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Saturation Flow Model at Signalized Intersection for Non-lane Based Traffic

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Abstract

The important parameters in the planning, design and control of a signalized intersection are saturation flows, lost times and passenger car units (PCU). These factors have been traditionally measured in most western countries based on the research carried on test tracks and on public roads where traffic is typically car-dominated with vehicles moving in clearly defined lanes. However, the traffic movement in Bangladesh and in other developing countries is rendered more complex due to the heterogeneous characteristics of the traffic stream using the same right of way. Another striking feature of the road traffic operating condition in developing countries is that, despite having lane markings, most of the time lane discipline is not followed no matter whether non motorized vehicle is present or not. At intersections, there is notable lateral movement and vehicles tend to use lateral gaps to reach the head of the queue. Due to fundamental differences in traffic characteristics, the standard western relationships for predicting the values of saturation flows, lost time, and PCU factors are not appropriate for developing countries. This paper first reviews principle methods of measurement of saturation flow and the selection of a proper method to measure this parameter for the traffic condition prevailing in developing countries. The research establishes that a unified PCU concept is not true for non-lane based traffic conditions and proposes a PCU and flow model for estimating the capacity of signalized intersection having no lane discipline.

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1.0 Introduction

Saturation flow is a very important road traffic performance measure of the maximum rate of flow and is used extensively in intersection design and control applications. The methods used to determine this performance measure have been developed in the industrialized countries. However, traffic conditions in the developing countries are often different. The difference arises from the influence of the following factors:

> **Vehicle mix** - a multitude of different types of vehicles, both motorized and non-motorized, with different operating performances;
> **Driver behavior** - poor lane discipline and observance of traffic rules;
> **Public transport** - varied mix of bus types, stopping places and driving styles;
> **Roadside activity** - roadside land-use generating parking and non-transport activities which reduce effective road width.

Due to these fundamental differences, the standard western relationships for predicting the values of saturation flows, lost time, and PCU factors are not appropriate for developing countries. For correct signal design these parameters should be estimated based on the local prevailing traffic conditions and hence require a different approach to the analysis.

2.0 Saturation Flow

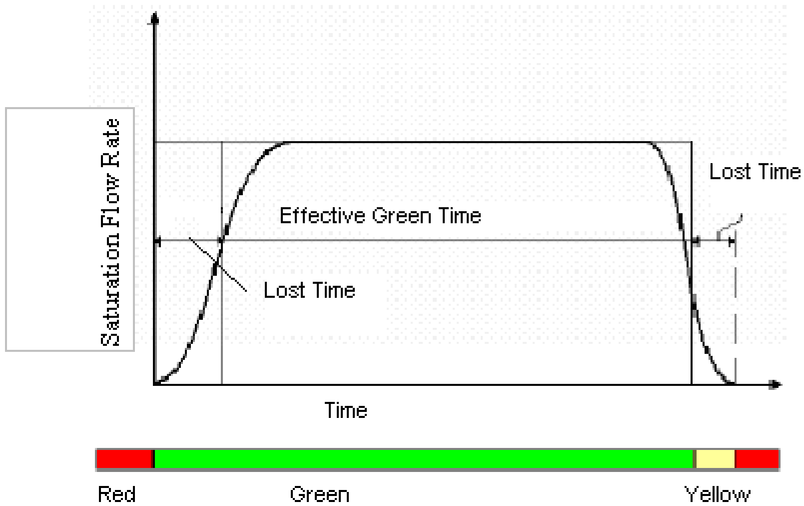
2.1 Concept

Saturation flow is a macro performance measure of intersection operation. It is an indication of the potential capacity of an intersection when operating under 'ideal' conditions.

