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Capacity of Saturated Streams at Manually Controlled Intersections

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Abstract

Manually controlled intersections are the traffic junctions where trained personnel, typically traffic constables, allocate the intersection right-of-way to road users. Unlike developed countries, where manual traffic control is used in case of emergencies and planned special events, this intersection control strategy is widely used in developing countries like India to handle busy intersections as a substitute for traffic signals. Although countries throughout the world have a long history of manual traffic control, studies on such traffic control mechanisms are still very scarce. This study proposes a methodology to determine the capacity of manually controlled streams under saturated conditions. The saturation flow rates of the streams are estimated using saturation flow models. The phase time ratio, which is the proportion of phase time that a manually controlled stream is given the right-of-way during a cycle, is estimated by quantifying the phase change behaviour of traffic constables using a logit model. The capacity of a manually controlled stream is estimated by multiplying the phase time ratio with the saturation flow rate.

Keywords: saturation flow rate; mixed traffic; manually controlled intersection; passenger car unit; phase change modelling; critical phase time

1. Introduction

Intersections are at-grade junctions on road network at which multiple pathways cross one another, which increases the probability of conflicts among road users. With increase in traffic flow, vehicular movements at intersections become very chaotic, turning them into accident hotspots. Intersections with heavy traffic volume need to be controlled by traffic signals which can facilitate the orderly movement of traffic. Installation and maintenance of traffic signals is costly, and in developing countries like India, intersections on the Central Business District (CBD) areas are signalized, where numbers of traffic accidents are alarmingly high or traffic flow is high enough to bring the vehicles to a standstill. But many other intersections, which also warrant for signalization in terms of traffic volume, are manually controlled by traffic constables.

The fundamental principle based on which a manually controlled intersection functions, is the periodic stopping and restarting of the traffic streams by the constable on duty. The schematic illustration of a three-legged manually controlled intersection is shown in Fig. 1. The constable usually positions himself/herself nearby the major conflict points (4, 5 and 6) to regulate the flows at streams B-A, A-C and C-B. It is also observed that the minor conflict points (1, 2 and 3) remain largely uncontrolled. So, traffic flows at streams A-B, B-C and C-A are not regulated by constables.

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When vehicles on stream B-A are released, vehicles of streams A-C and C-B are made to wait at the stop line. Similarly, vehicles on streams A-C and C-B are released one after another by restricting the movements on the other two manually controlled streams. Due to periodic stopping and restarting of stream flows, vehicles at manually controlled streams do not have continuous right-of-way. So, manually controlled streams are more likely to have reached capacity than the uncontrolled streams. Estimating the capacities of the manually controlled streams will be more relevant for assessing the performance of such intersections. Capacity of manually controlled intersection as a whole is not of much importance because by the time traffic flows at the uncontrolled streams increase to saturation flow level, the intersection will normally be signalized. In this study, a methodology has been proposed for estimating the capacities for streams B-A, A-C and C-B that are manually controlled by traffic constables.

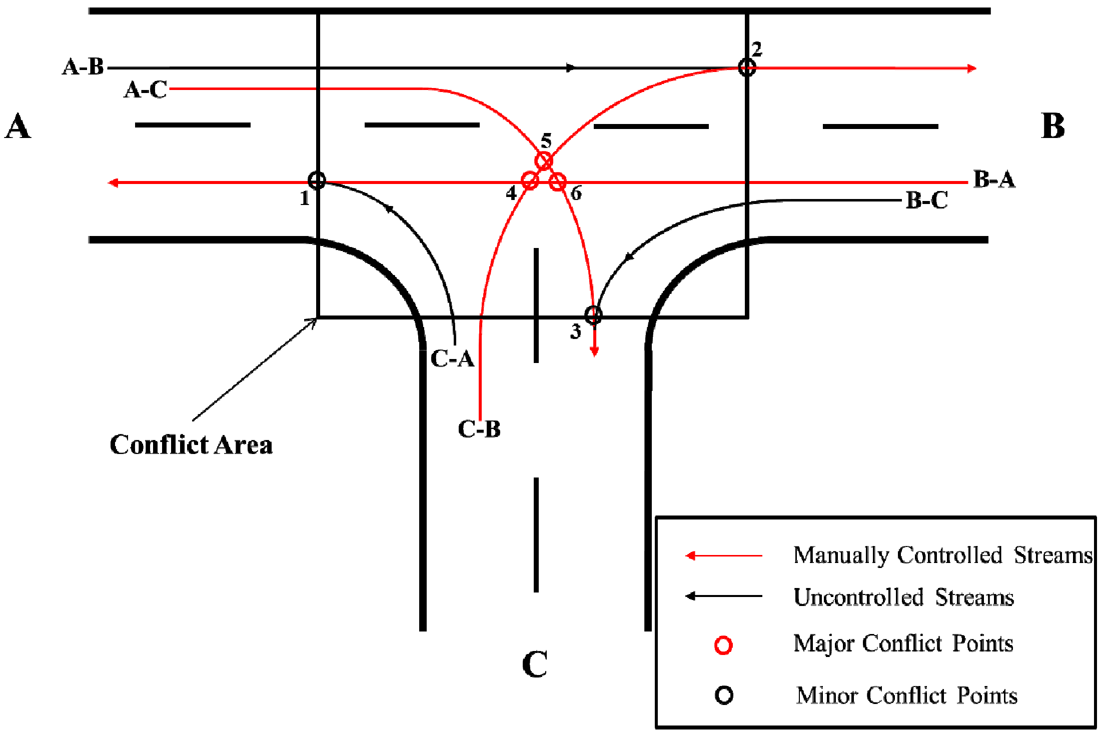


Figure 1: Conflict area at a manually controlled intersection

Capacity of a manually controlled stream is estimated by multiplying the saturation flow rate of the stream with the fraction of time span in a cycle that is effective green for the stream. Unlike pre-timed signalized intersections, the phase time of a certain stream is decided by the traffic constables in real time based on existing traffic scenario. Determination of field saturation flow rate using ‘base saturation flow’ has been developed to address homogeneous traffic condition (HCM 2010). Such an approach does not work very well on traffic having wide range of vehicular dimensions and loose lane discipline (Radhakrishnan and Mathew, 2011). These issues have been addressed in this study while determining the capacity of the manually controlled streams. Firstly, saturation flow models are developed to determine the saturation flow rate of the manually controlled streams. Secondly, the choice behaviour of traffic constables, which leads to changing of phase at their discretion, is modelled using logistic regression. Finally, capacities of the manually controlled streams are estimated based on the results obtained from the previous steps.

2. Literature Review

A review of the studies on saturation flow rate measurements and manual traffic control is discussed in the following sub-sections.

2.1 Saturation flow models

Some of the earliest studies on saturation flow rate were conducted by Greenshields et al. (1947). Those studies yielded saturation flow rate of 1714 vehicles per hour of green per lane. Later studies on saturation flow revealed wide variation in the observed saturation flow rate. This prompted the researchers to develop models for predicting saturation flow rate. Webster and Cobbe (1966) modelled saturation flow rate based on the width of road as in Eq. (1).

$$s = 180w \tag{1}$$

where,

s = saturation flow rate (PCU/hour/lane)
w = width of road approach (feet).

The above formula is not applicable to all range of road widths, but for roads having width greater than 5.5 m. The same formula is adopted in the Indian Road Congress (IRC) manual, with w in metres and making suitable adjustments to consider the effect of left turns and right turns (Eq. 2) (IRC, 1985).

$$s = 525w \tag{2}$$

Turner and Harahap (1993) compared the saturation flow rates predicted by several models from simple to multivariate ones. Highway Capacity Manual (2010) has defined a base saturation flow rate of 1900 passenger cars/hour/lane. This value is adjusted to reflect the prevailing conditions, as given by Eq. (3).

$$s = s_0 N \prod f_i \tag{3}$$

where,

s = saturation flow rate for subject lane group, expressed as a total for all lanes in lane group (vehicle/hour)
s_0 = base saturation flow rate per lane (passenger cars/hour/lane)
N = number of lanes in lane group
f_i = adjustment factors addressing various geometric features, presence of heavy vehicles in traffic stream, traffic features such as parking and bus stops, existence of left turns or right turns in lane group, pedestrians, etc.

