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Analysis and Estimation of Saturation Flow at Signalized Intersections in Mixed Traffic Conditions

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Abstract

Vehicular traffic in most of the developing countries is a mixed traffic flow condition with non- lane based behaviour in urban roads. Vehicles with different static and dynamic characteristics share a common lane. Signalized intersections provide sequential movements of vehicular traffic from one leg to another leg. Level of service offered by a signalized intersection depends on delay incur for a queued vehicle. Saturation flow is an important parameter for the measurement of Level of Service at signalized intersections. Researches around the world estimated saturation flow of a signalized intersection for a homogeneous traffic, and lane- based behaviour conditions. The various equations, developed for the estimation of saturation flow, for a mixed traffic flow condition do not consider the non- lane based traffic conditions. There is a need to establish a model to estimate the saturation flow of a signalized intersection for a non-lane based vehicular movement in mixed traffic flow conditions. This research work presents the findings of the analysis of saturation flow conducted at signalized intersections in two different cities, Warangal and Calicut, in India. Flow rate and traffic volume data are collected using video graphic technique and Transportation Research Record Laboratory (TRRL) direct vehicle count method is used to estimate saturation flow. The developed model shows good predictability in comparison with observed data and can be used to estimate saturation flow in non-lane based traffic conditions.

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Keywords: Saturation flow, Heterogeneous traffic, Signalized intersection, TRRL direct vehicle count method, INDO HCM method.

1. Introduction

Intersections are nodal points in an urban road network and are the most complex locations on the road network, where the vehicles and pedestrians moving in different directions want to occupy same space at the same

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point of time. The advantage of signal control is that it minimizes the number of conflict points by clearly separating the available time among all the approaches. Signalized intersections at which the signal timings remain constant over a period of time are said to be fixed time signals. The signal can also be semi actuated or fully actuated. Semi actuated signals are used when the intersection is between a major street and a minor street. Fully actuated signals are used when there will be fluctuating flows on all approaches. Saturation flow is the major parameter required for the estimation of capacity and level of service at signalized intersection. Most of the literature has been studied for estimating the performance measures of signalized intersections based on homogeneous traffic conditions. But, for a country like India, where heterogeneous traffic conditions prevail, homogeneous traffic relations does not fit. In the present study TRRL direct vehicle count method (Chand et al 2016) is used to estimate field saturation flow and an attempt has been made to develop a model for the estimation of saturation flow for signal controlled intersection. The model saturation flow values were compared with those obtained using Indian Highway Capacity Manual (INDO HCM).

2. Literature review

TRRL, Transport Road Research Laboratory., (1963) proposed a method for estimating Saturation flow in the field. The saturation flow is estimated as the flow corresponding to a stable moving queue that crosses the stop line. The flow corresponding to 98^{th} percentile flow is taken as saturation flow. Arasan et al., (2006) studied the effect of the width of approach on saturation flow. The study was mainly concerned with the application of model to determine the saturation flow rate of heterogeneous traffic. Results show that, there is a significant increase in the saturation flow rate with width of approach under heterogeneous traffic condition. Chodur et al., (2011) investigated the impact of adverse weather conditions on the capacity of entry lanes. It was found that the saturation flow in traffic signal cycles at individual intersections is a random variable which can be described by Gamma or Normal distribution. The study results show a reliable impact of different weather conditions on the saturation flow. Anusha et al., (2013) analyzed the effect of two wheelers on saturation flow rate at signalized intersections. A strong correlation was observed between the measured saturation flow rate and the proportion of two wheelers. Results indicated that the saturation flow measured using modified HCM equation was closer to the observed saturation flow values. Shrestha et al., (2014) used multiple linear regression method for the estimation of passenger car unit (PCU) values of different vehicle categories. For the estimation of saturation flow, saturated green time is divided by the number of different categories of vehicles that have been converted into passenger car units to get the time headway. Inverse of the headway is taken as saturation flow.