An idealized view of saturation flow at a signalized intersection is illustrated in Figure 1. As the traffic signal aspect shows green, there is first a very short gap as the first driver reacts to the change. The rate of vehicles crossing the stop line then rises at an increasing rate, as vehicles accelerate to the speed determined by the cars they are following. Vehicles soon reach a state where they are following one another across the stop line at a constant gap or headway. This constant rate is represented by the plateau of this flow profile. In a saturated intersection, the queue formed when the lights were at red will be too long to clear in the green period and so cars will be following each other at constant spacing during the green period. The flow rate will only drop as the lights show an amber aspect. Here the rate will decrease at an increasing rate as initially vehicles carry on through the stop line on amber and then stop as the signals show red. The saturation flow is calculated by making the curved profile into a rectangle from which the dimensions can be measured. This is achieved by introducing the idea of lost time and effective green time. The lost time is the time from the start of green to a point where vehicles are flowing at half the maximum flow plus the time from where vehicles are flowing at half the maximum flow at the end of saturation to the beginning of the red period.

To compare flows from different sites with different traffic composition, saturation flows are expressed not in vehicles but in generic units called Passenger Car Units (PCU). These units are an indicator of the space different vehicle types occupy, expressed relative to that of a passenger car.

Figure 1
The flow of traffic during the green period from a saturated approach



2.2 Methods of Measurement
There are three principle methods available for the calculation of saturation flows:

The Road Note 34 Method (1963)

The procedure used in this method consists of taking classified counts of vehicles crossing the stop line, within the approach width, in six second intervals during the green and amber period of the cycle under saturated flow condition (Williams *et al*., 1987). An average number of 30 cycles is recommended to be used for each approach.

The Average Headway Method

This is the most commonly used alternative to the counting method. Based on Scraggs (1964), this method requires data on time headway between vehicles as they cross the stop line. Time headway of a vehicle is measured as the time between the crossing of the stop line by the rear bumper of the vehicle preceding it, and its own rear bumper.

Multiple Liner Regression Methods

In recent years a number of alternative methods of processing the data collected in classified vehicle counts format have been developed, in an attempt to obtain simultaneous estimations of all properties of the discharge process. These methods involved a multiple linear regression technique, which has been used by a number of researchers (Branston *et al*., 1978, 1981; Holroyd 1963). By the use of extensive statistical manipulation, Branston *et al*. (1978) introduced two methods known as 'asynchronous' and 'synchronous' multiple regressions based on the counting method. In the asynchronous multiple regression vehicle departures are recorded over time periods which begin and end at an arbitrary point of time. However, a number of researchers (Branston *et al*., 1978, 1981; Martin *et al*., 1981) have used 'synchronous' regression for the calculation of saturation flows and lost times. In this method the number of vehicle departures of each class is recorded over time periods beginning and ending with the instant of departure of a vehicle (the first few second due to start up loss time being excluded). and the counting periods are defined as:

For both methods, the green period is divided into three time periods; the first period begins at the start of green, contiguously, the middle period covers the time when the departure period is constant and in saturated state, and the last period ends when the amber light shows. The end of the last counting period of fully saturated cycles is fixed at the change to the amber light, but the ends of either the first or middle may be chosen either:

i) as an arbitrary point of time, termed as in asynchronous counting or

ii) to correspond with the instant of departure of a specific vehicle, termed as synchronous counting.

2.3 Previous Studies

A number of studies have dealt with saturation flow at signalized intersection and most of them work for lane based traffic condition. Webster *et al*. (1958) made an extensive study of intersections in the London area and also in some larger cities, supplemented by controlled experiments at a laboratory test track. He developed a linear relationship between saturation flow and lane width for lane based traffic having no parked vehicles. Later on the first US Highway Capacity Manual (1965) provided a detailed guideline for signalized intersection capacity analyses and design. Branston (1977) investigated the variations of saturation flow for different times of a day and he suggested two linear relationships, one for the peak period and the other for the off peak period of traffic flow considering lane width as independent variable. Working on lane width varying from 3.0 - 4.3 meters, he observed that there is a variation of saturation flow with lane width for individual lanes although the values for nearside and offside lanes of two-lane approaches were not significantly different. However, in a full scale TRRL test track experiment for lane based traffic, Kimber *et al*. (1983) found no significant difference between nearside, central and offside lanes at multi-lane approaches. For approach widths ranging from 2.5 m to 12 m and lane width varying from 2.5 m to 4 m, they found that saturation flow per lane for lane based traffic increased non-linearly with lane width. They developed a two degree equation having an intercept term. In order to obtain saturation flow for the whole approach at the stop line they suggested using as many narrow lanes as possible. In Kimber *et al*.(1986), based on database from 64 sites throughout UK, they suggested a basic saturation flow of 2080 PCU/hr for a lane width of 3.25 m and an increase of 100 PCU/hr per meter width in excess of the standard width. They also found a reduction of 140 PCU/hr for the nearside lane. These values were obtained from the mean saturation flow over all sites where gradients were not found to affect flows.