The above equation shows that HCM method accounts for the effect of heavy vehicles which contributes to heterogeneity in traffic. However, in developing countries like India, traffic stream consists of vehicles with wide range of dimensional and operational characteristics. Besides, aggressive driving and loose lane discipline are also associated with roads having heterogeneous traffic. Such traffic conditions demand a relook into the factors that could lead to a realistic estimation of saturation flow rate.

Various studies have been conducted by researchers to estimate the saturation flow rate under mixed traffic conditions. Shao et al. (2011) modified the values of adjustment factors for traffic composition, lane width, approach grade, and left-turn radius so that the HCM equation can be used in Chinese traffic conditions. Radhakrishnan and Mathew (2011) estimated the saturation flow rate of a traffic stream by optimizing the PCUs so that the difference between the observed flow curve and ideal saturation flow curve can be minimized. Saturation flow models were then developed based on the traffic composition of vehicles. Anusha et al. (2012) estimated the value of an adjustment factor for motorcycles so that the saturation flow equation in the HCM can be modified for mixed traffic conditions in India. Radhakrishnan and Ramadurai (2015) developed discharge headway models using linear regression and linear mixed regression. Vehicle type, lateral position of vehicles in the road section, and elapsed green time were found to be influencing the discharge headway which is used in estimating the saturation flow rate. Patel et al. (2015) analysed the impact of mixed traffic behaviour on saturation flow rate and PCUs at signalised intersections. It was found that saturation flow rates under mixed traffic conditions are particularly sensitive to small-sized vehicles such as two-wheelers.Chand et al. (2017) estimated saturation flow rate at signalized intersections by converting the flow into units of passenger cars using dynamic PCUs.

2.2 Manual traffic control

Studies conducted by researchers on manual and automated traffic control show that in oversaturated conditions manual traffic control outperforms automated control if the intersection is isolated (Mahalel et al., 1991; May and Montgomery, 1986; Sutermeister, 1956). However, if the intersection is under-saturated, automated control performs better (Pretty, 1974; Ye et al., 2009). Simulation of manually controlled intersections has been done by various researchers assuming that traffic constables direct the traffic movements keeping constant cycle lengths and phase splits (Mahalel et al., 1991; Pretty 1974; Ye et al. 2009). Hakkert and Gitelman (2005) has suggested a set of guidelines for systematic monitoring of traffic police performance at manually controlled intersections. This would help the authorities in implementing effective enforcement strategies and tactics.Marsh (1927) suggested that the efficiency of manually controlled intersections is derived from its variable cycle length and phase splits. Oversimplifying manually controlled intersections in simulation models by assuming fixed cycle length and phase splits could lead to an unrealistic comparison between manual traffic control and automated control (Parr and Wolshon, 2016). So et al. (2013) compared the performance of manual traffic-signal control with optimized signal control during oversaturated conditions. The results revealed that manual traffic-signal control leads to a statistically significant reduction in vehicle delay. Ding at al. (2015) and Parr et al. (2016) have also shown that manual traffic-signal control strategy helps in improving the intersection performance by stepping outside the constraints of a traditional automated signal control.Parr and Wohlson (2016) quantified the effect of manual traffic control on operation of intersections during emergencies and special events using logistic regression. Time and gap were two parameters considered for developing the logit models. Time refers to the number of seconds for which the current phase is green, whereas ‘gap’ is the number of intersection approaches that were having a breakdown of vehicle platoon.

2.3 Inferences

The review of existing studies reveals that studies on saturation flow rate have been mainly conducted under homogeneous traffic conditions. Although a few studies were conducted under mixed traffic conditions, research on saturation flow rate has been restricted to signalized intersections. So far, none of the studies have reported saturation flow rates for manually controlled intersections. Studies on manually controlled intersections have been limited to delay measurement and phase change modelling, but, to the best of our knowledge, capacity analysis at manually controlled intersection under mixed traffic conditions has not been done before. Hence, establishing a suitable methodology for estimating capacity at such intersections is considered essential.

3. Methodology

A methodology for estimation of capacity of manually controlled streams based on microscopic traffic data is proposed here. The methodology flowchart is presented in Fig. 2. Detailed explanations of these steps are given below.

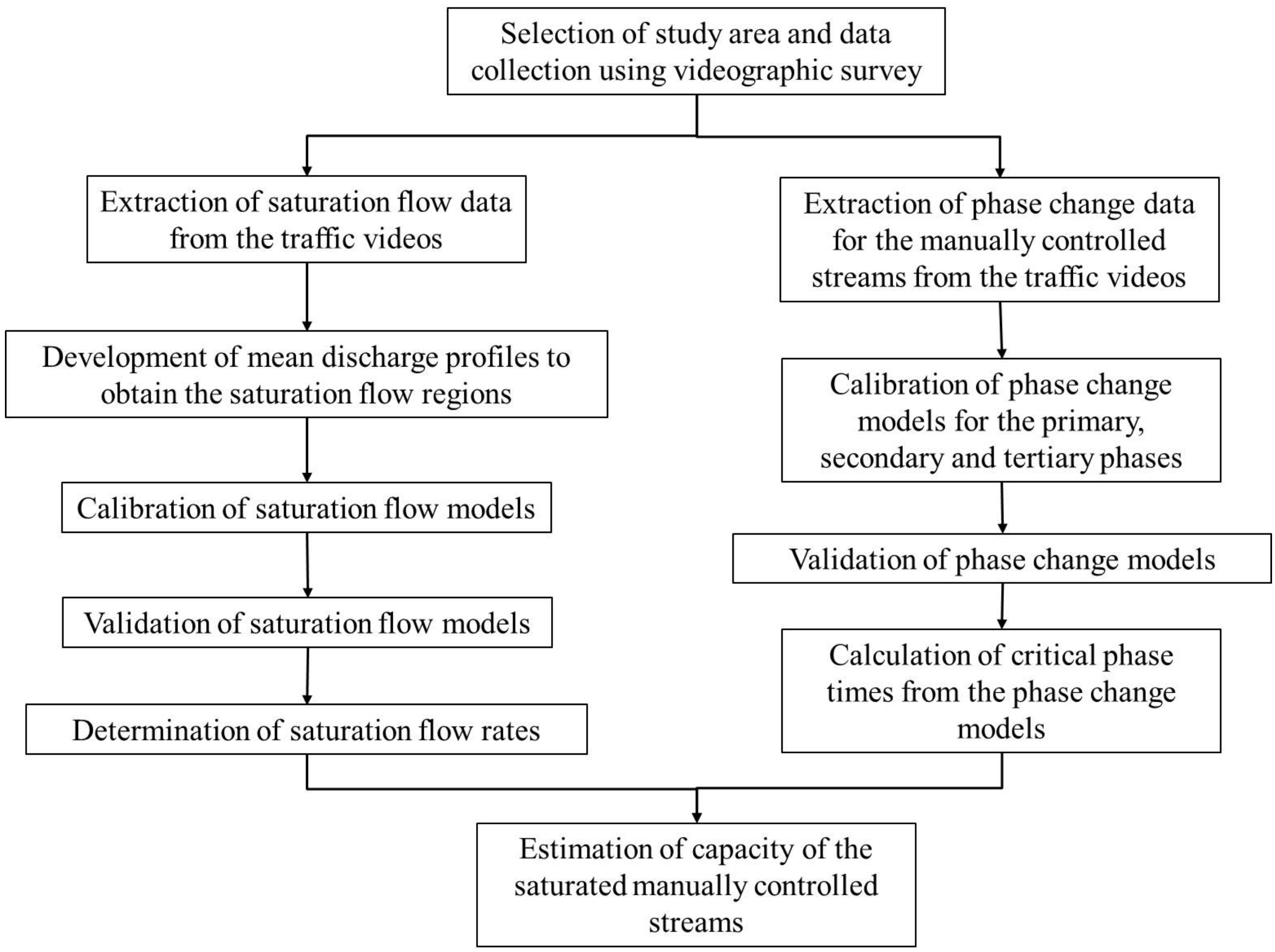


Figure 2: Study methodology flowchart

3.1 Saturation flow data

Traffic constables regulate the manually controlled intersections by allocating the right-of-way to streams B-A, A-C and C-B one after another (Fig. 1). Traffic flow at these streams can be saturated if sufficiently long queues are formed during their restricted period. The traffic flow behaviours of these streams are different from each other due to variation in their turning radii, traffic composition, queue formation, etc. So, flow data are collected to develop individual saturation flow models for these streams. Traffic flow at a manually controlled stream is measured at regular intervals by dividing its phase time into time-slices. The value of the time slice is sensitive, as a smaller value can improve the accuracy of calculation in mixed traffic condition (Nguyen 2016).

