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Impact of Side Friction on Saturation Flow at Signalized Intersections in Mixed Traffic Conditions

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Abstract
Saturation flow rate is the prime important parameter for the design of capacity of signal-controlled intersections. The width of the approach is one of the most important factors for the evaluation of saturation flow. But, in countries like India, due to the increase in commercial and social land usage, especially on roadsides, there are many factors that affect road width performance, among which side friction is one of the most important factors. In the present research study, an attempt is made to find the impact of side friction on saturation flow at signalized intersections in mixed traffic conditions. For this purpose, the data was collected from four different cities: Hyderabad, Hanmakonda, Raipur and Calicut. A multiple linear regression model is developed for estimating saturation flow in the present study. In addition to the saturation flow model, the present work provides adjustment factors for side friction to calculate saturation flow.

Author Keywords. Saturation Flow. Side Friction. Adjustment Factors. Signalized Intersections. Mixed Traffic Condition.

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1. Introduction

In India, most of the urban signalized intersections exhibit a noticeable value of reduction in saturation flow and capacity due to the presence of roadside activities like parking, pedestrian movement, auto stands, bus stands, vendors, non-motorized vehicles, etc. These activities usually occur on roadsides near the approaches of signalized intersections, resulting in a reduction in the usage of approach width for vehicular traffic movement. The side friction activities are observed as auto stands, bus stops, illegal pedestrian movements, on-street parking, street vendors, non-motorized vehicles, etc. These activities on the roadside attract the persons to purchase items from vendors and also to hire an auto or bus, which causes pedestrian movement across or along the road at signalized intersections. This, in turn, causes reduction in the usage of the approach width. Also, it is observed that most of the non-motorized vehicles, two-wheelers, three-wheelers and some other categories of vehicles park on the roadside to procure items from the vendors and roadside shops. Moreover, in India, the lack of lane discipline causes ineffective usage of approach width, especially at urban signalized intersections.

These activities may occur either for a short or long duration, occupying a noticeable portion of road width. So, the interference of this type of activity with vehicular traffic adversely affects vehicular flow, resulting in a reduction in capacity and may lead to congestion. Then, the calculated capacity will be obviously different from the actual capacity of the intersection, which causes improper estimation of the Level of Service. Therefore, it is important to propose a methodology that considers side friction when calculating actual saturation flow and capacity. Even though there are many side friction parameters that affect the performance of vehicular traffic, only a few factors were observed to be dominating: wrong vehicular movements, illegal pedestrian crossings, parking movements and movement of non-motorized vehicles.

The *Highway Capacity Manual* (2010) provides a saturation flow model considering the effect of pedestrians, but it does not consider the effect of side friction. It is, in general, not applicable to heterogeneous traffic conditions. The *Indian Highway Capacity Manual* (2017) provides a saturation flow model for mixed traffic conditions, which considers adjustment factors: bus blockage, blockage due to right-turning vehicles and initial surge. But, the *Indian Highway Capacity Manual* (2017) does not consider the effect of side friction factors. Biswas, Chandra, and Ghosh (2021) studied the influence of the side friction parameter on the capacity of undivided urban streets in India. Chauhan et al. (2019) studied the impact of side friction on urban road traffic in mixed traffic conditions. Pal and Roy (2019) studied the impact of side friction on travel speed on Indian rural roads. Irawati (2015) estimated the impact of side friction on delay in heterogeneous traffic using VISSIM simulation. Thus, the side friction parameters adversely affect the capacity of roadway facilities, especially in India. Therefore, there is a need to study the impact of side friction on the performance of signalized intersections and develop a saturation flow model that takes it into consideration.

2. Background

A comprehensive literature of earlier studies has been collected. Several earlier studies on the effect of side friction parameters on different roadway facilities and various parameters affecting saturation flow are presented in this section. A detailed study on the side friction effect was conducted (Chiguma 2007) on Indonesian urban arterial roads. In order to analyse the effect of side friction on urban arterials, the study performed a detailed microscopic and macroscopic analysis. Shao, Rong, and Liu (2011) studied several influencing factors on saturation flow rates in China. The effect of approach grade, width of lane and traffic composition on saturation flow was studied. The passenger car equivalent values for cars, motorcycles and buses were developed and lane width adjustment factor, approach grade adjustment factor and turning radius adjustment factors were developed. The study results showed that the approach width and turning radius affect the saturation flow and capacity of signalized intersections. The effect of side friction on highway traffic performance was found (Patel and Joshi 2014). The study analyzed the impact of side friction on the speed of the stream, LOS and capacity.

