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FIELD SATURATION FLOW MEASUREMENT USING DYNAMIC PASSENGER CAR UNIT UNDER MIXED TRAFFIC CONDITION

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Abstract: Saturation flow is a very important input variable for the design of signalized intersections. Saturation flow measurement is well established for homogeneous traffic. However, saturation flow measurement and modeling is a challenging task in heterogeneous characterized by multiple vehicle types and non-lane based movement. Present study focuses on proposing a field procedure for Saturation flow measurement and the effect of typical mixed traffic behavior at the signal as far as non-lane based traffic movement is concerned. Data collected during peak and off-peak hour from five intersections with varying approach width is used for validating the saturation flow model. The insights from the study can be used for modeling saturation flow and delay at signalized intersection in heterogeneous traffic conditions.

Keywords: signalized intersection, saturation flow, passenger car unit, optimization.

1. Introduction

The saturation flow is defined as the maximum hourly rate at which vehicle can pass a stop line during the green phase. This maximum flow rate is present only a short duration after the start of the green phase and is assumed to continue until the queued vehicles have discharged. In the beginning of the green phase the drivers need time to react and to accelerate. That transitional phase is not effectively used to serve the traffic. At the end of the green phase the traffic flow can still continue during the first seconds of the yellow phase, giving an extension of the effective time that a flow has access to the intersection. The saturation flow occurs between these. Although this concept is simple, however, due to large spatial and temporal variation in traffic, considerable research has taken place in the saturation flow measurement and subsequent modeling. As per HCM 2010, first four vehicles are ignored from saturation flow considering the startup lost time and the saturation flow is measured till the last vehicle joined the Queue during the red time is cleared. The Highway Capacity Manual (Highway Capacity Manual, 2010) has defined a base saturation flow, which should be adjusted to the prevailing conditions using several multiplicative factors. However, the traffic in several cities across the globe is heterogeneous, characterized by the existence of the mixed vehicle type and non-lane based movement. Such traffic has certain peculiar behaviors that are not observed in homogenous traffic where most of the vehicles have more or less same characteristics and follows good lane discipline. Typical traffic

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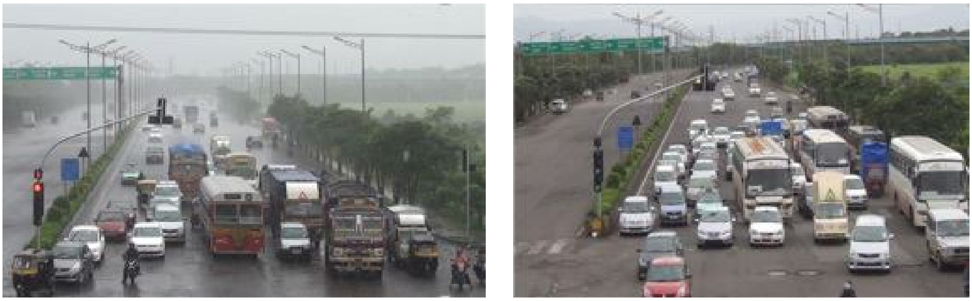
movement in a heterogeneous traffic is shown in Fig. 1. One of the important characteristic affecting the saturation flow modeling is the dense packing of the front of the queue. The vehicles have a tendency to occupy the front position ignoring the lane discipline. This is also facilitated by small-sized vehicles which can occupy the gap between the large vehicles. Such small vehicles normally sneak through the traffic and come to the front line. When the signal turns green, all these vehicles discharge immediately.



(a) **(b)**

Fig. 1.
Snapshots of Typical Approach for Signalized Intersection (One Could Observed Dense Packing of Vehicle in the Front and High Proportion of Non-Standard Vehicles in the Steam)

1.1. Saturation Flow Measurement

There are basically two popular methods for measuring field saturation flow: HCM method TRL method The former is based on the concept of saturation period which is the time taken to cross the intersection by the last vehicle which has joined the queue just before the red turns into green and the number of vehicles passed during that time gives the saturation flow. This method assumes the existence of saturation headways and is suitable only if the traffic has good lane discipline. On the other hand, the latter is based the number of vehicle discharge in short time slices, a graphical plot of the discharge over green time, and the steady rate at which vehicles are discharging gives the saturation flow. Although, this method is more suitable for heterogeneous traffic, the steady discharge rate is not conspicuous due to random arrival of diverse vehicle-types.

