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ESTIMATING SATURATION FLOW UNDER WEAK DISCIPLINE TRAFFIC CONDITIONS, CASE STUDY: IRAN

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Abstract:

Intersections, as the critical elements and the major bottleneck points of urban street networks, may have inconsistent performances in different countries. This is largely due to the fact that the factors affecting their performance e.g. driving behavior, vehicle characteristics, control methods, and environmental conditions may vary from one country to another. It is, therefore required to take into account these factors when developing or applying available models and methodologies for their capacity analysis or signal control setting. This is particularly important for the countries with heterogeneous and weak discipline traffic streams such as Iran. Meanwhile, estimating the saturation flow rate, which is a key parameter in capacity and delay analysis and in optimal timing of traffic signals, is of great importance. In this study, the possibility of identifying and or developing appropriate models for estimating the saturation flow rate at the signalized intersections in these situations has been explored. For this purpose, a case study performed at the signalized intersections located in the city of Yazd, a medium sized city located in the middle of Iran. Using the data obtained from several intersections together with the application of analytical procedures proposed by American, Australian, Canadian, Indonesian, Iranian and Malaysian highway capacity guides, the saturation flow rate was estimated from both field observations and analytical methods. A comparison of these results indicated that in the protected left-turn situations, the Australian guide produced the best comparable results with the field data. On the other hand, in the permitted left-turn situations, the method proposed in the American Highway Capacity Manual guide produced the best comparable results with the field data. Furthermore, three new models were developed for estimating the saturation flow rate in three different situations namely, unopposed mixed straight and turning traffic movements, opposed mixed straight and turning traffic movements and merely straight through movement. The effective width, traffic composition, and opposite oncoming through traffic flow were considered as the effective parameters in the proposed models. Moreover, using the multivariate regression analysis, the Passenger Car Equivalent coefficients for motorcycles and heavy vehicles were calculated as 0.51 and 2.09, respectively.

Key words:
saturation flow rate, signalized intersections, heterogeneous traffic, weak discipline traffic

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1. Introduction

Previous studies on the estimation of the saturation flow rates for the signalized intersections can be divided into two general categories. The methods in the first category are based on estimating the saturation flow rate for each lane of an intersection entry approach. On the other hand, the second-category of methods estimate the saturation flow rates by taking into account the effective width of a lane group or overall lanes within each entry approach. Over the past decades, various studies have been conducted, using either of these two methods, to identify the involved factors and parameters, and to provide some appropriate models for estimating the saturation flow rates at the signalized intersections, some of which are reviewed below.

Branson (1977), in his study, proposed two linear equations for estimating the traffic saturation rates for the peak and off-peak periods. The only parameter, applied in these formulas, was the width of each entry approach lane. He concluded that the saturation flow rates are not significantly different between the slow lane and the fast lane in a two-lane entry approach. In another study, Kimber et al. (1983) concluded that the saturation flow rates are not significantly different for the middle and outside lanes of multilane entry approaches. Besides, they found out that with an increase in the width of each lane from 2.5 to 4 meters, the saturation flow rate of that lane would be increased nonlinearly. Conducting a study in Malaysia, Hussein et al. (2007) showed that the value of the adjustment factor for the left-turn movements will be reduced with an increase in the proportion of the turning vehicles and reduction in the turning radius. They noticed that the application of the American Highway Capacity Manual (HCM) is not suitable for calculating the saturation flow rates in Malaysia. In a research study conducted in Poland, Tarko and Tracz (2000) studied 38 entry approaches containing straight through traffic, 21 entry approaches containing left-turn traffic and 10 entry approaches containing right-turn traffic. By performing a multiple regression analysis, they showed that four factors namely, the proportion of heavy vehicles, effective entry approach width, turning radius and the lane location in the entry approach have a significant effect on the saturation flow rate at the signalized intersections in Poland.

Sutomu (1992) initiated one of the first researches on the estimation of saturation flow rates in heterogeneous and non-lane based traffic conditions, e.g. weak lane keeping, in Indonesia. In a research conducted in two cities in India, Maini and Khan (2000) investigated the effect of discharge rate on the saturation flow rates in heterogeneous traffic conditions for signalized intersections. They realized that the discharge rate is an effective parameter in determining the passenger car equivalent values. Equation (1) is proposed in Indian Guide (1994) for calculating the saturation flow rate.

$$S = 525 \times W \tag{1}$$

In the above equation, W represents the effective width of the entry approach (meter) and S indicates the saturation flow rate of the entry approach in passenger car equivalent per hour of green time.

