Investigation of saturation flow rate using video camera at signalized intersections in Jordan

Abstract: This study aimed to investigate a potential list of variables that may have an impact on the saturation flow rate (SFR) associated with different turning movements at signalized intersections in Jordan. Direct visits to locations were conducted, and a video camera was used. Highway capacity manual standard procedure was followed to collect the necessary traffic data. Multiple linear regression was performed to classify the factors that impact the SFR and to find the optimal model to foretell the SFR. Results showed that turning radius, presence of camera enforcement, and the speed limit are the significant factors that influence SFR for shared left- and U-turning movements (LUTM) with $R^2 = 76.9\%$. Furthermore, the presence of camera enforcement, number of lanes, speed limit, city, traffic volume, and area type are the factors that impact SFR for through movements only (THMO) with $R^2 = 69.6\%$. Also, it was found that the SFR for LUTM is 1611 vehicles per hour per lane (VPHPL), which is less than the SFR for THMO that equals to 1840 VPHPL. Calibration and validation of SFR based on local conditions can improve the efficiency of infrastructure operation and planning activities because vehicles’ characteristics and drivers’ behavior change over time.

Keywords: Intersection, Traffic Signal, Saturation Flow Rate, Turning Movements

1 Introduction

Intersection is one of the essential elements that should be carefully analyzed in any roadway network. Some several fundamental issues and measures must be taken into consideration when studying an intersection such as demand, capacity, saturation flow, control, delay, lost time, headway, and gaps [1]. Intersections can be classified according to the number of approaches entering the intersection area, or type of control used. There are several ways to control traffic at an intersection, and one of the practical and common ways is the use of traffic signals. Traffic signals can be applied to systemize the flow at intersections and remove many struggles because various traffic streams can be assigned the use of the intersection at various times. For this reason, it should be well-designed in a way to give the intersection maximum efficiency and make the traffic movement easy, rapid, and comfortable, besides, to reduce delay. As signalized intersections can be considered as an essential element in the road network, traffic engineers need to consider a variety of elements such as capacity and delay when planning, designing, operating, and evaluating a system for signalization at an intersection.

Saturation flow rate (SFR) can be identified by the maximum hourly rate of flow passing a traffic lane at an intersection-approach, assuming the traffic signal is always green with no lost time [1]. SFR is considered as one of the key parameters in defining the capacity, delay, and level of service (LOS) of intersections controlled by traffic signals [2]. The HCM introduced a model, base value with adjustment factors, for estimating the SFR [1]. The base SFR estimate based on field measurements in the United States is equal to 1900 vehicles per hour per lane (VPHPL) for regions of $\geq 250,000$ population and 1750 VPHPL of $< 250,000$ population [1].

Many studies assessed the SFR default parameters in several countries around the world. In the United States, it was shown that the presence of the U-turning movement negatively affects the capacities of signalized intersections and the value of left-turn SFR in Florida [3]. This study estimated the SFR (1565 VPHPL) at three intersec-
tions in Tampa, Florida, based on the widely used headway method proposed by HCM, which can be estimated in the field by recording the discharge headway following the fourth discharged vehicle [3]. Another study conducted in North Carolina at 20 intersections in Raleigh, Charlotte, and Asheville, revealed that the mean SFR, based on the headway method proposed by HCM, was around 1750 VPHPL for 250,000 or more population and 1497 VPHPL for populations less than 250,000, which are below the default values suggested by HCM [4]. Furthermore, in an SFR study performed by Arhin et al. [5, 6] for different lane groups at 81 intersections in the urban area of District of Columbia (DC), United States, results showed that the mean SFR that can be used in the future analysis in the DC area was for left only (1460 VPHPL), shared left and through (1566 VPHPL), through only (1595 VPHPL), and shared through and right (1461 VPHPL). This study concluded that the SFR values for all turning movements were statistically alike.

