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## Comparative analysis of saturation flow using various PCU estimation methods

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### Abstract

The magnitude and nature of traffic flow in developing countries are difficult to evaluate due to its mix traffic conditions. In transportation network, intersection plays a vital role to increase the efficiency of the entire road network. Analysis of these nodal points (intersection) is required to evaluate the performance of the intersection through the assessment of operational parameters such as saturation flow and its level of service (LOS). However, the complexity of discharge flow in Indian scenario is mainly due to its mixed properties of traffic stream where both motorized and non-motorized vehicles are traveling in the same stretch without any lane discipline. Also, no single vehicle dominates the traffic stream consequently prediction of saturation flow is more sensitive to that mixed traffic. The passenger car unit is a common platform for the conversion of mixed traffic into a standard unit by taking passenger car as a conventional vehicle. The present study focuses towards the analysis saturation flow at signalized intersection using various PCU estimation methods under mixed traffic conditions. A detailed comparison of the saturation flow obtained by the each methodology with standard saturation flow value given in HCM (2010) is also presented. Traffic and vehicular data were collected from six signalized intersections from three Indian cities such as Delhi, Chandigarh and Allahabad using video graphic method. The prospective method resulted in a lower difference in saturation flow respect to HCM (2010) is proposed for non-lane based mixed traffic stream.

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## 1. Introduction

In last few decades, substantial development is observed in India both in industrialization as well as urbanization. The economy of India has been growing day by day, has a significant impact on its transportation system. In transportation network, intersection plays a vital role to increase the efficiency of the entire road network. The magnitude and nature of traffic flow in developing countries are difficult to evaluate due to its mix traffic conditions. Indian traffic stream is highly heterogeneous, consist of variety of vehicles with widely varying static and dynamic characteristics, traveling in the same stretch without any lane separation. In such mixed traffic stream, no single vehicle dominates the traffic stream consequently prediction of saturation flow is more sensitive to that mixed traffic than in western countries where the traffic is mainly motorized and car-dominated. Also, lane discipline is not followed during the entry and exit from the intersection instead the vehicles have a tendency to use lateral gaps to acquire more advantageous position in the queue while waiting for clearance through filling the small gaps between the larger vehicles. This practice mainly makes the intersection more congested with uneven distribution of traffic over it. The most common platform for analyzing traffic flow in developing countries is to convert the mixed traffic into homogeneous one using passenger car unit (PCU). The HCM 2000 defined passenger car equivalent (PCE) as the number of passenger cars which will result in the same operational condition as a single heavy vehicle of a particular type under specified roadway, traffic and control conditions. IRC SP 41:1994 is the only guideline for the design of at-grade intersections in rural and urban areas for Indian traffic stream. In a number studies, PCU proposed as a static parameter though it changes with several factors like traffic and vehicular characteristics, road geometry even with the timing of the control system makes it dynamic. Due to fundamental differences, the standard western relationships for predicting the value of saturation flows and PCUs are not appropriate for developing countries having mix traffic conditions. The present study focuses towards the appropriate estimation of passenger car unit and a step towards the assessment of saturation flow for non-lane based mixed traffic stream.

