Analysis of the Impact of users' Violations on the Saturation Flow Rate at Signalized Intersections

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Abstract

Accurate estimation of saturation flow rate is a prerequisite for accurate estimation of level of service and delays of signalized intersections. Saturation flow rate of intersections depends on many factors, including traffic behavior and culture. One of the important problems of traffic behavior in Iran is the violation of law at the physical region of intersections. The main purpose of this paper is to study the effects of violations such as pedestrians and motorcyclists ignoring the red light and vehicles changing their lanes at the physical region of intersections on the saturation flow rate.

Data were gathered through monitoring from 100 cycles of traffic light at Valiasr-Taleghani intersection in city of Tehran during evening peak hours and recording about 3000 headways. The study is based on the use of linear and nonlinear regression models. The results show that users'violations affect saturation flow rate; one unit increase in the traffic light violations by motorcyclists (per hour) leads to 0.66 unit decrease in the saturation flow rate, and one unit increase in the violations by pedestrians passing the crosswalk near the intersection entrance reduced the saturation flow rate by 0.43. The non-linear regression model was used to estimate the coefficients for each of the violations and to adjust the base saturation flow rate values suggested by the highway capacity manual of United State.

Keywords: Saturation flow rate, intersection capacity, traffic behavior, traffic law violation

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1. Introduction

Intersections are the points of convergence of multiple traffic flows, and therefore, play an important role in the quality of urban transportation network. Most of the delays and travel time of a given transportation network can somehow be traced back to its intersections. At the majority of signalized intersections, the presence of conflict between users, the time lost at the onset of green phase, and other such issues cause the capacity of these intersections to be far less than that of approaches connected to them. Therefore, intersections are commonly considered as the bottlenecks of transportation networks [Lu, Shi and Masato, 2006].

Estimation of saturation flow rate is an important step of any analysis on the performance of urban signalized intersections. In fact, accurate estimation of saturation flow rate is a prerequisite for proper estimation of delays and level of service at a signalized intersection [Shang, Zhang, and Fan, 2014]. Imprecise estimation of saturation flow rate and thus the capacity of the intersection injects an error in all stages of timing, delay calculation, and the resulting level of service. Consequently, function of intersection will be different from what it has been designed for, and the result will be congestion, delays, long queues and poor level of service. To improve the performance of a system, the influencing factors need to be identified and the existing problems have to be studied. In the systems wherein human behavior plays a significant role, this study becomes much more important [Khabiri, 2018].

Intersections are among those systems whose performance are directly dependent on the behavior of users. Saturation flow rate is a major factor in determination of capacity of signalized intersections, and depends on various factors such as geometric characteristics, flow characteristics, type of movement and traffic behavior. Identification of influencing factors and the extent to which they impact the saturation flow rate has always been a challenge. One of the major problematic traffic behaviors in Iran is the violations which occur at physical region of intersection by users. One example of these violations is the motorcyclists and pedestrians crossing the red traffic light, which lead to not only decreased safety and increased traffic accidents, but also reduced flow rate and capacity and increased delay. The main purpose of this study is to investigate and analyze the impact of violation at physical region of the intersection by users on the saturation flow rate of through movement.

This paper consists of six sections; after the introduction presented in the first section, sections 2, 3, and 4 present, respectively, a review of previous studies, methodology and analysis of sample data. Sections 5 describes the modeling and interpret the results, and sections 6 concludes the paper.

2. Literature Review

Saturation flow rate and capacity of intersections depend on many factorswhich have been the subject of extensive studies, but only few studies have assessed the effect of traffic behavior at physical region of intersections on the saturation flow rate and capacity. Viney and Pretty assessed the effect of pedestrians on saturation flow rate of turning vehicles [Viney and Pretty, 1982].

