differential GPS speed data recorder was extracted using the VBOXTools software. Figure 3 shows the VBOX software interface. It consists of four windows in which the main window displays the vehicle trajectory for the entire run. The second window which shows the video player provides the information about the actual traffic condition when the survey was performed. The third window, which gives the graph data, provides information on speed, distance, latitude, longitude, and number of satellites available at a particular location. The fourth window gives a graph map, which shows the path of the probe vehicle.

Figure 4 shows the speed and acceleration profile of a stopped vehicle at signalized intersection. The wavy nature of the trajectory indicates the speed noise (fluctuation of speed). Most of the previous studies assumed some thresholds for stopped delay (Colyar and Rouphail, 2003; Mousa, 2002). In the present study, there is no need of assuming any thresholds for stopped delay as from the speed and acceleration profile (shown in Figure 4) all the critical points explained in the methodology can be easily identified and extracted. For estimating the conversion factor, speed profile of the vehicle is carefully examined. Whenever there is a reduction in the speed, the trajectory data is cross-checked with the video data to ensure that the speed reduction is only because of the upstream intersection not because of any other obstructions. From the vehicle trajectory, the average speed of the vehicle crossing the intersection is noted down. Although the delay components are measured by manually examining the speed profiles of the vehicle, identifying when vehicles begin to decelerate or stop accelerating is not always a straightforward task. Hence, along with the speed profile, the acceleration-deceleration profile of the vehicle is also looked into. The time when which the vehicle reduces the speed because of the control device (t1) and the time at which the vehicle regains the average speed (t5) was noted. The time the vehicle will take to cover the same distance if moving at the average speed is calculated $\left(t = \frac{(L_5 - L_1)}{V_f}\right)$. The time difference (t5-t1) gives the time taken to regain the average speed. The time difference (t5-t1)-t gives the control delay. The time for which the vehicle is actually stopped due to the control device, i.e. the stopped delay (t3-t2) was also calculated. All the critical points from t1 to t5 were extracted for each run at the intersection using the VBOXTools software.

The descriptive statistics of the extracted data are given in Table 3. The stopped delay is a function of signal timing, traffic composition and saturation flow (Mousa, 2002). Hence, depending upon the arrival of the vehicles with respect to the start of the red signal wide variation in the stopped delay value was observed. In the study sample, the value of stopped delay ranges from 6.84 seconds to 128.50 seconds, while control delay ranges from 14.06 seconds to 139.41 seconds. This wide variation in delay depends on the time of arrival of the probe vehicle in the queue at signalized intersection. A close examination of the data point of 6.84 seconds of stopped delay revealed that the probe vehicle joined the queue of vehicle during the end of red time.

Table 3: Descriptive Statistics of the Stopped Delay and Control Delay Data

	Minimum	Maximum	Mean	Standard Deviation
Stopped delay (sec)	6.84	128.50	50.41	31.99
Control delay (sec)	14.06	139.41	63.82	35.62