In Australia, Leong (1968) investigated the effect of lane widths on saturation flow for lane based traffic condition. He applied headway ratio method to calculate saturation flow values. The majority of his lane widths were in the range 2.75 m to 3.5 m and he concluded that lane width had very little effect upon saturation flows. Results from subsequent investigations by the Australian Road Research Board confirmed his conclusion. Miller (1968), dealt with lane width instead of approach width and observed that the lane width in the range 2.0 to 4.8 meters had a small effect on saturation flow. Akcelik (1981), affirmed that there is no need for adjustment for saturation flow within a lane width range of 3.0 m to 3.7 m. In this range, he proposed a single saturation flow i.e. 1850 PCU/hr. For lane widths outside this range an adjustment factor is to be applied against the standard value with the value of the adjustment factor depends on lane width.

The first research on saturation flow for non-lane based traffic was performed by Sutomu (1992). He derived a model for saturation flow for Javanese cities in Indonesia. Later Turner *et al*. (1993) showed another model based on the data collected from the same cities. Both of those models relate the saturation flow to the approach width. Maini and Khan (2000) conducted a study on clearing speeds of heterogeneous traffic at signalized intersections in two Indian cities. Findings of this study show that the intersection clearing speed is relatively constant for different vehicle types and has the potential to affect the method for determining PCU values. Given the findings of this study, platoon-clearing speed may be more relevant to estimating intersection capacity. Ibrahim *et al*. (2002) carried out a study to determine the ideal saturation flow at signalized intersections for Malaysian road conditions. They adopted the method of measuring saturation flow published by the (then) Road Research Laboratory (1963). The averaged flow values were then regressed with lane widths to obtain a linear regression model. Later in 2003, Vien *et al*. carried out a study to determine the ideal saturation flow at signalized intersections for Malaysian road conditions. Kidwai and Tan (2004) studied about the effect of various traffic, highway geometrics and control parameters on urban intersection capacity in Malaysia.

All of the previous studies for both lane and non-lane based traffic scenarios focused mainly on the effect of approach width or sometimes lane width on saturation flow. Though several previous studies attempted to show the effect of road geometry or signal parameter separately but none of them devoted to correlate their influence on saturation flow concurrently.

3.0 Proposed Method of Measurement

As in developing countries when lack of lane discipline together with a wide range of vehicles of various sizes encourages drivers to occupy any position across the road width, it produces a disordered pattern of traffic both when queuing as well as when discharging. Consequently it makes the measurement too complicated to be approximated by a lane-by-lane approach. As a result, for the present study, measurement of saturation flow and PCU factors has been done based on total width of approach.

It has been found from a previous study (Hounsell, 1989) that the average headway method is the best for estimating saturation flows, lost times and PCU factors. The Road Note 34 also gives good prediction of saturation flows and lost times, even though it sometimes underestimates the lost times. But compared to these two methods the former one requires data in time headway format which is usually very difficult to collect, especially in non-lane based traffic condition where due to the lack of lane discipline, vehicles form a queue with no clear pattern and during subsequent discharge due to the penetration effect narrower vehicles occupy the front of the queue and discharge in a group. Although it is possible to record individual headways of vehicles crossing the stop line, nonetheless the headway method cannot be applied because the vehicles are not moving in a line and one vehicle may have more than one leader. Consequently, the headway ratio method cannot be applied for this study purpose. Because of the difficulties in measuring headways of vehicles in non-lane based traffic conditions and due to the fact that total approach width is adopted for analysis of saturation flows in the current study, the option of counting is more appropriate in this respect.