1.2. Passenger Car Unit

Passenger Car Unit (PCU) or Passenger Car Equivalent (PCE) is a metric used to assess traffic parameters in a heterogeneous traffic. It is a measure of the impact a particular mode of transport on traffic variables (such as flow, speed, density, etc.) compared to a standard passenger car. Various methods have been proposed for the computation of PCU. Regression methods have been used by many researchers. A significant study carried out by (Branston and Zuylen, 1978; Branston and Gipps, 1981) showcased the use of traditional regression method by dividing into two categories based on counting methods as synchronous and asynchronous. (Partha *et al.,* 2009) computed PCU at a saturated intersection of Dhaka city (in Bangladesh) by headway ratio method. (Hadiuzzaman and Rahman, 2010) used the multiple linear regressions between saturated green time and the no. of vehicle of each category type. The ratio of their coefficients in the regression equation represents the PCU vehicle type. It can be concluded that (i) delay based PCU estimation is best applicable for heavy vehicles since the additional delays as for rest of the vehicle types is insignificant; (ii) Headway based PCU is not suitable for non-lane following traffic stream; and (iii) Coefficient method are very sensitive to traffic composition.

1.3. Saturation Flow Models

Wide variation in traffic flow results in computational difference in measurement of saturation flow. (Rahman *et al.,* 2005) described the comparative analysis of saturation flow in Yokohama and Dhaka city by using conventional headway method. They assumed that saturation flow starts after fourth queued up vehicle by using ANOVA test for saturation flow region. (Susilo and Solihin, 2011) used regression model for their analysis. They considered Indonesia HCM as their reference model. The model proposed by them is shown in Eq. (1):

$$S = 500W_e + 400 \tag{1}$$

where: We is the approach lane width. Indian Road Congress (IRC) use the model proposed by (Webster and Cobbe, 1966). Suitable adjustment factors are provided to account for the effect of left turns and right turns as shown in Eq. (2):

$$S = 525W_e \tag{2}$$

(Liang *et al.,* 2011) proposed a capacity model which is based on first discharge headway method rather using HCM model for finding capacity. (Zhang and Chen, 2009) used the HCM model but did some modification to get the saturation flow. In their formulation, only heavy vehicle adjustment factor was introduced. (Shao *et al.,* 2011) used method of least square. Three categories of vehicle and nine types of headways were considered with the possible combination followed by linearly regressed saturation flow model. (Shao and Liu, 2012) studied stochastic nature of queue discharge headways. In their study, Distribution characteristics of headways were not considered and there was no consistency between both distributions applied to the headways (at 95% significance level). Alam *et al.,* 2011) used the HCM method for finding out saturation flow in Makah but introduced some adjustment factors to get accuracy in the result. (Kockelman and Shabih, 2000) improvised the heavy vehicle adjustment factor by introducing new factor for light duty trucks. Most of these studies could produce a reasonable representation of heterogeneity. (Anusha *et al.,* 2013) did extensive study on adjustment factor for saturation flow measurement. They proposed a two wheeler adjustment factor as the population of two wheeler contributes significantly in the traffic mix. The empirical equation (Eq. 3) proposed by them for the calculation of adjustment factor is given below:

$$f_{tw} = 0.378 - 0.8P_{tw} + 0.004 * \frac{vol}{w} \tag{3}$$

where: P_{tw} is the percentage of two wheeler, vol is the volume of traffic and w is the width of road. In their study, saturation flow rate has been considered in veh/hr which is untrue in case of Indian traffic.

