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Delay in Oversaturated Flow Condition at Signal Controlled Intersection under Heterogeneous Traffic Scenario

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Abstract

The delay in travel time varies based on the traffic flow conditions. Undersaturated flow condition requires less time to clear the traffic at the stop line of a signal than oversaturated traffic flow. Several models are available to estimate the delay due to oversaturated flow conditions at intersections but they are mainly based on homogeneous traffic conditions. To address this issue, a modified delay model is developed for oversaturated flow conditions at signal controlled intersections under heterogeneous traffic scenarios. Different ranges of volume capacity ratio have been considered and the duration of the red phase has been added while developing the model. The queue length concept was used for measuring the field delay. The model was generated using the data from three cities and validation was done based on the data of four different cities. Ninety-five percent accuracy in delay estimation was observed using the modified delay model.

Keywords: Signalized intersection; Delay; Oversaturation; Heterogeneous traffic.

1. Introduction

The planning of the journey involves the estimation of the time required to reach the desired destination with a minimum amount of delay. While traveling through a signal-controlled intersection, vehicles experience the maximum amount of delay during oversaturated flow conditions. Oversaturated flow condition arises when the vehicles enter an intersection during a cycle and are unable to cross it before the cycle ends and eventually form a queue. Hence, due to the existing queue length, the vehicles that reach that intersection in the next cycle will have to wait for more time to cross the stop line. Whereas, in undersaturated flow conditions vehicles do not form a queue as all the

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vehicles that enter the intersection during a cycle can cross it before completion of the cycle length and thereby experience a minimum amount of delay. The situation is more critical in heterogeneous traffic scenarios as motorized and non-motorized vehicles share the same lane without maintaining lane discipline. The performance of a signal-controlled intersection is primarily dependent on the amount of delay vehicles experience while traveling through the intersection. Moreover, undersaturated and oversaturated flow scenarios affect the design of cycle length and phase length significantly. If the oversaturated flow condition is not controlled properly by analyzing the amount of delay experienced by the vehicles and designing the signal according to the demand then oversaturation will extend to the nearby intersections. Eventually, the entire network of the signalized intersection will collapse. Therefore, it is necessary to estimate the delay accurately and design the signal accordingly to control the movement of traffic on time without collapsing the entire network.

To estimate the delay due to oversaturation or excess queue length, HCM 2010 has developed a model based on the homogeneous and lane disciplined traffic condition of the USA. This type of traffic condition exists in almost all the developed countries such as the UK, USA, Australia, Germany, etc. However, in developing countries (India, Bangladesh and Sri Lanka) heterogeneous traffic exists with minimum lane discipline. Hence, the applicability of the existing widely adopted models for heterogeneous traffic conditions is really doubtful. In recent past years, several researchers worked on delay due to oversaturation; Engelbrecht et al. (1994), Benekohal and Kim (2000), Dion et al. (2004), Li and Prevedouros (2004), Kim and Benekohal (2005), Murat (2006), Kim et al. (2011), Ghasemlou et al. (2015), Wang et al. (2016), Quiroga and Bullock (1999), Ancker et al. (1968), Cheng et al. (2017), Feng et al. (2014) and Shafii et al. (2020) are a few of them. Engelbrecht et al. (1994) validated HCM 2000 (same as HCM 2010 model) oversaturated delay model using a proposed TRAF-NETSIM simulation model and observed a significant amount of accuracy in delay estimation. Janson and Buchholz (1998) proposed a delay estimation equation for permitted left turning vehicles at signalized intersections by modifying the delay equation of US HCM (1994). The modification is carried out by altering the left turn adjustment factor and thereby reducing the green time for left turning vehicles also the saturation flow rate of the left turning lane group. This modification leads to an increase in delay for vehicles moving in the exclusive left turning lane and may increase or decrease the amount of delay experienced by vehicles moving in shared lanes. However, the study did not consider the oversaturation and undersaturation flow scenario at the signalized intersection.