In China, several studies investigated the factors affecting SFR. It was observed that the lane width and turning radius [7], rainy weather [8], queue length [9], pavement markings [10], and lane width plus the proportion of heavy vehicles [11] were significant in the SFR estimations. Shao et al. [7] estimated that the mean value of SFR based on 18 cities field measurements in China equals 1800 VPHPL. Another study performed by Wang et al. [12] estimated the SFR to be 2011 VPHPL in Qujing city, Yunnan Province, based on 80% quantiles, automatic video detector data, and time series of actual headways. Moreover, Zhao et al. [13] analyzed the SFR at tandem controlled intersections based on field data in Shenzhen. A Tandem intersection (TI) is a type of intersection layout that increases the capacity of approaches by utilizing the space operated via traffic and reducing the conflicts between left- and other turning movements. Results showed that tandem control decreased the value of SFR because of the distribution of traffic, red-light violations, and incomplete discharge [13].

In Japan, Chen et al. [2] studied the SFR for a shared left-turn lane at six intersections using the HCM and Japan Society of Traffic Engineering (JSTE) procedures. Logistic regression results showed that both procedures overestimated the value of SFR for a shared left-turn lane [2]. In India, several studies investigated the factors affecting SFR. It was found that the turning radius and gradient [14, 15], the proportion of turning vehicles [14–16], right-turning movements [17, 18], road width and the number of lanes [17–19], and the percentage of heavy vehicles [18] had a significant effect on the estimation of SFR.

In Europe, a study performed in Serbia by Stanic et al. [20] to estimate the SFR for through movement, results showed that values of SFR were 1600 VPHPL for through movement and opposing left lane served in the same phase, and 2120 VPHPL for through movements only with no opposing conflicts. It was also concluded that intersection geometric conditions such as gradients and lane widths had a significant effect on SFR for through movements. Another study was performed in Munich, Germany, by Fourati and Friedrich [21] to measure the capacity of the intersection approach based on crowd-sourced trajectories. The measured capacity can be used to estimate the SFR, cycle time, and approach green time.

In the middle east, several studies were performed to estimate the SFR based on field measurements. It was found the SFR equals to 2500 VPHPL in Saudi Arabia [22], 2323 VPHPL in Qatar [23], 2050 VPHPL in Jordan [24], 2100 VPHPL in Kuwait [24]. It can be seen that all studies performed in the middle east resulted in higher values compared to the proposed 1900 VPHPL value by HCM [1]. Additionally, Hamad & Abu Hamda [23, 25] found that the U-turn movement significantly reduced the SFR value. Moreover, Al-Omari and Musa [24] found that variables such as speed limit, lane marking, and the location in the city had a significant effect on SFR using one-way ANOVA. Furthermore, AlRukaibi et al. [26] studied the effect of SFR adjustments on Kuwait’s environmental parameters. Analysis results based on SFR equals 1800 VPHPL showed a 34% reduction in fuel consumption and vehicles’ emission.

In summary, the literature presented a broad variation of SFR values for different locations, site conditions, and turning movements. SFR in Jordan must be revised due to the different driver behavior in this developing country to interpret the local conditions. Therefore, it is proposed to consider the effects of several factors’ variation on SFR estimation. This research aimed to investigate a potential list of variables that may influence SFR associated with different turning movements at signalized intersections in Jordan. Variables include pavement marking, area type, number of lanes, lane width, approach width, turning radius, speed limit, being in a central business district (CBD), as well as a unique factor that was never studied before as an influential factor, which is the presence of camera enforcement under Jordanian conditions. This research was also designed to develop prediction models that can help local researchers, engineers, and authorities estimate and predict a proper value of SFR at signalized intersections. Also, this research comes to play a role in finding more fitting estimates of SFR by investigating the potential list of variables that may show the impact of turning movement factors in the overall performance. Video camera applica-
tion was applied to record traffic data, obtain the needed characteristics, and observe the prevailing SFR.

2 Methodology

In Jordan, a middle eastern country, the total population reached 10,101,694 citizens in 2019 [30], with total registered vehicles of 1,677,061 [34]. Based on the population and registered vehicles, the three principal cities with high populations and large registered vehicles compared to other cities in Jordan are Amman, Irbid, and Zarqa. Amman population reached 4,430,700 people, while Irbid city 1,957,000 people, and Zarqa 1,509,000 people by the end of 2017 [30]. Nineteen urban signalized intersections were selected in the principal cities in Jordan; Amman, Irbid, and Zarqa. Nine intersections were with camera enforcement, and another ten intersections were without camera enforcement. Three- and four-legs signalized intersections were considered with a typical lane width of 12 ft (3.65 m) and level gradient. Also, no parking permitted adjacent to a travel lane within 250 ft (75 m) of the stop line. Additionally, no bus stop allowed in the exit point of the approach roads. Finally, pedestrians and bicycle activities were ignored. Table 1 shows the signalized intersection approaches which were monitored in this study.