(Radhakrishnan and Mathew, 2011) used an optimization model for getting dynamic PCU value and the model was developed using multiple linear egression. Independent variables were taken as the percent composition of vehicle type. The proposed saturation flow model was (Eq. 4):

$$S = 25.99P_{cr} + 60.11P_{tw} + 18.25P_{auto} + 14.82P_{car} \quad (4)$$

where S is the saturation flow in vehicles/3.6 m/hour of green, P_{cr}, P_{tw}, P_{auto} and P_{car} are percentages of cycle rickshaw, two-wheeler, auto-rickshaw and car, respectively. For the research methodology, the base saturation flow was considered as 1900pcu/hr which might not be true always when it comes to heterogeneous traffic. In most of the studies, it has been assumed that Saturation flow starts from the fourth queued up vehicle which might not be true in case of heterogeneous traffic. In the rest of the section, an attempt is made to develop an accurate procedure for the field estimation of saturation flow, passenger car equivalent, and saturation flow models considering proportion of various types of vehicles. First, data collection and analysis is presented below.

2. Data Collection and Extraction

Video graphic data was collected in both peak and off-peak hour from four intersections in Mumbai city. The characteristics of these intersections are shown in Table 1, which indicate some reasonable diversity in the intersection characteristics.

Table 1

Geometric and Control Characteristics of Intersection Approaches Considered

Sl. No	Intersection Name	Approach No.	Road Width (meter)	Cycle Length (Sec)	Green Time (Sec)	Red Time (Sec)	No. of lanes
1	Belapur Chowk	1	8.0	110	65	42	2
		2	7.5	110	45	62	2
		3	11.5	110	65	42	3
		4	9.0	110	40	67	2
2	Keshab Chowk	5	8.1	102	15	85	2
		6	8.5	102	25	75	2
		7	11.0	102	20	80	3
3	Hiranadani Chowk	8	12.0	135	65	67	3
		9	13.5	135	25	107	4
		10	19.5	135	86	46	6
4	Maharana Chowk	11	9.3	88	61	25	2
		12	8.5	88	16	70	2
5	Tagore Chowk	13	19.5	135	50	82	5

Classified flow (discharge) at the stop-line is measured by dividing the entire green interval into 5 second time slice. Discharge profile of each type of vehicle (car, motorbike, three-wheeled auto rickshaw, and heavy vehicle) discharging from a typical approach during the green time in each cycle and the average (solid line indicates the average value) is plotted in Fig. 2. It can be seen clearly that the discharge in the first interval is consistently high for the all the vehicle types. Further, there is significant fluctuation in the number of each vehicle-type discharged in these cycles. This fluctuation is due to random arrival of each vehicle type and their mutual interactions. This is also corroborated by the plot of all the vehicles (Fig. 2(e)). The average vehicle behaviour shown in Fig. 2(f) indicates there is some saturation period. These behaviours make measurement and modelling of saturation flow challenging under such traffic conditions.

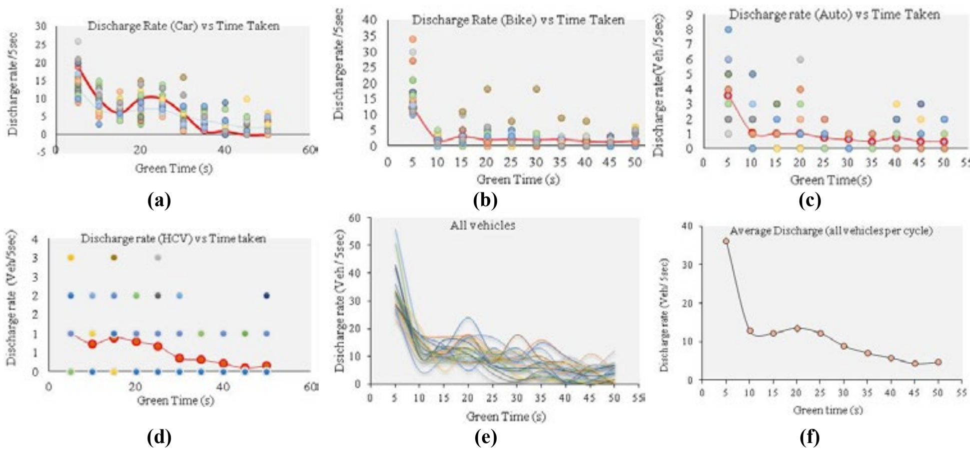
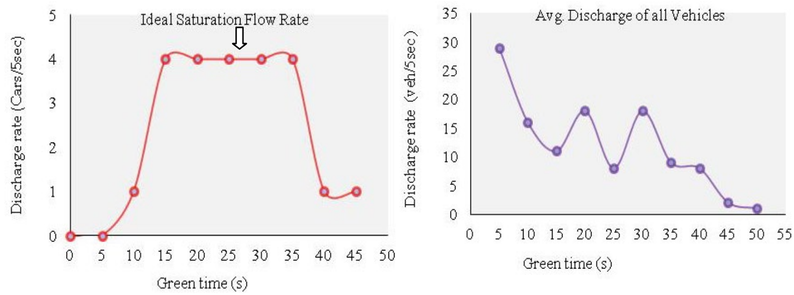