Delay estimated using both CORSIM and HCM methods were compared by Kim and Benekohal (2005) and concluded that the HCM method cannot estimate oversaturated delay in case of homogeneous traffic accurately; it can be either lower or higher than the CORSIM estimated delay for different arrival types. So, Kim et al. (2011) modified the uniform control delay model for both queue and no queue conditions and observed that the results were pretty much similar to the CORSIM simulated results. However, the study was mainly based on the traffic scenario of a developed country. So, there is a necessity to compare the proposed model with the oversaturation delay estimation model, especially for heterogeneous traffic scenarios. In this context, Ghasemlou et al. (2015) compared several over saturated delay estimation models and suggested that for more accurate estimation, signal duration should take into account while developing the model. Moreover, Artificial Neural Network (ANN) was used for estimating the delay in oversaturated traffic conditions. Later on, Murat (2006) carried out a comparison of the proposed method with the conventional models and came up with higher accuracy in estimation. However, using ANN is a time-consuming process, requires a large number of training data sets and no explicit form of delay model is available. Saha et al. (2017) developed a delay model for heterogeneous traffic conditions. The model estimate delays accurately for under saturated flow scenario. But, oversaturated flow condition is not considered while developing the model. So, a modification is required to use this model globally under heterogeneous traffic scenarios. Preethi et al. (2016) modified Webster's delay model for heterogeneous traffic conditions in India. The artificial neural network (ANN) approach was used to introduce an adjustment factor based on the observed field delay of the study sites. The study was based on Thiruvanathapuram and Kochi, cities in the state of Kerala, India. While developing the model, variation in the degree of saturation, green time to cycle length ratio, approach width and volume of right turning traffic of only two cities were considered. However, the effect of the above-mentioned parameters was already considered while developing Webster's model except for the volume of right turning traffic. The effect of substantial parameters i.e., length of red phase, amount of oversaturation, platoon ratio and traffic composition was not considered while modifying the model. Study locations from different parts of India were also not considered to justify the applicability of the modified model. Moreover, Sushmitha and Ravishankar (2021) developed a non-linear model to estimate control delay at a signalized intersection under mixed traffic conditions. The model was developed based on the data of two cities in India. The study was carried out only for undersaturated flow conditions. Oversaturated flow condition was not considered while developing the model. The study locations are situated in two cities in the southern part of India. So, a wide range of variation in traffic composition was not observed in the collected field data. Hence, the applicability of the proposed model is doubtful for any locations where heterogeneous traffic conditions exist. Consequently, it is concluded from the past studies that –

(i) Most of the studies on delays have been carried out based on the traffic conditions of developed countries which are different than the traffic conditions of a developing country. In developing countries traffic is generally mixed or heterogeneous and drivers do not strictly follow the lane discipline. Therefore, the amount of delay vehicles experiences in mixed traffic scenarios is significantly higher than the homogenous and lane disciplined traffic condition.

(ii) HCM 2010 delay model cannot estimate the delay accurately in case of oversaturated flow conditions under heterogeneous traffic scenarios. A modification is required in HCM 2010 delay model to make it useful in heterogeneous traffic scenarios. Saha et al. (2017) have modified HCM 2010 model for heterogeneous traffic conditions. But, the developed model is applicable only for the undersaturated flow scenarios.

(iii) Several studies have been carried out to develop a delay model for heterogeneous traffic conditions. However, the proposed models were developed based on undersaturated flow conditions only. So, the delay estimation in oversaturated flow conditions using those models will not be accurate.

(iv) Very few studies have proposed delay estimation models considering both undersaturated and oversaturated flow conditions under mixed traffic scenarios. But, the studies were carried out based on the field data of only one or two cities. Therefore, the variation in traffic composition, cycle length, green time to cycle length ratio and length of red phase is not significant. So, the applicability of the proposed models in other cities or in other countries where heterogeneous traffic conditions exist is really doubtful. Moreover, the developed models did not consider the effect of length of red phase,

amount of oversaturation, platoon ratio and traffic composition. Adding to this, these parameters can significantly affect the amount of delay a vehicle experiences while traveling through a signalized intersection.
Therefore, there is a need to modify or develop a delay model specifically for oversaturated flow conditions under heterogeneous traffic scenarios. In that context, the present study aims to address all the above-mentioned drawbacks observed in past studies and develop a simple and accurate delay model by modifying one of the existing delay models for oversaturated flow conditions under heterogeneous traffic scenarios. For this purpose, seventeen signal-controlled intersections from seven cities in various parts of India during oversaturated flow conditions were considered. The large data set introduced the effect of the wide variation in traffic composition while developing a modified model. Moreover, effective parameters like the amount of oversaturation and length of the red phase and platoon ratio were also considered. So, the modified delay model will be applicable globally for signalized intersections of heterogeneous and lane indisciplined traffic conditions.

2. Objectives of the Study

In recent past years, various models have been proposed around the globe to estimate delay at signal-controlled intersections. Among them, HCM, Webster, Australian (Akcelik's) and Canadian delay models are widely adopted. However, the existing traffic scenario is not similar in all the countries. Therefore, the relevance of these models to be used globally is doubtful. Moreover, limited studies have been carried out in the case of heterogeneous traffic scenarios; generally observed in developing countries. So, the present study is focused on the modification of an existing delay model for oversaturated flow conditions in heterogeneous traffic scenarios. The accuracy of the modified model is checked by comparing it with the existing popular models.