These researchers divided the green phase to five parts based on three possible modes for the pedestrians and showed the significant effects of pedestrians on the reduction of saturation flow rate. In a study conducted in Santiago, Chile, Herrera and Coeymans presented a new regression model for estimating saturation flow rate of turning vehicles by taking the effect of pedestrians into account [Coeymans and Herrera, 2003]. In a study in China, Wei et al. investigated the decreasing effect of pedestrians and bicyclers on saturation flow rate and capacity of turning vehicles [Wei et al. 2003]. These researchers presented some quantitative values to incorporate the effects of non-motorized vehicles (bicycles and pedestrians) for correction of saturation flow rate and capacity. Tian et al. assessed the effect of conflicting pedestrians on capacity and delay of actuated signalized intersections in Japan[Tian and Xu, 2006]. They presented a new probabilistic model for estimating the capacity and delay in actuated signalized intersections. Validation of the model showed better results than the Highway Capacity Manual of United States [HCM], and it was also shown that the process of HCM has many errors in low volumes of pedestrians. Chen et al. assessed the capacity reliability of signalized intersection through the assessment of saturation flow rate in mixed traffic conditions (presence of motorized vehicles, pedestrians and bicycles) and found that the capacity reliability is sensitive to the average volume of pedestrians and bicyclers conflicting with the motorized flow and this sensitivity is much greater in high volumes of vehicles [X. Chen, Shao, and Dong, 2009]. Shaw et al. in a study conducted in China found that base saturation flow rate and its adjustment coefficients mentioned in the HCM were not appropriate for China due to differences in culture and traffic behavior [Shao, Rong, and Liu, 2011]. They suggested that 1800 vehicles per hour in lane (pc / h / ln) is appropriate for the base saturation flow rate at signalized intersections of China. Jie et al. studied the capacity of signalized intersection through assessment of saturation flow rate in China and the Netherlands and observed that the performance of intersections in China is 20 to 30 percent weaker than in the Netherlands [Jie, van Zuylen, and Lu, 2012]. These researchers attributed this issue to difference in traffic culture and behavior such as long start lag due to excessive conflict of vehicles with pedestrians at the start of green phase, irregular behavior and sudden lane changing of drivers and limited use of space in China.

Jiang assessed the impact of conflict between the pedestrians and vehicles on reduction of saturation flow rate and delay of turning vehicles in Sweden [Jiang, 2014]. The results of this study showed that the impact of conflict on saturation flow rate and delay depends on the volume of pedestrians and vehicles. They reported that a 500 unit increase in the number of pedestrians leads to 100 units decrease in the saturation flow rate of turning vehicles. It was also reported that during peak hours, pedestrians increase the travel time by 100 percent.

Hunter et al. surveyed 975 recorded events in the US between vehicles and pedestrians during the survey days to determine drivers' performance models at pedestrian crossings [Hunter et al., 2015]. The results of logistic regression analysis show that the probability of drivers' ability to perform performance increased by observing pedestrians due to the effect of factors such as vehicle distance to the crosswalk, low speed of vehicles, presence of pedestrian on the crosswalk edge, and performance of vehicles in the opposite direction of passage. Chen et al. assessed the effect of pedestrians violating the traffic laws on reduction of saturation flow rate of protected left turn lanes in Beijing, China. These researchers divided the pedestrians to 4 levels and reported that violating pedestrians can reduce saturation flow rate by up to 15.7 percent[Chen, He, and Sun, 2015]. They observed that the amount of reduction in saturation flow rate also depends on the distance between the pedestrian and the vehicle, as a distance of less than 4 meters showed more impact on the reduction of saturation flow rate.

As already observed most studies have assessed the reduction of saturation flow rate and capacity of turning vehicles facing the pedestrian in the green phase. But the important difference in Iran is the phenomenon of pedestrians and motorcyclists violating of law by crossing the red light in conflict with the incoming flow. This phenomenon is a problem concerning with traffic behavior and can be seen in many intersections and streets in Iran. This study seeks to assess the impact of this type of violations on the saturation flow rate.

3. Research Methodology

This section consists of two parts; the first part defines and introduces the method of estimation of saturation flow rate, and the second part describes the theory of linear and non-linear (power) regression models.

3.1 Estimation of Saturation Flow Rate

Saturation flow rate is a qualitative measurement of intersection performance and represents the intersection capacity during operation [falaki, 2009]. When the light turns green, vehicles attempt to cross the intersection. The headway of vehicles in this case can be described as the elapsed time between the passage of rear axle of two consecutive vehicles over the stop line. In HCM method, the effect of drivers' reaction towards green light and start of acceleration has been assumed for only the first four vehicles in the queue. In this method, time saturation headway is calculated by average of time headways of the fifth vehicle to last one in the queue before the light turns red. If the flow does not get saturated during the whole cycle, the saturation headway must be calculated for at least 10 vehicles in the queue. Saturation flow rate is defined as the amount of flow that would cross a line of intersection during a one-hour long green light [HCM, 2010].
Saturation headway can be calculated through equation (1) and saturation flow rate can be obtained from equation (2).

$$h = \frac{\sum_{i=5}^{n} h_i}{n-4} \quad (1)$$

$$S = \frac{3600}{h} \quad (2)$$

In the above equation:
h_i: is the headway of vehicle i,
h: is the saturation headway and
S: is the saturation flow rate (vehicle per hour per line).