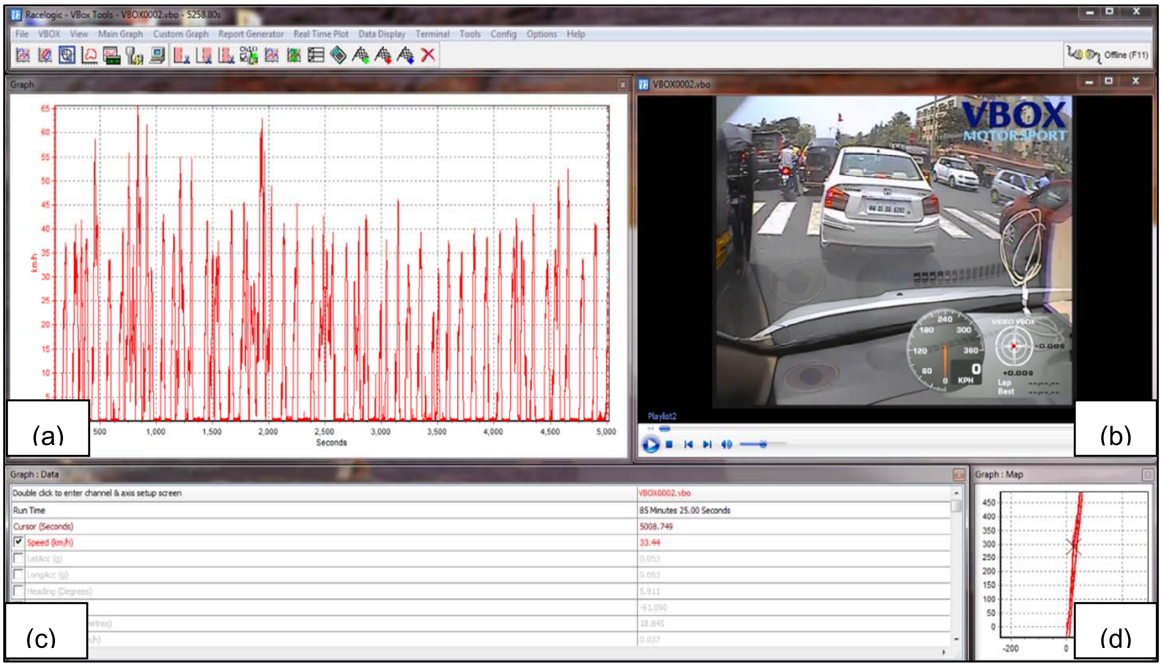


Figure 3: (a) Main window displaying speed against time (b) Video player window (c) The graph data (d) Graph map showing the path of vehicle.

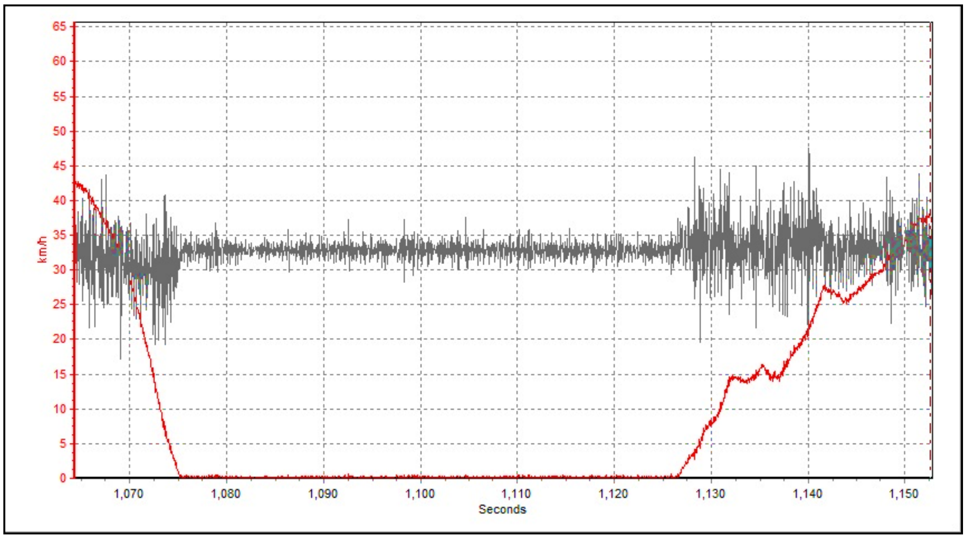


Figure 4: Speed and acceleration profile of a stopped vehicle at signalized intersection.

5.1 Approximate relation

Regression analysis was used to establish the relation between the control delay and stopped delay. The regression coefficient gives the stopped delay to control delay conversion factor. The observations with the difference between control delay and stopped delay less than 6 seconds was omitted as these observations pertain to the aggressive driving behavior of high order. Table 4 shows the results of regression analysis. The coefficient of determination of the model is 0.93. This indicates that the model is able to predict 93% of the variability in the control delay. The model is statistically significant at 5% significance level, with F-value = 4570.88 and p-value = 0.00. The regression coefficient, which is the stopped delay to control delay conversion factor is obtained as 1.19 (t-statistic = 67.61, p-value = 0.00). t-static is the ratio of the coefficient to the standard error. As the p-value is less than 0.05, it can be said that the stopped delay is having a significant influence on control delay value at 5% significance level. The conversion factor of 1.19 indicates that the stopped delay at the study intersections is about 84% of the control delay. Figure 5 shows the correlation between the stopped delay and control delay. The correlation coefficient is 0.96 indicating there is a strong positive correlation between the stopped delay and control delay. As stopped delay increases, the control delay also increases.