3. Conventional Delay Models

The delay faced by the vehicles while traversing through a signal-controlled intersection can be used as a measure of the level of service. Vehicular delay is a measure of the performance of an intersection. It can be measured in two different ways i.e. observing the total time a vehicle spent at an intersection while waiting and comparing the expected and actual travel times of a vehicle. Several delay estimation models have been developed by researchers around the globe. Out of these, Highway Capacity Manual (HCM 2010) model, Webster's delay model, Akcelik delay model and Canadian delay models are the most popularly used methods.

3.1 US HCM Delay Model

According to HCM 2010, the average amount of delay faced by the vehicles can be split into three different parts i.e. delay experienced by the vehicles due to their random arrival, due to oversaturated flow conditions, and due to existing queues in the intersection approach. Therefore, equation (1) represents the average total delay of a vehicle (d_{total}).

$$d_{\text{total}} = d_{\text{uniform}}(f_{\text{pf}}) + d_{\text{oversaturation}} + d_{\text{queue}} \tag{1}$$

$$d_{\text{uniform}} = \frac{0.5 \times C \times \left(1 - \frac{g}{C}\right)^2}{\left(1 - \frac{g}{C} \times X\right)} \tag{2}$$

$$d_{oversaturation}=900T\left[(X-1)+\sqrt{(X-1)^2+\frac{8KIX}{Tc}}\right] \tag{3}$$

$$d_{queue}=\frac{3600\times Q_b}{c}-1800T(1-X) \tag{4}$$

$$f_{pf}=\frac{(1-P)f_p}{1-\frac{g}{C}} \tag{5}$$

Here, d_{total} = average total delay of each vehicle (s/veh); $d_{uniform}$ = delay experience by the vehicles during uniform arrival (s/veh), $d_{oversaturation}$ = delay due to oversaturated flow condition (s/veh), d_{queue} = delay due to existing queue length in the intersection approach (s/veh), f_{pf} = modification factor with respect to the progression quality of vehicles, X = ratio of volume and capacity of an intersection approach, c = capacity of an intersection approach (veh/hr), C = cycle length (s), g = amount of green time effectively used by the vehicles (s), T = time of assessment, P = vehicle entered into an intersection during green time of a cycle (%), Q_b = existing queue length at the beginning of assessment period T (veh), K= incremental delay factor (0.50 for pre timed signals), I = upstream filtering adjustment factor (1for an isolated intersection), f_p = progression adjustment factor.

3.2 Webster's Delay Model

Webster developed a delay estimation model in 1958 for the traffic conditions of the UK. The model is developed based on deterministic queuing theory. It can be expressed as:

$$d=\frac{C\left(1-\frac{g}{C}\right)^2}{2\left(1-\frac{g}{C}\times X\right)}+\frac{X^2}{2v(1-X)}-\frac{0.65C^{1/3}}{v^2}\times X^{2+5\lambda}+\frac{T}{2}\left(\frac{v}{c}-1\right) \tag{6}$$

Where, d = average total delay experienced by each vehicle (s); λ = ratio of effective green time and cycle time of an individual intersection approach; C = cycle time (s); g = amount of green time of a cycle that is effectively used by the vehicles (s); X = ratio of volume and capacity of an intersection approach; v and c are traffic flow (veh/s) and capacity (veh/s) of an intersection approach respectively and T = assessment time (s). The first and second terms of the equation (6) indicate the delay due to uniform and random arrival of the vehicles at the intersection respectively. The third term is an adjustment factor and the fourth term gives delay due to initial queue length at the intersection approach.

3.3 Akcelik's Delay Model

Akcelik proposed a delay estimation model for signalized intersections in 1981 and it was used by Australia's Road Research Board. The model is given as:

$$d=\frac{C}{2}\left(1-\frac{g}{C}\right)+\frac{cT}{4}\left[(X-1)+\sqrt{(X-1)^2+\frac{12(X-X_0)}{cT}}\right] \tag{7}$$

$$X_0 = 0.67 + \frac{sg}{600} \tag{8}$$

The first term of the equation (7) indicates delay in case of uniform arrival of the vehicles and the second term indicates delay due to oversaturated flow condition. Here, d = average delay of individual vehicle (s), C = cycle time (s); g = amount of green time of a cycle that is effectively used by the vehicles (s); X = ratio of volume and capacity of an intersection approach; v and c are traffic flow (veh/s) and capacity(veh/s) of a particular approach respectively, T = time of assessment (s) and s = saturation flow of an individual approach (veh/ sec of green).