Intersections selected in this study have highly mixed traffic with wide range of dimensional and operational characteristics of vehicles. Due to loose lane discipline and aggressive behaviour of drivers, multiple vehicles are found to cross the stop line simultaneously. Thus, in order to capture the flow variation at close intervals, it is decided to record the number of classified vehicles crossing the stop line at every two second intervals (time slice = 2s).

3.2 Determination of saturation flow region

Once the classified volume count is completed, the flow values are converted to PCU/2s using the PCUs recommended in the IRC SP-41 (1994) as shown in Table 1. The flow values obtained from several cycles are used to prepare mean discharge profile by plotting a graph of the average flow values vs time slice number. The saturation flow region of the mean discharge profile is considered to be the region where the flow value remains fairly consistent. This region is determined by considering a maximum tolerance interval of 0.25 PCU/2s, which means the variation in traffic flow does not exceed ± 0.25 PCU/2s after the beginning of saturation flow region (Eq. 4).

$$-0.25\ PCU/2s \leq X_n - X_i \leq 0.25\ PCU/2s \tag{4}$$

where,
X_i = flow at the i^{th} 2 second interval when the saturation flow begins (PCU/2s)
X_{i+n} = flow at the n^{th} 2 second interval after the beginning of saturation flow (PCU/2s)

Table 1**:** Passenger Car Units recommended by IRC SP-41

Vehicle Types	**Abbreviations**	PCU
Two-wheeler	TW	0.50
Auto-rickshaw	AR	1.00
Standard Car	SC	1.00
Light Commercial Vehicle	LCV	1.50
Heavy Vehicle	HV	3.00
Bicycle	BC	0.50
Cycle Rickshaw	CR	1.50

3.3 Calibration of saturation flow model

Radhakrishnan and Mathew (2011) developed saturation flow model by regressing the saturation flow rate of the stream against the percentage of each vehicle type. The general form of the model is as presented in Eq. (5).

$$S = a_1 p_1 + a_2 p_2 + \ldots\ldots\ldots\ldots\ldots + a_n p_n \tag{5}$$

where,
S = saturation flow rate in PCU/hour
$a_1, a_2, \ldots a_n$ = regression coefficients
$p_1, p_2, \ldots p_n$ = percentage composition of vehicle types

As explained in the introduction, the minor conflict points at manually controlled intersections aren't regulated by traffic constables (Fig. 1). Due to this, the saturation flow rate of a manually controlled stream is influenced by flow of vehicles on the corresponding uncontrolled stream. For example, when stream B-A is given the right-of-way, vehicles on stream C-A interferes with its movement, resulting in reduction of flow at stream B-A (Fig. 1). Similarly, saturation flow rates of manually controlled streams A-C and C-B are interfered by flows at uncontrolled streams B-C and

A-B respectively. So, in order to model the saturation flow rate of a manually controlled stream, the influence of conflicting flow rate at the corresponding uncontrolled stream needs to be considered. Conflicting flow rate of an uncontrolled stream is the traffic flow during the time span when its corresponding manually controlled stream has the right-of-way. The saturation flow model considered by Radhakrishnan and Mathew (2011) for signalized intersection has been modified for manually controlled intersections to incorporate the effect of conflicting flow rate (Eq. 6).

$$S_f = a_{\text{tw}}p_{\text{tw}} + a_{\text{ar}}p_{\text{ar}} + \ldots\ldots\ldots\ldots\ldots + a_{cr}p_{cr} + a_c f_c \tag{6}$$

where,

S_f = saturation flow rate of the manually controlled stream (PCU/hr)

p_j = percentage composition vehicle type 'j' (*j= tw, ar, sc*, etc, which corresponds to various vehicle types TW, AR, SC, etc)

a_{tw}, a_{ar}, a_{sc}….. a_{cr}, a_c = regression coefficients

f_c = conflicting flow rate of the corresponding uncontrolled stream (PCU/hr)

Multiple linear regression is used to develop the saturation flow models for predicting saturation flow rates. One of the essential criteria for performing multiple linear regression is that there should be a linear relationship between the outcome variable and the independent variables. Scatter plots are made between conflicting flow rate (f_c) and saturation flow rate (S_f), and it was found that there is a linear relationship between the two. Similarly, linear relationships are also obtained for percentage composition of vehicles as obtained by Radhakrishnan and Mathew (2011). Since, the assumption of multiple linear regressionis met, the models are calibrated using multiple linear regressions. The datasets for regression are extracted from each cycle by determining the average traffic flow (PCU/hr) and percentage composition of vehicles of the saturation flow region, and the corresponding conflicting flow rate. The models are developed for each saturated manually controlled stream taking 75% of the datasets, and the remaining is kept for validation.

3.4 Saturation flow model validation

Saturation flow models are validated using 25% of the data collected from the same intersections. The flow values obtained from the field is compared with the flows predicted by the saturation flow models. Scatter plots are prepared by plotting observed flows against predicted flows to assess the validity of the model.

3.5 Determination of saturation flow rate

The calibrated saturation flow models are used to determine the saturation flow rates of the manually controlled streams by substituting the percentage compositions of vehicles and the corresponding conflicting flow rates. The percentage compositions of vehicles of the manually controlled streams and the corresponding conflicting flow rates are obtained from the video data collected during traffic survey.

3.6 Phase change data

Binary logistic regression is used to model the phase changing decisions made by constables. A timeline of events, which took place in the traffic streams, is prepared on a second-to second basis. The time interval considered is one second. The traffic constable allocates the right-of-way to the manually controlled streams in three phases. The three phases are named as primary, secondary and tertiary according to the priority received from the traffic constables based on traffic flow.

3.7 Phase change model

The traffic constable on duty has a utility for changing or not changing a phase. If the constable changes the primary phase (say) and gives the right-of-way to the secondary phase, vehicle starts accumulating at the primary phase stream. If the constable decides not to change the phase, flow of vehicles on the primary phase will not be hampered. But, vehicles on the other two manually controlled streams will have to wait further. A simple utility function to represent this situation is as shown in Eq. (7).

$$U_i = V_i + \varepsilon_i \tag{7}$$

whereU_i = total utility, V_i = observed utility, and ε_i = unobserved portion of the utility (error). The observed utility, V_i, is a function of the variable(s) that influence the phase change decision. The two independent variables considered in this study are time and gap. The time variable is the phase length duration, or how long a phase has received the right-of-way. The gap variable refers to the breaking down of vehicle platoons on the stream that has the right-of-way. The gap is a binary variable which takes a value of 1 if the stream under consideration has a break in platoon; and 0 if no break in platoon is observed. The utility equation for the phase change model is taken as shown in Eq. (8).

$$\ln \frac{\mathrm{P(t)}}{1-\mathrm{P(t)}} = V_i = \alpha + \beta.\mathrm{t} + \gamma.\mathrm{g} \tag{8}$$

where,

P(t) = probability of changing a phase

V_i = observed utility or deterministic component of utility

α, β, γ = unknown coefficients to be estimated

t = phase time (s)

g = gap (0 or 1)

The phase change models are developed separately for each phase to estimate the critical phase times. The phase change models for primary, secondary and tertiary phases are given by Eqs. 9-11. Out of the total data, 25% observations are selected randomly and kept for validation, and the remaining data are used for calibrating the models.