Data collection was conducted for four months, started in March 2019, and lasted till June 2019 in the afternoon hours on weekdays, with good weather and dry pavement conditions under mixed traffic conditions. Mixed traffic conditions are represented by the presence of different vehicle types and multiple lanes at the studied locations. Diverse vehicle types result in different maneuvering capabilities, with a vehicle-type dependent longitudinal and lateral movement driving behaviors. Additionally, the existence of multiple lanes enables drivers to look for possible lateral movements while moving. Thus, a comprehensive understanding of this mixed driving behavior while monitoring the traffic system may adjust the perception of SFR associated with different turning movements at signalized intersections.

Direct visits to locations were conducted to collect approximately two hours, 03:00-05:00 PM, of video recordings using Samsung Galaxy A7 rear camera (48 MP Quad 1080p @ 30 fps FHD) at enough height upstream of the intersection for 62 intersection approaches. Figure 1 shows a sample of intersection (I-3) studied in the city of Irbid.

Several characteristics were obtained through field measurements and observations, including turning radius (m), presence of camera enforcement (Yes/No), number of

<table>
<thead>
<tr>
<th>No.</th>
<th>Intersection</th>
<th>ID</th>
<th>Coordinates</th>
<th>Location</th>
<th>No. of Legs</th>
<th>Camera Enforcement</th>
</tr>
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<tbody>
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<td>Wadi Saqra</td>
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<td>A-3</td>
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<td>Irbid</td>
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<td>19</td>
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<td>I-6</td>
<td>32.523881°, 35.901079°</td>
<td>Irbid</td>
<td>4</td>
<td>No</td>
</tr>
</tbody>
</table>
Investigation of saturation flow rate using video camera at signalized intersections in Jordan

lanes, lane width (m), being in a central business district (CBD), presence of pavement marking (Marked, and Unmarked), speed limit (40, 50, 60, 70, and 80 km/hr), city (Amman, Zarqa, and Irbid), level of traffic volume (High, Medium, and Low), and area type (Urban, and Suburban).

The HCM standard procedure was followed for field data collection and in computations of SFR at signalized intersections, as shown in Equations 1 to 3 [1]. The estimation of average headway evaluated based on video recordings. This research focused only on the shared left- and U-turning movements (LUTM), and on the through movements only (THMO). The shared through with left- and right-turning movements were not considered. Also, the cycles with heavy vehicles or pedestrians or any unusual conditions were excluded.

\[
S_{\text{base,local}} = 1900 \sum_{i=1}^{m} \frac{S_{\text{prevailing}}}{S_{\text{adjusted}}} 
\]

\[
S_{\text{prevailing}} = \frac{3600}{\text{average headway}}
\]

\[
S_{\text{adjusted}} = S_{o}f_{w}f_{HV}f_{p}f_{bb}f_{LU}f_{LT}f_{RT}f_{Lpb}f_{Rpb}
\]

Where:

\(S_{o}\): Base saturation flow rate per lane group.

\(N\): Number of lanes in lane group.

\(f_{w}\): Adjustment factor for lane width.

\(f_{HV}\): Adjustment factor for heavy vehicles in traffic stream.

\(f_{g}\): Adjustment factor for approach grade.

\(f_{p}\): Adjustment factor for existence of a parking lane and activity adjacent to lane group.

\(f_{bb}\): Adjustment factor for blocking effect of local buses that stop within intersection.

\(f_{a}\): Adjustment factor for area type.

\(f_{LU}\): Adjustment factor for lane utilization.

\(f_{LT}\): Adjustment factor for left turns in lane group.

\(f_{RT}\): Adjustment factor for right turns in lane group.

\(f_{Lpb}\): Pedestrian-bicycle adjustment factor for left-turn movements.