3.4 Canadian Delay Model

To estimate the amount of control delay at signal-controlled intersections, Teply (1992) proposed a model based on the traffic conditions of Canada. This model is popularly known as the Canadian delay estimation model. The model can be written as:

$$d = \frac{C(1-\lambda)^2}{2(1-\lambda X)} + 900T\left[(X-1) + \sqrt{(X-1)^2 + \frac{4X}{cT}}\right] \tag{9}$$

Here, d = total control delay of individual vehicle (s), C = cycle time (s); λ = effective green time to cycle length ratio of an individual intersection approach; g = amount of green time of a cycle that is effectively used by the vehicles (s); X = ratio of volume and capacity of an individual intersection approach; T = assessment time (hr) and v and c are traffic flow (veh/s) and capacity(veh/s) of an approach respectively.

4. Data Collection and Extraction

In the present study, data were collected from seven cities situated in various parts of India. Seventeen signal-controlled intersections of Delhi, Chandigarh, Patiala, Punch Kula, Mumbai, Surat and Vadodara were selected as study locations. The selected intersections were isolated, right angled, four- legged and the left turning lane was provided with channelization. The intersections were free from the effect of a bus stop, pedestrians, on street parking and grade. The geometric details and signal related information of all the study locations is represented in tabulated form (Table 1). To collect data from sites, a video was recorded from 8 a.m. to 11 a.m. (morning hours) and 3 p.m. to 6 p.m. (evening hours). Information on the vehicles entering and leaving the intersection and signal timings were captured during the same time. The entry of the vehicles and cycle length were recorded by installing a camera on the front side of the approach. Whereas, the exit of the vehicles was recorded simultaneously with another camera installed on the backside of the approach. At every location, only one leg or approach of the intersection was chosen for data collection. Fig.1 shows the formation of the trap at sites to indicate the vehicles entering and leaving the intersection.

(a) (b)

Figure 1: Formation of trap from (a) stop line to (b) end of the queue at study locations

Table 1: Description of Sites Selected for Data collection

Intersection Number	*Location*	*Name of Site*	*Approach Width (m)*	*Cycle Time (sec)*	*Number of Cycles Recorded*	*Range of Platoon Ratio*
I-1	Delhi	Sector 5 Square, Dwarka	10.2	170	50	0.7-1.7
I-2	Delhi	Sector 6 Square, Dwarka	10.2	170	45	0.6-1.8
I-3	Patiala	Parshuram Square	7.3	110	50	0.6-1.6
I-4	Patiala	Viswakarma Square	7.3	110	60	0.7-1.7
I-5	Patiala	State Bypass Square	8.0	120	40	0.6-1.8
I-6	Chandigarh	Sector 46c Square	12.1	120	49	0.5-1.8
I-7	Chandigarh	Sector 47c Square	7.7	120	60	0.6-1.8
I-8	Chandigarh	Sector 45c Square	10.0	135	25	0.6-1.8
I-9	Chandigarh	Manimajhra Square	14.6	130	20	0.8-1.8
I-10	Chandigarh	Railway Square	13.6	150	50	0.7-1.5
I-11	Punch Kula	Bhagwan Parshuram Square	8.9	100	20	0.6-1.7
I-12	Punch Kula	Sector 8 Square	9.1	100	20	0.8-1.5
I-13	Punch Kula	Sector 9 Square	9.1	100	20	0.6-1.4
I-14	Mumbai	Chatrapati Shivaji Square	10.4	150	40	0.3-1.8
I-15	Mumbai	Belapur Kila Square	10.4	150	40	0.4-1.7
I-16	Vadodra	GEV Circle Square	7.5	100	45	0.6-1.7
I-17	Surat	Rangila Park Square	7.5	100	45	0.6-1.5

Further, the recorded video data were played in the laboratory and required information was extracted thereafter. The heterogeneous traffic was grouped into five categories namely, motorized two wheelers, motorized three wheelers, small cars, big cars and heavy vehicles. The videos of entry and exit were extracted cycle wise. Each cycle length was split into five seconds intervals. The entry time of a vehicle is recorded when it entered the longitudinal trap and exit time is marked when it crossed the stop line. Queue length, saturation flow, traffic volume and capacity of each cycle were estimated from the recorded videos. Queue length was measured as per HCM 2010 i.e. the summation of total vehicles entering the intersection during five seconds intervals and the vehicles already waiting in the queue, excluding the vehicles that departed from the stop line during that five seconds.

5. Saturation Flow and Delay Estimation

According to HCM 2010, saturation flow is used to measure the capacity of an intersection. If vehicles are present in a queue at the startingstart of the green phase, then the maximum rate of discharge of the vehicles at the stop line is termed saturation flow. To estimate saturation flow, departure rate (vehicles) at the stop line was plotted at every 5 seconds interval. It was observed that two bikes or scooters can conveniently pass the stop line of an intersection along with a car or a bus or a truck within 5 seconds intervals. Therefore, the time during which a minimum of 3 vehicles were waiting in the queue to pass the stop line was considered as effective green time. Equation (10) was used to estimate saturation flow in terms of veh/hr of effective green time.

$$S=\frac{N}{g_e}\times 3600 \tag{10}$$

Here, S = Saturation flow (veh/ hr of effective green), g_e = amount of green time of a cycle that is effectively used by the vehicles (s) and N = Total number of vehicles passing the stop line during g_e .