Table 4: Model Coefficient and Statistics Results

	Coefficients	Standard Error	t Stat	P-value
Stopped delay	1.19	0.018	67.61	0.00

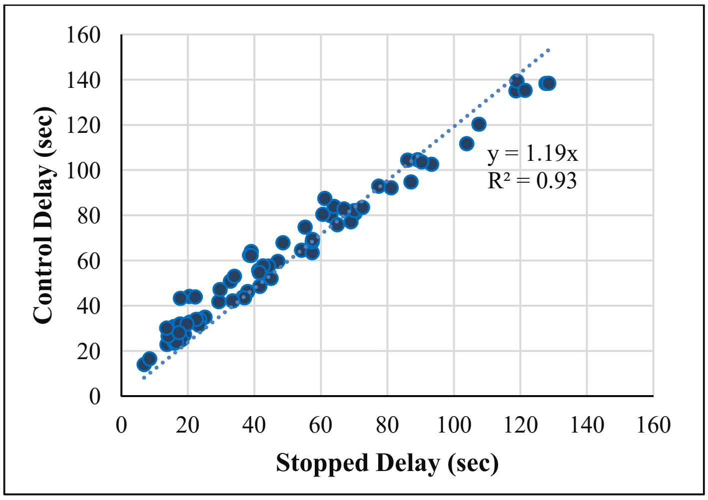


Figure 5: Relation between stopped delay and control delay

5.2 Exact relation

Even though, considering the stopped delay to control delay conversion factor as a linear multiplicative is simple and reasonable, the varied acceleration and deceleration behavior of Indian drivers make the relationship between stopped delay and control delay complicated. Hence, an attempt has been made to estimate the exact relation between the stopped delay and control delay which incorporates the effect of varied acceleration and deceleration behavior of the drivers. Regression analysis was carried out to establish the relation between stopped delay and control delay. The exact relation obtained is given by Equation 15.

$$d_s = 0.97d_c - 11.38 \tag{15}$$

where, d_s is the stopped delay in seconds and d_c is the control delay in seconds.

The developed model results are compared with the HCM relation, models developed by Quiroga and Bullock, and Mousa. Figure 6 shows the exact relation between stopped delay and control delay along with the results of other models.

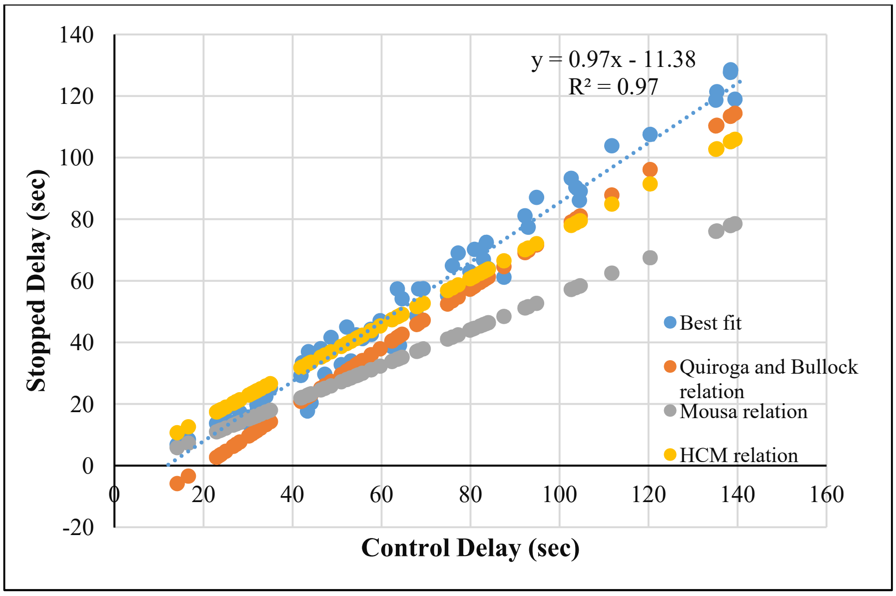


Figure 6: Comparison between stopped delay and control delay.

From the figure, it is clear that none of the previous relations are appropriate for the data collected for the present study. The best fit line lies much above all the models considered in the study. Up to control delay value of 60 seconds, the HCM relation tends to overestimate the stopped delay thereafter the relation tends to underestimate. Both the Quironga and Bullock model and Mousa model underestimates the stopped delay values. The Quironga and Bullock model was developed by considering only the stopped vehicle whereas Mousa model considered both the stopped and non-stopped vehicles. This is the reason for the smaller constant term in Mousa model compared to Quironga and Bullock model. The constant term for the developed model is 11.38 which is much higher than the constant term in Mousa model and much lower than that of Quironga and Bullock model. Also, it can be noted that the Quironga and Bullock model gives negative stopped delay estimates for control delay values less than 20 seconds. From this, it is clear that the previously developed models cannot be applied to Indian traffic conditions because of the varied traffic and driver behavior characteristics. The developed model provides excellent fit of the data with R^2 value of 0.97.