The delay parameter was evaluated (Irawati 2015) considering the effect of side friction under heterogeneous traffic conditions using VISSIM microsimulation and it was found that the delay occurred on the road segment with side friction is 128.838 s/veh and the delay occurred on the road segment without side friction is 96.310 s/veh. The impact of side friction on travel speed was studied on urban arterial roads (Salini, George, and Ashalatha 2016). The study developed speed prediction models for urban arterial roads in India, considering the effect of side friction and traffic composition. The impact of side friction on travel speed was studied on Indian rural roads (Pal and Roy 2019). The study proposed a roadside friction index for a trap length of 100m. Chauhan et al. (2019) studied the impact of side friction on the capacity of urban roads in mixed traffic conditions. The study proposed the product limit method for estimating capacity and a microsimulation model was developed considering the impact of side friction.

The saturation flow was estimated under heterogeneous traffic conditions in Surat (Kulkarni et al. 2015). The headway method was used to estimate saturation flow in the field. The study developed PCU values and dynamic saturation flow values using VISSIM 7.0. The impact of vehicle composition on saturation flow (Ramireddy, Sala, and Ravishankar 2020) in India. The saturation flow was estimated using TRRL (Transportation Research Record Laboratory) Road Note 34 method. A MLR (Multiple Linear Regression) model was developed to estimate saturation flow considering the effect of vehicle composition. Arya V. S et al. (2020) studied the effect of side friction on urban roads in India. The study found the percentage of reduction in speed from a free flow speed for different categories of vehicles and the Level of Service was defined considering the impact of side friction.

The impact of encroaching vehicles on saturation flow was studied (Sushmitha and Ravishankar 2020) in mixed traffic conditions. The study developed two multiple linear regression models for finding saturation flow: one with considering encroaching vehicles and another one without considering encroaching vehicles. The results of the study showed that the percentage reduction in saturation flow was 8.5% when the percentage of encroaching vehicles was 27%. Various methods were presented for estimating saturation flow (Mondal and Gupta 2021) and various factors affecting saturation flow under various traffic conditions. The Approach width, Intersection geometry, Vehicle type, Pedestrian crossing, Parking activity and Signal time were found to affect saturation flow. Sushmitha and Ravishankar (2021) studied the impact of pedestrian crossing on saturation flow at signalized intersections. The study developed a multiple linear regression model for estimating saturation flow, considering geometric, signal control, vehicle composition and illegal pedestrian crossings. Also, the pedestrian adjustment factors were found to estimate saturation flow in the presence of illegal pedestrian crossings.

From the literature review of the earlier studies, it can be concluded that side friction is one of the most important factors which affects roadway performance. On the other hand, experts who conducted their studies on saturation flow developed various saturation flow models considering several parameters like traffic composition, geometric factors, signal control factors, turning movements, pedestrians, etc. But the effect of side friction factors on saturation flow at signalized intersections has not been reported in earlier studies. The *Highway Capacity Manual* (2010) and the *Indian Highway Capacity Manual* (2017) explain various adjustment factors for saturation flow in homogeneous and heterogeneous traffic conditions, respectively. But these manuals are also not explaining the effect of side friction factors on saturation flow at signalized intersections. So, there is a need to find the impact of side friction on saturation flow and to develop adjustment factors for the side friction parameters.

3. Method

Figure 1 shows the flow chart of the methodology proposed in the present study to develop the saturation flow model and side friction impact, as well as the conceptual framework of the present research work. In the present study, the variables considered for saturation flow modelling are approach width, green time, percentage of two-wheelers, percentage of three-wheelers, percentage of cars, percentage of LCV (Light Commercial Vehicles), percentage of heavy vehicles (HV), percentage of turning vehicles and various side friction factors (auto stands, bus stops, illegal pedestrian movements, on-street parking, street vendors and non-motorized vehicles).