$$\ln \frac{\mathrm{P(t)}}{1-\mathrm{P(t)}} = \mathrm{V_p} = \alpha_\mathrm{p} + \beta_\mathrm{p}.\mathrm{p} + \gamma_\mathrm{p}.\mathrm{g_p} \tag{9}$$

$$\ln \frac{\mathrm{P(t)}}{1-\mathrm{P(t)}} = \mathrm{V_s} = \alpha_\mathrm{s} + \beta_\mathrm{s}.\mathrm{s} + \gamma_\mathrm{s}.\mathrm{g_s} \tag{10}$$

$$\ln \frac{\mathrm{P(t)}}{1-\mathrm{P(t)}} = \mathrm{V_t} = \alpha_\mathrm{t} + \beta_\mathrm{t}.\mathrm{t} + \gamma_\mathrm{t}.\mathrm{g_t} \tag{11}$$

where,

P(t) = probability of changing a phase

V_p, V_s, V_t = observed utility or deterministic component of utility

α_p, α_s, α_t, β_p, β_s, β_t, γ_p, γ_s, γ_t = unknown coefficients to be estimated

p = primary time, which is the time allocated for the primary phase (s)
s = secondary time, which is the time allocated for the secondary phase (s)
t = tertiary phase time, which is the time allocated for the tertiary phase (s)
g_p= gap variable for primary phase (0 or 1)
g_s= gap variable for secondary phase (0 or 1)
g_t= gap variable for tertiary phase (0 or 1)

3.8 Phase change model validation

The models are validated using 25% of the data, randomly selected from the collected data. The probability values derived from the model is rounded to zero or one to compare with the actual observation. It is assumed that, if the probability of changing phase is less than 0.5, the traffic constable doesn't change the phase, and it is designated as 0. Similarly, if the probability is found to be greater than or equal to 0.5, the phase is changed, and it is identified as 1. The validity of the models is assessed by estimating Type I error, Type II error, sensitivity, and specificity. Type I error is said to have occurred when the null hypothesis is rejected, but it is, in fact, true. Type II error occurs when a null hypothesis is accepted, but it is, in fact, false. Sensitivity (one minus type II error) represents the ability of a model to identify correctly whether a phase is changed, whereas specificity (one minus type I error) shows the ability of a model to identify correctly whether a phase remains unchanged.

3.9 Determination of critical phase times

The logit model gives a relationship between the phase time and the probability of changing the phase. A typical plot of logistic regression curve showing probability of changing phase and phase time is shown in Fig. 3. Critical phase time is defined as the time at which the phase is equally likely to be changed or not changed by the constable. Thus, the critical primary time (p_{cr}), critical secondary time (s_{cr}) and critical tertiary time (t_{cr}) are computed by setting the probability of changing phase to 0.5 in Eqs. 9 - 11.

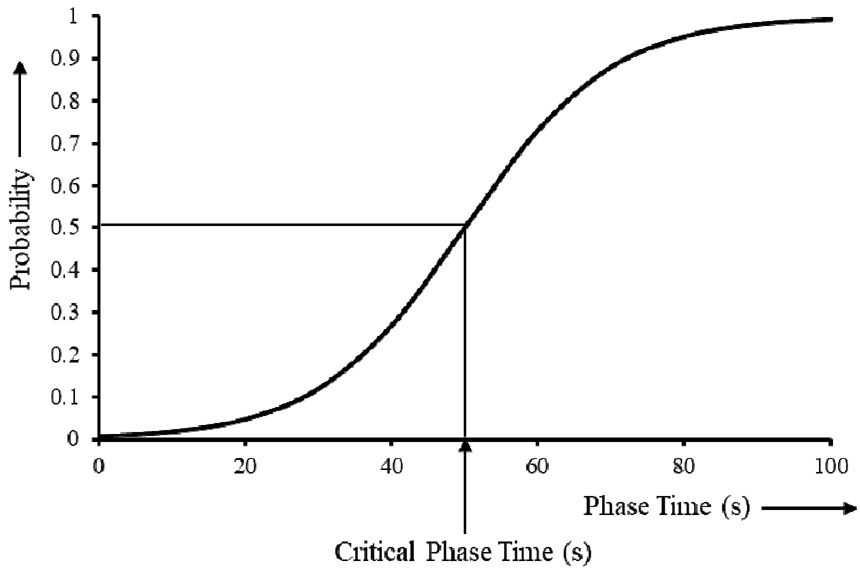


Figure 3: Probability curve for a logit model

3.10 Determination of capacity of saturated stream

The capacity of a manually controlled stream is obtained by multiplying the saturation flow rate of the stream with the proportion of time in a cycle it is assigned the right-of-way. The capacities of the manually controlled streams that have been assigned the primary, secondary and tertiary phase are determined by multiplying the saturation flow rates with the corresponding phase time ratios as shown Eqs. 12 - 14.

$$C_p = \frac{p_{cr}}{p_{cr} + s_{cr} + t_{cr}} \cdot S_{f,p} \tag{12}$$

$$C_s = \frac{s_{cr}}{p_{cr} + s_{cr} + t_{cr}} \cdot S_{f,s} \tag{13}$$

$$C_t = \frac{t_{cr}}{p_{cr} + s_{cr} + t_{cr}} \cdot S_{f,t} \tag{14}$$

where,

C_p= capacity of the primary phase stream (PCU/hr)
C_s= capacity of the secondary phase stream (PCU/hr)
C_t= capacity of the tertiary phase stream (PCU/hr)
p_{cr} = critical primary time (s)
s_{cr} = critical secondary time (s)
t_{cr} = critical tertiary time (s)
$S_{f,p}$, $S_{f,s}$, $S_{f,t}$ = saturation flow rate (PCU/hr) of the streams that have been allocated primary, secondary and tertiary phase respectively as determined from saturation flow model (Eq. 6).

However, at some manually controlled intersections, it is possible that queues may not be long enough at the tertiary phase to sustain saturation flow. Capacity analysis requires saturation flow rate, which cannot be developed for the tertiary phaseif the hourly volume is low. Due to low traffic volume, the traffic constable will change the phase after all the vehicles of tertiary stream have cleared the intersection. In such situations, the decision for changing the tertiary phase is not a binary choice, as it depends solely on the time required to clear the queued vehicles on that stream. So, logit model for tertiary phase cannot be developed. The critical tertiary time is replaced by average tertiary time (t_{av}). This is estimated by calculating the average time for which the constable gives the right-of-way to the tertiary phase. The capacity of the manually controlled streams that has been assigned the primary and secondary phase will be estimated by Eqs. (15) and (16) respectively.

$$C_p = \frac{p_{cr}}{p_{cr} + s_{cr} + t_{av}} \cdot S_{f,p} \tag{15}$$

$$C_s = \frac{s_{cr}}{p_{cr} + s_{cr} + t_{av}} \cdot S_{f,s} \tag{16}$$

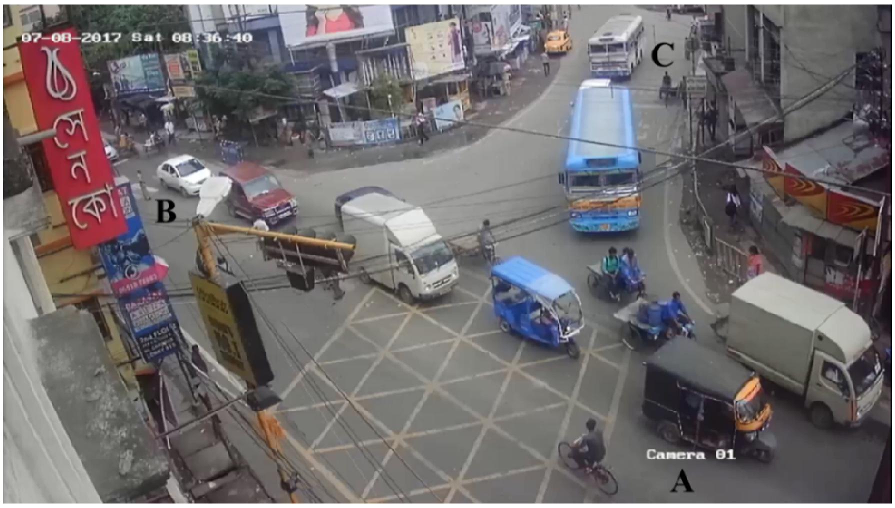
where,

C_p= capacity of the primary phase stream (PCU/hr)
C_s= capacity of the secondary phase stream (PCU/hr)
p_{cr} = critical primary time (s)
s_{cr} = critical secondary time (s)

t_{av} = average tertiary time (s)
$S_{f,p}$, $S_{f,s}$ = saturation flow rate (PCU/hr) of the streams that have been allocated primary and secondary phase respectively as determined from saturation flow model (Eq. 6).