Patel et al., (2015) studied the impact of mixed traffic behavior on saturation flow and PCU. The study covers the queue release rate during the saturation green time by observing arrival rate, compositions and intersection geometry. Study results shows that the saturation flow rises with the rise in arrival rate per meter width and percentage share of two wheelers. Nguyen et al., (2016) investigated and analyzed the effects of motorcycle on heterogeneous traffic at signalized intersections. Saturation flow model converting all the volume in motor cycle unit was developed. It was found that the homogeneous motorcycle saturation flow rate in the 3.5 m width reach around 11,300 MCU/h, which is higher than 5.8 time of the saturation flow rate of homogeneous car flow 1900 PCU/h. Rajgor et al., (2016) conducted a study on saturation flow rate which was obtained by counting the number of vehicles during the saturated green intervals. Approach width, percentage of cars and percentage of two wheelers are the three different factors considered for the development of saturation flow model. Arpitha saha et al., (2017), presented a formula for calculating the saturation flow rate under mixed traffic conditions based on road width, composition of traffic and percentage of right turning vehicles. Saturation flow rate was calculated as the number of vehicle crossing the stop line during effective green time divided by effective green time multiplied with 3600. The saturation flow model was presented in terms of vehicles/hr of green/lane. Mostafa Roshani et al., (2017), calculated the saturation flow rate using average headway of queued vehicles. In this study, different relationships between flow of vehicles and pedestrians were examined and it was found that linear model is best fit. It was found that the saturation flow rate per lane width is a variable between 414 and 682 vehicles per hour of green per lane width unit.

Studies across the world identified width of approach, percentage right turning vehicles, vehicle composition, cycle time, green time, number of lanes etc., affect vehicular traffic flow characteristics at signalized intersections. There is a need to address capacity of signalized intersection in a heterogeneous mixed traffic flow condition and non-lane based driving behavior. In this present research work, an attempt is made to understand the effect of width of approach, cycle time, green time, volume, percentage right turning vehicles, percentage two wheelers, and percentage cars and percentage heavy vehicles on saturation flow rate at a signalized intersection in a mixed traffic flow condition on urban roads.

According to Indian Highway Capacity Manual (INDO HCM) saturation flow rate is defined as "the study state discharge rate of queued vehicles from an approach at a signalized intersection with continuous green and an infinite queue". In practice, it is measured as the maximum departure rate of queued vehicles from an approach during the green interval measured at the stop line under prevailing conditions. It is expressed in PCU/hour of green. In the present study INDO HCM is used to estimate saturation flow for comparison purpose.

3. Methods of estimating Saturation flow

Saturation flow is defined as the maximum constant departure rate during the green time, calculated in PCU/hr for heterogeneous traffic conditions. Saturation flow is the basic parameter affecting capacity and signal design, so it is important to measure saturation flow accurately. The following methods have been used in the present study for estimating saturation flow.

3.1 TRRL direct vehicle count method

The various methods were available to measure saturation flow. Among them, TRRL direct vehicle count method was selected for the present study. Because, the method is simple as it involves only the collection of classified volume count at regular interval period. Once the green interval commences, the queued vehicles will start clearing the intersection. Flow rate after the clearance of each vehicle is obtained by recording the time at which they crosses the stop line and the total number of vehicles crossed the stop line till that time. Scatter plots were drawn between flow rate and green interval for a number of cycles. The saturation flow rate is taken as the maximum study flow rate, obtained from each of the scatter plot. Saturation flow for a particular approach is finalized as the 98th percentile saturation flow and the same procedure was continued for all the approaches and it is expressed as PCU/hr. The flow rate obtained in vehicles/hr is converted into PCU/hr using IRC SP 41 PCU values.