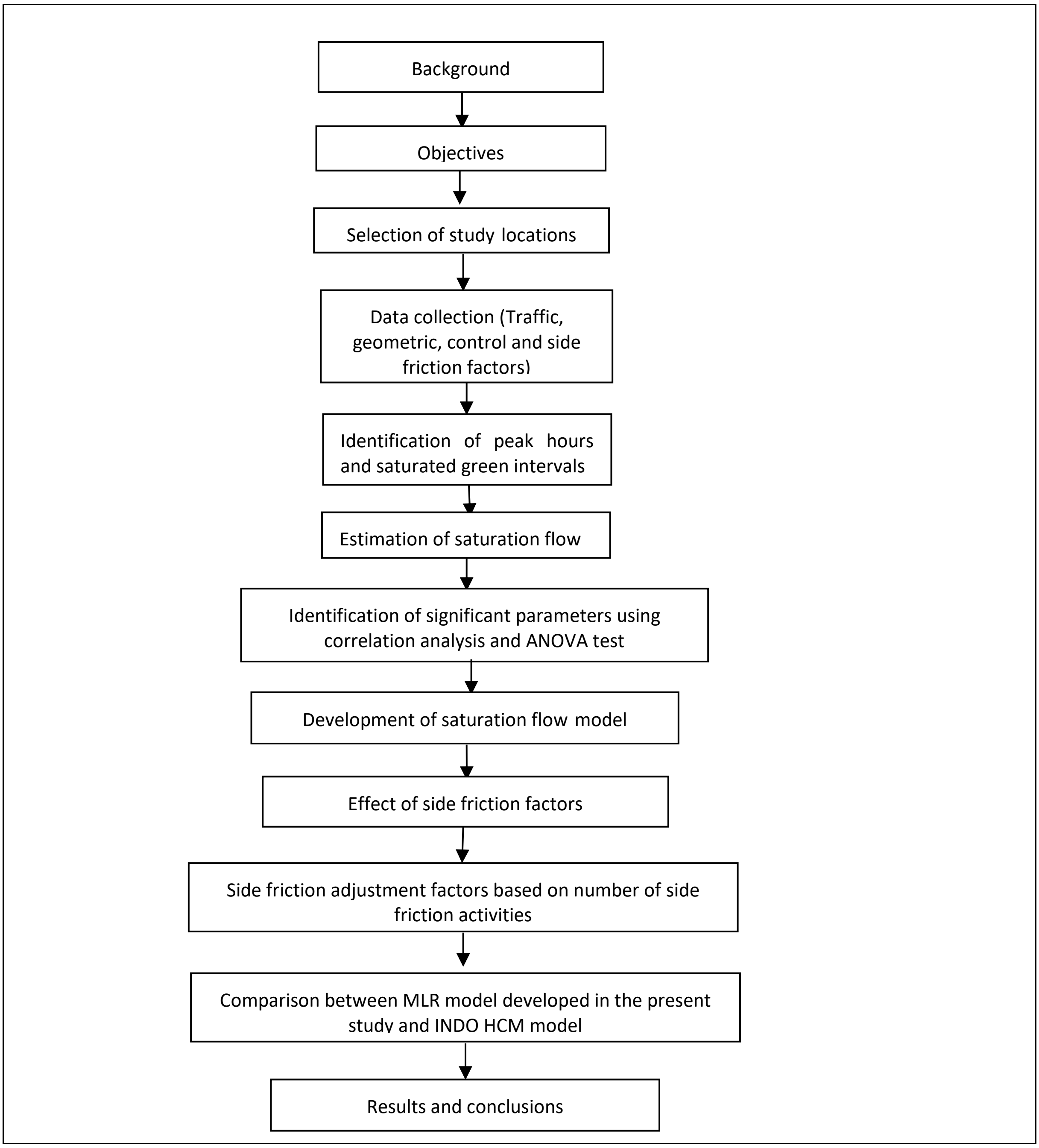

Figure 1: Methodology

4. Study Locations and Data Collection

Field data for the present study was collected from eight signalized intersections from four different cities: Hanmakonda, Hyderabad, Calicut and Raipur. The study locations were selected based on the criteria of varied approach widths, varied traffic composition, varied turning movements, varied number of side friction factors and also based on the convenience of collecting data. All eight intersections are four-legged intersections with permitted through, right and left movements. Bachupally, Gandimaisamma, Suchitra and Patny circle intersections are located in Hyderabad, Kazipet and KU intersections are selected from Hanmakonda, Gurunanakdwar intersection is selected from Raipur and Eranhipalam intersection is selected from Calicut. The satellite images of the study intersections are shown in Figures 2-5.

