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# Lane-based analysis of the saturation flow rate considering traffic composition

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**ABSTRACT**
Saturation flow rate (SFR) is an essential metric for estimating the capacities of signalized intersections. Many factors, including traffic composition, configuration and geometry of the intersection, and driver behavior, which is typically characterized by social and cultural norms, influence SFR. Most of the previous studies estimated the SFR and adjustment factor to be applied independently without considering the interaction impact between influencing factors. This study aims to empirically examine the influence of the number of lanes, the heavy vehicle proportions, and their interaction effect on the SFR of through movements. A new model was developed to magnify the HV Impact on SFR value considering the number of lanes at the upstream approach. The outcome of this study helps to improve the multiplicative model's structure for SFRs adjustment factors. Adopting the outcome of this study by the responsible transport authority would optimize the road infrastructure provision.

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**KEYWORDS**
Signalized intersection; mixed traffic flow; through turn; saturation flow rate

## 1. Introduction

Saturation flow rate (SFR) is a primary input used for planning and operational design of signalized intersections. Conventionally, SFR is defined as the maximum queue discharge rate observed shortly after the onset of the green interval, which is assumed to remain stable until the queue is discharged. The Highway Capacity Manual (HCM 6th Edition 2016) (Transportation Research Board 2016) suggests estimating SFR using stable discharge headways, i.e. saturation headway observed after the fourth queuing vehicle clears the stop bar.

Several published standards provide detailed calculation methods of the saturation flows for different types of intersections. Among them, the HCM 6th Edition (2016) (Transportation Research Board 2016), Transport and Road Research Laboratory (TRRL) in the UK (Transport and Road Research Laboratory (TRRL) 1986) and the Australian Road

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Research Board (ARRB) in Australia (Miller n.d.) are the most commonly used sources. In each case, a standard SFR for a single lane is defined. This may be used when all the conditions of the approach are considered to meet theoretically ideal conditions. The base standard SFR for a single lane is generally reported as being between 1800 and 2000 Passenger Car Units (PCUs) per hour. PCU is defined in the HCM 6th Edition (2016) as 'the number of passenger cars that are displaced by a single heavy vehicle of a particular type under prevailing roadway, traffic, and control conditions'.

Many agencies and practitioners use the approach described in HCM 6th Edition (2016) (Transportation Research Board 2016) to estimate the SFR by adjusting the base saturation flow rate (BSFR) while taking into account various geometric and operational factors that may affect the SFR, such as truck or heavy vehicles percentage, approach grade, type of turning movement (left and right turning), and other Factors. The Canadian Capacity Guide for Signalized Intersections (Institute of Transportation Engineers 2008) prepared by the Institute of Transportation Engineers (ITE) (Institute of Transportation Engineers 2008) measured the standard SFR values for exclusive through and left-turn lanes located at suburban and downtown intersections in nine Canadian districts. The results showed that the BSFR ranges between 1700 and 1900 veh/hr/ln, and the average BSFR in downtown areas can be 93% of the average BSFR in suburban areas. BSFR as per HCM 6th Edition (2016) (Elefteriadou 2016) is 1900 pc/h/ln. Design manuals (i.e. HCM) (Gao and Alam n.d.) are useful for designing and planning intersections as they provide computational steps considering a variety of possibilities that could affect the design of new intersections (Mondal and Gupta 2020).

To estimate the capacity of a signalized intersection, it is essential to accurately estimate the amount of traffic throughput; by measuring the maximum number of vehicles that can pass through an intersection lane group over a given period of time and based on prevailing road conditions. BSFR represents the SFR for a traffic lane that is 12 ft wide with no longitudinal grade, heavy vehicles in traffic, on-street parking, bus stop, or turning vehicles. The BSFR value proposed in HCM 6th Edition (2016) is 1900 veh/hr/ln, and the adjustment factors for the BSFR are based on surveys conducted at various intersections in the US. However, for countries outside the US, the BSFR values, as well as the adjustment factors, need to be calibrated to reflect the local conditions, including driving behavior, intersection layout, and its prevailing traffic condition (Alam et al. 2011).