3.2 Regression Model

Many studies have shown that the saturation flow rate has a normal distribution. Therefore, regression model can be used to estimate saturation flow rate. According to equation (3), linear regression model links the observed saturation flow rate in each phase of the green light to a set of explanatory variables.

$$Y_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \cdots \beta_k X_{Ki} + \mathcal{E}_i \quad (3)$$

In the above equation: k is the index of explanatory variables, Y_i is the i-th observed saturation flow rate, X_{ki} is the value of explanatory variable k for observation i, β_k is the estimated coefficients corresponding to X_{ki} , and β_0 is the model constant, which here is equal to base saturation flow rate (saturation flow rate in ideal conditions). It is assumed that error term $\mathcal{E}_i$ has a normal distribution with a mean of zero and variance of σ^2. Non-linear regression has different forms such as second order, third order and exponential polynomial and power models.
This study uses the power non-linear regression model shown in equation (4), which is a common method for the modeling of saturation flow rate.

$$\log y_i = \log C_0 + C_1 \log X_{1i} + \cdots C_k \log X_{Ki} \quad (5)$$

After obtaining the coefficients of independent variables, equation (4) can be rewritten as equation (5):

$$Y_i = C_0 {X_{1i}}^{C_1} {X_{2i}}^{C_2} \ldots {X_{ki}}^{C_K} \quad (6)$$

where cvalues are the constant coefficients (similar to β in linear regression), X_{ki} are the explanatory variables, and C_0 equals the base saturation flow rate.

4. Sample Data

The intersection studied in this paper is Valiasr-Taleghani intersection in Tehran. This intersection is located in the crowded area of the city center and has mixed traffic (composed of pedestrians, motorcyclists and vehicles). This intersection has two one-way movements, west-to-east and south-to-north each with three lanes. The required data was recorded through monitoring from 100 cycles of total 110 cycles of traffic light during evening peak hours. The MAGIX Movie Edit video editing software was used to ensure the good accuracy of recording. In this study, the saturation headway was recorded
To properly observe the effect of violations of pedestrians and motorcyclists at the physical region of intersection on the saturation headway at the start line, vehicles' headway over the period of 30 seconds after the passage of first four vehicles was recorded, and saturation flow rate of each cycle was estimated.

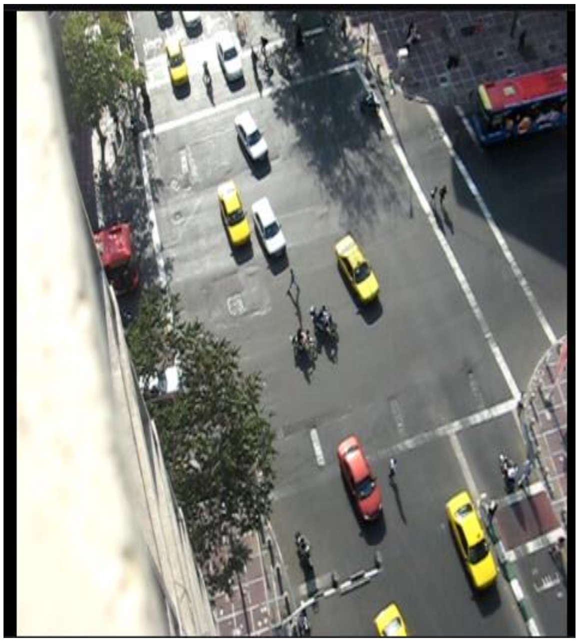

Figure 1. a view of Valiasr-Taleghani intersection

Figure 2. an image of MAGIX software environment

. **Table 1. Variables used in modeling**

Type of Variable	category	Description	symbol	unit
Independent	Variables concerned with violation of physical region of the intersection by users	the number of pedestrians violating the traffic light in crosswalk 1 (entrance)	VPED1	Number (hour)
		the number of pedestrians violating the traffic light in crosswalk 2 (exit)	VPED2	Number (hour)
		the number of motorcyclists violating the traffic light	VMOT	Number (hour)
		The number of lane changes by vehicles on the physical area of intersection (between the entrance and the exit of intersection(	Lchge	Number (hour)
	Variables of flow properties	Percentage of motorcycles	Pmot	Percentage
		Percentage of buses	Pbus	Percentage
Dependent	-	Saturation flow rate	S	vehicles per hour per lane (vphpl)