Patil et al. (2007) presented a series of simple regression models for estimating the saturation flow rate at signalized intersections in heterogeneous traffic conditions. These models were developed based on the parameters such as the entry approach width, the proportion of heavy vehicles and the ratio of turning vehicles. These models were then validated using the data collected from Mumbai in India. Vinh and Tuan (2013), in their research, collected the traffic data from 7 intersections located in Ho Chi Minh, Vietnam. They proposed a model that was based on the four parameters namely, the entry approach width, traffic composition, duration of the green interval, and the right turn flow rates (similar to the left turn flow rate in the right-hand side driving conditions). In another research, Anusha et al. (2013) explored the effect of two-wheelers on the saturation flow rate at signalized intersections in Bangalore, India. They concluded that there was a strong correlation between the saturation flow rate and the percentage of two-wheelers. Raval and Gundaliya (2012) proposed two models for calculating the saturation flow rate. These models were derived from a study on the heterogeneous traffic behavior and geometric conditions of 3 signalized intersections located in Ahmedabad, India. Two parameters were used in their models namely, the effective entry approach width and the traffic composition. The first proposed model, as indicated in equation (2), has only incorporated the effective width of the entry approach. The second model, indicated in equation (3), has incorporated the proportion of various vehicle types as input parameters as well.

$$S = 626 \times W + 268 \quad (2)$$

$$S = 647W + 709t_w + 270b + 702a_u - 1568\,car - 1552\,bic \quad (3)$$

In the above equations, S - the saturation flow rate in passenger car equivalent per hour of green time, W - the effective width of the entry approach in meter, t_w - the percentage of the two-wheelers, b - the percentage of buses, car - the percentage of passenger cars, bic - the percentage of bicycles, and a_u - the percentage of tricycles in the traffic composition.

Bargegol et al. (2016) developed a model to predict the saturation flow rates for near-side and far-side approaches (entry and exit approaches) at the signalized intersections. They examined five signalized intersections, located in the city of Rasht in Iran, using microscopic and macroscopic methods. Only the effective width of the intersection approach was incorporated in their final models. The equation (4) was proposed for the near-side or entry approaches and the equation (5) was proposed for the far-side or exit approaches.

$$S = -226.55\ln(W) + 1901.44 \quad (R^2 = 0.105) \quad (4)$$

$$S = 484.45W - 409.52 \quad (R^2 = 0.957) \quad (5)$$

In the above equations, S represents the saturation flow rate in vehicle per hour green time and W represents the effective width in meter.

To complement this review, a review of the methodologies proposed for the calculation of saturation flow rate in the formal highway capacity guides of a number of countries follows. The American HCM was the first guide to present a, a methodology for analyzing the capacity of signalized intersections in 1965. In the latest edition of this guide which was published in 2016, a comprehensive methodology is presented to calculate saturation flow rate for each lane group of an entry approach. The Indonesian Highway Capacity Manual, first published in 1993, has presented a methodology for the analysis of signalized intersections. It is based on the study of 52 signalized intersections in 15 cities in Indonesia. This methodology is based on the effective approach width. The method presented in the Malaysian HCM for estimating the saturation flow rate is structurally similar to the American HCM. One of the major differences between these two methods is in the calculation of traffic composition adjustment factor. The Australian methodology for estimation of saturation flow rate is also similar to the American HCM methodology. It is based on the study of 18 signalized intersections in Melbourne and Sydney. Using the data obtained from these intersections and their analysis, a model is proposed for estimating the saturation flow rate for each lane of an entry approach. The methodology proposed in the Iranian guide, published by the Planning and Management Organization of Iran, for the estimation of the saturation flow rate is based on a field study of 13 entry approaches of the signalized intersections in Tehran. The proposed methodology only considers the effective width of the approach. Three distinct models are presented for three modes of traffic flow passing through the intersection including the protected left-turn, permitted left-turn, and straight through movements. For comparison, a summary of the parameters involved in either of these methodologies is presented in Table 1.

The review indicates that there has been considerable efforts in the past to develop models for the calculation of saturation flow at signalized intersections. However, these models have mainly been derived for the high quality driving conditions and therefore, may not be appropriate for heterogeneous and weak discipline traffic conditions, e.g. weak lane keeping conditions. These traffic conditions can be observed in many developing countries such as Iran. There has been some efforts to develop appropriate models or methods for these conditions but they seem to be inadequate. Furthermore the models and procedures applied in developed countries are quite comprehensive and require substantial information which are not easily available in developing countries. Therefore, it would be reasonable to develop simpler methods for such countries. Hence the objective of this study was set to examine the accuracy of well-known saturation flow estimation methods, introduced in the national highway capacity guides of a number of countries, when applied for the signalized intersections in Iran and to develop new appropriate models, based on the observed site data.

Table 1. Parameters involved in the estimation of saturation flow in the national codes of different countries

Parameter	**Iran**	**Malaysia**	**Indonesia**	**Australia**	**Canada**	**USA**
Lane width	√	√	√	√	√	√
Traffic composition		√		√		
Heavy vehicles only	√					√
Grade		√		√	√	√
Parking					√	√
Bus blockage					√	√
Area type			√			√
Lane utilization		√				√
Right turns		√	√		√	√
Left turns		√	√		√	√
Left Turns conflict with pedestrians and bicyclists					√	√
Right turns conflict with pedestrians and bicyclists					√	√
Turning radius					√	
Queue length					√	
Green time					√	

2. Research methodology

2.1. Data collection

A combination of video recording and manual data collection methods were used to provide required traffic data and geometric features of each site. This information were collected from 14 entry approaches of 7 signalized intersections in the city of Yazd, a medium sized city located in the middle of Iran. Basic information related to the geometric features of these entry approaches and the signal settings of their corresponding intersections are presented in Table 2. The effective width of each entry approach, was measured and used in the computations. Furthermore, due to the weak lane keeping behavior by drivers in Iran, the equivalent lane width for each entry approach was calculated by dividing the effective width of the entry approach by the number of vehicle columns usually formed in that approach during the saturated traffic flow conditions. In this study, vehicles were categorized in three categories, namely passenger cars, heavy vehicles, and motorcycles.