Adjustment variables have been the common topic of research by most researchers to enhance the precision of intersection capacity estimation. Turning movement type, lane width, vehicle composition, and shared lanes are common adjustment variables considered in previous studies. Having said that, practitioners in transportation agencies outside the US continue to use the same empirical factors and coefficients developed by HCM 6th Edition (2016), disregarding possible differences that can undermine signal performance characteristics. Inaccurate SFR use during the design of intersections may lead to inefficient estimation for the number of turning lanes and other geometric characteristics. Underestimating SFR during the intersection's operation phase would result in longer average green times than required, resulting in longer cycle lengths and unnecessary delays. Overestimation of SFR, on the other hand, may result in insufficient green times, causing the intersection to oversaturate. Many studies, however, discovered that even after calibrating the adjustment factors, there was still some error in estimating the SFR. Many researchers found that saturation flow estimates have a very high standard error of the mean ranging between 8 and 10 percent (Transport and Road Research Laboratory (TRRL) 1986). This issue may occur due to the multiplicative structure of the SFR model. This illustrates the need for empirical studies to investigate the multiplicative model structure for SFRs adjustment factors, considering the relationship between adjustment factors and their combined effect (Rahmi Akcelik 1981). Therefore, to improve the accuracy of SFR estimation, it is necessary to investigate not only the values of SFR's adjustment factors but also to improve the model structure to account for the relationship and combined effect of adjustment factors considering local conditions. Many of the HCM 6th Edition (2016) adjustment factors shown in Equation (1) are only relevant to specific conditions to cater for roads that have evolved over many decades, whereas new intersections would be designed according to standards to avoid geometric effects on BSFR as well as intersection capacity. With the development of design standards and successful application, the turning movement and the number of lanes are normally predominant in intersections design and operation, which usually dictates the throughput volume, signal timing, delay, and level of service. Moreover, the adjustment factor related to Heavy Vehicles percentage (HV%) is the most critical traffic-related factor which would affect the signalized intersection timing and operation. In the last few decades, many new roads and intersections have been developed in Qatar following standard designs, i.e. typical lane widths of 12 feet, minimal gradients, restricting parking on intersection approaches, signal-control for pedestrian and cyclist crossings, bus stops located at the layby, and generally good visibility on the intersection approaches. Therefore, acquiring relevant data from Qatar would be very suitable for studying BSFR and the combined effect of lane configuration and traffic composition.

The hypothesis in this research is that the interaction effect between the number of lanes and the HV% would influence the SFR value. The primary aim of this research is to improve the accuracy of SFR estimation by taking into account the relationship between adjustment factors for more efficient intersection design and operation. The significance of this study is to develop new models that reduce SFR estimation errors for optimizing the intersection design and operation. This was achieved in this research by using field observations in Qatar to (1) estimate BSFR considering the effect of the number of lanes at upstream approach, (2) Investigate the impact of lane configuration and HV% on BSFR, and (3) explore the combined effect between SFR adjustment factors based on the number of lanes for through and HV% on SFR.

The main contribution of this study is to investigate the influencing factors on SFR variations in developing countries like Qatar and study the interaction effect of heavy vehicles and the number of lanes on SFR for through lanes which address the gap in existing literature.

The outcomes of this research provide traffic engineering professionals in Qatar with realistic and reliable SFR values to be adopted for intersection signal timing design and operation. It would also help practitioners in optimizing intersection design by providing more efficient and reliable design values for SFR, which is a key factor in reducing traffic congestion and promoting sustainable urban development.

## 2. Literature review

According to past studies, heavy vehicles, such as trucks, pose significant challenges to road management as a result of their larger dimensions, specifications, and limited maneuverability (Zhao et al. 2018), which can impact SFR as well. Many factors need to be considered in estimating SFR, such as heavy vehicles, geometric characteristics, traffic factors, turning movement type, and driver behavior. Driver behavior is a key influential factor in SFR estimation and can vary considering local conditions. For example, when approaching congested intersections, some drivers tend to use the gaps between the vehicles to change their lane and reach the front of the queue. Such behaviors (i.e. unnecessary overtakes at through lanes) could critically affect SFR estimation assumptions and adjustment factors, especially if the proportion of heavy vehicles in traffic flow is significant (Gao and Alam n.d.).