A significant effort has been made in last few years to evaluate the operational parameters of a signalized intersection, especially for mixed traffic conditions. Characteristics of discharge vehicle mainly the saturation flow is an utmost parameter for the evaluation as well as measurement of performance parameters. HCM 2010 presents a methodology for analyzing signalized intersection considering details of each parameter for a lane based car dominated traffic stream, with limited applicability for the mixed traffic conditions. Researchers have estimated the saturation flow value for mixed traffic conditions through converting the mixed traffic into a homogeneous one using PCUs of vehicles. A number of methodologies have proposed by the various researchers in previous studies to evaluate PCUs of vehicles at signal controlled intersection using various traffic stream parameters. Headway ratio method (Greenshields et al., 1947, Saha et al., 2009 and Biswas and Ghosh, 2017) is one of the useful technique to calculate the PCUs of vehicles. This method considers the ratio of headway of a particular vehicle type to the headway of car. Some other methods that are effectively utilized by the various researches are Delay Method (Rahman et al., 2003, Benekohal and Zhao, 2000), Regression analysis (Branston and Zuylen, 1978), Saturation flow ratio method (Demarchi and Setti, 1852), Optimization technique (Radhakrishnan and Mathew, 2011 and Mondal and Gupta, 2018), and Queue clearance rate method (Mohan and Chandra, 2017). Among them, regression technique is one of the most useful tool to calculate the PCUs of vehicles at signalized intersections. Though most of the methods are developed based on homogeneous lane based traffic stream. However, India has a non-lane based mixed traffic stream with variety of vehicles travelling in a same stretch. Therefore, the selection of an appropriate method is difficult to identify, suitable for mixed traffic stream due to different methodological background in each approach. Thus, PCUs of vehicles are estimated using four different methods and further used to evaluate the saturation flow value. A comparative analysis is also done between the obtained saturation flow using each methodology with standard saturation flow value given in HCM (2010) to identify the most rational and appropriate methodology for mixed traffic stream.

## 2. Data collection and extraction

The methodology for data collection is being adopted as per the guidelines of HCM (2010). Presently, six signalized intersections were selected for the data collection from three different cities of India. All the intersections are having a channelized section for left turn movement; there is no nearby bus stop and no roadside parking. Percentage of non-motorized vehicles are also negligible. All the selected intersections are free from pedestrian activities with a pre timed

signal characteristics. The details of the intersections are listed in Table 1. The data were collected at peak hours using the video-graphic technique. The camera was mounted at vantage point nearside the intersection to cover the upstream traffic from approach stop line. Once the video is recorded, it is played at the workstation to extract several traffic stream parameters. The entire traffic was classified into six different categories such as two-wheelers (2W), motorized three-wheelers (M3W), Car (C), Big Car (BC), BUS and LCV. These classifications were based on the static (Physical dimension) and dynamic characteristics (Engine capacity) of each vehicle. Classified vehicles count was done to obtain the traffic volume and compositional share of individual vehicle class at each study section. The compositional share of single vehicle class is shown in Fig 1. The proportion of each vehicle type at the selected signalized intersections are varied from 25 to 66% for 2W, 6 to 13% for M3W, 18 to 52% for Car, 5 to 9% for BC, 1 to 3% for LCV and 1 to 6% for Bus respectively.

Table 1. Details of signalized intersection.

No of Intersection	City	Approach width (m)	Cycle Length (sec)	Green time (sec)	No of Cycles Observed
I-1	Allahabad	7.13	122	42	77
I-2		8.95	145	36	75
I-3		8.35	112	30	55
I-4	Delhi	10.2	170	56	51
I-5		10.2	170	60	40
I-6	Chandigarh	7.70	120	30	44

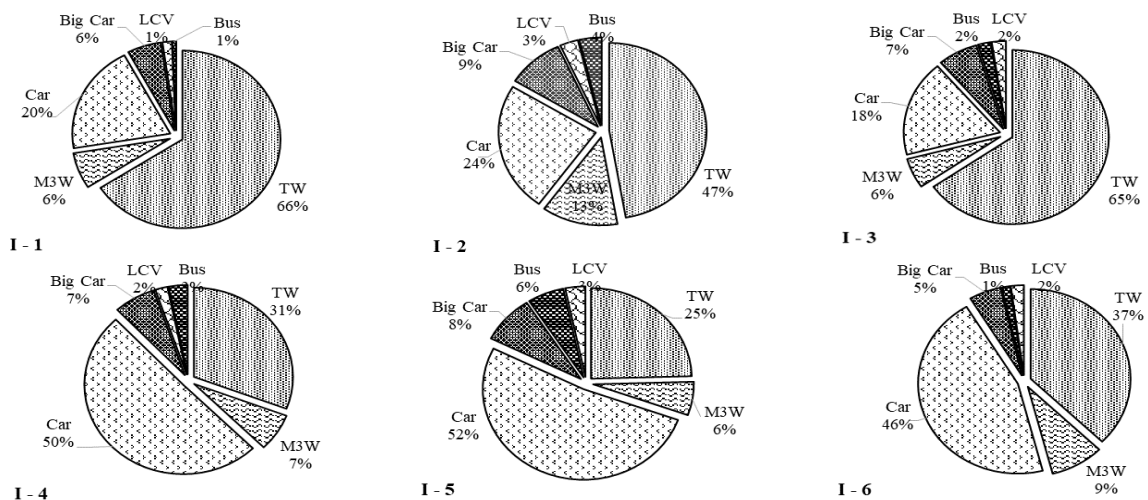


Fig. 1. Vehicular composition at all the selected intersections.