Table 2. Basic characteristics of the examined entry approaches and the signal control setting of their intersections

Intersection Name	**Entry approaches**	**Number of Effective Lanes**	**Effective Lane Width (m)**	**Total Effective Width (m)**	**Green Time (s)**	**No. of Phases**	**Cycle Time (sec)**
Pajouhesh Intersection	Atlasi Roundabout Bound	4	3	12	15-26	4	95-142
	Alem Roundabout Bound	4	2.8	11	11-32		
	Aram Street Bound	2	3.7	7.3	16-36		
Amir-al-momenin Intersection	Abouzar Roundabout Bound	5	2.5	12.5	20-28	3	80-92
	TV and Radio St. Bound	4	3.3	13.2	21-28		
Shehnah Intersection	Navab Boulevard Bound	4	3.05	12.2	23	3	89
	Motahhari Street. Bound	2	3.3	6.6	33		
Dowlat Abad Intersection	Navab Boulevard Bound	4	3.7	11	22	4	98
	Shehnah Intersection Bound	3	3.5	10.5	21		
Iran Shahr Intersection	Imam-zadeh Boulevard Bound	3	3.06	9.2	28	2	63
	Paknezhad Boulevard Bound	3	3.3	10	28		
Farhangian Intersection	Imam-zadeh Boulevard Bound	3	3.2	9.7	19	2	51
Mahdi Intersection	Basij Boulevard Bound	3	2.9	8.6	29-31	2	59-71
	Asi-zadeh Boulevard Bound	3	3.1	9.4	29-31		

2.2. Estimation of the passenger car equivalent coefficients

Traffic passing through the urban signalized intersections is usually composed of various types of vehicles, e.g. passenger cars, motorcycles and heavy vehicles such as trucks and buses. In order to consider this effect, equivalent Passenger Car Unites (PCU) for each class of vehicles are estimated and used to convert the vehicle flow into its equivalent passenger car flow. Various methods have been proposed to estimate appropriate PCUs over the last decades (e.g. see Werner and Morrall, 1976; Chandra et al., 1997; Chandra and Kumar, 2003; Minh and Sano, 2003; Srikanth and Mehar, 2017). In this study, a regression method was used to estimate the PCU coefficients as it has been identified to be appropriate for the weak discipline traffic conditions (Minh and Sano, 2003). The regression method comprised the following steps:

– Each green interval was sub-divided into the 5 second time periods and then the time periods in which more than three passenger car equivalents had successively passed through the stop line of the approach were considered as the time periods with saturated traffic flow. At this stage, since the passenger car equivalent coefficients were not yet identified, the default values proposed for the intersections in India were adopted. These values are presented in Table 3.
– The sum of the saturated time periods, in each cycle, and the number of different types of vehicles exited the approach at these periods were measured.
– For each entry approach, the results obtained from a number of signal cycles were used in a linear regression analysis, using a general equation presented in equation (6).
– Using the coefficients developed for the regression model, the passenger car equivalent coefficients for heavy vehicles and motorcycles were estimated using equation (7). This method has previously been used by Minh and Sano (2003) as well.

Table 3. Passenger car equivalent proposed by the Indian Road Congress

Vehicle	PCE
Motorcycle	0.5
Auto rickshaws	0.7
Bus	2

$$t = n_1 a_1 + n_2 a_2 + n_3 a_3 \qquad (6)$$

$$p_i = a_i / a_1 \qquad (7)$$

In the above equations, n_i indicates the number of vehicles in the i^{th}category that have passed through the entry approach in each cycle; a_1, a_2 and a_3, represent the coefficients obtained from the regression analysis for the passenger cars, heavy-vehicles, and motorcycle respectively, t represent the total saturated green periods during each cycle in second, and p_i represents the calculated passenger car equivalent coefficient for the i^{th} category of vehicles.
In this study, this methodology was applied on four entry approaches. The regression models obtained for each entry approach are presented in equations (8) to (11). The average passenger car equivalent coefficients for each entry approach and all of these approaches were then calculated as indicated in Table 4.

$$\text{Model1}: \; t = 0.482n_1 + 0.943n_2 + 0.268n_3 + 3.632 \qquad (8)$$

$$\text{Model2}: \; t = 0.569n_1 + 1.226n_2 + 0.278n_3 + 1.959 \qquad (9)$$

$$\text{Model3}: \; t = 0.807n_1 + 1.89n_2 + 0.415n_3 + 3.467 \qquad (10)$$

$$\text{Model4}: \; t = 0.92n_1 + 1.799n_2 + 0.437n_3 + 6.347 \qquad (11)$$

Table 4. The calculated passenger car equivalent coefficients

Vehicle	Model 1	Model 2	Model 3	Model 4	Average
Heavy vehicles (Bus, Minibus and Lorry)	1.95	2.15	2.33	1.96	2.09
Motorcycle	0.55	0.48	0.51	0.48	0.51

In the current Iranian guide, only the effect of heavy vehicles is considered. To implement this effect, reduction factors to the calculated saturation flow in passenger car unit are suggested. These reduction factors are defined in accordance with the percentage of heavy vehicles in traffic flow.