The delay of each cycle was estimated based on the existing queue length (Q_L) of that cycle for every 5 seconds interval. A graph was prepared to measure delay by plotting queue length against cycle time. Fig.2 shows a pictorial representation of the graph between queue length and cycle time. The area covered by the graph was calculated with the help of Simpson's 1/3rd rule as shown in equation (11). The area estimated was taken as the total delay of a cycle. The average delay of each vehicle of that cycle was calculated by diving the total delay with the total number of vehicles entered into the approach during that cycle time. The delay was expressed as sec/veh.

$$\int_0^c f(Q_L)\,dq=\frac{h}{3}\left[(q_0+q_n)+4(q_1+q_3+\ldots q_{n-1})+2(q_2+q_4+\ldots q_{n-2})\right] \tag{11}$$

Where,$h = \frac{C-O}{n}$, C – O = Difference in the time duration between initial and final queue length observation of each cycle, Q_L = Length of the existing queue, C = Cycle time, n = Total number of five seconds intervals the cycle length is split into and q_0, q_1, q_2, ….q_n = Existing queue length at 0, 1st, 2nd … nth interval.

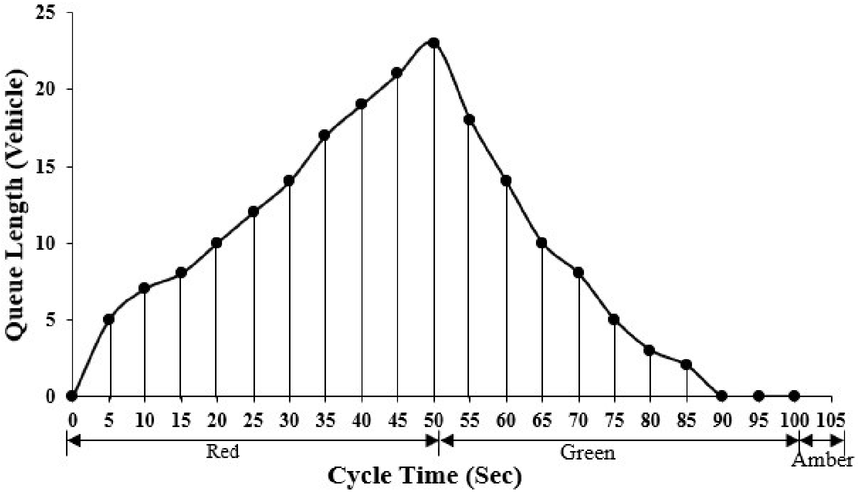


Fig.2 Delay Measurement using Graphical Method

6. Advancement of Delay Model

In a signal-controlled intersection, vehicles experience under-saturated and oversaturated flow conditions. In under-saturated conditions, a vehicle experiences delay mainly due to the uniform arrival and random arrival whereas in oversaturated conditions vehicles face an extra amount of delay due to the spillover or excess queue length. Therefore, the delay experienced by a vehicle during oversaturated flow conditions is the summation of delay experienced during under-saturated flow conditions and delay due to spillover or excess queue length. To estimate delay in case of oversaturated flow conditions, HCM (2010) model was modified in the present study for heterogeneous traffic conditions of developing countries. Having said so, it has been observed that Saha et al. (2017) have modified HCM (2010) model for heterogeneous traffic scenarios (Eq.12). However, the model is applicable for undersaturated flow conditions only. Hence, considering the performance and accuracy of the model, in the present study while modifying the HCM (2010) delay equation, the modification proposed by Saha et al. (2017) was adopted and further modification was carried out for oversaturated flow conditions only. In that context, Equations (3) and (4) were modified to quantify the delay in oversaturated flow conditions under heterogeneous traffic scenarios.

$$d = \frac{C\left(1-\frac{g}{C}\right)^2}{2\left(1-X\times\frac{g}{C}\right)} + 6.23-15.35\times R_P \tag{12}$$

Here, d = delay due to undersaturation (sec/veh), X = degree of saturation, g/C = green time to cycle length ratio, R_p = platoon ratio and C = cycle length (sec).