\(f_{Rpb}\): Pedestrian-bicycle adjustment factor for right-turn movement.

The turning radius of the vehicle was measured by taking a longitudinal line from the upstream-lane median (center) to the downstream-lane median in the other approach, and this was performed using AutoCAD based on both field measurements and drivers behavior in video recordings. There are some benefits for using a large radius, such as allowing a large space for heavy vehicle maneuverings and enabling higher speeds for the turning vehicles, which can lead to lower speed differences in the following vehicles and are therefore less severe for colli-
sion conflicts [27]. However, there are advantages of using smaller radius such as the relatively shorter crossing time of vehicles, shorter crossing time of pedestrians, and the smaller need for large pavement areas [27].

Traffic volume was classified into three categories: low (queue length less than eight vehicles), medium (queue length is more than eight vehicles but the green time is enough to cross all queued vehicles), and high (queue length is more than eight vehicles and the green time is not enough to cross all the queued vehicles). The direct measurement procedure was followed, and observations from video camera recordings obtained all movements.

3 Results and discussion

Approximately 40 hours of video camera recordings were done to get a total of 119 movements for 19 intersections with 62 approaches, as previously shown in Table 1. Video recording distribution was as follow: 22 approaches from seven intersections in Amman, 18 approaches from six intersections in Zarqa, and 22 approaches for six intersections in Irbid. Table 2 and Figure 2 show the summary results for base SFR estimations for THMO and LUTM using HCM standard procedure for the three principal cities in Jordan: Amman, Irbid, and Zarqa.

The values of base SFR for THMO (1840 VPHPL) were less than LUTM (1611 VPHPL). However, the value of base SFR for all movements (1720 VPHPL) prevails between THMO and LUTM. This refers to the fact that drivers need more time to complete the turning operation for U- and left-turns because of the reduced speeds and the accumulation of vehicles that impede the flow of vehicles in the queue within these lanes, which increases the delay and headway. The mean value of base SFR for all movements is equal to 1720 VPHPL, which is below the HCM default value of 1900 VPHPL. These results differ with Al-Omari and Musa [24], who estimated the base SFR in Jordan to be 2050 VPHPL.

The normal probability plots and histograms, shown in Figure 2, confirm no extreme values and the residuals appear to follow a normal distribution (data points clustered around the fitted “blue” line). The Anderson-Darling test for normality is one of the normality tests considered to identify all departures from normality [28]. The Anderson-Darling normality test results (Table 2) showed that the p-value for THMO, LUTM, and All movements was equal to 0.327, 0.758, and 0.822, respectively. All p-values were more than 0.05, which means that the data fit the normal distribution with 95% confidence, and no significant departure from normality was found.

This research used regression analysis to observe the effect of the studied variables on SFR. The developed models can predict the effect of each variable on the value of SFR. Minitab statistical software [28] was used to conduct this multiple regression analysis. Multiple linear regression model has the following general form:

\[ y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \ldots + \beta_k x_k + \epsilon \]  

(4)

Where \( k \) is the number of independent variables. The parameters \( \beta_j \), \( j = 0, 1, 2, \ldots, k \), are called the regression coefficients [29]. Two regression models were developed: the first one was for THMO-SFR and the second for LUTM-SFR. The investigated factors are:

- **Turning radius**: continuous variable (measured in meters).
- **The presence of camera enforcement**: categorical variable (0: No, 1: Yes).

<table>
<thead>
<tr>
<th>Table 2: Summary of Base SFR Results</th>
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<tbody>
<tr>
<td><strong>Location</strong></td>
</tr>
<tr>
<td>Amman</td>
</tr>
<tr>
<td>Zarqa</td>
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<tr>
<td>Irbid</td>
</tr>
<tr>
<td>Jordan</td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>Standard Deviation</td>
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<tr>
<td>P-Value</td>
</tr>
</tbody>
</table>
- **Number of lanes**: categorical variable (from 1 to 6 lanes).
- **Lane width**: continuous variable (measured in meters).
- **Being in a central business district (CBD)**: categorical variable (0: No, 1: Yes).
- **Presence of pavement marking**: categorical variable (0: unmarked, 1: marked).
- **Speed limit**: categorical variable (40, 50, 60, 70, and 80 km/hr),
- **City**: categorical variable (Amman, Zarqa, and Irbid),

Figure 2: Statistical Base SFR Summary for (A) THMO, (B) LUTM, (C) All Movements.
- **Level of traffic volume**: categorical variable (high, medium, and low).
- **Area type**: categorical variable (urban, and suburban).