The average deceleration-acceleration delay (dda) of the study sample was obtained as 11.4 seconds. Previous studies in developed countries reported an average deceleration-acceleration delay of 20 seconds. This difference in the delay values can be attributed to the aggressive driving behavior of Indian drivers. Hence, further analysis was carried out to investigate the relation between stopped delay and control delay at two regimes – one for the deceleration-acceleration delay less than 11.4 seconds and other for the delay more than 11.4 seconds. Figure 7 shows the relation between stopped delay and control delay for the deceleration-acceleration delay less than 11.4 seconds and more than 11.4 seconds. For dda < 11.4 seconds, the stopped delay to control delay conversion factor is obtained as 1.13 and that for dda > 11.4 seconds is 1.24. There is no statistical difference between the conversion factors for the deceleration-acceleration delay less than and more than 11.4 seconds.

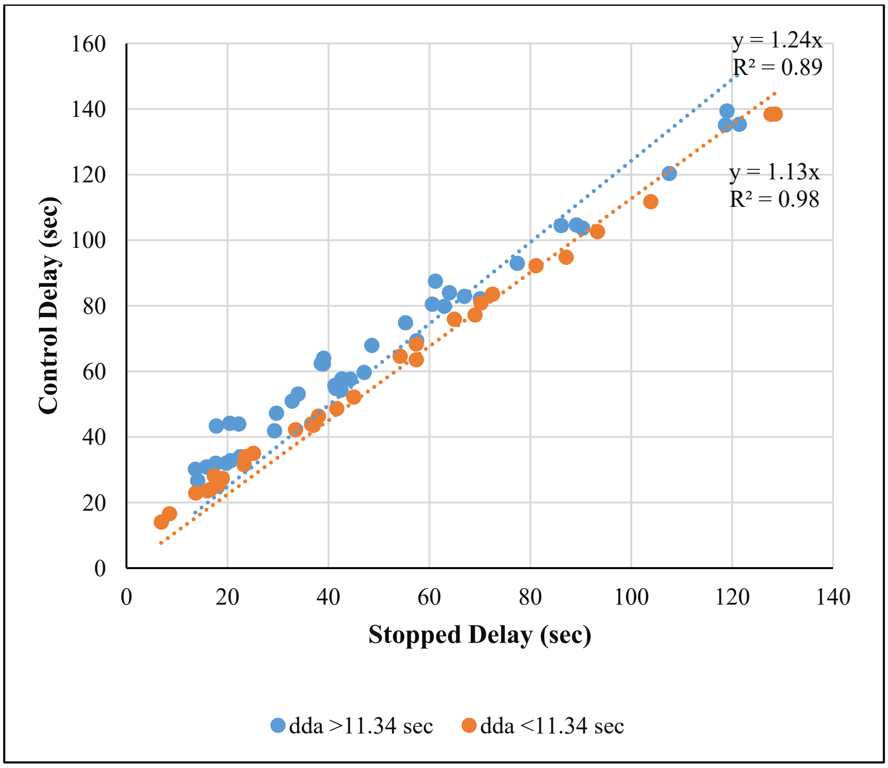


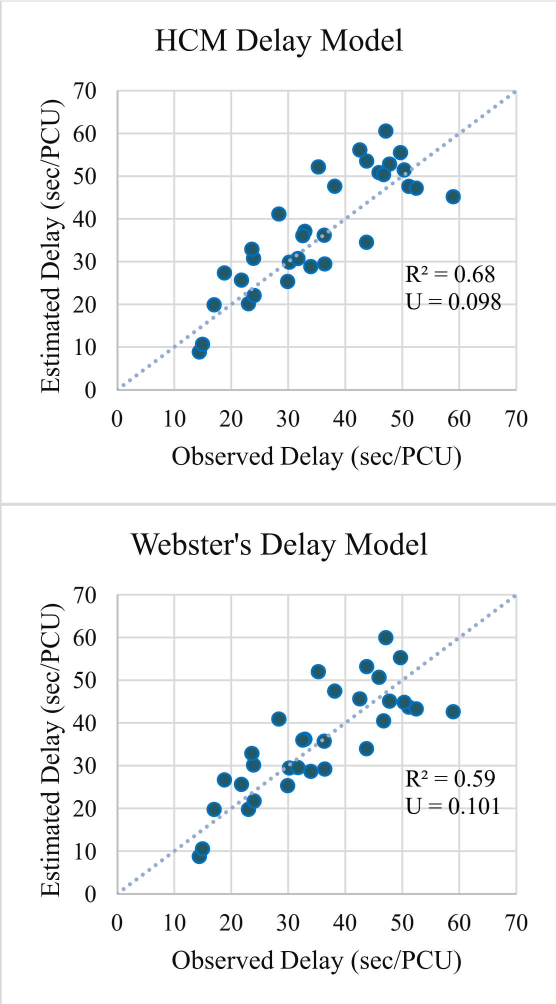
Figure 7: Relation between stopped delay and control delay for different deceleration-acceleration delay.

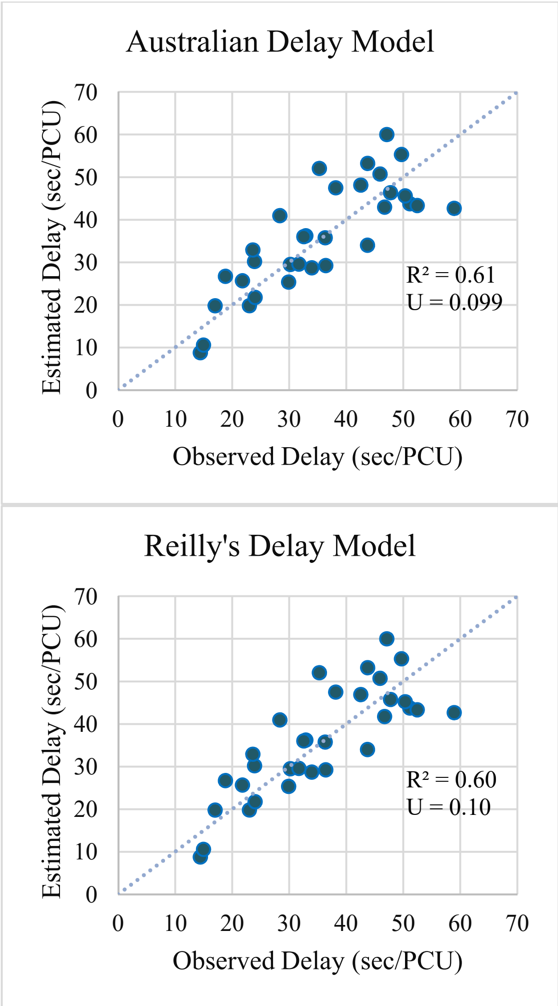
6. Delay Model for Non-Lane Based Heterogeneous Traffic

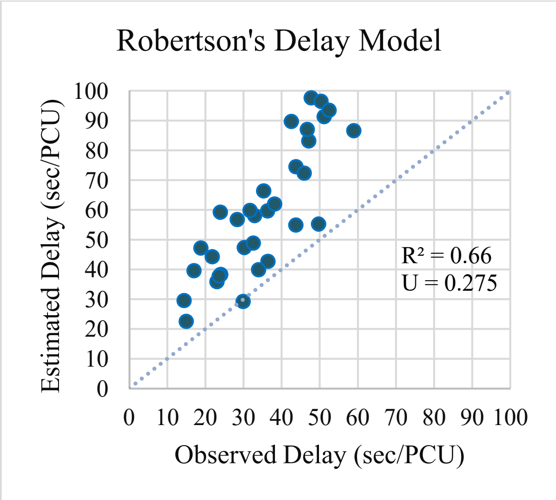
The analytical delay models mainly consist of three distinct components of delay, namely, uniform delay (that part when vehicles arrive at a deterministic uniform rate), incremental delay or random delay (that part accounts for random nature of arrivals) and overflow delay (that part which accounts for the presence of initial queue before the start of analysis period).