4. Case Study

Traffic data are collected by video recording two intersections, one in Silchar, Assam (named as intersection A) and the other in Kolkata, West Bengal (named as intersection B) (Fig. 4). The data are collected for three working days at each intersection during morning peak hours (10:00 a.m.-12 noon). The major road and minor road are both two-lane undivided at both the intersections. The camera is placed on the roof-top of an adjacent building to get a wide view of the intersection area. A total of 47 cycles from intersection A, and 42 cycles from intersection B are used for extracting the data required for this study. The vehicles are grouped into six categories based on their dimensions and dynamic behaviour. The stream-wise vehicular compositions of the two intersections are presented in Table 2 and 3.



(a)

(b)

Figure 4: (a) Intersection A and (b) intersection B with legs named as A, B and C

Table 2: Traffic composition of intersection A

Streams	Vehicle Types							Total (%)
	TW (%)	AR (%)	SPC (%)	LCV (%)	HV (%)	BC (%)	CR (%)	
AB	18.49	18.49	23.97	2.74	8.22	17.12	10.97	100
BA	9.9	24.75	16.83	5.94	14.85	15.84	11.89	100
AC	16.76	3.91	7.26	1.68	3.91	35.75	30.73	100
CB	17.54	7.02	14.04	1.75	31.58	10.53	17.54	100
CA	17.09	6.84	5.98	0.85	2.56	38.46	28.22	100
BC	24.14	17.24	13.79	3.45	6.9	24.14	10.34	100

Table 3: Traffic composition of intersection B

Streams	Vehicle Types					Total (%)
	TW (%)	AR (%)	SPC (%)	BC (%)	CR (%)	
AB	39.61	37.20	9.63	8.10	5.47	100
BA	36.96	44.56	9.37	6.58	2.53	100
AC	55.77	2.88	18.27	12.50	10.58	100
CB	63.64	6.06	12.12	12.12	6.06	100
CA	43.56	18.81	9.90	22.77	4.95	100
BC	62.50	3.13	21.88	9.38	3.13	100

4.1 Calibration of saturation flow models

All three manually controlled streams (B-A, A-C and C-B) are found to be saturated at intersection A, whereas streams B-A and A-C are found to be saturated at intersection B. Mean discharge profiles of the saturated streams are indicated in Figs. 5-9. It is clearly evident from the figures that the flow attains a high value initially, but reduces gradually before attaining a stable flow. The time spans for which flow remain stable are marked in the graph, and are considered as saturation flow region. The vehicle composition of these spans for all the cycles and the corresponding conflicting flow rates are noted for saturation flow modelling.