Table 3 showed that the significant variables, with a p-value less than 0.05, for THMO-SFR ($R^2 = 71.3$) were the presence of camera enforcement, number of lanes, speed limit, the city, traffic volume, and area type. Also, it showed that the significant variables for LUTM-SFR ($R^2 = 82.1$) were turning radius, presence of camera enforcement, speed limit, the city, and traffic volume.

Table 4 and Figure 3 show the models review, regression equation, and residual plots for both THMO-SFR and LUTM-SFR with the least significant variables excluded.

The coefficient of determination ($R^2$) shows the amount of variability clarified by the model (goodness of fit) for each one and is stated in the output tables shown in Table 4. The $R^2$ estimates were 69.6% for THMO-SFR and 76.9% for LUTM-SFR, which indicates that both two models fit the data well. All terms for both models had a p-value less than 0.05, which confirms that each variable is significant and must be included in the model. The normal probability plots and histograms show that there are no extreme values, and the residuals seem to follow a normal distribution. The generalized regression models developed for THMO-SFR and LUTM-SFR are listed below:

\[
\text{THMO-SFR (VPHPL)} = 619 + 124 \text{ Camera Enforcement} + 148 \text{ Number of Lanes} + 6.82 \text{ Speed Limit (km/hour)} + 109 \text{ City} - 89.8 \text{ Traffic Volume} + 127 \text{ Area Type}
\]
Figure 3: Minitab Output Residual Plots.

The performance of each model is indicated by the values of the respective independent variables. In the THMO-SFR developed model, the significant variables include camera enforcement, number of lanes, speed limit, city, traffic volume, and area type. As well, the significant variables for the LUTM-SFR developed model include turning radius, camera enforcement, and speed limit. According to Table 2, the values of THMO-SFR were 1889, 1832, and 223.
The value of SFR at intersections in urban areas and CBDs is typically less than suburban areas due to the lower volumes and traffic densities [31]. Almost 32% of the studied approaches were in suburban areas. The other 68% of studied approaches were placed in urban areas. It was found that area type was significant in the THMO-SFR model with p-values (0.004), and not significant in LUTM-SFR model with p-values (0.184). Similarly, traffic volume was significant in the THMO-SFR model with p-values (0.003), and not significant in LUTM-SFR model with p-values (0.064). This result is consistent with other research outcomes [9]. Nevertheless, the CBD variable was not significant in both models with p-values equal to 0.377 and 0.275 for THMO and LUTM, respectively.

Pavement markings usually employed on paved roads to provide guidance and information to drivers and pedestrians. Only 16% of the studied approaches were marked. The other 84% locations did not have any pavement markings. It was not significant in both models, p-value = 0.195 and 0.165 for THMO and LUTM, respectively, since aggressive drivers’ do not adhere even when lanes marked exist. In contrast, previous studies concluded that lane marking was significant in the SFR estimations [10, 24].

The typical lane width suggested by FHWA is 3.6 meters [32]. It was observed that only 29% of the studied approaches had a lane width equal to 3.6 meters. The other 71% approaches lane width distributed between 2.5 meters and 3.3 meters. It was not significant in both models with p-values equal to 0.930 and 0.843 for THMO and LUTM, respectively. On the contrary, previous studies concluded that lane width was significant in the SFR estimations [7, 11, 17–20]. On the other hand, the number of lanes variable was significant in THMO-SFR, but not significant in LUTM-SFR model. The increase in the number of lanes will give the through-lanes approach more capacity to process more vehicles so that the value of SFR will increase. These results are consistent with other research outcomes [17–20].