Using TRRL direct vehicle count method, classified vehicle volume count is observed for every 3 sec time interval. The flow corresponding to a stable moving queue that crosses the stop line is taken as saturation flow. One saturation flow value is obtained for each cycle and 98th percentile saturation flow is taken as final saturation flow for that particular approach. The 98th percentile saturation flow approaches the capacity and there is only 2% chance to exceed this flow.

3.2 Indian Highway Capacity Manual method (INDO HCM):

In INDO HCM, an attempt has been made to correlate base saturation flow with geometric and traffic characteristics. It has been proved that there is a good correlation between unit base saturation flow and the width of approach. The unit base saturation flow is calculated using equation1 and saturation flow rate is calculated using the equation 2.

$$\mathrm{USF_0} = \begin{pmatrix} 630 & \text{for} & w < 7.0m \\ 1140 - 60w & \text{for} & 7.0 \le w \le 10.5m \\ 500 & \text{for} & w > 10.5m \end{pmatrix} \qquad (1)$$

Where, $\mathrm{USF_0}$ = unit base saturation flow rate (PCU/hour/m), w = effective width of approach (m)

The prevailing saturation flow rate of the intersection approach for the movement group under consideration is then obtained as presented in equation 2.

$$\mathrm{SF} = \mathrm{W} \times \mathrm{USF_0} \times f_{bb} \times f_{br} \times f_{is} \qquad (2)$$

Where, SF = Prevailing saturation flow rate in PCU/hour, W = effective width of the approach in m, $\mathrm{USF_0}$ = Unit base saturation flow rate, f_{bb} = adjustment factor for bus blockage due to curb side bus stop, f_{br} = adjustment factor for blockage of through vehicles by standing right turning vehicles waiting for their turn, f_{is} = adjustment factor for the initial surge of vehicles due to approach flare and anticipation effect.

The adjustment factors are computed using the following equations.

3.2.1 Adjustment factor for bus blockage

The adjustment for bus blockage results in the reduction in saturation flow due to the presence of bus stops within 75m of the intersection. The adjustment factor for saturation flow due to bus blockage is computed as shown in equation 3.

$$f_{bb} = \frac{w-3\left(\frac{t_b \times n_B}{3600}\right)}{W} \tag{3}$$

Where, w = approach width in m, t_b = average blockage time (s) during green, n_B = number of buses stopping in an hour (buses/hr), if there are more than 200 buses per hour, then should be limited to a practical value of 200.

3.2.2 Adjustment factor for blockage by standing right turning vehicles

This adjustment factor is applied when the through movement cannot use the full width of approach due to the presence of standing vehicles along the median lane waiting for their exclusive green phase. This adjustment factor is computed using the equation 4.

$$f_{br} = \frac{w-w_r}{w} \tag{4}$$

Where, w = approach width of the through movement, m, w_r = width of the approach in m along the median occupied by the standing vehicles waiting for the exclusive right turn phase, f_{br} =1, either exclusive right turning lanes are present or no right turning vehicles.

3.2.3Adjustment factor for the initial surge of vehicles

This adjustment factor is applied is applied when there is a flare effect or anticipation effect observed at the intersection. The factor is equal to 1 if the initial surge is not present. INDO HCM has given a formula to calculate the saturation flow based on three adjustment factors. In the present study saturation flow is also estimated using INDO HCM and a comparison study is done between estimated saturation flow and field observed saturation flow.

4. Study Area and Data Collection

Two signalized four legged intersections are selected for this study. Malaparamba intersection is located in Calicut city and Kakatiya University (KU) intersection is a located in Warangal city. Figure 1(a) shows line diagram of Malaparamba intersection and figure 1(b) shows line diagram of KU intersection.