. Table 2. Statistical description of data

	Min	Max	Mean	standard deviation
S	1260	2160	1648	226.20
H	1.67	2.86	2.225	0.301
Pmot	0	33.33	18.489	7.052
Pbus	0	10.53	2.85	3.017
VPED1	0	7	2.2	1.528
VPED2	0	11	2.6	2.29
VMOT	0	4	1.2	1.041
Lchge	0	7	2.65	1.77

Table 3. Frequency distribution of the number of motorcyclists violating the traffic light

The number of motorcyclists violating the traffic light	absolute frequency	Relative Frequency (percent)
0	32	32
1	29	29
2	29	29
≥3	10	10
Total	100	100

At this intersection, lanes width are almost standard (3.6 meters), and there are no parking lanes near the entrances. In this study, the slope of intersection is assumed to be zero, and the effect of presence of bus stations in the intersection area on the flow rate is assumed to be negligible. Moreover, heavy vehicles in the area inside Tehran do not have the right to drive, and saturation flow rate is evaluated for through movement and the impact of CBD area was ignored. Variables concerned with violation of physical region of the intersection by users.

The presence of motorcycles and buses in the traffic flow can have substantial effects on the variations of headway and saturation flow rate. Therefore, in addition to variables related to violations, two additional variables, including percentage of motorcycles and buses to all vehicles were also considered as independent variables.

Table 1 shows the variables used in modeling. Table 2 shows the description of variables, all defined for a period of 30 seconds after the passage of first four vehicles in each green phase. According to Table 2, the average value of saturation flow rate is estimated to be 1648 vehicles per hour per lane (hereafter abbreviated as vphpl), and the average headway of vehicles is 2.22 seconds. The vehicles flow through entrance and exit lanes is faced with approximately 5 violations by pedestrians.

About 60 percent of pedestrians violating the traffic light are men and the remaining 40 percent are women, which may be due men's greater inclination to take risks or their less patience for waiting for the traffic lights. The average number of motorcyclists violating the traffic lights is 2.1 per green phase.

The average presence of motorcycles in the traffic flow is 18.5%, but it sometimes reaches up to more than 30%; while for buses these values are 3% and 10% respectively.

According to Table 3, in more than two-thirds of cycles motorcyclists have violated the traffic light, and in more than 40 percent of cycles there

have been 2 or more of these violations, which indicate the fundamental problems in traffic behavior of motorcyclists in Iran. Table 3 also shows the frequency of violations by motorcyclists in each phase of green light for 100 cycles. The high number of violations by pedestrians and motorcyclists can lead to a significant decrease in the saturation flow rate and increase the delay value, and serious problems in term of safety issues may arise. This shows the need to imposing strict laws and making efforts to reform the traffic culture.
Since the saturation flow rate is estimated in hours, the independent variables used in the modeling procedure are also in hours.

5. Results Of Analysis and Modeling

This section presents the results obtained by estimating the coefficients of linear regression model by the use of STATA software and through ordinary least squares (OLS) method. To fit the regression model in many research and reference books, at least a ratio of 10 data per 1 independent variable is proposed in the model [Harrell, 2013] In this research, the independent variables entered in each regression analysis were maximum 7. As shown in the results of the analysis, the maximum number of coefficients of variables in the model is 5. Accordingly, the minimum observation volume required is 50 to 70. Therefore, the adequacy of the sample number for constructing the regression model is in the current research.

To initiate the process of modeling, different types of variables and their logical combination were assessed, and, ultimately, the model with the greatest improvement in the explanatory value (R2) and the best fit (F test) was selected. The results of this part of work are presented in Table 4. The following results are obtained from Table 4:

- The variable representing the percentage of motorcycle in the traffic flow is statistically significant (t-statistic=3.55) and has an increasing effect on the saturation flow rate. The positive impact of this variable is due to lower headway of motorcycle compared with other vehicles and the significant presence of motorcyclists in the traffic flow. The coefficient of variable representing the percentage of buses is -17, which shows the significant negative impact of this variable on the saturation flow rate. Naturally, this negative effect can be attributed to slow acceleration and large size of buses.
- The variables representing the number of pedestrians and motorcyclists violating the traffic light at crosswalk 1 (entrance) both showed significant impact (with T-test of respectively 5.11 and 5.57 at a confidence level of 99%) on the reduction of flow rate. Here, the interesting point is the higher significance and the greater coefficient of the number of violating motorcyclists comparted with pedestrians. This difference is reflected in the results showing as one unit increase in violations by motorcyclists per hour, the value of saturation flow rate decrease 0.66 unit decreases, while for the counterpart pedestrians, this value is 0.43. This results show that motorcyclists make a greater disturbance in the traffic flow. Violating motorcyclists to pass through the vehicles at saturation time (vehicles moving consecutively with minimum headway with respect to each other) use spiral movements, and once crossed a lane should stop and find the right moment to cross the next lane; furthermore, in many cases, this motorcyclist should travel a distance along the lane to find an opportunity for crossing. But pedestrians violating the traffic light can easily pass through the vehicles at saturation time. The other reason could be the excessive drivers' fear from motorcyclist in Iran, which cause them to act with extra caution and

reduce acceleration and speed when observing motorcycles.

- Since the saturation headway is measured on the start line (stop line), according to Table 5, the impact of violating pedestrians at the crosswalk closer to the start line (entrance) is far greater than the impact of those at the farther crosswalk (exit).
- The combination (product) of variables representing the number of lane changes and the one representing the number of pedestrians violating the traffic light at crosswalk 2 (exit) showed a statistical significance. As can be observed in the presented images, this result can be attributed to the fact that many of the lane changes occur at the end of physical region near the exit crosswalk. Some of these lane changes is from central lanes toward the side lane (right) for picking up or discharging passengers at the intersection area. On the other hand, these stops lead to congestion and low speed at the side lane and encourage many drivers to change their lanes toward the center so as to avoid this traffic. The increased number of lane changes in combination with violations of pedestrians near the exit of intersection creates a traffic block causing an extremely slower flow rate and those effect at time headway are transferred toward start line.
- The constant obtained from the model is equal to base saturation flow rate (ideal conditions, the absence of explanatory variables). This value is estimated to 1804 passenger cars per hour per lane (pcphpl).

Table 4 shows that all variables in the model are statistically significant at the 95% confidence level, and the R2 of the model is about 0.65, which means that 65% of the variations in saturation flow rate can be explained by the five independent variables used in the model. Meanwhile, the value of F-test is 6.35, and its significance level is zero, which indicates that the combination of independent variables is important in explaining the saturation flow rate.

Table 4. Results obtained by the linear regression model

variable	coefficients		
	value	T-test	Significance level
Pmot	7.12	3.55	0.001
Pbus	-17.01	-3.24	0.002
VPED1	-0.43	-5.11	0.000
VMOT	-0.66	-5.57	0.000
Lchge*VPED2	-0.033	-2.28	0.025
Constant	1804	37.42	0.000
F	35.6		
$P_{rob} > F$	0.000		
R^2	0.65		

One of the assumptions of the classical regression model is that the functional form of model has been chosen properly, but this assumption can be wrong and the model may be in another form. The validity of the estimated functional form of the model was checked with the Ramsey test. The null hypothesis of Ramsey test represents correct estimation of functional form or absence of omitted variable in the model. Table 5 shows the values obtained from Ramsey test.

Table 5. Results of Ramsey test

test	F statistic	Significance level
Ramsey test	1.63	0.19

According to Table 5, the F statistic is equal to 1.63 and its significance level is 0.19, so the null hypothesis (correctness of estimated functional form) cannot be rejected.

Another assumption of classical linear regression model is the homoscedasticity of error terms. In case of heteroscedasticity of error terms, OLS will be the best estimator for the task, and the values of F and T statistics will not be reliable. In this paper, the heteroscedasticity of error terms was checked with the White test.

Table 6. Results of White test

test	$\chi 2$ statistic	Significance level
White test	18.62	0.54

The null hypothesis of White test is the homoscedasticity of error terms. Table 6 shows the results of White test. According to Table 6, the $\chi 2$ test is equal to 18.62 and its significance level is 0.54, which indicates that, at 95% confidence level, the null hypothesis (homoscedasticity of error terms) cannot be rejected.

According to Table 7, there is a 7 unit increase in the saturation flow rate per unit increase in the percentage of motorcyclists in the traffic flow, while the counterpart value for the buses is -17.