The departure of vehicles was extracted at the 6-second interval (equal slot of green time) from the collected data as shown in Fig 2. At the initiation of green, vehicles start to cross the section at an increasing rate. Vehicles soon reach a stable state where they are following one another with a constant gap or headway. At the end of the green, flow decreases with an increasing rate and become zero when the signal shows red. The fluctuation in flow is due to the heterogeneity of the traffic stream.

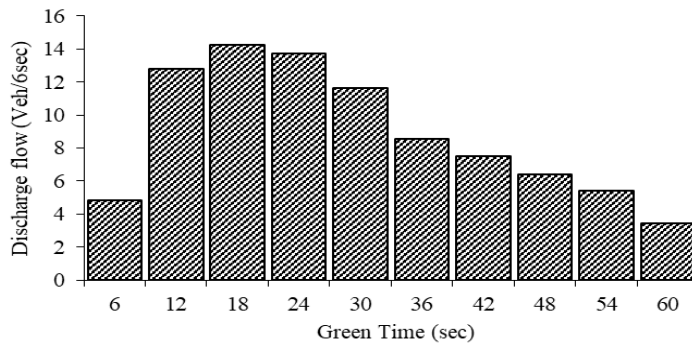


Fig. 2. Discharge of vehicles through the intersection during green time.

### 3. Research methodology

Previous studies show that different methods can be used for the estimation of PCU at a signalized intersection. Among them, regression was effectively used by the researches to find out PCU values of vehicles. The present study adopts four different methods namely Queue clearance rate method, Regression method, Optimization by using Theil’s coefficient and Optimization through normalizing the flow to estimate the PCUs of vehicles and corresponding to evaluate the saturation flow value at the signalized intersection for mixed traffic conditions. The background of the current methodology can be depicted from the flowchart given in Fig 3.

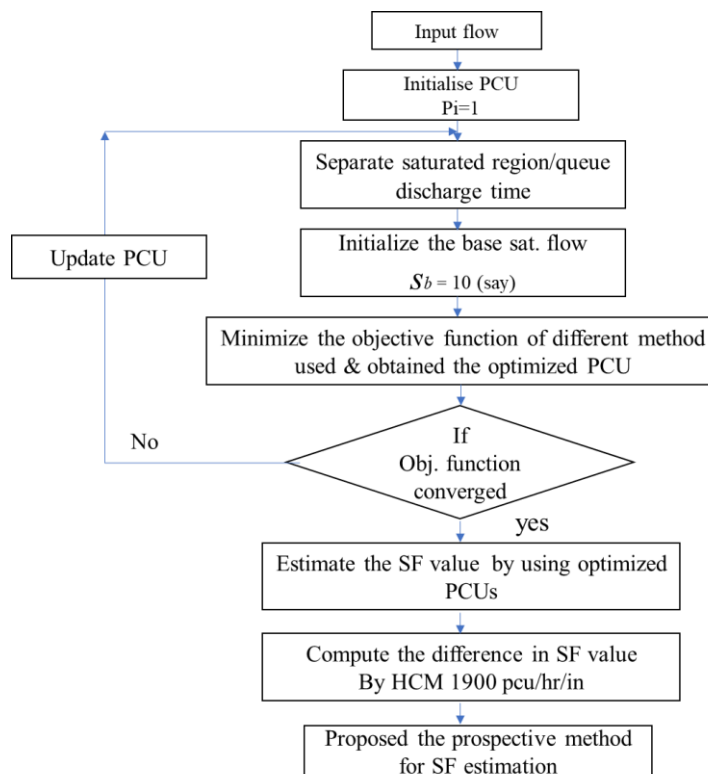


Fig. 3. Flow chart of the present methodology.