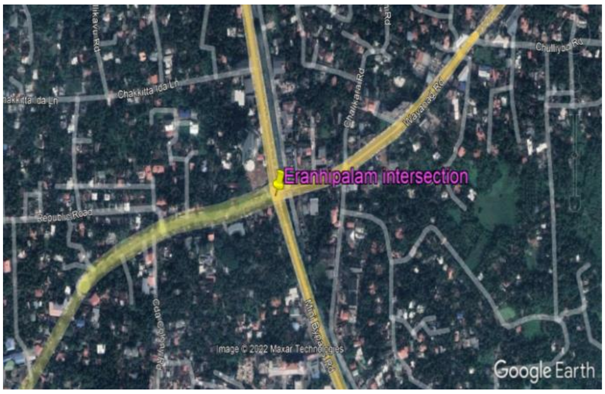

Figure 2: Satellite image of intersection from Calicut

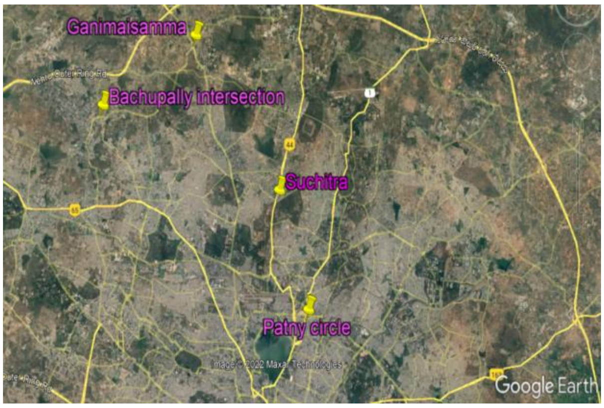

Figure 3: Satellite image of intersections from Hyderabad

Figure 4: Satellite image of intersections from Hanmakonda

Figure 5: Satellite image of intersection in Raipur

The traffic data such as vehicle composition and turning movements, the side friction activities such as wrong vehicular movements (especially two-wheelers, three-wheelers, and buses), illegal pedestrian crossings, parking movements and movement of non-motorized vehicles were collected using a video-graphic method. Traffic data was collected in the morning from 7 to 11 and in the evening from 4 to 8. The approach widths of the selected intersections were calculated using an oedometer and tape. The green time, amber time and cycle time details were collected using a stopwatch during data collection. The approach width and signal control details are presented in Table 1.

Intersection	Approach	Width of approach (m)	Green time (s)	Amber time (s)	Cycle time (s)
	Bowenpally	10	30	2	230
Suchitra	Bashirabad	10	40	2	230
	Suchitra	10.5	80	2	230
	Old alwal	9.5	70	2	230
	Balnagar	7.5	45	3	170
Gandimaisamma	Miyapur	5.5	35	3	170
	Maisamma	5.6	35	3	170
	Narsapur	6	43	3	170
	Mallampet	6.4	40	4	180
Bachupally	Miyapur	7.3	45	4	180
	Gandimaisamma	7.5	50	4	180
	Nizampet	5.3	30	4	180
	Secunderabad	8.2	25	2	110
Patny circle	Begumpet	7.9	25	2	110
	Paradise	6.5	25	2	110
	Rastrapati bhavan	7.6	25	2	110
	Hyderabad	8.8	35	5	130
Kazipet	Hanmakonda	8	35	5	130
	Railwaystation	6.7	25	5	130
	Vishnupuri	6	15	5	130
	100 ft road	5.9	27	3	130
KU	KU bypass	5.8	27	3	130
	Hanmakonda	7	32	3	130
	Karimnagar	7	32	3	130
	Telibandha	6.7	30	4	110
Gurunanakdwar	Gadichowk	7.2	30	4	110
	Gurunanakdwar	5.8	20	4	110

Eranhipalam	Fruit market	3.7	15	4	110
	Calicut	7.1	38	3	180
	REC	7.9	44	3	180
	Kannur	7.9	46	3	180
	Ariyadthupalam	10.5	40	3	180

Table 1: Approach width and signal control data

All the selected intersections are four-legged intersections and have one, two and up to three lanes.