6.1 Comparison of existing delay models

From the video data, the classified count of vehicles in the queue at every five-second interval during the red time was noted. Also, the count of vehicles discharging without stopping was noted for every cycle. The count of vehicles in the queue at every 5-second is multiplied by the sampling time interval (5 seconds). This gives the total delay in vehicle seconds on the approach. Approach delay is obtained by dividing the total delay by the approach volume. The stopped delay is obtained by multiplying the approach delay by an empirical correction factor of 0.9 (HCM 2010). The stopped delay is then multiplied by the stopped delay to control delay conversion factor to obtain the field control delay. The delay estimates obtained from the analytical delay models are compared with the field observed control delay. Figure 8 shows the relation between the field observed delay and the various delay model estimates.




Australian Delay Model
Estimated Delay (sec/PCU)
Observed Delay (sec/PCU)
R² = 0.61
U = 0.099
0
10
20
30
40
50
60
70
Reilly's Delay Model
Estimated Delay (sec/PCU)
Observed Delay (sec/PCU)
R² = 0.60
U = 0.10



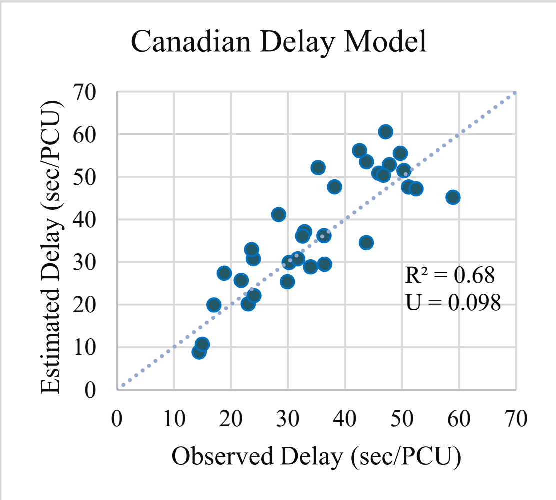


Figure 8: Relation between the field observed delay and the various delay model estimates.

The field data and the delay estimates from the various analytical delay models were compared using statistical performance measures like Mean Absolute Percentage Error (MAPE), Root Mean Square Error (RMSE), coefficient of determination (R^2) and Theil's coefficient of inequality (U). A lower value of Theil's coefficient of inequality indicates better performance. Table 5 gives the comparison of the various delay models. For pre-timed isolated intersections, the Canadian delay model becomes the same as the HCM delay model. Hence, only one results are shown in the table. The MAPE, RMSE and Theil's inequality coefficient are minimum for HCM delay model. Hence, based on the statistical performance measures, the HCM delay model estimates are showing closer agreement with the field observed delay values.

Table 5: Comparison of Various Delay Models

Delay Model	MAPE	RMSE	R^2	Theil's coefficient (U)
HCM model	3.48	7.56	0.68	0.098
Webster's model	5.32	8.55	0.5	0.101

			9	
Australian model	6.71	9.52	0.6 1	0.099
Reilly's model	6.97	9.53	0.6 0	0.100
Robertson's model	18.85	26.67	0.6 6	0.275

6.2 Modified delay model

As the HCM control delay model was found to be in close agreement with the observed control delay of the study intersections, the theoretical form of the same has been adopted for modification. The HCM 2010 delay model is given by

$$d = d_1 PF + d_2 + d_3 \tag{16}$$

where, d is the average control delay in sec/vehicle, d1 is the average uniform delay per vehicle, d2 is the average incremental delay per vehicle, d3 is the average delay due to pre-existing queue.

From the field observed data, it was observed that initial queues do not exist, as most of the signalized intersections are operating at under-saturated conditions. Hence, the third term, d3 in the HCM delay model does not exist for the study intersections. The average incremental delay term is found to be negligible and hence modification is done only to the average uniform delay component. The modified delay model can be written as

$$d = \alpha\, d_1 + d_2 \tag{17}$$

where, d is the average control delay in sec/PCU, α is the calibration parameter, d1 is the average uniform delay in sec/PCU, d2 is the average incremental delay in sec/PCU.

The average uniform delay and average incremental delay for an isolated pre-timed signal are given by

$$d_1 = \frac{C}{2}\frac{\left(1-\frac{g}{C}\right)^2}{\left(1-\frac{g}{C}x\right)} \tag{18}$$

$$d_2 = 900T\left[(x-1) + \sqrt{(x-1)^2 + \frac{8\mathrm{kI}x}{cT}}\right] \tag{19}$$

where, T is the analysis period in hours, g is the effective green period in seconds, C is the cycle time in seconds, x is the degree of saturation in PCU/hour, c is the capacity in PCU/hour, k = 0.5 and I = 1 for isolated intersections.