## 4. Analysis of PCUs using various estimation methods

### 4.1. Methodologies of PCU estimation

#### 4.1.1 Optimization technique (Theil's coefficient)

An optimization technique is a process of minimizing the difference between an ideal saturation flow curve and the observed saturation flow curve. HCM 2010 has suggested that the base saturation flow should be estimated with an assumption that vehicle moves in a queue. Whereas in mixed traffic, vehicles occupy the position as per the gaps available in a queue and haphazardly discharge through the intersection. Therefore, a significant difference is observed between the ideal flow and observed flow. In this optimization technique, this difference can be minimized using Theil's coefficient ( $Z_{\min}$ ) as the objective function. This optimization problem is formulated as:

$$Z_{\min} = \frac{\sqrt{1/N \sum_{i=1}^N (S_b - S_i)^2}}{\sqrt{1/N \sum_{i=1}^N (S_b)^2 + 1/N \sum_{i=1}^N (S_i)^2}} \quad (1)$$

$$S_i = \sum_{j=1}^m n_j P_j, P_j \geq P_{j_{\min}}$$

Where  $S_b$  is the base saturation flow,  $S_i$  is the saturation flow during interval  $i$ ,  $n_j$ ,  $p_j$  are the number and PCE of vehicle type  $j$ . following steps are used for the computation of optimized PCU values.

Step 1: Initialize the all PCU values equal to 1

Step 2: Separate the saturated portion and estimate the saturation flow value at initial PCUs

Step 3: Using solver in excel solve the formulation (equation 1) to get the optimized PCUs of vehicles.

#### 4.1.2 Regression technique

Regression technique (RT) is one of the useful methodology for the analysis of different traffic stream parameters. Number of vehicles are calculated that are crossing the intersection during the saturated green time. The background of the methodology given in the following equation.

$$\tau = \varepsilon + \sum a_i n_i \quad (2)$$

Where,  $\tau$  represents saturated green time (excluding start-up lost time and end loss time) and  $a_i$  is the weight associated with  $n_i$ ,  $n_i$  is the number of classified vehicles,  $\varepsilon$  stands for fixed error term.

The ratio of the coefficient  $a_i$  for particular vehicle type to the coefficient of car  $a_c$  is known as the PCU factor for the corresponding vehicle type as:

$$PCU_i = \frac{a_i}{a_c} \quad (3)$$

Where,  $a_c$  =Coefficient for car

Following are the steps used for the computation of PCU values by regression method.

Step 1: Counting of the vehicle during queue discharge time (T, sec).

Step 2: Compute the coefficient  $a_i$  by using queue discharge time (T) and classified vehicle count in the form of equation (2)

Step 3: solve Equation (3) to obtain the PCU for different category of vehicle.

#### 4.1.3 Queue clearance rate method

Queue Clearance Rate (QCR) method was developed to estimate the PCU at un-signalized intersections for heterogeneous traffic conditions (Mohan and Chandra, 2017). This method shows a reasonable estimation of PCU for non-lane based traffic behavior. This method estimates the ratio between a numbers of vehicles in the queue (N) upon the time taken by the queue to clear the conflict area given in equation 4.

$$QCR = \frac{N}{T} \quad (4)$$

Where N is the number of vehicles in the queue (in PCE), T is the time taken by the queue to clear the intersection area (in second). Here Denominator ‘T’ shows the time elapsed between the arrival of the front end of the first vehicle of the queue and exit of the rear bumper of the last vehicle in the queue from the conflict area. The numerator in equation 5 can be formulated as:

$$N = \sum_{j=1}^k n_j \frac{W_{car}}{W_j} PCE_j \quad (5)$$

Where  $W_{car}$  is the width of the standard car (m),  $W_j$  is the width of vehicle type j (m),  $PCE_j$  is passenger car equivalent for vehicle type j, k is the number of vehicle categories in the traffic stream.