The speed limit on the studied approaches in this paper ranged from 40 km/hour to 80 km/hour. Almost 45% of approaches had speed limit of 50 km/hour. The other 55% distributed uniformly between 40, 60, 70, and 80 km/hour. According to a previous study, an increase in the speed limit leads to an increase in the SFR [33]. Speed limit found to be significant in both models with p-values equal to 0.001 and 0.000 for THMO and LUTM, respectively. These results are consistent with other research outcomes [24]. Moreover, the speed of turning vehicles usually drops with a decrease in the turning radius, which results in a reduction in the SFR. It is logical not to include the turning radius in the THMO-SFR model since there is not turning for through movement. However, it was found that the turning radius significantly affects the value of SFR with a p-value equal to 0.000 for the LUTM-SFR model. These results are consistent with other research outcomes [7, 14, 15].

Drivers’ behavior is usually more controlled with the presence of camera enforcement. This makes the number of vehicles crossing the intersection relatively smaller, with fewer red-light running violations, which cause a reduction in the value of SFR. Almost 42% of approaches had camera enforcement at the time of the study. It was discovered that the presence of camera enforcement is significant in both models with p-values equal to 0.013 and 0.019 for THMO and LUTM, respectively. This research is the first study that examined the relationship between camera enforcement and SFR.

4 Conclusions

This study investigated several variables that may affect the SFR associated with two turning movements scenarios at signalized intersections in Jordan. This research focused only on LUTM and THMO movements. The shared through with left- and right-turning movements were not considered. Nineteen signalized intersections were selected in the principal cities in Jordan: Amman, Irbid, and Zarqa. HCM standard procedure was followed. Direct visits to locations were conducted, and a video camera was used. Approximately 40 hours of video camera recordings were accomplished to get a total of 119 turning movements for 19 intersections with 62 approaches. A vast quantity of field measurements and observations were obtained to collect several characteristics including turning radius (m), presence of camera enforcement (Yes/No), number of lanes, lane width (m), being in a central business district (CBD), presence of pavement marking (Marked, and Unmarked), speed limit (40, 50, 60, 70, and 80 km/hr), city (Amman, Zarqa, and Irbid), level of traffic volume (High, Medium, and Low), and area type (Urban, and Suburban).

It was found that the values of base SFR for THMO (1840 VPHPL) were less than LUTM (1611 VPHPL). However, the value of base SFR for all movements (1720 VPHPL) lies between THMO and LUTM. This refers to the fact that drivers need more time to complete the turning operation.
for U- and left-turns because of the reduced speeds and the accumulation of vehicles that impede the flow of vehicles in the queue within these lanes, which increases the delay and headway. Anderson-Darling normality test results showed that p-values for THMO, LUTM, and All movements were equal to 0.327, 0.758, and 0.822, respectively. All p-values were more than 0.05, which means that the data does fit the normal distribution with 95% confidence, and no significant departure from normality was found. Minitab statistical software [28] was utilized to perform multiple regression analysis. Two regression models were developed: the first one was for THMO-SFR and the second for LUTM-SFR. The R² estimates were 69.6% for THMO-SFR and 76.9% for LUTM-SFR, which indicates that both two models fit the data well. All terms for both models had a p-value less than 0.05, which confirms that each variable is significant and must be included in the model. The normal probability plots and histograms show that there are no excessive values and the residuals seem to follow a normal distribution. In the THMO-SFR developed model, the significant variables include camera enforcement, number of lanes, speed limit, city, traffic volume, and area type. As well, the significant variables for the LUTM-SFR developed model include turning radius, camera enforcement, and speed limit. This research is the first study that examined the relationship between camera enforcement and SFR.

This research was designed to develop a prediction model that can help local researchers, engineers, and authorities in estimating and predicting a proper value of SFR at signalized intersections. Validation of SFR based on local conditions can improve the efficiency of infrastructure operation and planning activities because vehicles’ characteristics and drivers’ behavior change over time. Also, this research comes to play a role in finding more fitting estimates of SFR by investigating the potential list of variables that may show the impact of turning movement factors in the overall performance. Future work for this research includes the investigation of SFR for the right turning movement. Furthermore, an examination of additional variables such as turning angle, vehicle classification, vehicle size, pedestrians and bicycle activities, and weather condition would also be beneficial to the overall estimation of SFR at signalized intersections. Further studies should cover these issues. Besides, this study was conducted in Jordan; validation of the models in other regions can improve the efficiency of city planning and design activities.

References