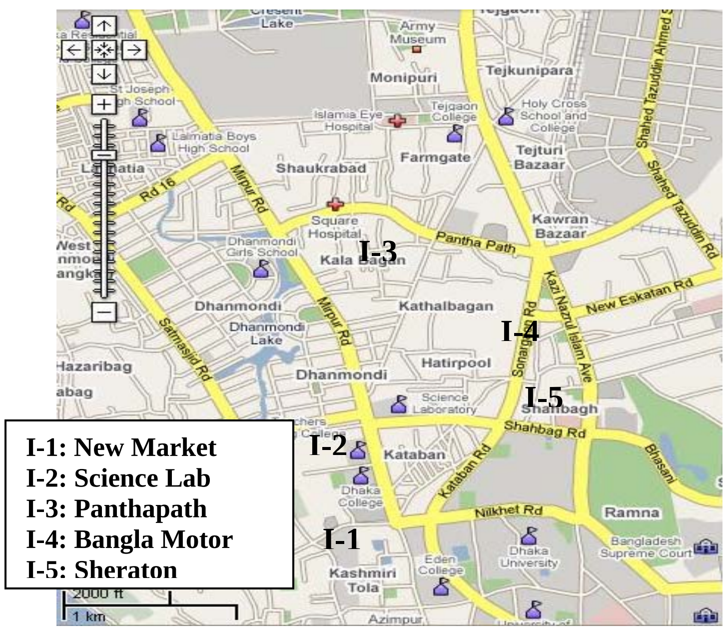
Although the Road Note 34 method requires data in simple classified vehicle count format, it does not allow one to calculate PCU values which are essential for saturation flow (in

PCU) measurement. Due to this limitation it is also not considered here as an alternative method. The option left is the regression method which gives saturation flow and PCU values simultaneously and is therefore attractive. However, investigation by Kimber *et al.* (1986) revealed that while the synchronous regression method produced a good approximation of PCU factors as well as saturation flow, corresponding values produced by the asynchronous multiple regression method underestimate the true factors from those of the headway ratio method. Hence, the synchronous counting method is more attractive in terms of data collection and analysis.

4.0 Study Area and Data Collection

For the present study five intersections have been selected in Dhaka city, which is shown in Figure 2. All signals are pre-timed signals. The intersections are selected considering the geometry of the intersection and availability of a high-rise building near the intersection. A description of the study intersection approach is presented in Table 1.

Figure 2
Map of Dhaka city showing study intersections



4.1 Data Collection

A video camera was used to collect data in the field. A video camera was mounted at the roof of the building located near the intersection and focused on the stop line. The recording was done for from 90 to 120 minutes during peak traffic conditions. Simultaneously data on signal timing (*i.e.* cycle length, number of phases, phase length) were collected manually using a stopwatch. The number of approaches was recorded. The width of approaches was measured using a measuring wheel.

Table 1

Description of study intersection approach

Intersection	Approach Width (m)	Cycle Time (Sec)	Green Time (Sec)	% of cars	% of Left turn traffic	% of Through traffic	% of Right turn traffic
New Market							
South approach	11.6	219	32	24	3	88	9
North approach	11.9	219	47	36	0	53	47
Bangla Motor							
South approach	9.2	135	100	29	0	100	0
North approach	10.6	135	100	31	0	100	0
Panthapath							
East approach	12.97	190	47	49	10	83	7
Science Lab							
North approach	6. 8	167	107	39	0	100	0
East approach	7.8	167	47	44	0	0	100
Sheraton							
East approach	12.7	158	68	35	0	0	100

5.0 Development of Passenger Car Unit (PCU)

In this study, PCU values were found using a synchronous regression method. Following this method, classified vehicle counts were started after 3 sec. of green initiation (start up lost time was found to be within 2-4 sec for the selected intersections that was measured using the ROAD NOTE 34 method). The saturated green time was regressed against the number of each category of vehicles crossing the stop line during the saturated green time, assuming a linear relationship between the variables. The vehicles were grouped into five categories: large bus, mini bus, car, auto rickshaw and motor cycle. The general form of equation is given in equation 1.