Fig. 2.
Discharge Profile of Each Type of Vehicles (a. Car, b. Motorbike, c. Three-Wheeled Auto Rickshaw, and d. Heavy Vehicle) Discharging from a Typical Approach (No 13) During the Green Time in Each Cycle (Solid Line Indicates the Average Value). Sum of all Vehicles for Several Cycle (e) and Average per Cycle (f).

It is also interesting to compare the discharge pattern of heterogeneous traffic (currently studying) and a lane based homogeneous traffic (an intersection video data taken from West Lafayette, Indiana in United States). The discharge profile from a typical cycle of homogeneous and heterogeneous traffic is show in Fig. 3a and Fig. 3b respectively. It is clear from Fig. 3(a) that the discharge profile follows an expected pattern of an initial start-up lost time and a saturated flow region till the queue is cleared. However, the discharge profile of the heterogeneous traffic under study (Fig. 3b) has a behaviour not normally expected. The basic hypothesis of this study is the existence of saturated region, but obscured due to multiple vehicle type. Hence, if the effects of diverse vehicle types are properly represented by passenger car units, then, saturated region could be established. In other words, there exist some passenger car units for each vehicle types, if accounted in the total number of vehicles discharged, will give a clear saturated region. The methodology proposed in the following section is an attempt to compute passenger car unit that will simultaneously give passenger car units and saturated flow.



(a) (b)

Fig. 3.
Comparison of Discharge Profile From a Typical Cycle from (a) Homogeneous Traffic Comprising of Passenger Cars Only and (b) Heterogeneous Traffic Consisting of Several Types of Vehicles

3. Methodology for Saturation Flow

A methodology for field saturation flow measurement in mixed traffic condition at signalized intersections based on the microscopic traffic aspects is proposed here and shown in Fig. 4 below. The detail methodology includes the measurement of vehicle discharge during green time, development of PCUs using optimization technique, development of saturation flow model and validation using field data as well as from delay analysis. The overall methodology for present study is explained below in the form of flow chart. Because of high discharge in first 5 second, it is assumed that saturation period starts from second interval onwards and higher discharge rate in the first interval is accounted by a multiplicative adjustment factor.

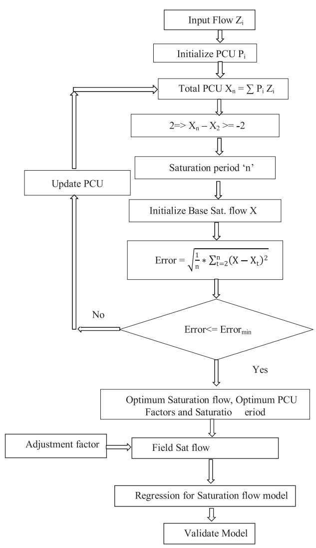


Fig. 4.
Methodology for Field Saturation Flow Measurement

3.1. Formulation

The optimization technique discussed here attempts to minimize the difference between the flat portion of an ideal saturation curve and the observed flow value curve. The proposed formulation is as below, (Eq. (5)):

$$\text{Minimize } Z = \sqrt{\frac{1}{n}} * \sum_{i=2}^{n} \sum_{j=1}^{m} (x - y_i^j p^j)^2$$