2.3. Calculation of the saturation flow rate based on the field observations

Three methods are usually used to measure the saturation flow rates based on the field observations. Appropriateness of each method depends on the factors such as the homogeneity of the traffic flow and the quality of driving, e.g. the degree of lane keeping by drivers. These three methods are outlined as follows:

1) Methods based on the calculation of saturation flow rate through the calculation of saturated discharge headway mean, applicable for situations in which high driving standards such as lane discipline or lane keeping is respected (e.g. Greenshields et al. (1947)).
2) Methods based on the calculation of the saturation flow rate by counting the number of vehicles in the saturated time slots (e.g. UK Road Research Laboratory Method).
3) Methods based on the calculation of the saturation flow rate using the regression method, applicable for situations in which the quality of driving is low, e.g. for non-lane based or weak lane keeping situations, or when there are high heterogeneity in traffic stream due to the presence of a wide range of different class of vehicles in traffic stream (e.g. Minh and Sano (2003)).

Features such as heterogeneity of traffic streams and weak lane discipline can largely been observed throughout street networks in Iran, especially in the intersection areas. Therefore, it was decided to use the third method to estimate saturation flow rate based on the field observations. For this purpose, the average passenger car equivalent coefficients (p_i) obtained from the regression analysis and the number of vehicles in each class (n_i) measured during the overall saturation periods (t) was used in equation (12) to obtain the mean saturated discharge headway (h).

$$h = t \big/ \left(n_1 p_1 + n_2 p_2 + n_3 p_3\right) \qquad (12)$$

Then, using equation (13), the saturation flow rate was calculated.

$$S = 3600 / h \qquad (13)$$

In the above equation, S represents the saturation flow rate in passenger car equivalent per hour of green time. The calculated saturation flow rates for each entry approach, on this basis, are presented in Table 5 and Table 6.

2.4. Calculation and control of the required number of samples

In this study, equation (14) was used to control the minimum number of signal cycles needed for collecting the data.

$$N \geq \frac{s^2 \sigma^2}{e^2 \mu^2} \qquad (14)$$

Table 5. Measured saturation flow rate in the protected left turn mode

Intersection Name	Entry approaches (protected left turn)	Observed Saturation Flow Rate (PCU/h)	Total effective Width (m)
Pajouhesh Intersection	Atlasi Roundabout Bound	6000	12
	Alem Roundabout Bound	5812	11
	Aram Street Bound	3788	7.3
Amir-al-momenin Intersection	Abouzar Roundabout Bound	7020	12.5
	TV and Radio St. Bound	6559	13.2
Shehnah Intersection	Navab Boulevard Bound	6153	12.2
	Motahhari Street. Bound	3510	6.6
Dowlat Abad Intersection	Navab Boulevard Bound	5081	11
	Shehnah Intersection Bound	4996	10.5

Table 6. Measured saturation flow rate in the permitted left turn mode

Intersection Name	Entry approaches (permitted left turn)	Observed Saturation Flow Rate (PCU/h)	Total effective Width (m)
Iran Shahr Intersection	Imam-zadeh Boulevard Bound	3471	9.2
	Paknezhad Boulevard Bound	2754	10
Farhangian Intersection	Imam-zadeh Boulevard Bound	3290	9.7
Mahdi Intersection	Basij Boulevard Bound	3043	8.6
	Asi-zadeh Boulevard Bound	2372	9.4

In this equation, N represents the required number of samples at each site, s indicates the standard deviation of the data, σ represents the reliability of the data that at 95% confidence interval is equal to 1.96, e is the acceptable error rate and μ represents the mean of the data. The acceptable error rate is generally considered to be 5%, but as indicated in the American HCM, for the saturation flow rate estimation, an error rate of 8% to 10% would still be acceptable. In this research, the acceptable error rate is considered to be 5%. The results of the sample size control for the minimum number of cycles needed for data collection are presented in Table 7.The results indicates that the sample size of the collected data is sufficient.

2.5. Data analysis and discussion

In this section, the measured saturation flow rates for the 14 examined entry approaches are compared with their corresponding calculated values, using procedures proposed in the highway capacity analysis guidelines of six countries. The saturation flow rate was calculated for traffic conditions governing each signal cycle and then the average saturation flow was calculated for each entry approach. The results for the protected and permitted left turn traffic conditions are separately presented in Table 8 and Table 9, respectively.

Table 7. Control of the required number of cycles for data collection

Intersection Name	Entry approaches	Saturation flow (pcph)		Min. Required No. of Cycles	Collected No. of Cycles
		Average	Standard deviation		
Amir-al-Momenin Intersection	Abouzar Roundabout Bound	7019.378	97.821	12	40
	TV and Radio Station Bound	6558.581	77.150	9	38
Pajouhesh Intersection	Aram Street Bound	3787.074	102.076	34	34
	Alem Roundabout Bound	5812.320	88.199	12	32
	Atlasi Roundabout Bound	5999.779	88.81	11	32
Dowlat Abad Intersection	Navab Boulevard Bound	5080.671	51.41847	6	35
	Shehnah Intersection Bound	4995.751	41.882	4	35
Shehnah Intersection	Navab Boulevard Bound	6152.708	88.027	12	37
	Motahhari Street. Bound	3509.878	59.195	18	40
Iran Shahr Intersection	Imam-zadeh Boulevard Bound	3470.672	40.896	8	33
	Paknezhad Boulevard Bound	2753.834	29.104	6	33
Mahdi Intersection	Asi-zadeh Boulevard Bound	2371.409	38.926	15	34
	Basij Boulevard Bound	3042.515	30.185	6	34
Farhangian Intersection	Imam-zadeh Boulevard Bound	3289.474	55.549	21	46