5. Data Retrieval

From the collected video data, the classified vehicle volume count, the turning movement proportions and the number of side friction activities were collected for each cycle and for every 15 minutes time interval. Based on the extracted traffic volume data, the peak hours and saturated green intervals are found. The side friction activities are observed at every leg of each study intersection, which includes street vendors encroachment, illegal pedestrian movements, parking activities near roadside shops, on-street parking, wrong vehicular movements and movement of non-motorized vehicles. The proportion of different vehicle categories, right turning movements and number of side friction activities are presented in Table 2.

Intersection	TW	3W	Car	LCV	HV	RT	Side friction activities (activities/hr)
Suchitra	0.55	0.21	0.25	0.008	0.03	0.16	1109
Gandimaisamma	0.44	0.13	0.25	0.11	0.07	0.37	2383
Bachupally	0.48	0.14	0.24	0.08	0.04	0.35	2064
Patny circle	0.41	0.17	0.31	0.05	0.04	0.27	1625
Kazipet	0.41	0.11	0.32	0.11	0.05	0.35	2236
KU	0.40	0.13	0.29	0.09	0.07	0.40	2231
Gurunankdwar	0.39	0.09	0.33	0.09	0.08	0.39	2695
Eranhipalam	0.45	0.15	0.28	0.07	0.05	0.33	1889

Table 2: Proportion of vehicles, right turns and side friction activities

It is observed that the traffic composition at the selected locations consists of 40-50% of two-wheelers and the maximum number of side friction activities is 2695 activities/hr.

6. Field Saturation Flow

In the present study, the saturated green intervals were identified from video-recorded data. The vehicle composition and turning movements were extracted during every 5-second count interval. The flow values corresponding to each 5-second count interval are extracted for about 40 cycles during saturated green intervals. If there are less than two vehicles passed through the stop line in any count interval, then that particular count interval has been omitted from the analysis. In the present study, to convert the saturation flow rate from veh/hr to pcu/hr, the *Indian Highway Capacity Manual* (2017) pcu values are used (Chand, Gupta, and Velmurugan 2017).

$$S = \sum_{Xn} \frac{3600}{T} \quad (1)$$

Where, S is the saturation flow rate in pcu/hr, X is the pcu value of corresponding vehicle category, n is the vehicle count passed through the stop line in each count interval and T is the saturation green interval in seconds.

7. Modelling of Saturation Flow

The signal control characteristics, such as green time and cycle time, the geometric characteristics, such as approach width and number of lanes, percentage of different vehicle categories, such as two-wheelers, three-wheelers, cars, light commercial (LCV), heavy vehicles (HV) and right turning movements are considered in the present study, in order to develop a saturation flow model. The correlation and regression analyses were performed in order to identify the significant variables. From the ANOVA analysis, the green time, the approach width, the percentage of two-wheelers, the percentage of right-turning vehicles and the side friction activity number are found to affect the saturation flow significantly. The data points used in the present study for the development of the saturation flow model are 32 points (8 intersections X 4 approaches). The correlation matrix of the significant variables is shown in Table 3.