This method assumes that the variation in QCR will be the minimum if the queues were comprised only of passenger cars. Hence, a linear programming problem could be developed using equation 4 and 5 with the objective of minimizing the coefficient of variation in QCR for different queues by considering PCE of different vehicle types as the design variable. Following are the steps used for the computation of PCU values by QCR method.

Step 1: Initialize the all PCU values to 1.

Step 2: Compute the time (T) taken by the vehicle to clear the intersection.

Step 3: Compute the value of (N) by using equation 5.

Step 4: Compute QCR using equation 4.

Step 5: Minimize the error obtained by the ratio of stddev. of QCR to the mean of QCR and get the optimized PCUs.

#### 4.1.4 Optimization by normalizing the flow

Optimization technique (OPT) (Mondal and Gupta, 2018) attempts to minimize the difference between an ideal saturation flow curve and the observed flow curve. Saturation green region is estimated using statistical test analysis of variance (ANOVA) to separate the saturated zone from the entire green time in a cycle. The flows within the saturated intervals are normalized as per Standard Score Method.

$$Normalizedflow = \frac{x - mean}{stddev} \quad (6)$$

Where x is the Flow within saturated green intervals.

Following are the steps used for the computation of PCU values by optimization approach.

Step 1: Initialize the all PCU values to 1.

Step 2: Perform the ANOVA test for finding statistical equivalency among the flow in successive intervals determine the saturated green region.

Step 3: Normalized the flow within the saturated intervals using equation 6.

Step 4: minimize the error (using SOLVER) obtained by the summation of the stddev of the saturated interval and get the optimized PCUs.

Table 2. Comparison of PCUs obtained by four different methods.

Vehicle type	IRC PCUs	PCU (in literature)		QCR		RT		TC		OPT	
		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
2W	0.5	0.18a	1.22a	0.2	0.253	0.04	0.511	0.2	0.7	0.15	0.36
M3W	1.0	0.79a	3.48a	0.7	1.20	0.52	2.33	0.7	1.4	0.7	1.2
CAR	1.0	1.00	1.00	1.0	1.0	1.00	1.00	1.0	1.0	1.0	1.0
BC	1.0	1.25b	1.99b	1.2	1.6	0.156	1.33	1.4	1.8	1.2	1.6
BUS	3.0	1.23a	5.16a	2.9	4.0	0.03	2.485	2.9	4.0	1.4	2.9
LCV	1.50	1.09a	3.63a	1.4	1.62	0.53	2.86	1.4	1.9	1.4	2.9

a: Praveen and Arasan (2013)(13)

b: Chandra, S (2004)(14)

### 4.2 PCU Estimation

The above four methods are utilized to estimate the PCU values of individual vehicle type shown in Table 2. Values listed in IRC and previous literature are also shown in Table 2, where a significant difference is observed between the values given in IRC and estimated PCU values. Fig 4 shows the average PCU value of individual vehicle type obtained by each method.

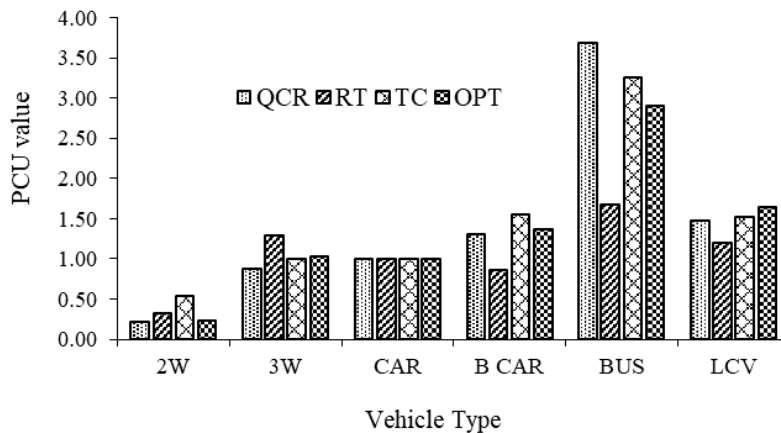


Fig. 4. Mean PCU values of each vehicle type.