To execute the modification process, initially, delay due to excess queue was measured cycle wise by subtracting the delay due to undersaturation from the total field observed delay of a cycle. For calculating delay due to undersaturation Eq. (12) was used and field observed delay of a cycle was calculated using Eq. (11). Subsequently, the co-relation of delay due to excess queue (d_3) was checked with all the possible affecting parameters like length of red phase, volume capacity ratio, capacity of an intersection approach, number of vehicles standing in a queue and the amount of delay analysis period. Table 2 shows that a significant co-relation of delay due to excess queue (d_3) was found with v/c ratio and length of red phase (R) of a cycle. Other parameters like no. of vehicles remaining in the queue, capacity and analysis period do not have a significant effect on delay due to excess queue (Ratner, 2009).

Table 2: Co-relation Co-efficient of Delay due to Excess with Different Parameters

Variable	*Vehicles Remain in Queue*	*Capacity*	*v/c ratio*	*Length of Red Phase*	*Analysis Period*
Co-relation coefficient	0.249	0.0009	0.824	0.788	0.337

In a signal-controlled intersection, oversaturated flow condition arises when the traffic volume of a cycle is more than its capacity i.e. v/c > 1. With an increase in the value of the v/c ratio, the length of the excess queue at the intersection approach also increases. Therefore, as the amount of oversaturation increases, the delay experienced by the vehicles eventually increases. The amount of oversaturation was calculated as (v/c-1). To check the variation in delay due to excess queue (d_3), the amount of oversaturation was plotted against the delay. The amount of oversaturation was categorized as low, medium and high (Table 3). As the length of the red phase also significantly affect the delay due to excess queue, so, while plotting the graph the length of the red phase (R) was classified into three different ranges i.e. (65 sec - 90 sec, 90 sec - 115 sec and 115 sec – 130 sec). It is observed from fig.3 that the delay due to excess queue varies linearly with the change in the value of (v/c-1) i.e. amount of oversaturation for a particular range of red time. It also gives an idea about the change in delay (d_3) for different categories of oversaturation amount. Therefore, three linear regression models (Eq. 13 – Eq. 15) were developed to estimate the delay due to excess queue (d_3) for different ranges of v/c ratios. These models are useful for oversaturated flow conditions under heterogeneous traffic scenarios. The RMSE and R^2 values in table 4 indicate that the linear regression equations developed for a particular range of v/c ratio are best fitted within the mentioned ranges.

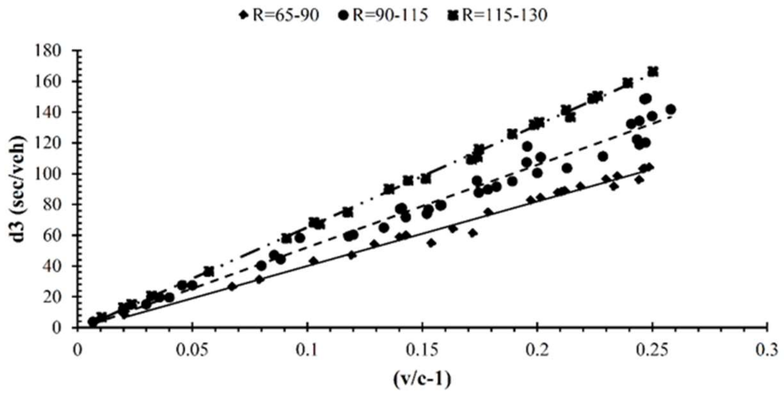
Table 3: Categorization of Oversataturaion Amount

Amount of Oversaturation (v/c-1)	*Category*
0.0-0.25	Low
0.25-0.50	Medium
≥ 0.50	High

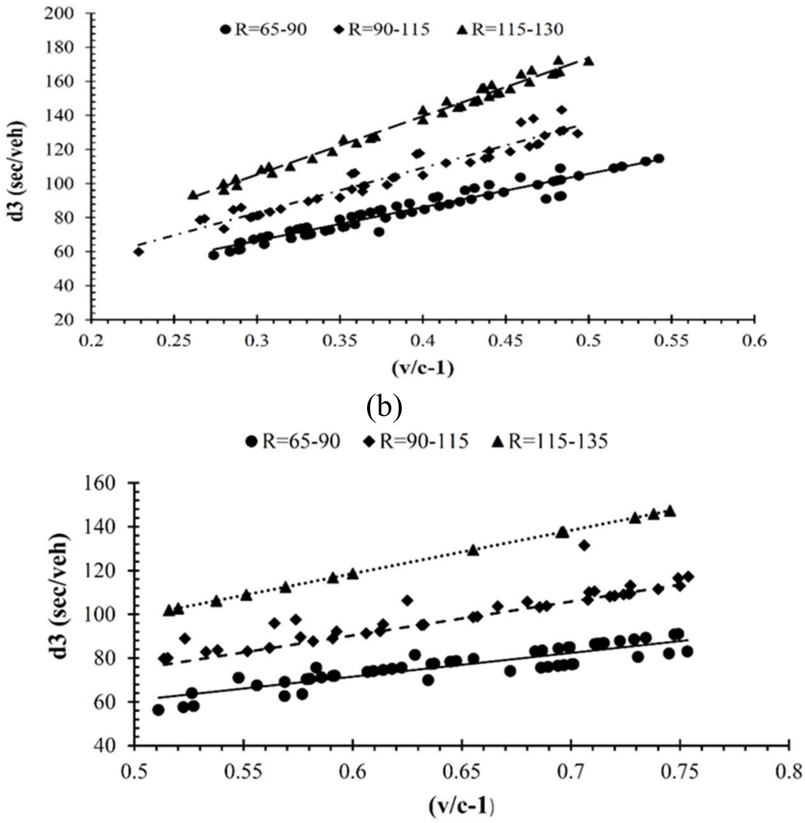
$$d_3 = 5.23\times\left(\frac{v}{c}\text{-}1\right)\times R \qquad \text{for } \left(\frac{v}{c} > 1.0 \leq 1.25\right) \tag{12}$$