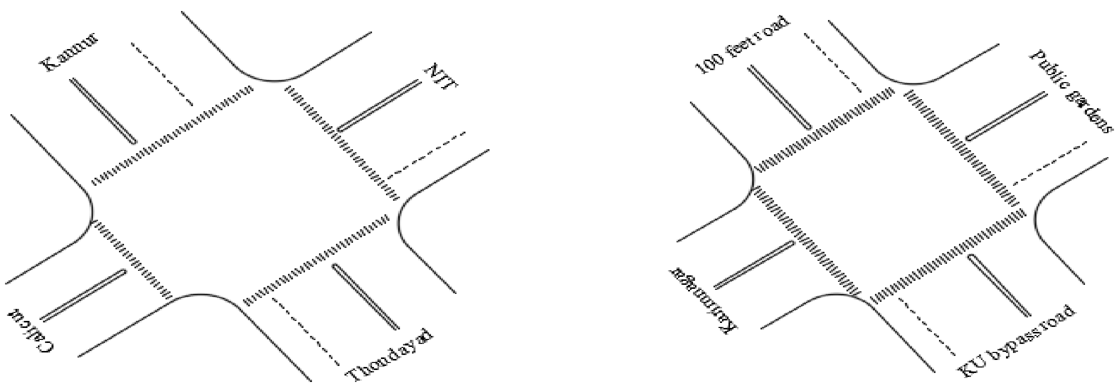

Figure 1(a) Malaparamba Intersection; (b) KU Intersection

Video graphic technique is used to collect the field data. Video recording is done by placing the camera at appropriate vantage point at the intersection so that all the four stop lines of intersection are visible. Roadway data that includes width of approach, number of lanes are collected manually from the site. Geometric and control details of Malaparamba and KU intersections are given in table 1.

Table 1 Geometric and control details of Malaparamba and KU intersection

Location	Name of the intersection	Approach name	Approach width (m)	Cycle time (sec)	Green time (sec)	Amber time (sec)
Calicut	Malaparamba	Kannur	5.6	180	32	3
		Thondayad	7		33	3
		Calicut	7.5		60	3
		NIT	7.2		43	3
Warangal	KU	karimnagar	7	150	45	3
		Public gardens	7.5		30	3
		KU Bypass road	9		45	3
		100ft road	7		30	3

5. Data Extraction:

From the playback videos, required data is extracted manually. Traffic volume and turning movement volume during saturated green intervals are extracted from the traffic videos for each cycle. Saturation flow was obtained from classified vehicle count and the time at which each vehicle is crossing the stop line. PCU values recommended by IRC SP 41 are used to convert the traffic flow from veh/hr into PCU/hr are given in the Table 2. IRC SP 41 is providing guidelines for the design of at grade intersections. IRC SP 41 page number 15, table number 3.1 defines PCU values for various vehicle types for at grade intersection design in mixed traffic conditions prevailing in rural and urban areas, India.

Table 2 IRC SP 41 PCU values

Type of vehicle	PCU
Passenger car, tempo, auto, van	1
Motor cycle, scooter	0.5
LCV	1.5
Truck, Bus, MCV	3
Truck trailer Unit	4.5

6. Field measurement of saturation flow

TRRL direct vehicle count method is used in the present study. The flow corresponding to stable moving queue that crosses the stop line is taken as saturation flow. It is clearly observed from the column chart, that for a particular approach itself the saturation flow values are varying from time to time. 98th percentile of all the saturation flow values observed during the study period is taken as final saturation flow of an approach. Figure 2(a) and figure 2(b) shows 98th percentile value for one approach of KU signalised intersection of Karimnagar approach. Figure 3(a) and 3(b) shows 98th percentile value for one approach of Malaparamba intersection of NIT approach