SFR modeling is essential for estimating queue backup in oversaturated intersections. Gao and Alam (2014); Hussayin and Shoukry (1986) established a model for estimating SFR adjustment factor for continuous flow intersection (CFI) type and revealed that SFR decreased at CFI compared to the conventional intersection. Studies, such as (Hossain 2001), developed a regression model for PCE values for easier calculation and estimation of SFR that stresses on vehicle types and their characteristics such as width and type of the vehicle. (Dumitru et al. 2016) developed a mathematical model based on a set of matrices to estimate SFR considering the influence of lane grouping and the concept of a critical lane group.

SFR on dual lane exclusive left turn was studied and compared with single-lane exclusive left turn SFR (Federal Highway Administration 1996). The results showed that the SFR is affected by the number of lanes, and it was suggested to conduct future studies to investigate the effect of the number of lanes on SFR. Helmy, Hashim, and El-Desoky (2018) also found that SFR for the middle lane is generally higher than the inner and outer lanes with an average of 1750 vehicles per hour (vph) while SFR for the outer lane is 1664 vph. They also reviewed several studies from the literature related to multiple lanes for left turns at signalized intersections and found that left turn adjustment factor (fLT) ranged between 0.915 and 1.00, and intersection geometry such as skewness, gradient, and the number of lanes will affect the SFR. The middle lane SFR is slightly higher than that for outer and inner lanes. Helmy, Hashim, and El-Desoky (2018) also examined the effect of traffic and geometric conditions on SFR. They found that BSFR is about 1788 pc/hr/ln and developed a regression model to reflect the combined effect of lane width, turn type, and traffic composition (heavy vehicles). Empirical models to estimate the effect of heavy vehicles and U-turn traffic volume share for left-turn lanes at signalized intersections were developed for Qatar's conditions (Abuhijleh et al. 2020). However, the interaction between these factors was not studied.

L. Wang, Wang, and Bie (2018) examined the interaction effect of adjustment factors for heavy vehicles percentage, lane width, and left-turn traffic volume share on SFR for through movement. A minimum of 15 cycles was collected per lane for a total of 60 lanes at Washington DC and Beijing Cities and used for the development of a regression model considering interaction effects. The mean absolute percentage error was used to compare the developed model with the HCM method.

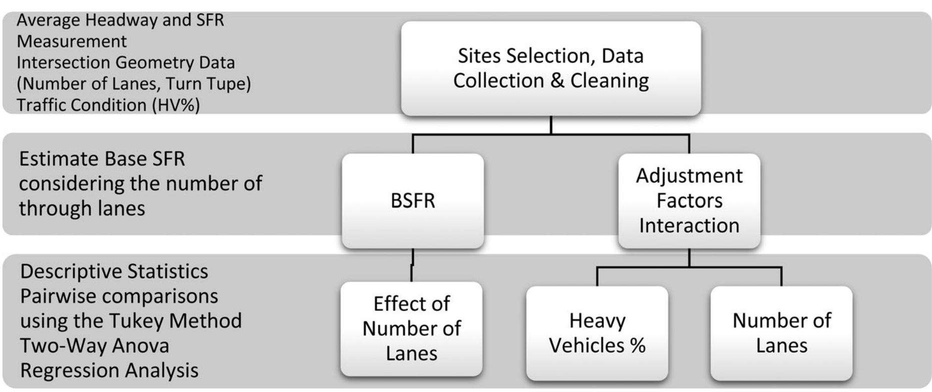
Recent research by Y. Wang et al. (2020) has developed a dynamic method for SFR estimation using a neural network considering the ability to receive continuous traffic data from intersection sensors and detectors. The proposed dynamic method for SFR estimation was found to be an accurate representation of SFR that overcame the HCM 6th Edition (2016) (Transportation Research Board 2016) method limitation with respect to the dynamic change of SFR due to continuous advancement in vehicle's technology and variability of driving behavior. Their model would enable a better understanding of the complex shift in SFR and influencing variables, especially when interactions of complicated traffic and intersection geometric factors would affect the drivers' decisions and their headway. The findings indicated that the Artificial Neural Network-based models and the regression methods have better performance and accuracy compared to the HCM method with a reduction of 14–19% for the mean absolute percentage error when compared to field observations. The main factors considered in these models are lane width, percentage of heavy vehicles, percentage of left-turn share, multiple lanes for through movement. The following is a summary of the main findings and gaps found while reviewing the available research described in this section:

- The HCM 6th Edition (2016) method is widely used but requires continuous calibration for BSFR and adjustment factors to reflect the local traffic and driving behavior conditions
- HCM 6th Edition (2016) does not consider the interaction between adjustment factors which may lead to unnecessary errors in estimating SFR, especially for a complex condition
- The BSFR is generally estimated as a constant value without considering the effect of the number and type of the lanes, although this has been highlighted by several studies.

It is noted that there are limited studies investigating the influencing factors on SFR variations in developing countries like Qatar, which is experiencing rapid changes in local and driving conditions. In this paper, the combined effect of heavy vehicles and the number of lanes on SFR of through lanes will be investigated and modeled using the data collected in Qatar by applying statistical methods, which are explained in the next section.

## 3. Methodology

The following framework explain the main steps within the following described methodology:



### 3.1. Description of selected sites

Turning Movement Counts (TMC's) for many types of intersections across Qatar were carried out during the period from August 2017 until December 2018 using recorded videos. The cameras were installed at each approach by taking into consideration the sun-glare/distance of vehicles from camera/angles and high enough to view both stop line and queued vehicles. Twenty-four sites were carefully selected to ensure that the sites are not affected by traffic diversion, bus stop and on-street parking within 75 m of the stop line and downstream, uncontrolled pedestrian crossing, and narrow lane width (standard lane width 3.65). These recorded videos were utilized to manually measure the headway time and the number of passing vehicles from the recorded 9 h of videos during peak periods which were used to calculate the SFR value as per Equation (2). Table 1 provides a summary of the selected sites used for data collection and Figure S3 depicts selected intersections location. Almost more than 3335 cycles and 62,000 vehicles were observed to measure the headway at the 24 sites described in Table 1. Many readings were observed where three through lanes exist at intersections since most signalized intersections in Qatar have three lanes through. Notwithstanding, a considerable amount of measurements were observed at other intersections with various through lanes arrangement (almost more than 1000 cycles and 19,000 vehicles used for headway measurements). The analyzed lanes are those with exclusive through movement which is not shared with right turn movement or left-turn movement. The study sites had level upstream and downstream approaches (level: grade < ±2%). In each analysis signal cycle, a minimum of 10 queued vehicles at the end of the red phase should be