$$d_3 = 2.82\times\left(\frac{v}{c}\text{-}1\right)\times R \qquad \text{for } \left(\frac{v}{c} > 1.25 \leq 1.50\right) \tag{13}$$

$$d_3 = 1.62\times\left(\frac{v}{c}\text{-}1\right)\times R \qquad \text{for } \left(\frac{v}{c} > 1.50 \leq 1.75\right) \tag{14}$$



(a)



(c)

Figure 3: Variation of d_3 with (v/c-1) for different ranges of v/c ratio

Table 4: Measures of Accuracy for Different Ranges of v/c Ratio

Now, the total delay (D) experienced by a vehicle during oversaturated flow situation under a mixed traffic scenario can be estimated as the summation of delay due to an undersaturation flow situation (Eq. 12) and delay due to excess queue length (d_3). Therefore, the modified HCM (2010) delay model can be expressed as-

$$D=\frac{C\left(1-\frac{g}{C}\right)^2}{2\left(1-X\times\frac{v}{c}\right)}+6.23-15.35\times R_P+a\times\left(\frac{v}{c}-1\right)\times R \tag{16}$$

Range of v/c Ratio	*R^2*	*RMSE*
v/c > 1.0 ≤ 1.25	0.894	10.391
v/c > 1.25 ≤ 1.50	0.776	11.338
v/c > 1.50 ≤ 1.75	0.919	13.786

Here, D = overall delay experienced by a vehicle in oversaturated flow condition (sec/veh), X = degree of saturation, g/C = green time to cycle length ratio, R_p =p ratio, C = cycle length (sec), R= length of red phase (sec), a = constant for various ranges of v/c ratio as per Eq. (13)- Eq.(15) = 5.23, 2.82 and 1.62.

The modified model is applicable for heterogeneous traffic conditions of developing countries like India, Bangladesh, Srilanka etc. where motorized and non-motorized vehicles share the same lane without strictly maintaining lane discipline.

7. Validation of Modified Model

The modified model was formulated based on the data of the first seven (I-1 to I-7) signal-controlled intersections and the data of the remaining ten sites i.e. I-8 to I-17 were used for validating the model. It is to note that the data used for validation purposes were not used for modifying the model i.e. while developing Eq. (13)- Eq. (15). The validation was done for different ranges of v/c ratios. Delay due to oversaturation was measured from field data as well as estimated using equation (16). The field measured delay of over saturated cycles was plotted against model estimated delay as shown in Fig. 4. A good match is observed between the delay values as all the data points lie near to 45° line. The maximum difference observed between them is quite acceptable i.e. 12.92 sec.