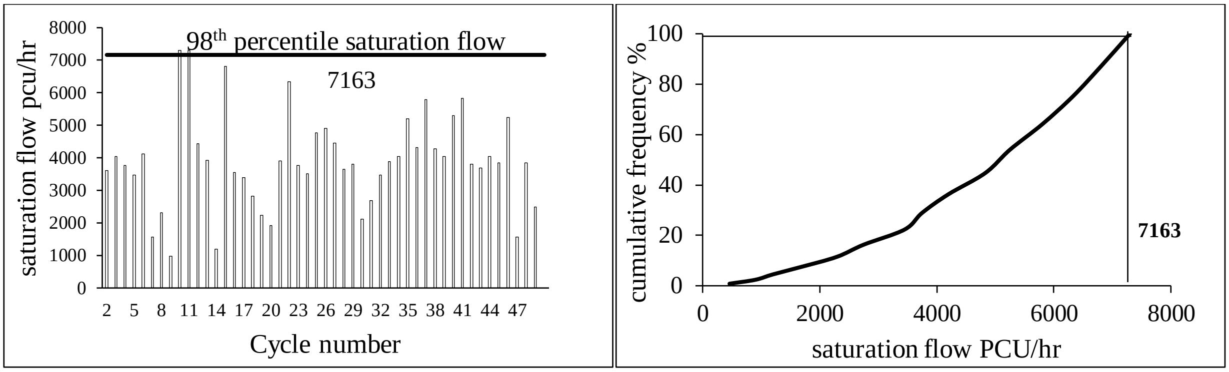

Figure 2(a) Variation of saturation flow from cycle to cycle; (b) cumulative percentage frequency

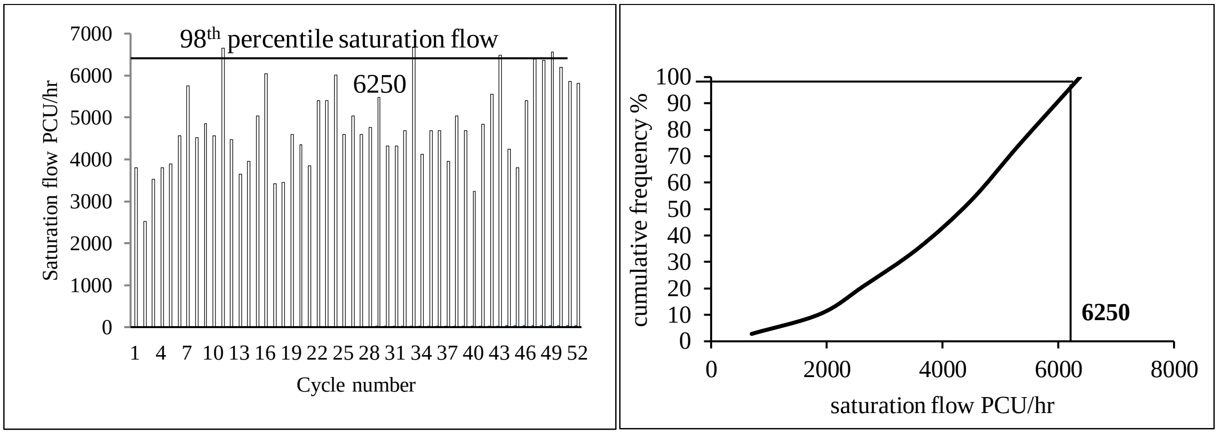

Figure 3(a) variation of saturation flow from cycle to cycle; (b) cumulative percentage frequency

7. Development of saturation flow model

In the present study, various factors like width of approach, green time, cycle time, volume of the approach, proportion of right turning vehicles, proportion of two wheelers, proportion of cars and proportion of heavy vehicles are considered for the purpose of modelling saturation flow at signalised intersections. Correlation is observed between saturation flow and green time, proportion of right turning vehicles and proportion of heavy vehicles with dependent variable saturation flow. The correlation coefficients obtained for significant variables are presented in table 3. The equation 5 shows the model obtained for the estimation of saturation flow.