**Table 1.** Description of sites used for data collection.

| | Number of Through Lanes per approach (number of observed cycles) | | | | |
|---|---|---|---|---|---|
| Site ID | Eastbound | Northbound | Southbound | Westbound | Total |
| Int#1 | 2 (30) | 3 (45) | 3 (135) | 3 (135) | 345 |
| Int#2 | 3 (45) | 3 (45) | 4 (60) | 3 (45) | 195 |
| Int#3 | 3 (45) | 3 (45) | 3 (45) | 3 (45) | 180 |
| Int#4 | 3 (45) | 3 (45) | 3 (45) | 2 (30) | 165 |
| Int#5 | *NA | 1 (15) | *NA | 2 (30) | 45 |
| Int#6 | 3 (45) | 3 (45) | 3 (45) | 2 (30) | 165 |
| Int#7 | 3 (45) | 3 (45) | 3 (45) | *NA | 135 |
| Int#8 | 3 (45) | 3 (45) | 3 (45) | 3 (45) | 180 |
| Int#9 | 5 (75) | 4 (60) | 4 (60) | 5 (75) | 270 |
| Int#10 | 2 (30) | 3 (45) | 3 (45) | 2 (30) | 150 |
| Int#11 | *NA | 3 (45) | *NA | NA | 45 |
| Int#12 | 3 (45) | 3 (45) | 3 (45) | 3 (45) | 180 |
| Int#13 | *NA | 2 (30) | *NA | NA | 30 |
| Int#14 | 3 (45) | 3 (45) | 3 (45) | 3 (45) | 180 |
| Int#15 | 2 (30) | 3 (45) | 3 (45) | 2 (30) | 150 |
| Int#16 | *NA | *NA | 2 (30) | *NA | 30 |
| Int#17 | 2 (30) | 2 (30) | 3 (45) | 2 (30) | 135 |
| Int#18 | 2 (30) | 3 (45) | 3 (45) | 2 (30) | 150 |
| Int#19 | 1 (15) | 3 (45) | 3 (45) | 1 (15) | 120 |
| Int#20 | 1 (15) | 2 (30) | 2 (30) | 2 (20) | 95 |
| Int#21 | 1 (15) | *NA | *NA | 1 (15) | 30 |
| Int#22 | 3 (45) | 3 (45) | 3 (45) | 3 (45) | 180 |
| Int#23 | 4 (60) | 3 (45) | 3 (45) | *NA | 150 |
| Int#24 | *NA | *NA | *NA | 2 (30) | 30 |
| **Total** | **735** | **885** | **945** | **770** | **3335** |

*The recorded video at approach did not provide stop line visibility and the queued vehicles to observe the saturated headway and estimate SFR.

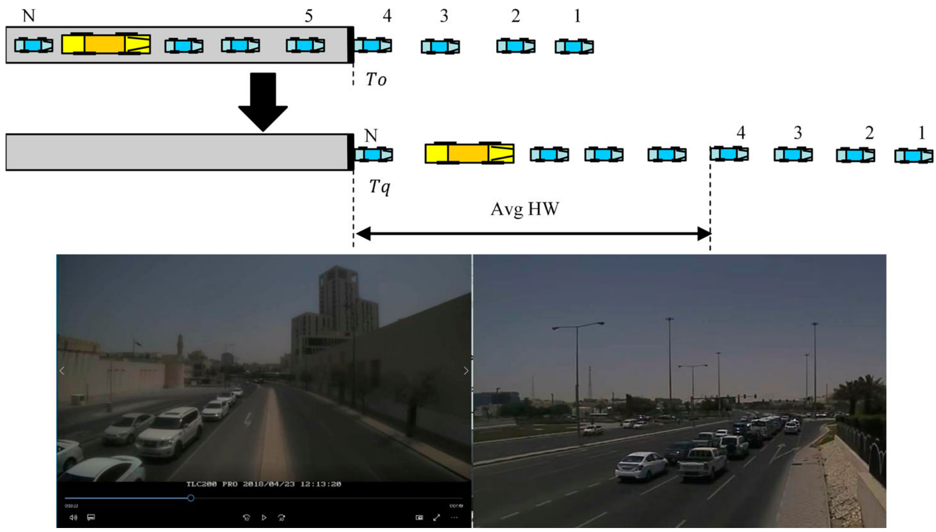



**Figure 1.** Illustration of headway measurement to estimate SFR for through lanes at intersections.

present to undertake the SFR analysis. This is in line with HCM 6th Edition (2016) (Transportation Research Board 2016) which suggests that after the fourth vehicle has been discharged, the saturation flow is achieved and sustained. Figure 1 illustrates the method used to measure the headway to estimate SFR for through lanes at Intersections. The data of outer through lane at approaches that do not have exclusive right turn lane were not used to remove the right turn effect. It is also important to mention that all sites had a median separated left turn lanes, which indicates no interaction between left turning and through movements.

### 3.2. Data collection

The following approach was adopted to measure the average headway and to calculate the SFR:

a. Collect the relevant information on turn movement and traffic composition (i.e. number of through lanes for lane group at each approach) for all 24 sites.
b. Headway estimation using TMC videos in which vehicular movement, queue lengths, and stop lines were visible for all selected approaches.
c. Observe the TMC videos to record the following information for each approach lane:
   - At the start of the green phase, identify the last vehicle in the queue in the lane at the end of the red phase (N); within this case, a maximum value of 20 is adopted. The SFR was calculated when the discharge rate was steady as suggested in the literature review that headway was stable after the 4th vehicle as per HCM 6th Edition (2016) SFR measurement process, and the minimum headway did not occur before the 8th vehicle [41]. It is therefore important to calculate the queue of traffic beyond the 10th vehicle to measure the maximum SFR.