To obtain the calibration parameter, optimization was carried out by minimizing the sum of square of the error between the field measured delay and the modified delay model estimate. From the results, the calibration parameter α is obtained as 0.9. Substituting the value of k, I and α, the proposed delay model can be written as

$$d = 0.9 * \frac{C}{2} \frac{\left(1-\frac{g}{C}\right)^2}{\left(1-\frac{g}{C}x\right)} + 900T\left[(x-1)+\sqrt{(x-1)^2+\frac{4x}{cT}}\right] \tag{20}$$

Figure 9 shows the correlation between the observed delay and the modified delay model estimate. For the modified delay model, the MAPE is 0.99, RMSE value is 4.18, the R^2 value is 0.81 and the Theil's inequality coefficient is 0.066. From the figure, it is clear that the calibrated model is providing a better fit to the field observed delay values.

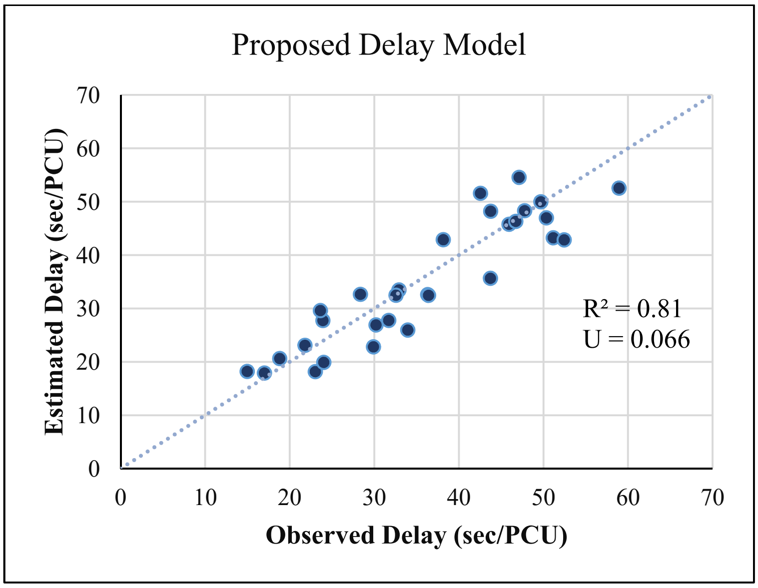


Figure 9: Correlation between the observed delay and the modified delay model estimate

7. Conclusion

Delay is the most commonly used service measure at signalized intersection as it represents the driver's discomfort and frustration. Various studies have been carried out in the past to establish the relationship between the stopped delay and control delay at signalized intersection. But those relations cannot be directly applied to Indian traffic, as the traffic is highly heterogeneous and does not follow any lane discipline. The same is the case with the delay models. The analytical delay models are mostly developed for catering the needs of the homogeneous traffic condition. The direct applicability of these models to the heterogeneous traffic may give erroneous results. Hence, there is a need for estimating the stopped delay to control delay conversion factor and for developing a delay model for Indian traffic condition. In view of this, the authors have estimated the relationship between the stopped delay and control delay based on the data obtained using VBOX speed data recorder. Regression analysis was used to establish the relation between the control delay and stopped delay. The stopped delay to control delay conversion factor for Indian traffic condition is obtained as 1.19. Through the study, it was found out that the stopped delay is 84% of the control delay. The average deceleration-acceleration delay was obtained as 11.4 seconds.

Further, from the extensive video data at the signalized intersection, the field stopped delay values were extracted and converted to control delay using the obtained conversion factor. For investigating the applicability of the existing delay models to the Indian traffic, the field observed control delay values were compared with the delay estimates of the various analytical delay models. The delay models considered include Webster's delay model, Robertson's delay model, Australian HCM delay model, Canadian HCM delay model, Reilly's delay model, and HCM delay model. Based on the statistical performance measures, it was found that the HCM delay model is showing closer agreement to the field data. As pre-existing queues does not exist for any of the study intersection, the third term of the HCM delay model does not exist. The average incremental delay term is found to be negligible and hence the uniform delay component of the control delay equation has been modified. The comparison between the field observed delay values and the proposed model estimates show that the proposed delay model is providing a better fit to the field observed delay values.

The probe vehicle considered in the study for the estimation of control delay conversion factor is medium sized car. One has to see whether the developed relation is applicable to other modes also. This can be taken up as a future research direction.

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