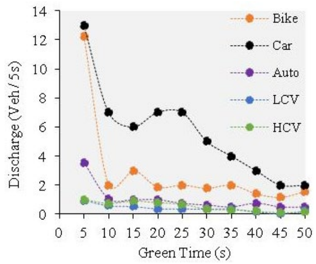
$$\text{Subject to } p_{\min}^j \le p^j \le p_{\max}^j \tag{5}$$

where: n is the saturation period expressed in terms of number of time intervals, p^j is the passenger car equivalent of vehicle type j, m is the number of vehicle types in the stream, y is the number of vehicle of type j discharged in the j^{th} interval, and x is the base saturation flow. The formulation essentially computes a passenger car equivalent which provides a constant saturated period. As stated earlier, the assumption behind this formulation is the effect of vehicle type is the one that is not able to produce a constant saturated region (ref. Fig. 2e and Fig. 2f). The objective function minimizes the error between the unknown saturated flow and actual flow observed in each interval. The decision variables of this problem include passenger car equivalent of each vehicle type (p^j), saturated region (n), and the base saturation flow (x). It is assumed that saturation flow starts from second interval onwards because of very high discharge in the first 5 second. The constraints simply stipulate a search bound by specifying minimum and maximum possible values of passenger car equivalents. The implementation steps include:

- *Step 1:* Determination of classified vehicle flow in each 5sec interval during green;
- *Step 2:* Initialization of passenger car units (p^j) within minimum and maximum limits;
- *Step 3:* Initialization of the base saturation flow (flow in the 2nd interval computed using current passenger car units);
- *Step 4:* Computation of flow in each interval using current passenger car units;
- *Step 5:* Computation of the error which is the difference between the base saturation flow and flows up to nth interval;
- *Step 6:* Minimize this error using any solver to get optimum p^j, x and n;
- *Step 7:* Multiplication of adjustment factor to base saturation flow (x) to get actual saturation flow.

4. Data Analysis

The vehicle type discharge profile from a typical approach observed in 42 cycles is shown in Fig. 5a. The discharge from the first interval is ignored for the moment as it has very high flow compared to rest. As stated earlier, the objective here is to find a straight flow regime which is obtained by multiplying the each vehicle type flow by the respective passenger car unit. Results obtained after implementing the optimization algorithm is given in Fig. 5b. The discharge without considering the optimization (purple colour) and with the proposed passenger car unit (red colour) is shown in the figure. Further, the green line indicates the base saturation flow and saturation period obtained also by the above algorithm. It can be seen that proposed algorithm is able to provide some rationality to the saturation flow estimation.



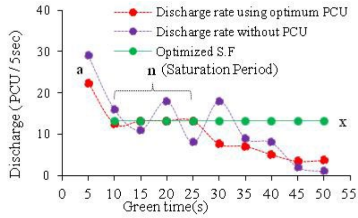


Fig. 5.
Discharge of Vehicles (a) Disaggregate Vehicle Discharge; (b) Saturation Discharge

Since the flow in the first interval was ignored in this computation, an adjustment factor needs to be arrived at to account for the large flow in the first interval. A multiplicative adjustment factor (AF) as given below is proposed (Eq. (6)):

$$AF = \frac{a + nx}{x(n+1)} \tag{6}$$

where: *a* is the peak discharge obtained in the first interval using the optimized passenger car units, ***x*** is the Base Saturation flow and ***n*** is the saturation period, both obtained by the optimization model. The final saturation flow to be adopted is computed as Eq. (7):

$$\text{Field Saturation flow} = \frac{3600 * x * AF}{5\,\text{sec}}\ pcphpl \tag{7}$$

The passenger car unit and saturation flow values obtained from various approaches is show in Table 2 below. It can be observed that the passenger car unit is highly influenced by the vehicle composition which is expected.

This also explains the variation in the wide variation in the saturation flow estimate. In order to get saturation flow for design purposes, one should have some model which relates the saturation flow with vehicle composition. The next section is an attempt towards this.