	S	W	G	Ptw	Prt	Side friction
S	1					
W	0.83	1				
G	0.67	0.31	1			
Ptw	0.71	0.24	0.38	1		
Prt	-0.92	-0.02	-0.22	-0.26	1	
Side friction	-0.83	-0.17	-0.32	-0.13	0.11	1

Table 3: Correlation matrix of the significant variables

Where, S= saturation flow in pcu/hr, W= width of approach in meters, G= green time seconds, Ptw= percentage of two-wheelers, Prt= percentage of right turning vehicles and Side friction is the number of side friction activities/hr. Based on the significant variables, a multiple linear regression (MLR) model is developed in the present study. In general, the MLR model develops linear relations between dependent variables and independent variables. Each MLR model must follow the assumptions: all independent variables should be independent of each other, all variables must be normally distributed, all variables must be continuous, dependent and independent variables must have a linear relationship. The MLR model developed for saturation flow in the present study is given in Equation 2.

$$S = 140W + 13G + 0.73Ptw - 54PPrt - 0.25SIDE\ FRICTION + 4184 \quad (2)$$

The R^2 value of the model is 0.924 and the standard error of the estimate is 112. From the model, it is very clear that, as the approach width increases, the saturation flow is also increasing because the wider approaches allow a greater number of vehicles to pass through the intersection. As the green time increases, the saturation flow is also found to increase because these two-wheelers occupy the empty spaces between vehicles and try to escape from the queue very easily. As the percentage of right-turning vehicles is increasing, the saturation flow is found to decrease because the right vehicles may cause obstruction through traffic. As the number of side friction activities increases, the saturation flow is found to decrease because these side friction activities are occupying a noticeable portion of roadway width and they are also causing obstructions to vehicular movement when green time is given to vehicles.

8. Side Friction Adjustment Factors

In the present research work, the side friction adjustment factors were determined for saturation flow by comparing the saturation flow model developed in the present study with the same equation under ideal conditions (when side friction=0 activities/hr.) The side friction adjustment factors are given in Table 4.

Range of side friction activities (activities/hr)	Adjustment factor
845-1250	0.85-0.76
1435-1658	0.64-0.59
1745-2034	0.54-0.32
2135-2568	0.29-0.16
2685-3245	0.14-0.09

Table 4: Side friction adjustment factors

The side friction activities observed in the field at study locations range from 845 activities/hr to 3245 activities/hr.

9. Comparison of Saturation Flow Values from Different Methods

In this section, the saturation flow values are compared among those obtained from the field, MLR model (developed in the present study), *Indian Highway Capacity Manual* (2017) and *Highway Capacity Manual* (2010). The saturation flow values are given in Table 5.

Approach	Field SF pcu/h	SF using MLR (considering side friction)	% reduction in SF	SF using INDO HCM (2017)	% reduction in SF	SF using HCM (2010)	% reduction in SF
Bowenpally	4748	4754	0.12	5400	13.73	7564	59.03
Bashirabad	4878	4902	0.49	5400	10.70	7685	57.24
Suchitra	5765	5776	0.19	5355	7.11	6985	21.07
Old alwal	5283	5302	0.36	5415	2.49	8560	62.45
Balnagar	4012	4006	0.15	5175	28.98	5956	48.45
Miyapur	2650	2612	1.43	3465	30.75	4356	64.37
Maisamma	1802	1823	1.16	3528	95.78	4254	136.01
Narsapur	2890	2899	0.31	3780	30.79	4876	68.71
Mallampet	3161	3183	0.69	4032	27.55	4674	47.86
Miyapur	3695	3724	0.78	5124	38.69	5676	53.60
Gandimaisamma	3874	3882	0.21	5175	33.58	5946	53.48
Nizampet	2440	2455	0.62	3339	36.84	4325	77.25
Secunderabad	4200	4275	1.78	5314	26.50	6845	63.22
Begumpet	3944	3954	0.25	5261	33.43	6486	65.34
Paradise	3432	3456	0.69	4095	19.32	5467	59.09
Rastrapati bhavan	3887	3892	0.13	5198	33.78	5347	37.56
Hyderabad	3650	3642	0.22	5386	47.50	6879	88.46
Hanmakonda	4447	4432	0.33	5280	18.75	6035	35.79
Railwaystation	2540	2510	1.18	4221	66.18	5897	132.5
Vishnupuri	1660	1675	0.91	3780	127.7	5435	227.0
100 ft road	2603	2614	0.42	3717	42.79	5421	108.97
KU bypass	2528	2503	0.98	3654	44.54	4867	92.45
Hanmakonda	3365	3361	0.12	5040	49.76	7249	115.23
Karimnagar	3521	3530	0.25	5044	43.15	5768	63.34