- After the rear bumper of the 4th vehicle in the queue has passed the stop line, record the time that the fourth vehicle passes (To).
- Count the number of vehicles passing the stop line separated by light vehicles and heavy vehicles up to vehicle (N), the last queued vehicle. In the case where the queue comprised 20 vehicles, then the count of vehicles passing the stop line would be 16 vehicles after extracting the first four vehicles. Queue vehicles (N) less than ten vehicles were disregarded.
- As the rear bumper of the last queued vehicle (N) passes the stop line record the time (Tq).

d. Vehicles were classified into two groups: Light Vehicles (LV) and Heavy Vehicles (HV). The LV includes vehicle classes 1, 2, and 3 as per Figure S1, which shows Federal Highway Association (FHWA) vehicle classification categories, while HV includes the other ten categories.
e. The average headway was calculated, which is the time difference between $To$ and $Tq$. Please refer to the below Equations. The minimum queue considered is ten vehicles at the end of the red phase. The time recording will start after passing the 4th vehicle's discharge rate is steady until passing the last vehicle in the queue.
f. The number of passing vehicles during $To$ and $Tq$ is divided by the average headway to obtain the SFR, as given in the below equations

$$\text{Headway} = (Tq - To)/(N - 4) \tag{1}$$

$$\text{Saturation flow} = 3600*(N-4)/(Tq - To) \tag{2}$$

$Tq$ is the Time that nth vehicle passed the stop line; $To$ is the Time that 4th vehicle passed the stop line; $N$ is the number of vehicles passing the stop line in the time ($Tq$–$To$)

g. The above method was repeated for 15 signal cycles on each approach lane at the selected TMCs site.
h. Derive the BSFR by excluding all measurements with HV vehicles present for Through Movement and examine the effect of the number of through lanes.
i. Derive the SFR considering the HV vehicles present for Through Movement. The influence of the interaction of the number of through lanes, and HV percentage on the SFR will be investigated and regression analysis for developing a new model.

### 3.3. Statistical analysis approach

The SFR data with no HV was extracted and used to answer if the number of lanes for the through lane group influences the BSFR. The outliers, shown in Figure S4, were identified and removed using Grubbs's test (the maximum normalized residual test) with the assumption of normality and at a 0.05 significance level [42]. The descriptive statistics for SFR (Mean, Mode, Standard Deviation, etc.) were conducted before drawing whisker boxes for all variables to understand the correlation between the SFR and number of lanes and SFR with HV%. HCM 6th Edition (2016) defines the BSFR as a constant value regardless of the number of lanes at the upstream approach. The hypothesis in this research is that the interaction effect between the number of lanes and the HV%

would influence the SFR value. To verify this hypothesis, the collected data were put in groups based on the number of lanes at the upstream approach (1, 2, 3, 4, and 5 lanes). Tukey comparison and one-way analysis of variance (ANOVA) were used to test if the number of lanes at the upstream approach would affect the BSFR. ANOVA was used to see if there is any evidence that the groups' means are statistically different. If the ANOVA reveals that there is evidence that the group means differ, then the Tukey multiple comparison tests were applied to find out which of the means is different. The reading measurement for SFR data with zero HV% was used to exclude any effect of traffic composition on BSFR. Once the hypothesis is answered, then the mean of BSFR was estimated based on the number of through lanes at the upstream approach.

The other hypothesis is to find the influence of the interaction effect between the number of lanes and the traffic composition (i.e. HV%) on SFR. Regression analysis was used to estimate the SFR's adjustment factor for the heavy vehicles considering the number of lanes for through movement. The data were divided into two groups (number of through lanes ≤ 2 Lanes and > 2 Lanes). The significance of the individual coefficients was obtained from the regression analysis based on the selected confidence level of 0.95. Minitab was used as statistical software to carry out the above-described statistical analysis. The intention of the new proposed model is to decrease the SFR estimation error considering the impact of the number of through lanes.