$$T = a_0 + a_1x_1 + a_2x_2 + a_3x_3 + a_4x_4 + a_5x_5 \quad (1)$$

where, T = saturated green time (sec),

a_0 = y-intercept,

a_1 = coefficient of car,

a_1, a_2, a_3, a_4, a_5 = coefficient for four types of vehicles: large bus, mini bus, auto rickshaw and motor cycle respectively,

x_1, x_2, x_3, x_4, x_5 = number of vehicles of each category in time T.

Table 2 represents the value of regression coefficient with statistical performance for five types of vehicle along with the y-intercept.

Table 2
Coefficients of Different Types of Vehicle from Synchronous Regression Analysis

Intersections	**Parameter**	a_o	a_1	a_2	a_3	a_4	a_5	R^2	**t-value (95%)**
Bangla Motor North	Coefficients	21.71	1.59	0.93	0.71	0.24	0.32	0.91	1.77
	t-value	2.85	1.57	2.04	2.22	1.08	0.70		
Bangla Motor South approach	Coefficient	23.46	1.17	0.86	0.37	0.27	0.11	0.86	1.77
	t-value	2.73	0.60	1.30	1.54	0.93	0.41		
New Market South	Coefficients	20.47	0.84	0.75	0.34	0.32	0.17	0.49	1.34
	t-value	3.56	1.24	1.68	0.85	0.60	0.22		
New Market North	Coefficients	15.39	1.83	0.91	0.78	0.28	0.36	0.82	1.78
	t-value	2.05	3.16	2.00	3.20	1.82	0.85		
Panthapath East approach	Coefficients	12.58	2.78	2.23	0.83	0.28	-0.88	0.99	1.90
	t-value	2.19	0.73	1.71	2.91	0.75	-1.23		
Science Lab North	Coefficients	13.28	2.97	1.99	1.15	0.25	1.03	0.82	1.70
	t-value	2.07	1.24	3.27	3.89	0.80	1.26		
Science Lab East approach	Coefficients	14.61	3.28	0.96	0.72	0.436	0.42	0.84	1.78
	t-value	1.41	2.34	0.31	1.81	0.62	0.61		
Sheraton Eastapproach	Coefficients	10.24	2.12	0.57	0.47	0.33	0.05	1.00	2.02
	t-value	2.05	1.04	1.54	3.52	5.15	0.12		

Following the synchronous regression method site-specific PCU values were obtained for each type of vehicle, which is shown in Table 3.

Passenger car unit of vehicle type $PCU_i = a_i / a_1$ (2)

Where, a_i= regression coefficient for a particular type of vehicle

From Table 3, it is clear that the PCU value for any type of vehicle is not constant for the different intersections. This supports the contention that the unified passenger car unit concept for different vehicles does not hold good for non-lane based traffic conditions. The PCU value for motor cycles at one intersection was found to be negative which may be explained as follows. As these vehicles are narrow and have high maneuverability, due to the lack of lane discipline they can easily avail themselves of any trapped gaps in the stream and come to the front of the queue by penetrating the standing queue using inter vehicular gaps. Moreover, as their initial acceleration rates are higher than any of the other types of vehicles they can discharge quickly when green starts. As a result they have no effect on saturated green time rather they increase the flow more than the capacity of the approach in terms of PCU. Hence, to adjust the flow a negative regression coefficient has been obtained from the regression analysis and consequently a negative PCU value has been measured.