Table 8. Calculated saturation flow, using highway capacity analysis guides (protected left turn mode)

Intersection Name	Examined Entry Approaches (with protected left turn movements)	Calculated Saturation Flow,Using Each Country's Guide (pcph)					
		USA	Canada	Indonesia	Malaysia	Iran	Australia
Pajouhesh Intersection	Atlasi Roundabout Bound	6109	7137	6963	6055	5136	7059
	Alem Roundabout Bound	6020	5761	6153	5443	4708	7286
	Aram Street Bound	3724	3558	4505	3490	3125	3630
Amir-al-momenin Intersection	Abouzar Roundabout Bound	6177	5465	7319	5681	5350	8178
	TV and Radio Station Bound	5349	5344	7902	5794	5650	7097
Shehnah Intersection	Navab Boulevard Bound	4097	5596	5615	5615	5222	7147
	Motahhari Street. Bound	3349	3566	3876	4238	2825	3486
Dowlat Abad Intersection	Navab Boulevard Bound	5190	4917	6524	5630	4708	5291
	Shehnah Intersection Bound	5129	4369	5815	5650	4494	5662

Table 9. Calculated saturation flow, using highway capacity analysis guides (permitted left turn mode)

Intersection Name	Examined Entry Approaches (with opposed left turn movements)	Calculated Saturation Flow Using Each Country's HCM Procedure (pcph)					
		USA	Canada	Indonesia	Malaysia	Iran	Australia
Iran Shahr Intersection	Imam-zadeh Boulevard Bound	3577	2773	3572	3801	3257	3733
	Paknezhad Boulevard Bound	3097	2222	4795	4167	3540	3311
Farhangian Intersection	Imam-zadeh Boulevard Bound	3036	2601	3327	4147	3434	4244
Mahdi Intersection	Basij Boulevard Bound	3318	3028	*	4717	3045	4798
	Asi-zadeh Boulevard Bound	2209	1894	*	4655	3328	3780

* At this intersection, due to the high volume left-turns, the Indonesian HCM guide did not provide reasonable values as it is not applicable for these conditions.

In order to provide a sound basis for the comparison of performance of these procedures in estimating saturation flow rate in this country, regression analysis was used to fit linear lines to the calculated-observed saturation flow data pairs. The results of this analysis are shown in Fig. 1 and Fig. 2 for the protected and permitted left turn movements, respectively. In the relationships presented in these two Tables, y represents the measured saturation flow rate and x shows the corresponding calculated values. For the permitted left turn situations, this comparison was not conducted for the Indonesian guide as only three data points were available.

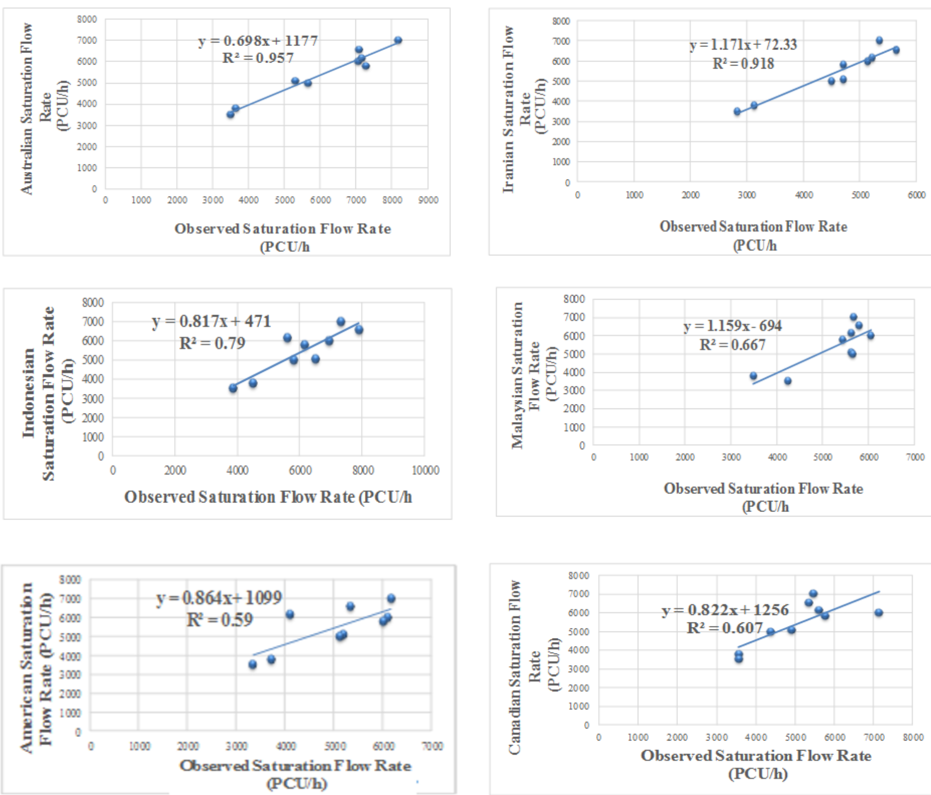

Fig. 1. The results of linear regression analysis on the calculated-observed saturation flow data pairs for the protected left turn movements