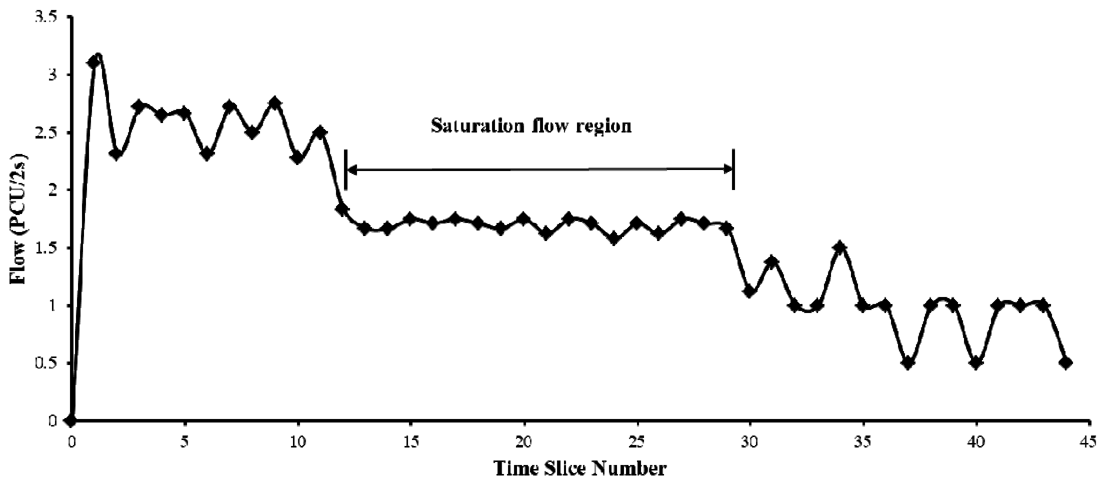


Figure 5: Mean discharge profile of stream B-A, intersection A

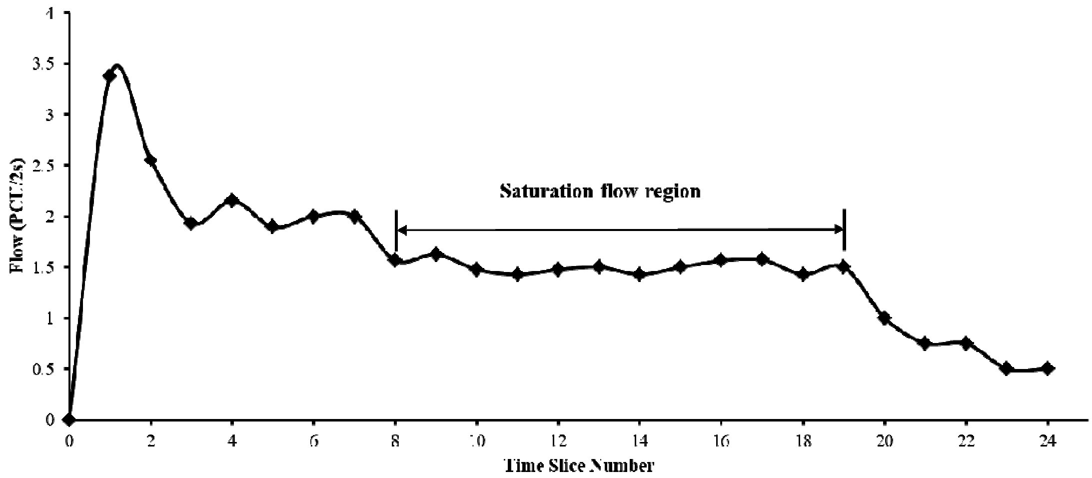


Figure 6: Mean discharge profile of stream A-C, intersection A

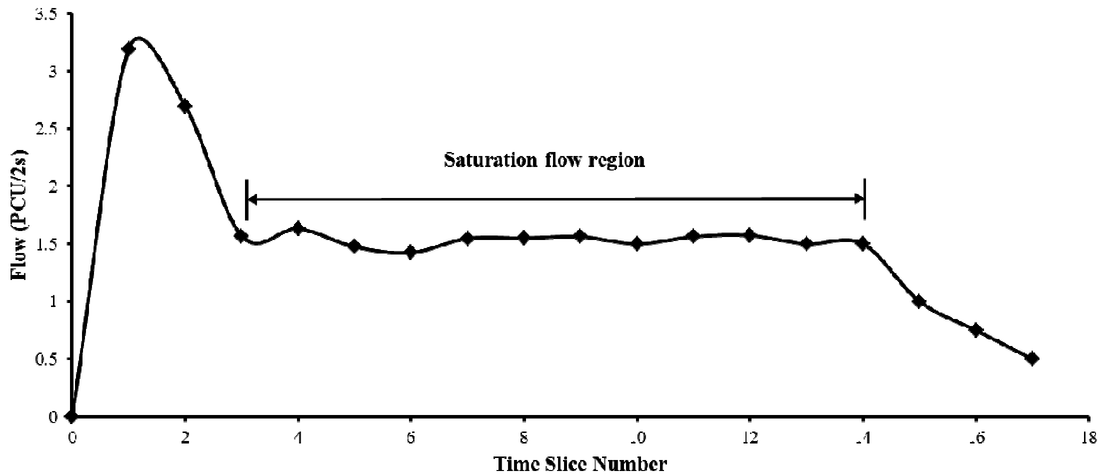


Figure 7: Mean discharge profile of stream C-B, intersection A

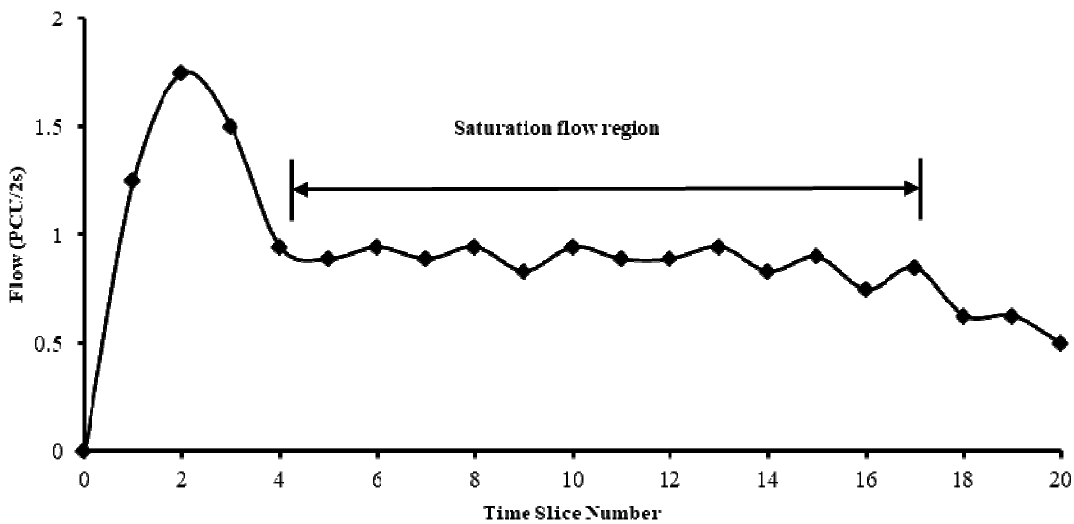


Figure 8: Mean discharge profile of stream B-A, intersection B

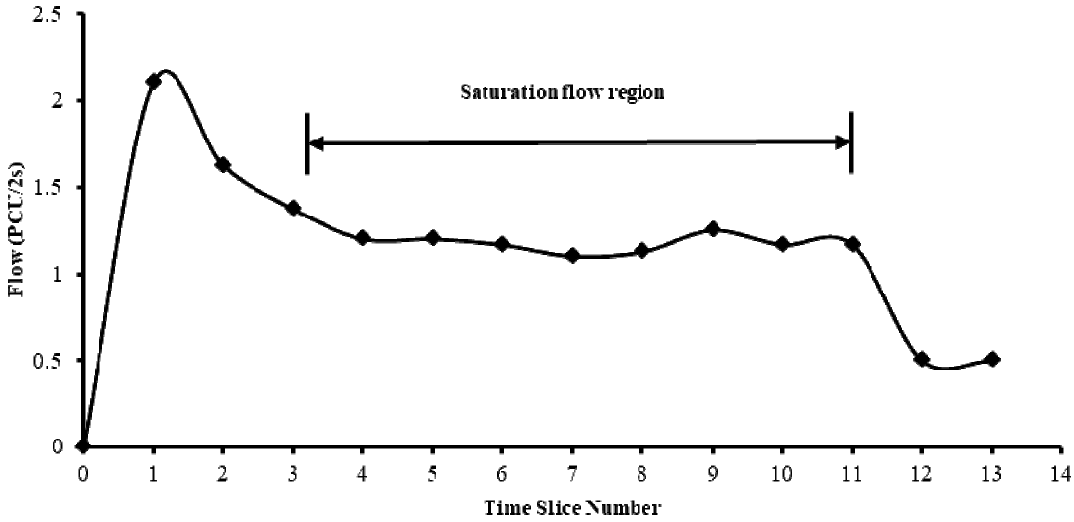


Figure 9: Mean discharge profile of stream A-C, intersection B

Saturation flow models are calibrated to predict the saturation flow rate based on percentage composition of vehicles and conflicting flow rate (Eq. 6).The Variance Inflation Factor (VIF) is a statistic to check the multicollinearity between the independent variables. A VIF of greater than 5 is generally considered evidence of multicollinearity (Craney and Surles, 2002). The regression results show that VIF of none of the variables have exceeded the value of 2.5, indicating that correlation between variables is within safe limit. Basic descriptive statistics and regression coefficients are shown in Tables 4-8. The VIF values of all the parameters are mentioned in the last column of both the tables. The R^2 and adjusted-R^2 values are reported at the bottom row of the tables.

Table 4: Descriptive statistics for saturation flow model of stream B-A, intersection A

coefficient	coefficient	standard error	t-statistic	p-value	VIF
p_{tw}	22.21	3.03	7.32	0.00	1.04
p_{ar}	28.76	2.34	12.29	0.00	1.18
p_{spc}	24.94	1.71	14.63	0.00	1.20
p_{lcv}	77.74	19.09	4.07	0.00	1.01
p_{hv}	57.83	3.05	18.94	0.00	1.00
p_{bc}	25.48	4.85	5.26	0.00	1.03
p_{cr}	57.96	4.27	13.57	0.00	1.02
f_c	-0.46	0.16	-2.95	0.00	1.36
	$R^2 = 0.895$		Adjusted $R^2 = 0.889$		

Table 5: Descriptive statistics for saturation flow model of stream A-C, intersection A

coefficient	coefficient	standard error	t-statistic	p-value	VIF
p_{tw}	19.29	2.82	6.85	0.00	1.09
p_{ar}	29.17	2.99	9.75	0.00	1.05
p_{spc}	22.62	3.41	6.64	0.00	1.01
p_{lcv}	27.00	5.73	4.71	0.00	1.00
p_{hv}	66.13	6.89	9.60	0.00	1.00
p_{bc}	22.52	2.25	10.03	0.00	1.05
p_{cr}	42.56	2.47	17.24	0.00	1.10
f_c	-2.50	1.21	-2.06	0.04	1.19
	$R^2 = 0.849$		Adjusted $R^2 = 0.841$		

Table 6: Descriptive statistics for saturation flow model of stream A-C, intersection A

coefficient	coefficient	standard error	t-statistic	p-value	VIF
p_{tw}	19.49	1.05	7.44	0.00	1.05
p_{ar}	30.63	1.10	10.11	0.00	1.10
p_{spc}	23.35	1.01	7.13	0.00	1.01
p_{lcv}	28.07	1.00	5.18	0.00	1.00
p_{hv}	66.14	1.00	9.90	0.00	1.00
p_{bc}	22.56	1.06	10.41	0.00	1.06
p_{cr}	42.24	1.10	16.89	0.00	1.10
f_c	-1.62	1.18	-2.26	0.03	1.18
	R^2 = 0.856		Adjusted R^2 = 0.848		

Table 7: Descriptive statistics for saturation flow model of stream B-A, intersection B

coefficient	coefficient	standard error	t-statistic	p-value	VIF
p_{tw}	27.56	2.03	13.58	0.00	1.15
p_{ar}	31.35	1.74	18.07	0.00	1.34
p_{spc}	25.29	2.77	9.14	0.00	1.31
p_{bc}	44.24	7.94	5.57	0.00	1.03
p_{cr}	79.89	20.58	3.88	0.00	1.04
f_c	-0.76	0.19	-3.98	0.00	1.58
	R^2 = 0.902		Adjusted R^2 = 0.896		

Table 8: Descriptive statistics for saturation flow model of stream A-C, intersection B

coefficient	coefficient	standard error	t-statistic	p-value	VIF
p_{tw}	30.52	1.69	18.05	0.00	1.14
p_{ar}	24.02	1.16	20.73	0.00	1.59
p_{spc}	21.83	1.89	11.57	0.00	1.25
p_{bc}	28.69	3.29	8.72	0.00	1.13
p_{cr}	36.42	4.42	8.23	0.00	1.09
f_c	-0.98	0.29	-3.41	0.00	2.08
	R^2 = 0.939		Adjusted R^2 = 0.936		

4.2 Validation of saturation flow models

Saturation flow models are validated using scatter plots of actual flow against flows predicted by the saturation flow models. The validation results for intersection A (stream B-A, A-C and C-B) and intersection B (stream B-A and A-C) are shown in Figs. 10-11. The scatter plot shows that the points are quite close to the 45 degree line. Thus, it can be inferred that the models can predict saturation flow rate with reasonable accuracy.