Table 7. Marginal effects of the independent variables

marginal effect	Variable
7.12	Pmot
-17.01	Pbus
-0.431	VPED1
-0.66	VMOT
-0.034	Lchge* VPED2

Also, a unit increase in the number of pedestrians and motorcyclists violating the traffic light per hour leads to, respectively, 0.43 and 0.66 unit decrease in the saturation flow rate. Table 7 shows the marginal effect of each independent variable on saturation flow rate.

HCM suggests that saturation flow rate should be calculated using the base saturation flow rate and then applying a number of adjustment factors (equation 7). Using equation (7) and assuming a standard lane width and a slope of zero, the coefficients of each independent variable for the HCM base saturation flow rate of S0=1900 were estimated through logarithmic regression model. The base saturation flow rate

is in passenger cars per hour per lane (pcphpl).

Table 8. Result of log-log regression model

variable (log)	HCM	
	value	t statistic
Pmot	0.0349	2.04
Pbus	-0.0292	-2.69
VPED1	-0.01868	-3.9
VMOT	-0.0216	-5.81
Lchge* VPED2	-0.0108	-3.3
Constant	-0.0047	1.42
F	31.5	
$P_{rob} > F$	0.000	
R^2	0.063	

Table 8, shows the results of calibration of logarithmic regression model, all independent variables are statistically significant at the 95% confidence level, The F-test is equal to 31.5 and its significance level is zero, which shows that the null hypothesis stating the lack of effect of independent variables cannot be confirmed. Here, the value of R2 is 0.63, which means that 63% of the variations in saturation flow rate can be explained by the independent variables. Table 9 shows the results of White and Ramsey tests for this model. According to Table 9, the results of Ramsey tests indicates that at 95% confidence level, the null hypothesis stating the correctness of selected functional form and the absence of any omitted variable cannot be rejected. The results of White test also show the absence of heteroscedasticity in the error terms.

In the log-log regression, the slope of each independent variable shows the partial elasticity of its dependent variable with the assumption of other variables being fixed. According to Table 8, one unit increase in the number of motorcyclists violating the traffic light –when other variables are hold constant- leads to -0.0216 reduction in the ratio of observed saturation flow rate to its theoretical value; the value of counterpart parameter for the pedestrians is -0.01868.

According to equation (7), when the base saturation flow rate (S0) is left uninitialized, the constant of the model is equal to logarithm of base saturation flow rate (logS0), and the base saturation flow rate can be estimated from there. After estimating the model coefficients, the value of constant was estimated to be 3.28, and the value of base saturation flow rate was estimated to be 1905 passenger cars per hour per lane (pcphpl), which is very close to the value suggested by the HCM.

Table 9. Results of White and Ramsey test

Test	F statistic	Significance level
Ramsey test	0.96	0.41
White test	27.47	0.12

6. Conclusion and Recommendations

Saturation flow rate depends on many factors, including traffic behavior and culture. One of the important problems of traffic culture in Iran is the violation of law at physical region of intersections. In this study, using linear and non-linear regression model, the effect of each of the factors, including violations occurred by pedestrians and motorcyclists while passing traffic light, and drivers' lane change on saturation flow rate and the capacity of intersection were assessd. The results showed the significant effect of users' violations on the saturation flow rate, and the effect of each of the variables was evaluated by the use of proposed models. The results also showed the greater effect of the number of violations by motorcyclists - comparted with pedestrians- on the saturation flow rate, which indicates that motorcyclists make a greater disturbance in the traffic flow. A nonlinear (power) regression model was used to estimate the coefficients of each of the explanatory variables based on the value of base saturation flow rate suggested by the Highway Capacity Manual of United States (HCM). These values can therefore be used as adjustment factors. The results of the work can be summarized as follows:

- On average, one unit increase in the traffic light violations by pedestrians (per hour per lane) leads to 0.43 decrease in the saturation flow rate.
- One unit increase in the traffic light violations by motorcyclists (per hour) leads to 0.66 average decrease in the saturation flow rate.
- On average, one unit increase in the percentage of motorcyclists in the traffic flow leads to 7 unit increase in the saturation flow rate; while the value of this parameter for the buses is -17.
- The linear regression model estimated the base saturation flow rate to be 1804 passenger cars per hour per lane.
- The nonlinear regression model estimated the base saturation flow rate to be 1905 passenger cars per hour per lane, which is close to the value suggested by the HCM.

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