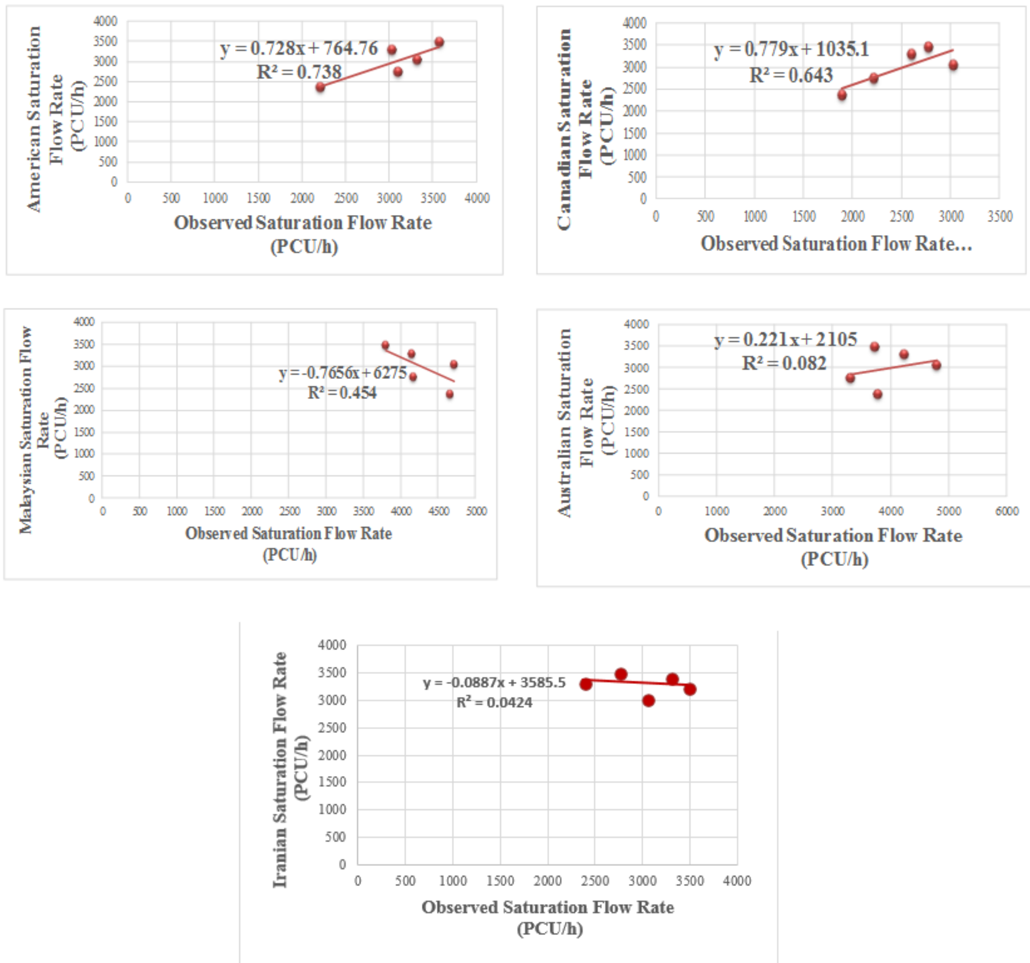

Fig. 2. The results of linear regression analysis on the calculated-observed saturation flow data pairs for the permitted left turn movements

The results presented in Fig. 1 indicates that the Australian guide has produced the best correlation to the field data related to the protected left-turn conditions, The current procedure in Iranian guide has ranked second, with a calculated correlation coefficient of 0.918. For the permitted left-turns, the American HCM guide, with a correlation coefficient of 0.738, showed the best performance for these traffic conditions at the Iranian intersections (see Fig. 2). As indicated in Fig. 2, the Australian, Iranian and Malaysian guides did not produce significant correlation with the field data. This could be attributed to the fact that these procedures do not consider the impact of opposite oncoming through traffic flow on the permitted left turn movements.

3. Proposed new models

One of the objectives of this study was to develop appropriate saturation flow estimation models in accordance with the traffic conditions and governing driving behavior in Iran. The proposed models are based on the effective width of the entry approach. This is due to the weak lane discipline or lane keeping behavior of drivers in Iran, especially in the intersection areas. This method has also been adopted by some of the national highway capacity analysis guides, e.g. by the Indonesian and Iranian guides. It has also been used in the models proposed by some researchers, e.g. Webster and Akcelik. Moreover, in the new models developed in this study, the effect of traffic composition is also taken into consideration, so that the saturation flow rate of these models would be measured in passenger car equivalent per hour of green time.