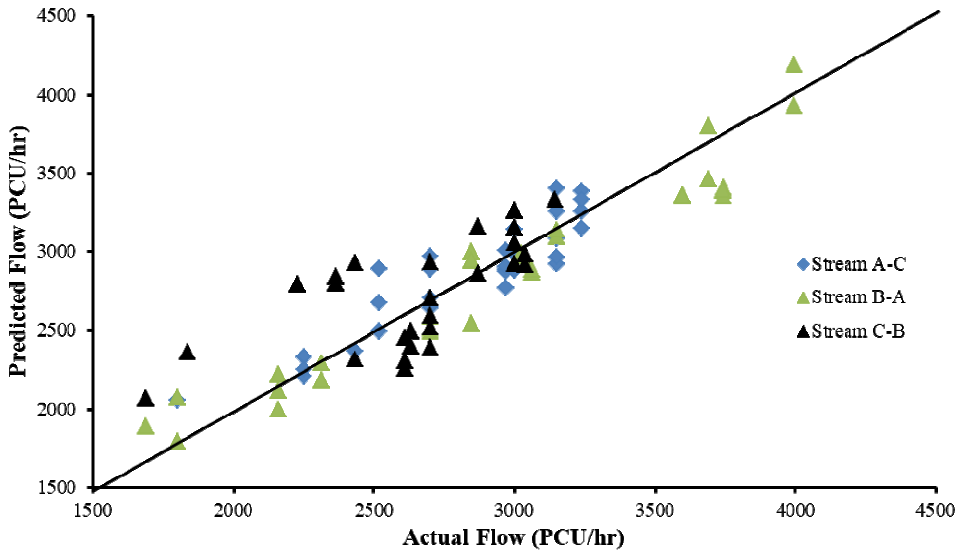


Figure 10: Results of validation of saturation flow models, intersection A

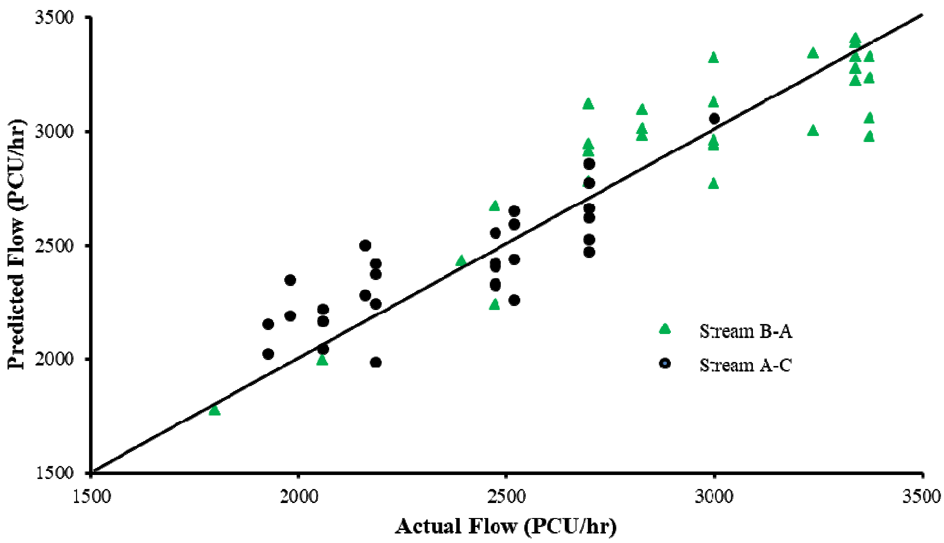


Figure 11: Results of validation of saturation flow models, intersection B

4.3 Determination of saturation flow rate

The saturation flow rates of the manually controlled streams are estimated from the saturation flow models by substituting the percentage compositions of vehicles and the corresponding conflicting flow rates. The percentage compositions of vehicles of the manually controlled streams are taken from Tables 2 and 3, and the conflicting flow rates (PCU/hr) of the corresponding uncontrolled intersections are obtained from classified vehicle counts estimated during the study period. The calculations of saturation flow rates of the two intersections are shown in Table 9 and 10.

Table 9: Estimation of saturation flow rates (S_f) for streams B-A, A-C and C-B of intersection A (PCU/hr)

Stream B-A				Stream A-C				Stream C-B			
Variables	Coefficients (a)	Values of Variable (b)	Calculation (a)*(b)	Variables	Coefficients (a)	Values of Variable (b)	Calculation (a)*(b)	Variables	Coefficients (a)	Values of Variable (b)	Calculation (a)*(b)
p_{tw} (%)	22.21	9.90	220	p_{tw} (%)	19.29	16.76	323	p_{tw} (%)	19.49	17.54	342
p_{ar} (%)	28.76	24.75	712	p_{ar} (%)	29.17	3.91	114	p_{ar} (%)	30.63	7.02	215
p_{spc} (%)	24.94	16.83	420	p_{spc} (%)	22.62	7.26	164	p_{spc} (%)	23.35	14.04	328
p_{lcv} (%)	77.74	5.94	462	p_{lcv} (%)	27.00	1.68	45	p_{lcv} (%)	28.07	1.75	49
p_{hv} (%)	57.83	14.85	859	p_{hv} (%)	66.13	3.91	259	p_{hv} (%)	66.14	31.58	2089
p_{bc} (%)	25.48	15.84	404	p_{bc} (%)	22.52	35.75	805	p_{bc} (%)	22.56	10.53	238
p_{cr} (%)	57.96	11.89	689	p_{cr} (%)	42.56	30.73	1308	p_{cr} (%)	42.24	17.54	741
f_c (PCU/hr)	-0.46	452.00	-207	f_c (PCU/hr)	-2.50	131.00	-328	f_c (PCU/hr)	-1.62	1524.00	-2472
	S_f		3558		S_f		**2691**		S_f		**1529**

Table 10: Estimation of saturation flow rates (S_f) for streams B-A and A-C of intersection B (PCU/hr)

Stream B-A				Stream A-C			
Variables	Coefficients (a)	Values of Variables (b)	Calculations (a)*(b)	Variables	Coefficients (a)	Values of Variables (b)	Calculations (a)*(b)
p_{tw} (%)	27.56	36.96	1019	p_{tw} (%)	30.52	55.77	1702
p_{ar} (%)	31.35	44.56	1397	p_{ar} (%)	24.02	2.88	69
p_{spc} (%)	25.29	9.37	237	p_{spc} (%)	21.83	18.27	399
p_{bc} (%)	44.24	6.58	291	p_{bc} (%)	28.69	12.50	359
p_{cr} (%)	79.89	2.53	202	p_{cr} (%)	36.42	10.58	385
f_c (PCU/hr)	-0.76	280.00	-213	f_c (PCU/hr)	-0.98	84.00	-82
	S_f		2933		S_f		2831

4.4 Calibration of phase change models

Field observation shows that the stream priorities are decided by traffic constables based on the traffic volume of the streams. Stream B-A receives the right-of-way for maximum time, followed by streams A-C and C-B. Thus, streams B-A, A-C and C-B receive the primary, secondary and tertiary phase respectively. The binary variable, gap (g), indicating whether there is a break in the vehicle platoon, is not found to be significant, thus not included in the models. Break in vehicle platoon typically occurs when all the queued vehicles have cleared the intersection. Field observation has shown that most of the time constables change the current phase before the platoon starts breaking up. Such behaviour of traffic constables is attributed to the fact that when one particular stream has the right-of-way, long queues form on the other manually controlled streams. Thus, constables are prompted to change phase when traffic flow falls below the saturation flow rate.