### 5. Saturation flow estimation

Saturation flow is one of the critical parameters to evaluate the performance of a signalized intersection. In the present study, the conventional method is used (equation 7) for saturation flow measurement for each study location. In the beginning, classified vehicles count was carried out to calculate the number of vehicles flowing through the intersection per green phase. The equivalence unit for each vehicle type was multiplied with corresponding its number of vehicle to estimate saturation flow value in terms of PCU/hr using equation 7.

$$\text{Saturation flow (SF)} = \left[ \sum n_i PCU_i \right] \frac{3600}{g_e} \tag{7}$$

Where,  $n_i$  is the number of the vehicle category  $i$ ,  $PCU_i$  is the PCU of vehicle category  $i$ ,  $g_e$  represents the effective green time (sec.)

Effective green time has a significant impact on saturation flow. It basically involves the green time and corresponding the lost times i.e. startup lost time (SULT) and clearance lost time (CLT). Initially at the beginning of green time, an amount of time is lost due the driver’s reaction time to start and accelerate the vehicle known as startup lost time. It is the total time consumed by all the driver’s standing in a queue to react and accelerate. A basic methodology is proposed by the HCM 2010 simply adding the difference between the saturation headway and vehicle’s headway upto a certain queue position (until it reaches saturation headway). But due to non-lane base mixed traffic stream, determination of vehicles headway is become a quite challenging one. Also, at the start of green, vehicles standing in front of queue (Generally Two wheeler observed in all the study locations) are moving haphazardly as per their static and dynamic characteristics. Therefore, the SULT is calculated using the average discharge flow through the section and the discharge flow at first green slice shown in equation 8.

$$SULT = t - \frac{q_0 t}{s} \tag{8}$$

Where, t is duration of the time slice,  $q_0$  is discharge flow at the first green slice and s is the average discharge flow. The clearance lost time (CLT) is often not perceived as the chances of some vehicles are waiting at the red time be still waiting after the green end is less. Therefore, it is also calculated as per the above equation using the flow value of the end green slice. Fig 5 shows the basic elements of lost time estimation.

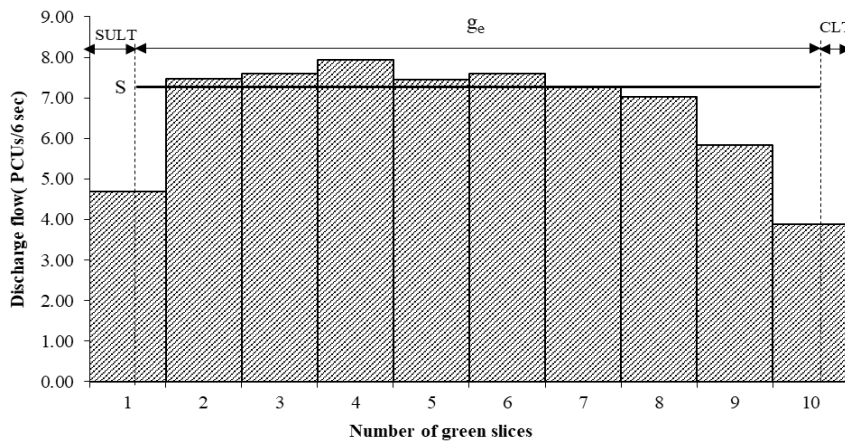


Fig. 5. Discharge of vehicles during the green time.

HCM 2010 has provided a basic formulation regarding the effective green ( $g_e$ ) using various parameters shown in equation 9.

$$g_e = G + A + AR - (SULT + CLT) \tag{9}$$

Where,  $g_e$  is the effective green time (sec), G is actual green time (sec), A is the provided amber time (sec), AR is all red (sec) time.

Table 3 shows the values of lost time and corresponding its effective green time for each selected signalized intersection obtained using the equation 9.



Table 3: Values of effective green time of the selected intersection.