Table 3

PCU values and regression statistics

Intersections	Parameters	Large Bus	Mini Bus	Car	Auto Rickshaw	Motor Cycle
Bangla Motor North Approach	PCU	2.252	1.313	1	0.338	0.453
	% Vehicle	2.273	6.993	43.794	40.253	6.687
Bangla Motor South Approach	PCU	3.135	2.311	1	0.727	0.421
	% Vehicle	2.429	13.046	40.319	38.931	5.274
New Market South Approach	PCU	2.454	2.188	1	0.922	0.493
	% Vehicle	12.195	30.488	32.622	19.207	5.488
New Market North Approach	PCU	2.362	1.169	1	0.365	0.461
	% Vehicle	5.819	11.792	56.662	20.980	4.747
Panthapath East Approach	PCU	3.346	2.682	1	0.34	-1.056
	% Vehicle	0.413	1.446	48.967	31.612	3.926
Science Lab North Approach	PCU	2.589	1.734	1	0.215	0.90
	% Vehicle	2.457	8.921	53.472	26.335	8.814
Science Lab East Approach	PCU	4.564	1.333	1	0.593	0.579
	% Vehicle	6.769	1.077	59.538	25.692	6.923
Sheraton East Approach	PCU	4.513	1.211	1	0.69	0.108
	% vehicle	6.60	10.80	48.136	46.515	5.348

Again, a close observation of the table shows that PCU value changes with the composition of vehicle. Lack of lanes to encourage lane discipline together with a wide range of vehicles of various sizes encourages drivers to occupy any position across the road width; it produces a disordered pattern of traffic both when queuing as well as when discharging. So, it is clear that road width is a parameter that has a strong influence on PCU values. To incorporate the effects of vehicle composition in the traffic stream and road width, the following models for different vehicle classes have been developed for non-lane based traffic:

PCU_{MC}= -9.293 + LB * 0.068 + MB * 0.105 + Car * 0.098 +AR * 0.082 + MC * 0.203 + W * -0.009; (R^2=0.992)

PCU_{AR}= 4.250 + LB * 0.033 + MB * 0.005 + Car * -0.008 +AR * 0.051 + MC * -0.353 + W * -0.290; (R^2=0.997)

PCU_{MB}= 20.141 + LB * -0.182 + MB *-0.063 + Car *-0.132 +AR *-0.011 + MC *-0.668 + W * -0.613; (R^2=0.889)

PCU_{LB}= 14.532 + LB * 0.078 + MB * -0.083 + Car * -0.028 +AR * 0.098 + MC * -0.852 + W * -0.741; (R^2=0.917) where, W is the approach width in meters and LB, MB, AR and MC stand for the percentage of large bus, mini bus, auto rickshaw and motorcycle in the traffic stream respectively.

6.0 Saturation Flow

6.1 Estimation of Saturation Flow (in PCU/hr)

Saturation flow is estimated in PCU/hr using the PCU values obtained at each intersection. The following conventional procedure is adopted to determine the saturation flow value for each approach. First, the saturated green time (T sec) is divided by the number of different categories of vehicles that have been converted into passenger car unit to get the headway time. The inverse of headway gives the saturation flow. Thus the saturation flow in PCU/hr is obtained as:

$$S = \frac{(PCU_{LB} * x_1 + PCU_{MB} * x_2 + PCU_C * x_3 + PCU_{AR} * x_4 + PCU_{MC} * x_5)}{T} \text{ X } 3600 \qquad (3)$$

6.2 Development of Saturation Flow Model

A study of the saturation flow of signalized intersections under non-lane based traffic would require a large database from the field over a range of traffic flow and geometric conditions. Such a large database from the relevant situation is not available. In the present study, field data have been collected at eight intersection approaches. Using this data, multiple regression analysis has been completed in order to estimate the saturation flow in passenger car units per hour. Out of the eight approaches two have not been considered for developing the models as those two approaches have right-turn traffic only. The independent variables used are listed in Table 4. Selection of these variables was largely on the basis of ease of collection and the experience of earlier studies.