Table 2
Passenger Car Unit and Saturation Flow Obtained From the Field Data

Approach No.	Passenger Car Unit (% Composition)					Saturation Flow (PCU/hr/lane)
	Car	Bike	Auto	LCV	HCV	
1	1.00 (57.8)	0.2 (27.0)	0.52 (8.2)	1.8 (5.0)	1.4 (2.1)	2612
2	1.00 (25.6)	0.8 (23.8)	0.68 (2.7)	0.6 (4.0)	1.4 (43.9)	2009
3	1.00 (62.2)	0.2 (28.39)	0.4 (3.32)	0.6 (5.08)	3.16 (1.02)	2652
4	1.00 (28.4)	0.3 (29.9)	0.4 (4.5)	0.6 (5.7)	1.2 (31.4)	1160
5	1.00 (22.0)	0.2 (35.80)	0.4 (33.0)	0.82 (4.0)	1.8 (6.0)	1567
6	1.00 (32.9)	0.8 (25.8)	0.95 (32.1)	0.4 (5.2)	3.0 (4.1)	1664
7	1.00 (21.8)	0.66 (35.4)	0.78 (34.2)	0.4 (3.1)	2.83 (5.5)	2120
8	1.00 (45.0)	0.5 (17.0)	0.7 (29.0)	1.8 (4.0)	3.5 (5.0)	1861
9	1.00 (40.3)	0.12 (20.9)	0.2 (18.7)	0.5 (7.7)	2.26 (12.3)	1817
10	1.00 (43.9)	0.7 (23.8)	0.5 (16.0)	1.8 (5.8)	1.4 (10.4)	2085
11	1.00 (37.8)	0.8 (20.0)	0.69 (36.0)	1.8 (3.7)	1.4 (2.5)	1982
12	1.00 (43.5)	0.7 (32.4)	0.63 (19.6)	1.7 (2.8)	2.1 (1.7)	2121
13	1.00 (56.4)	(0.4) (28.1)	0.31 (8.8)	0.5 (3.2)	6.49 (3.5)	2168

Note: LCV- Light Commercial Vehicle, HCV-Heavy Commercial Vehicle

4.1. Saturation Flow Model

A simple linear regression model is proposed relating the saturation flow to vehicle proportion as the independent variable. The general form of this model is shown below, Eq. (8):

$$S = \sum_{i=1}^{m} a_i \, p_i \tag{8}$$

where: S is the saturation flow rate in PCU per hour per lane, a is the coefficients of different vehicle types and p is the proportion of vehicles and m is the total no of vehicle types.

4.2. Model Validation

In this study, using the optimized PCUs, the discharge during each 5 second slice is converted to PCUs. PCU factors are found out for all thirteen approaches and to get the actual saturation flow, same factors are used. In the model development, T-Statistics for LCV Population was found out to negative but P-value was significant. Hence by taking into consideration both the values, LCV Population can't be ignored from the modelling approach. For model calibration, out of 13 study approaches, seven approaches are used and the remaining approaches are used for the validation using field data. The saturation flow predicted by this model is in PCU per hour, per Lane. The model is shown in Eq. (9).

$$S = 72.01P_{Car} + 12.43P_{Bike} + 37.1P_{Auto} - \\ - 456.91P_{LCV} + 36.77P_{HCV} \tag{9}$$

The model statistics obtained from linear regression analysis is shown in Table 3. Though Auto and HCV are having low t-stat value still it is considered because of considerable contribution to the vehicle composition. For the validation of the proposed model, six approaches are taken in different intersections having different discharge pattern with variant traffic mix. The result obtained is show in Fig. 6.