3.1. The proposed saturation flow model for the unopposed mixed straight and turning traffic conditions

Different types of models were examined for this case by conducting regression analysis on the data collected from these conditions using F statistic, Correlation Coefficient (R^2) and model simplicity as performance measures. Eventually, a linear model with the equation shown in Fig. 3 and Equation (15) was selected for this case.

$$S = 506W \quad R^2 = 0.975 \tag{15}$$

Where, S represents the saturation flow rate in passenger car equivalent per hour of green time and W reflects the effective width of the approach in meter. The values of statistical measures obtained for the finally selected model are presented in Table 10.

Table 10. The values of statistical measures obtained for the finally selected model for the protected left-turns

Equation	R^2	F	sig	constant	b_1
$S = 506W$	0.975	318.375	0.000	20.160	506.015

3.2. The proposed saturation flow model for the opposed mixed straight and left-turning traffic conditions (permitted left-turns)

A comparison of the methodologies proposed by the national highway capacity guides of six different countries in this study showed that in intersections with permitted left-turn movements, the opposite oncoming through traffic flow could be effective in estimating the saturation flow rate. Therefore, in order to consider this factor, an adjustment factor was added to the linear regression model developed for the protected left-turn situation in the previous section.

Several models were tested for the oncoming through traffic adjustment function. The examined models and the results of statistical tests conducted to evaluate their performance are presented in Table 11.

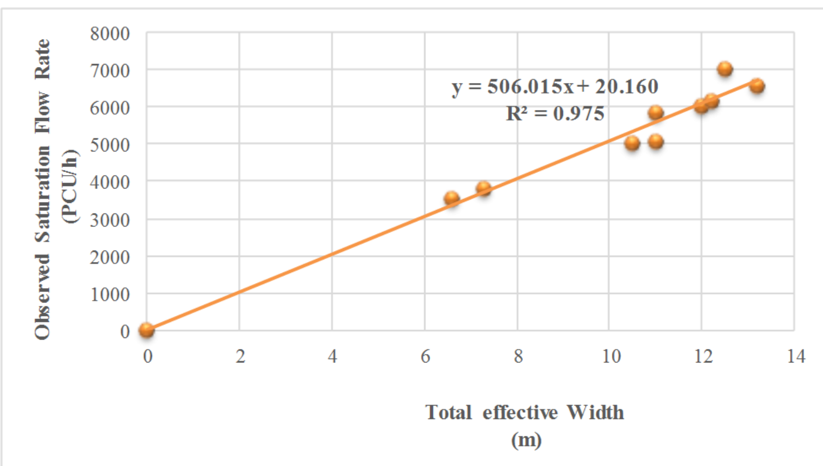

Fig. 3. Saturation Flow Model for the Unopposed Mixed Straight and Turning Traffic Conditions

Table 11. Models reviewed for the oncoming through traffic adjustment function

Model Type	Equations	R^2	F	sig
Cubic	$V = 1.243 - 0.00102568Q - 2.904 \times 10^{-10} Q^3$	0.970	32.352	0.030
Quadratic	$V = 1.315 - 0.001382Q + 5.711 \times 10^{-7} Q^2$	0.969	31.529	0.031
Logarithmic	$V = 3.165 - 0.387 \ln Q$	0.968	90.515	0.002
Inverse	$V = 0.231 + \frac{273.081}{Q}$	0.964	81.355	0.003
Linear	$V = 1.014 - 5.294 \times 10^{-4} Q.$	0.963	78.391	0.003
Power	$V = 38.379 \times Q^{-0.628}$	0.956	65.474	0.004
Exponential	$V = 1.164 \times e^{-8.624 \times 10^{-4} Q}$	0.955	63.739	0.004
Compound	$V = 1.164 + 0.999^{Q}$	0.955	63.739	0.004

According to Table 11, taking into account the correlation coefficient and F parameter, the logarithmic adjustment function has demonstrated the best performance. Therefore, the proposed model for the permitted left-turn mode is in accordance with equations (16) to (18) below.

$$S = F_W F_Q \qquad R^2 = 0.95 \qquad (16)$$

$$F_W = 506W \qquad R^2 = 0.975 \qquad (17)$$

$$F_Q = 3.165 - 0.387 \ln Q \qquad R^2 = 0.968 \qquad (18)$$

In the above equations, S represents the saturation flow rate in passenger car equivalent per hour of green time, W shows the effective width of the approach in meters, and Q is the opposite oncoming through flow rate in passenger car equivalent per hour. It should be noted that the opposite oncoming flow rate is considered to be the sum of the right-turn or the shared right-turn flow plus the straight through traffic flow of the far-side entry approach at the opposite direction.

3.3. The proposed saturation flow model for the unopposed straight through traffic conditions

When turning is not allowed or exclusive lanes and phases are provided for the turning traffic at an entry approach, the saturation flow rate for the straight through traffic should be estimated separately. In this situation, the straight through traffic movement is not affected by the lateral friction caused by the adjacent turning flows. In these situations, one or more lanes are exclusively assigned to the straight through traffic and it is expected that its corresponding saturation flow rate would be more than mixed straight and turning traffic conditions.

The developed saturation flow model for the straight through traffic is represented in Fig. 4 and equation (19).

$$S = 520.4W \qquad R^2 = 0.961 \qquad (19)$$

In this equation, S represents the saturation flow rate in passenger car equivalent per hour of green time, and W shows the effective width assigned to the straight through traffic in meter.