Table 4

Independent Variables for Saturation Flow Model

Variable	Description
WIDTH (w)	Width of lane or approach at stop-line being surveyed
SIGSET	Length of signal green time for approach being surveyed.
L/TURN W	Width of junction exit for left-turning traffic.
R/TURN W	Width of junction exit for right-turning traffic.
STR-ON W	Width of junction exit for traffic traveling straight through.
%RT	Percentage of right turning vehicle

Two of the most statistically significant models are shown below (95% t-values in brackets):

Simple method (Width only):

Model 1: S= 2217 + 140 w R^2 =0.198 (4)

(8.21) (5.24)

Multi-variate model:

Model 2: S= - 1662 + 24 SIGSET + 337 w + 45.5 STR-ON-W – 3.61 %RT – 1662 (5)
(5.95) (13.79) (8.78) (1.00) (-1.78)
$R^2 = 0.998$

7.0 Comparison of Saturation Flow Model with the Previous Studies

In this section a comparison has been made between Model 1 and the previous models which were developed for non-lane based traffic condition. Equations 6 and 7 represent the regression equation for Javanese cities developed by Sutomo (1992) and Turner *et al*. (1993) respectively.

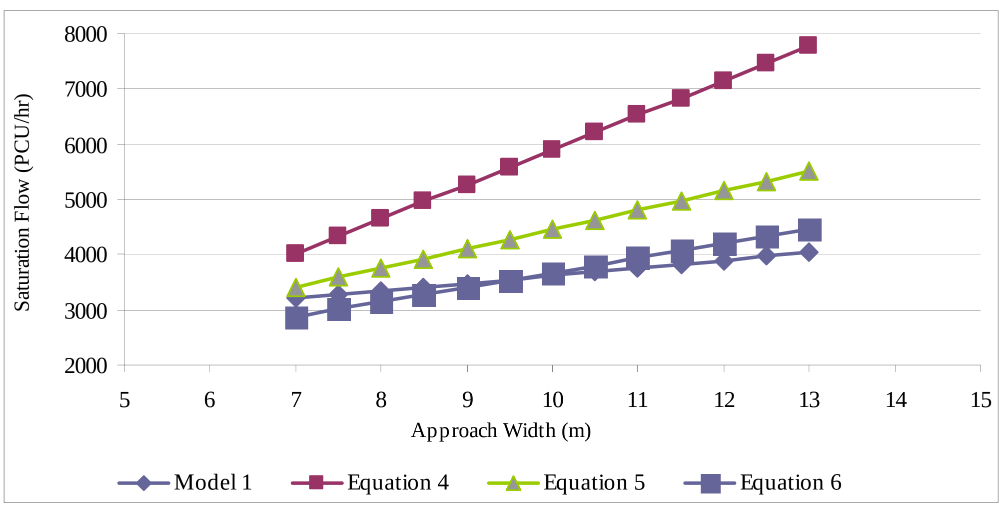
$$S= -376 + 627w \quad [6]$$
$$S= 964 + 349w \quad [7]$$

In their Malaysian study, Ibrahim *et al*. (2002) derived the following formula:

$$S = 1020 + 265w \quad [8]$$

The degree to which Model 1 compares with previous studies as stated earlier can be seen in Figure 4. From this figure, it can be seen that all the models predict higher saturation flow as a function of the approach width than the present model, though Equation 8 shows a close prediction of saturation flow up to an approach width of 10 meters. At the same time it is also clear that prediction of saturation flow does not depend only on approach width as considerable differences between saturation flow may be found for the same width from the previous studies and also among all the studies for the non-lane based traffic including the present one.

Figure 4
Comparisons of Model 1, Equations 6, 7 and 8



For the above reason Model 2 was developed for which much higher degree of explanation is achieved as a function of length of signal green time for approach being surveyed, width of approach at stop line being surveyed, width of intersection exit for traffic traveling straight through and percentage of right turning vehicle. In the previous study all the flow models were developed as a function of approach width only. So the multivariate model developed in this paper is not comparable.

8.0 Comparison of Saturation Flow Model with Field Observed Value

Saturation flow is calculated using regression Model 1 and 2. Figures 5 and 6 compare observed flow with the two models of this study. R^2 values are noted in the figures and show that Model 2 gives a much higher measure of fit than Model 1. Hence, Model 2 is proposed as appropriate for thr estimate saturation flow for non-lane based traffic condition for developing countries.