Table 3

Regression Model Statistics

Linear regression Model	$Y = 72.01P_{Car}+12.43P_{Bike}+37.1P_{Auto}-456.91P_{LCV}+36.77P_{HCV}$
R-Square	0.99
Adjusted R-Square Value	0.51
T-Stat Value	P_{car} = 19.24, P_{bike} = 2.1, P_{auto} = 8.67, P_{LCV} = -12.19, P_{HCV} = 11.02
P-Value	P_{car} = 0.0027, P_{bike} = 0.17, P_{auto} = 0.013, P_{LCV} = 0.006, P_{HCV} = 0.008
Standard Error	69.43
No. of Approach	7

Note: P_{car}, P_{bike}, P_{auto} and P_{HCV} are proportion of Car, Bike, Auto-rickshaw and HCV respectively

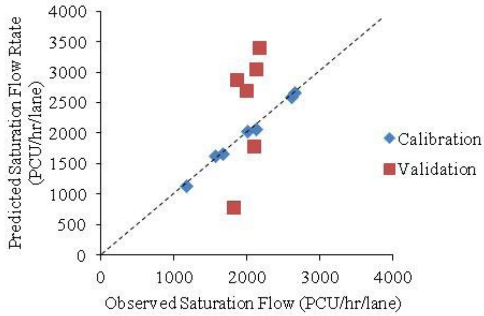


Fig. 6.
Calibration and Validation of Model

4.3. Discussion of Results

After calibrating the proposed model using seven study approach, it was observed that adjusted R^2 value was found out to be low at 0.51. But keeping into consideration only limited approaches were taken into consideration, the model shows satisfactory results with standard error as low as 69.43. Moreover the model accuracy can be improved by collecting enough samples from various intersections. This shows that model can estimate saturation flow with reasonable accuracy and hence can be used for further applications. A comparison of this saturation flow with the previous saturation flow studies reported by (Turner and Harahap, 1993) is shown in Table 4. From the table it can be seen that even in same country, there is a wide variation in saturation flow. This could be due to the nature of traffic, the geometric and the control factors and the methodology adopted for the study. It may be noted that the saturation flows shown in this table are only representative and these values will vary with location and time, however, the same methodology can be adopted.

Table 4
Comparison of Present Study with Previous Saturation Flow Studies

Study	Country	Mean Saturation Flow (PCU/hr/lane)
Webster and Cobbe (1966)	UK	1800
Kimber et al. (1986)	UK	2080
Branston (1979)	UK	1778
Miller (1968)	Australia	1710
Highway Engineering Laboratory (1990)	Athens, Greece	1972
Huzayyin and Shoury (1986)	Egypt	1617
De Andrade (1998)	Brazil	1660
Bhattacharya (1982)	India	1232
Present study	*India (Mumbai)*	*1986*

5. Conclusion

In this study, a procedure for the measurement of saturation flow under mixed traffic condition at signalized intersection is proposed. First, collected data from several intersections was analyzed to understand various modelling issues. The most crucial aspect is the existence of high discharge rate at the beginning of the green interval, especially happened due to zero start-up lost time which was analyzed in this study and found out to be important parameter in saturation flow modelling. In additions, well defined saturation period also was dubious due the presence of mixed vehicle types. Then, an optimization based approach is developed which gives saturation period, dynamic passenger car units, and Saturation flow values. The main contribution of this study is the development of this field procedure suitable for heterogeneous traffic condition. Moreover, a saturation flow model incorporating the proportion of the vehicle type in the traffic stream is proposed. Linear regression model is chosen to model the flow as the flow depends directly on variability in traffic composition. In the study it was found that vehicle composition has a large role to play in saturation flow as in case of heterogeneous traffic, traffic does not move smoothly rather the movement is haphazard and mostly occurs because of non-lane based movement by different drivers, but more importantly it is the two wheelers which plays a pivot role as they sneak through the traffic and always try to stay ahead of fleet causing the discharge rate erroneous. As it has been shown, discharge rate under mixed traffic condition is abnormally high contradicting the conventional traffic flow theory because of two wheeler traffic movement in the first 5sec interval under mixed traffic condition at signalized intersection.

Scope of this study is limited by ignoring side friction and turning movements due to time constraint and complex analysis. The study could be extended to arrive at various adjustment factors for geometric, traffic, and control conditions affecting the saturation flow. Intersection size is limited to five, hence the study can be extended for more intersections. As delay modeling deals with the vehicle arrival rate and arte at which the fleet disperse, it will be high importance to measure saturation flow correctly from the field by understanding their variability in vehicle composition as well as their driver behavior.

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