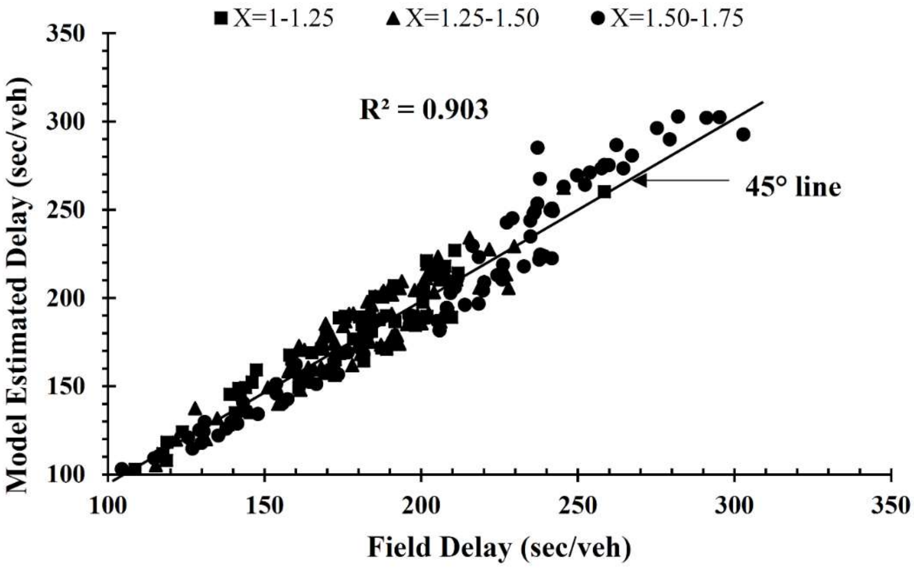


Figure 4: Validation of the Modified Delay Model

8. Comparison of Different Delay Estimation Models

The performance of the modified model is represented by comparing the results obtained using the model with the existing widely adopted methods. Table. 5 represents the comparison in results between various methods. The best outcome is obtained from the modified method with an accuracy of 94.8% followed by the HCM method (estimation accuracy of 62.2%). Canadian, Webster's and Akcelik's methods produced estimation accuracy of 50.5%, 48.9% and 41.8% respectively.

Table 5: Comparison of Delay Using Different Methods

Range of v/c	*Observed Field Delay (sec/vehicle)*	*Delay Using*				*Modified Method (sec/vehicle)*
		HCM Method (sec/vehicle)	*Webster's Method (sec/vehicle)*	*Akcelik's Method (sec/vehicle)*	*Canadian Method (sec/vehicle)*	
v/c > 1.00 ≤ 1.25	147.0	115.0 (31.7)	65.0 (54.4)	57.4 (58.8)	72.2 (51.1)	155.0 (5.6)
v/c >1.25 ≤ 1.50	152.0	179.6 (27.3)	83.5 (45.8)	60.0 (58.8)	88.8 (43.0)	145.2 (4.5)
v/c > 1.50 ≤ 1.75	125.4	193.8 (54.54)	92.9 (53.1)	55.5 (57.0)	98.0 (54.3)	131.7 (5.5)
Average error		**37.8**	**51.1**	**58.2**	**49.5**	**5.2**

Note: Figures in parenthesis represent mean absolute percentage error (MAPE) in estimation.

The modified model yields better performance mainly due to the following reasons-

a) Firstly, to estimate the delay of vehicles using the HCM method, a platoon adjustment factor is required. For different arrival types, the magnitude of this factor is nearly equal to one. Therefore, it leads to an error in estimation. In that place, the present study directly introduced the platoon ratio as a delay estimation parameter.
b) Secondly, Webster's method is mainly based on v/c and g/c ratios. In this method, the effect of different arrival types and duration of the red phase is not considered for estimation of delay due to random arrival and oversaturation respectively. On the contrary, the modified model introduced both the above-mentioned parameters for estimating delay, leading to a more accurate assessment.
c) Thirdly, Akcelik's and Canadian models did not significantly modify the HCM 2010 delay estimation model. Therefore, the errors of the HCM method also reside in these methods. Moreover, no separate formula was provided to consider the oversaturation flow condition. Therefore, both methods provide comparatively less accurate results. However, the modified method is free from such type of phenomenon.
d) Fourthly, the modified model was developed based on a broad range of data sets. Data from three cities were used to develop the model and data from another four cities were used to validate the same.

The above discussion is quite evident that the modified model is superior to the available oversaturated delay estimation models.

9. Conclusions

Estimation of delay at a signal-controlled intersection is challenging particularly in the case of heterogeneous oversaturated traffic flow conditions. While estimating delay in heterogeneous traffic scenarios in India, researchers usually prefer to use existing conventional delay estimation models. These models were developed based on the traffic conditions of developed countries; where homogeneous and lane disciplined traffic scenario exists. On the contrary, in developing countries, traffic is highly heterogeneous and lane discipline is not strictly followed. Therefore, using these methods produce estimation error. From this perspective, the present study represents a modified method for estimating the delay of oversaturated flow conditions at signalized intersections. Delay was estimated in sec/veh instead of PCU/veh. Simpson's 1/3rd rule was applied to measure delay at field depending on the existing queue of a cycle. A comparison was done between the delay observed on the field and the delay estimated using the modified model, HCM model, Webster's model, Canadian and Akcelik's delay model. The results showed that the delay estimated using the modified model gave more accurate results. Whereas, the conventional methods either underestimated or overestimated the delay. The modified model is mainly applicable to heterogeneous traffic conditions of developing countries like India where lane discipline is not strictly maintained. This model can be further tested by using the data from the developed countries and checked for its equal applicability for both heterogeneous as well as homogeneous traffic conditions.

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