Telibandha	3320	3311	0.27	4221	27.13	5678	71.34
Gadichowk	3618	3609	0.25	5098	40.89	6759	86.76
Gurunanakdwar	2096	2106	0.47	3654	74.34	4538	116.57
Fruit market	1152	1159	0.60	2331	102.32	4236	267.67
Calicut	3234	3245	0.34	5069	56.75	6435	99.09
REC	3970	4001	0.78	5261	32.53	6657	67.08
Kannur	3839	3842	0.07	5266	37.54	6745	75.76
Ariyadthupalam	2911	2932	0.72	5355	83.56	6298	116.56

Table 5: Saturation flow rates

From Table 5, it is very clear that the saturation flow values calculated using the MLR model are close to those attained from the field. The saturation flow values calculated using *Indian Highway Capacity Manual* (2017) deviated from those attained from the field; because the *Indian Highway Capacity Manual* (2017) saturation flow model considers three adjustment factors: bus blockage, blockage due to right turn and initial surge. The *Indian Highway Capacity Manual* (2017) is not considering the side friction effect. The saturation flow values calculated using *Highway Capacity Manual* (2010) model extremely deviate from those attained from the field; because the *Highway Capacity Manual* (2010) model was also not considering the side friction effect and was developed based on homogeneous traffic conditions.

10. Results

The Kolmogorov-Smirnov (K-S) test was done for the selected variables to check whether the variables followed a normal distribution. The variables approach width, green time, percentage of two-wheelers, percentage of right-turn vehicles, and side friction follow normal- distribution, so only these variables are used for modelling. The results of the K-S test are shown in Table 6. The t-stat, standard error, p-value, 95 percent Confidence Interval, Variance Inflation Factor (VIF) of the variables are given in Table 7.

Parameter	K-S test_ p-value
Saturation flow	0.879
Approach width	0.763
Green time	0.654
Percentage of two-wheelers	0.608
Percentage of right turn movements	0.724
Side friction	0.825

Table 6: K-S test P-values

Parameter	Std. error	p-value	t-stat	Lower 95% CI	Upper 95% CI	VIF
W	57	0.023	4.23	0.76	66.5	3.46
G	6.4	0.015	2.34	11.24	58.54	2.15
Ptw	16	0.029	3.55	10.76	60.08	1.56
Prt	11	0.012	2.56	4.67	52.57	3.08
Side friction	0.13	0.005	4.67	0.45	55.46	4.35
Intercept	1026	0.034	4.12	-1546	3124	-

Table 7: The MLR model statistical values

After analyzing the results of the K-S test, correlation analysis and statistical values, it can be concluded that the variables selected for the development of saturation flow satisfy the assumptions of the MLR model.

11. Conclusions

The present research work explains a methodology to understand the effect of side friction on saturation flow at urban signalized intersections where side friction activities prevail. From the field observations, it can be concluded that the reduction in the saturation flow is observed to increase by 4.8% with every 3.5% increase in the side friction activities. So, the side friction activities adversely affect the saturation flow. Also, the present study developed a MLR model for saturation flow in the presence of side friction activities. The model exhibited good prediction capability of saturation flow rate in the presence of side friction activities. The developed saturation flow model can be used to calculate saturation flow whenever there is a considerable number of side friction activities. Also, the field saturation flow values are compared with MLR, *Indian Highway Capacity Manual* (2017) and *Highway Capacity Manual* (2010) saturation flow values. The MLR saturation flow values are very near to those attained from the field. The *Indian Highway Capacity Manual* (2017) saturation flow values deviate from the field values because the *Indian Highway Capacity Manual* (2017) is not considering the side friction effect. The *Highway Capacity Manual* (2010) saturation flow values highly deviate from the field values because the *Highway Capacity Manual* (2010) was also not considering the effect of side friction and was developed for homogeneous traffic conditions. In addition to the development of the MLR model, the present research work provides the adjustment factors for side friction activities. Thus, the present study is helpful in evaluating the realistic values of saturation flow at urban signalized intersections.

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