4. Validation of the proposed models and discussion

In this section, for each proposed model, a new entry approach, whose data was not used to develop the proposed models, was selected. Then, the relative error of the proposed model in estimating saturation flow rate for this entry approach was calculated. The results are presented in Table 12 to Table 14.

The validation process indicated that these three models, while being simple, have produced an acceptable estimate of the saturation flow rate at the signalized intersections. The results of validation process indicated that the relative errors of the proposed models have been in the range of 1.59-6.18% which are less than the 8-10% error allowed by the American HCM. It is worth mentioning that one of the drawbacks of the current models proposed for the estimation of saturation flow in the Iranian guide is that they do not directly consider the effect of opposite oncoming through traffic for unopposed or permitted movements. This issue has been resolved in the models proposed in this study.

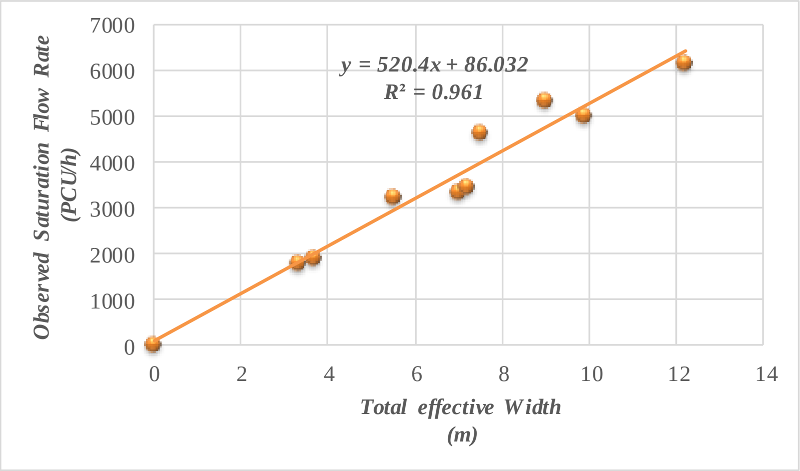

Fig. 4. Saturation Flow Model for the unopposed straight through traffic conditions

Table 12. Validation of the model proposed for estimating the saturation flow rate in the unopposed mixed straight and turning traffic conditions

Intersection	Total Effective Width(m)	Observed Saturation Flow Rate (PCU/h)	Calculated Saturation Flow Rate From Model (PCU/h)	Relative Error (%)
Dowlat abad intersection-Enqelab Bound	6.3	3386.2	3187.8	6.18

Table 13. Validation of the model proposed for estimating the saturation flow rate in the opposed left-turning traffic conditions

Intersection	Total Effective Width(m)	Opposite flow (PCU/h)	Observed Saturation Flow Rate (PCU/h)	Calculated Saturation Flow Rate From Model (PCU/h)	Relative Error (%)
Farhangian Intersection-Paknezhad Blv. Bound	9.9	704.4	3266	3142.431	3.78

Table 14. Validation of the model proposed for estimating the saturation flow rate in the unopposed straight through traffic conditions

Intersection	Total effective Width (m)	Observed Saturation Flow Rate (PCU/h)	Calculated Saturation Flow Rate From Model (PCU/h)	Relative Error (%)
Shehnah Intersection-Navab Boulevard Bound	9	4610.5	4683.6	-1.59

5. Summary and conclusions

The findings of this study can be outlined as follows:

- Using a special regression analysis method, the passenger car equivalent coefficients for different class of vehicles related to heterogeneous and weak lane discipline traffic conditions was estimated. These values were estimated as 0.51 and 2.09 for motorcycles and heavy vehicles, respectively. It is worth mentioning that in the current Iranian guide, only the effect of heavy vehicles is considered.
- Six national highway capacity analysis procedures proposed for the calculation of saturation flow at signalized intersections in 6 different

countries were applied for the estimation of saturation flow at the signalized intersections located in the city of Yazd. These procedures were related to the American, Australian, Canadian, Indonesian, Iranian, and Malaysian guides.

- The results indicated that for the unopposed mixed straight and turning traffic conditions, the Australian guide, with the correlation coefficient of 0.957, provided the closest results to the field observed data. The performance of Iranian guide ranked second for these conditions, with the correlation coefficients of 0.918. This indicates that the performance of the model proposed for this scenario in Iranian guide could be treated as acceptable.
- For the opposed mixed straight and turning traffic conditions, the American procedure, with the correlation coefficient of 0.738, showed the best performance when applied for the studied Iranian intersections. In fact, the performance of the model proposed for this situation in Iranian guide, with the correlation coefficient of 0.042, was the worst among reviewed procedures.
- Three distinct models were developed to estimate the saturation flow rate for the opposed mixed straight and left turn conditions, unopposed mixed straight and turning traffic conditions and the unopposed straight through traffic conditions, respectively. The validation results of these three models on the three entry new approaches, whose data was not used in the development of these models, showed that these models, while being simple, have produced an acceptable estimate of the saturation flow rate at the signalized intersections. Besides, the maximum estimated error was 6.2%, which is less than 8-10% maximum acceptable error margin suggested in the American HCM.
- One added advantage of the proposed model for the unopposed or permitted left turn movement is that it directly considers the effect of opposite oncoming through traffic on the saturation flow which is not considered in the current Iranian model for these situations.

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