The tertiary phase of intersection B has very low hourly volume (237 PCU/hr). Field observations have shown that the constable always changes phase when all the queued vehicles have clear the intersections. In such situation, the phase change behaviour is not a binary choice. So, phase change model for the tertiary phase (stream C-B) at intersection B could not be developed. The statistical results of the phase change models for intersection A (streams B-A, A-C and C-B) and B (streams B-A and A-C) are reported in Table 11-15. Log-likelihood function, McFadden R^2 values and percentage of right predictions are also shown in the tables. The results show that phase change probability increases with increase in phase time. It is so because the longer the right-of-way is given to a phase, queues keep forming up at the other two manually controlled streams. This increases the likelihood for the constable to change the current phase.

Table 11: Descriptive statistics for the phase change model, primary phase, intersection A

coefficient	coefficient	standard error	t-statistic	p-value
Intercept	-7.51	1.11	45.86	0.00
PT	0.08	0.02	17.62	0.00
McFadden R-square = 0.703		log-likelihood function = - 43.95		
percentage of right predictions = 0.982				

Table 12: Descriptive statistics for the phase change model, secondary phase, intersection A

coefficient	coefficient	standard error	t-statistic	p-value
Intercept	-5.54	0.87	40.92	0.00
ST	0.12	0.03	13.24	0.00
McFadden R-square = 0.652		log-likelihood function = - 42.62		
percentage of right predictions = 0.960				

Table 13: Descriptive statistics for the phase change model, tertiary phase, intersection A

coefficient	coefficient	standard error	t-statistic	p-value
Intercept	-6.36	1.28	24.49	0.00
TT	0.25	0.07	12.36	0.00
McFadden R-square = 0.743		log-likelihood function = - 26.41		
percentage of right predictions = 0.945				

Table 14: Descriptive statistics for the phase change model, primary phase, intersection B

coefficient	coefficient	standard error	t-statistic	p-value
Intercept	-4.90	0.73	45.03	0.00
PT	0.12	0.03	12.36	0.00
McFadden R-square = 0.626		log-likelihood function = - 45.76		
percentage of right predictions = 0.953				

Table 15: Descriptive statistics for the phase change model, secondary phase, intersection B

coefficient	**coefficient**	**standard error**	**t-statistic**	**p-value**
Intercept	-4.20	0.72	33.87	0.00
PT	0.20	0.06	11.03	0.00
McFadden R-square = 0.627		log-likelihood function = - 41.75		
percentage of right predictions = 0.915				

4.5 Validation of phase change models

The phase change models are validated with 25% of the randomly selected data. The prediction success tables for the phase change models are presented in Table 16-20. Sensitivity values are found to be above 0.75 and Type II error less than 0.25 for all the models.This shows that the models can correctly predict that the phase will be changedatleast 75% of the time. Specificity values were found to be above 0.90 and Type I error less than 0.10 for all the models. This indicates that the models can correctly predict that the phase will not be changed atleast 90% of the time. This shows that the models perform reasonably well in predicting the phase change behaviour of traffic constables.

Table 16: Prediction success table of the phase change model, primary phase, intersection A

	Success Observation	Fail Observation	Total
Success Prediction	12	11	23
Fail Prediction	3	889	892
Total	15	900	915
Sensitivity = 0.80		Specificity = 0.97	
Type II error = 0.20		Type I error = 0.03	

Table 17: Prediction success table of the phase change model, secondary phase, intersection A

	Success Observation	Fail Observation	Total
Success Prediction	12	12	24
Fail Prediction	3	402	405
Total	15	414	429
Sensitivity = 0.80		Specificity = 0.95	
Type II error = 0.20		Type I error = 0.05	

Table 18: Prediction success table of the phase change model, tertiary phase, intersection A

	Success Observation	Fail Observation	Total
Success Prediction	13	15	28
Fail Prediction	2	394	396
Total	15	409	424
Sensitivity = 0.87		Specificity = 0.93	
Type II error = 0.13		Type I error = 0.07	

Table 19: Prediction success table of the phase change model, primary phase, intersection B

	Success Observation	Fail Observation	Total
Success Prediction	7	11	18
Fail Prediction	2	175	177
Total	9	186	195
Sensitivity = 0.78		Specificity = 0.91	
Type II error = 0.22		Type I error = 0.09	

Table 20: Prediction success table of the phase change model, secondary phase, intersection B

	Success Observation	Fail Observation	Total
Success Prediction	10	6	16
Fail Prediction	2	234	236
Total	12	240	252
Sensitivity = 0.83		Specificity = 0.94	
Type II error = 0.17		Type I error = 0.06	

4.6 Calculation of critical phase times

The probability that the traffic constable will change the phase in a particular second is set to 0.5 and the critical phase times are calculated. The critical phase times are shown in Table 21. As explained previously, the phase changing decision of tertiary phase at intersection B is not found to be a binary choice due low hourly volume. So, average tertiary time is estimated instead of critical tertiary time. The average duration for which the tertiary phase of intersection B receives the right-of-way is found to be 15s.

Table 21: Critical phase times obtained from phase change models

Critical Phase Time	Intersection A	Intersection B
Critical Primary Time (s)	92	42
Critical Secondary Time (s)	45	21
Critical Tertiary Time (s)	25	Average tertiary time = 15s

4.7 Capacity of saturated streams

Capacity of manually controlled streams at intersection A (streams B-A, A-C and C-B) and intersections B (streams B-A and A-C) are determined using Eqs. 12-16 (Table 22). The capacities of manually controlled streams at intersections A are found to be 2020 PCU/hr, 748 PCU/hr and 236 PCU/hr at streams B-A, A-C and C-B, respectively, whereas capacities at intersection B are found to be 1579 PCU/hr and 762 PCU/hr at streams B-A and A-C, respectively.

Table 22: Capacities of manually controlled streams at the two intersections

Streams	Intersection A	Intersection B
B-A	2020	1579
A-C	748	762
C-B	236	-

5. Summary and Conclusion

A procedure for calculation of capacity of manually controlled streams under saturated conditions has been presented in this study. Two unique characteristics of manually controlled intersections under Indian road conditions are variable phase times based on choice behaviour of traffic constables and the mixed nature of traffic. These issues have been addressed in this study while estimating the capacity.

The methodology proposed in this research can be broadly divided into three steps: (a) development of saturation flow models to estimate the saturation flow rate (b) development of phase change models to estimate the critical phase times (c) determining capacity of manually controlled streams using critical phase times and saturation flow rates.

The proposed technique for capacity analysis has some significant advantages. Firstly, the saturation flow rate of manually controlled streams under mixed traffic conditions can be determined by this estimation technique. Secondly, it provides a mathematical model to analyse the choice behaviour of constables directing traffic. Thirdly, the optimum duration for which traffic constables allocates the right-of-way to a certain phase is determined by estimating the critical phase times. The critical phase time values are helpful in estimating the capacity of the manually controlled streams.

The proposed methodology for capacity estimation of saturated streams at manually controlled intersections can be applied at other intersection with similar geometry and traffic control measures. Furthur studies can be conducted to determine whether the proposed methodology can also be extended to four-legged manually controlled intersections.Although, the study has been conducted in India, the methodology can also be applied in developed nations with homogeneous traffic by replacing steps for calculating saturation flow rate with the Highway Capacity Manual (HCM) procedure.

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