R^2 value obtained for the model is 0.77, from the model it is clearly seen that saturation flow increases with increase in green time, decreases with increase in the proportion of right turning vehicles and decreases with increase in the proportion of heavy vehicles.

$$SF=(46.1\times G)-(17.05\times P_{RT})-(377.5\times P_{HV})+5815 \quad (5)$$

Table 3 Correlation matrix showing influencing variables

	SF	W	C	G	V	P_{RT}	P_{TW}	P_C	P_{HV}
SF	1								
W	-0.102	1							
C	0.199	-0.458	1						
G	0.493	0.397	0.229	1					
V	0.145	0.042	0.643	0.722	1				
P_{RT}	-0.307	0.124	-0.246	-0.645	-0.564	1			
P_{TW}	0.070	0.469	-0.927	-0.036	-0.584	0.191	1		
P_C	-0.115	-0.497	0.934	0.043	0.589	-0.246	-0.984	1	
P_{HV}	-0.704	0.200	0.197	0.033	0.449	-0.150	-0.320	0.405	1

Where, SF = saturation flow rate in PCU/hr, W= width of approach in meters, C= cycle time in seconds, G = green time in seconds, V= volume PCU/hr, P_{RT}= proportion of right turning vehicles, P_{TW}= proportion of two wheelers, P_C= proportion of cars and P_{HV}= proportion of heavy vehicles.

8. Comparison of saturation flow values

In this section, comparison is made between saturation flow rate estimated using INDO HCM and model developed in this research with that of observed field saturation flow rates for the two intersections, KU intersection and Malaparamba intersection. Table 4 shows comparison among field saturation flow values, model saturation flow values and saturation flow values obtained from INDO HCM.

Table 4 Comparison of saturation flow values

Location	Name of the intersection	Approach name	Observed field saturation flow PCU/hr	Saturation flow estimated using INDO HCM	Percentage Error between field and INDO HCM values	Saturation flow estimated using developed model	Percentage error between field and developed model values
Calicut	Malaparamba	Kannur	5530	3528	36.20	5038	8.89
		Thondayad	5640	5040	10.63	5604	0.63
		Calicut	8276	5175	37.47	7936	4.11
		NIT	6250	5098	18.43	6109	2.26
Warangal	KU	Karimnagar	6628	5040	23.96	6472	2.35
		Public gardens	7163	5175	27.75	7004	2.22
		KU Bypass road	5270	5400	-2.47	4882	7.36
		100ft road	5607	5040	10.11	5596	0.19

It is observed that the Indo HCM underestimated the saturation flow when compared with field saturation flow. There existed a maximum error of 37.47%. This is because, INDO HCM model is defined as a unanimous saturation estimation model irrespective of city size and land use characteristics prevail at the intersection. Considering medium sized cities, the present research work analysed and developed model to estimate signalized intersection saturation flow. When the estimated values of saturation flow are compared from the model developed and observed field saturation flow, there exists a maximum error of 8.89%. The present model estimated values are in a close range to the observed values. This is because, in medium size cities, land use characteristics are a mixed use type. It draws traffic from the connecting nearby rural roads unlike metro cities where traffic is from urban areas.

9. Conclusions

In this research work, the saturation flow of signalized intersections is analysed. For this study two cities Kozhikode and Warangal are considered. From the correlation analysis, green time, proportion of right turning vehicles and proportion of heavy commercial vehicles have been identified as influencing variables for saturation flow. INDO HCM defines a common saturation flow estimation model irrespective of city size, traffic and land use characteristics. Cities like Kozhikode and Warangal does not fall under metropolitan city categories and also the intersection characteristics vary as there is no provision for exclusive bus bays, right turning lanes and parking facilities. Hence these cities are to be exclusively identified and studied for the intersection improvement strategies. The developed linear regression model estimates saturation flow rates closely to the observed field saturation flows. This study helps in estimation of saturation flow for similar type of intersections and also can be used as input to the simulation and analyse the effect of various factors and variations.

This study has some limitations in which the approach width is not much varying in the two intersections. Hence there is a need to study the effect of width on similar type of intersections. In spite of these limitations, this study estimates saturation flow rate in a close range to observed field saturation flow rate values.

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