No of Intersection	Actual green time (sec)	Amber time (sec)	SULT (sec)	CLT (sec)	Effective green time (sec)
I-1	38	4	2.87	2.42	37.11
I-2	32	4	2.16	3.06	30.78
I-3	26	4	1.86	2.77	25.37
I-4	52	4	1.99	3.23	50.78
I-5	56	4	1.77	2.33	55.90
I-6	26	4	2.33	2.72	24.95

The mean PCUs presented in Figure 4 have been used to find out the flow values (in PCU) at each green slices for each cycle. The effective green time given in Table 3 has been used to estimate the saturation flow value of the each study location using equation 8. Table 4 depicts the mean saturation flow value obtained by the various PCU estimation methods. A comparative analysis has also been presented between the observed saturation flow value and saturation flow value prescribed in HCM 2010.

Table 4. Comparative analysis of SF values.

Methods	Saturation Flow Values (PCU/hr/ln)			
	QCR	RT	TC	OPT
Estimated Saturation Flow	1814	1784	2155	1830
Difference between HCM and estimated SF (%)	4.52	6.10	13.42	3.68

Table 4 shows that three different methodologies namely Queue clearance (QCR), Regression technique (RT) and Optimization technique (OPT) are quiet useful to estimate the PCU values as the variation of equivalent flow from the value mentioned in HCM is below 10% for each methods. Although, OPT gives best estimation of PCUs in terms of percentage difference (3.68%) in saturation flow value. Student t-test has been performed to check the statistical significance in the mean value of saturation flow between OPT and other methods. It can be found that the difference in saturation flow between OPT and other methods is significant in terms of t-statistics and p-values. Table 5,6 and 7 gives the result of the paired t-test between OPT and other methods. The accuracy of the optimization technique is due the consideration of saturated green time in its estimation procedure.

Table 5. Result of paired t-test between OPT and QCR

Group	Mean	Variance	SD	df	P value	t/tcritical	Significance
OPT	1830	209254.84	457.44	239	0.0011	3.319/1.974	Yes
QCR	1814	230514.04	480.12				

Table 6. Result of paired t-test between OPT and RT

Group	Mean	Variance	SD	df	P value	t/tcritical	Significance
OPT	1830	209254.84	457.44	239	2.03E-05	4.393/1.974	Yes
RT	1784	145204.28	381.0568				

Table 7. Result of paired t-test between OPT and TC

Group	Mean	Variance	SD	df	P value	t/tcritical	Significance
OPT	1830	209254.84	457.44	239	1.26E-63	-28.13/1.974	Yes
TC	2155	177801.64	421.67				

## 6. Conclusion

The present study analyzed the saturation flow of signalized intersection for heterogeneous traffic condition using various estimation methods. Data were collected from three different cities of India using the video graphic technique. Several traffic stream parameters were extracted from the collected data to analyze the PCUs and saturation flow value. Four different methods namely queue clearance rate method (QCR), regression technique (RT), optimization using Theil's coefficient (TC) and optimization by normalized flow (OPT) are utilized to estimate dynamic PCUs of different vehicle type. Saturation flow has been calculated using basic formulation provided in HCM 2010 using

effective green time at each location. SULT and CLT have been incorporate in effective green time by considering the average discharge flow through the section and the discharge flow at first green slice. A range of SULT of 1.77 to 2.87 sec and CLT of 2.33 to 3.23 sec is observed at each selected location. The mean PCUs obtained by each method are used to estimate the flow value. It has been observed that three different methodologies namely Queue clearance (QCR), Regression technique (RT) and Optimization technique (OPT) are quiet useful to estimate the PCU values as the variation of equivalent flow from the value mentioned in HCM is below 10% for each methods. Although, OPT gives best estimation of PCUs in terms of percentage difference (3.68%) in saturation flow value. Student t-test has been performed to check the statistical significance in the mean value of saturation flow between OPT and other methods. It can be found that the difference in saturation flow between OPT and other methods is significant in terms of t-statistics and p-values. The accuracy of the optimization technique is due the consideration of saturated green time between the entire green region and estimates the saturation flow value through normalizing the flow as per standard score method. Result gives a flow value of 1830 PCU/hr/lane which is near to the proposed saturation flow by the Highway Capacity Manual 2010. Therefore, the optimization technique through normalizing the flow as per score method can be used to estimate the dynamic PCUs and Saturation flow value for the non-lane based heterogeneous traffic.

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