Figure 5
Correlation between Observed and Model 1 Saturation Flow

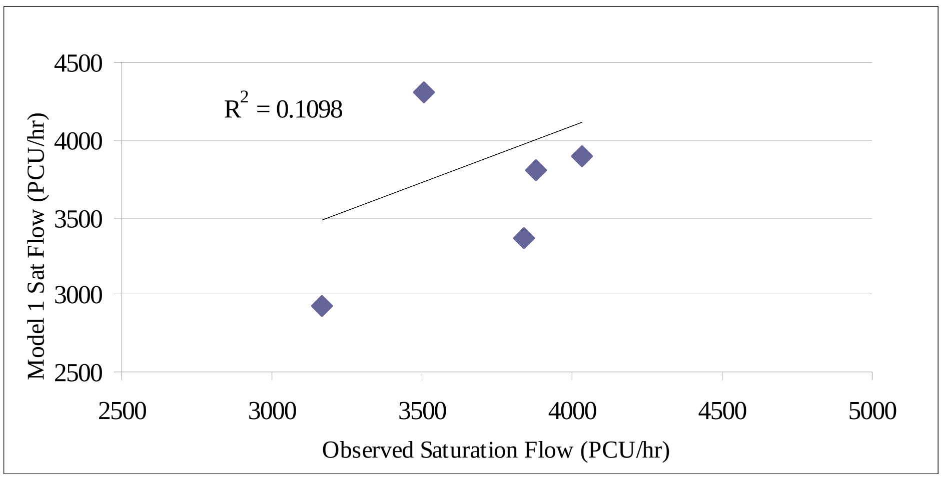
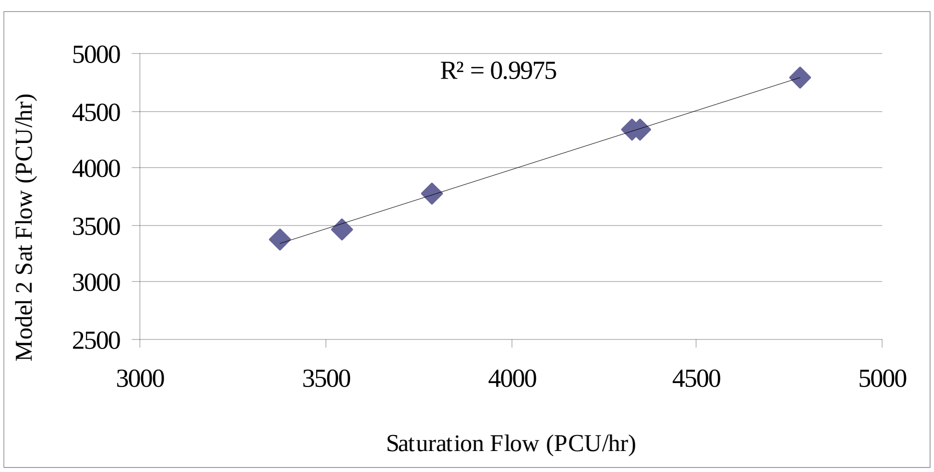


Figure 6
Correlation between Observed and Model 2 Saturation Flow



9.0 Conclusions

Accurate saturation flow values are a fundamental building block in the management of efficient urban traffic signal control and intersection design. In this research, the authors suggest a synchronous regression method to determine PCU values for non-lane based traffic condition. Initially a ranges of site-specific PCU values were obtained and it was observed that PCU values for a particular vehicle change significantly from intersection to intersection. So, this study strongly recommends that unified PCU concept not be used in non-lane based traffic conditions. Then, saturation flow for each survey approach was calculated using the individual PCU values and linear regression techniques were used to derive predictive saturation flow models. A large variation was observed in predicting the saturation flow if approach width is considered as the only independent variable. So the multiple regression technique was adopted to incorporate the effects of road geometry, signal parameter and traffic characteristics on saturation flow. Finally the study compares derived saturation flow models with the field values. Based on the statistical performance indicators the multivariate model was proposed as appropriate for estimating saturation flow for non-lane based traffic condition.

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