## 4. Analysis of results and discussion

### 4.1. SFR descriptive statistics

Measurements for SFR data with zero heavy vehicles proportion (HV% = 0) were used to estimate the BSFR considering the number of through lanes. The result of descriptive statistics for the saturation flow rates is summarized in Table 1 for a total of 1889 observations after removing the outliers as mentioned in section 3.3. The highest mean SFR was observed for five lane-through turn approaches, while one lane-through turn approach has the least average SFR, as shown in Table 1. It can be noticed that the BSFR is steadily increasing when the number of through lanes is increased while the variation between SFR reading represented in standard deviation is decreased. It can be observed that the average BSFR of a 5-lane road is approximately 14% more compared to a single-lane road. It shall be noted that the average SFR is not affected by the presence of heavy vehicles as it is not accounted for in the calculated average BSFR.

### 4.2. Evaluating lane configuration effect on BSFR

To find out how the number of through lanes affects the BSFR, a statistical comparison using one-way ANOVA was used to examine the significant effect of the number of lanes and the location of through lanes on the SFR at 95% confidence. The one-way ANOVA analysis is used to show whether there are any statistically significant differences between the means of three or more independent groups. The results of one-way ANOVA showed that the *P*-value is less than the significance level (0.05 assumed in this study). Therefore, it can be concluded that at least two of the group means are significantly different from each other at a 95% confidence level. To identify which means are significantly different from the rest, a Tukey comparison is used. The result of Tukey's comparison and interval plots for BSRF indicates that there is an effect of the change in the number of lanes on the SFR value as shown in Figure S2. For instance, the BSFR is significantly different for one and three lanes; however, changing the number of lanes from three to four has no significant effect on the SFR. It can be also concluded that the BSFR for one and two lanes is not significantly different.

Similarly, when the number of lanes is more than two, there is no significant difference in the BSFR with an increase in the number of lanes. It can also be seen that the mean of BSFR for through movement steadily increases from 2062 Veh/hr/ln for a single-lane approach to 2345 Veh/hr/ln for five lanes through movement approach. This lies within the range of recent studies in other regions, as shown in Table 2, which was reviewed by (Abuhijleh et al. 2020). However, these studies differentiate SFR based on the turning movement type but do not provide the relationship between the SFR and the number of lanes per movement Table 3.

To further investigate this phenomenon, the SFR was analyzed based on the number of lanes and the location of the lane at the upstream approach, i.e. Outer lane (the first lane from the right side or sidewalk curb), Middle lane (only for approach with three or more lanes), and Inner lane (the first lane from the left side or median/separator curb). Two-Way ANOVA, main effect, and interaction plots were used at a 95% confidence level.

As listed in Table S1, the mean BSFR for the outer and inner lanes are not significantly different. However, the middle lane has a considerably higher mean BSFR than the outer and inner lanes, as listed in Figure 2. The number of through lanes and lane location affect the SFR value since the *P*-value is less than the significant level (0.05). However, the interaction effect of both factors was not significant. From Figure 2(a), it can be noticed that the SFR at the middle lane has the highest SFR that is significantly different from the SFR at inner and outer lanes. The interaction plot in Figure 2(b) shows that the inner lane has higher SFR than the outer lane when the number of lanes increases to 4 lanes but decreases when the approach has five lanes, while the SFR for the middle lane increases when the number of through lanes increased.

It should be noted that the sample size for inner and outer lanes at the five-lanes approach is limited (i.e. only 9 and 12 cycles, respectively). Therefore, the results indicate that it is more likely that the SFR increases regardless of the location of the lane, while the increment is significant when the number of lanes is more than two. The SFR of the middle lane is significantly higher than the inner and outer lanes. This could be explained as a result of the more space and less friction between vehicles. Tukey comparison and interval plot for each type of lane location based on the approach number of lanes can be found in Figure 3. The sample for inner and outer lanes at five lanes approach is

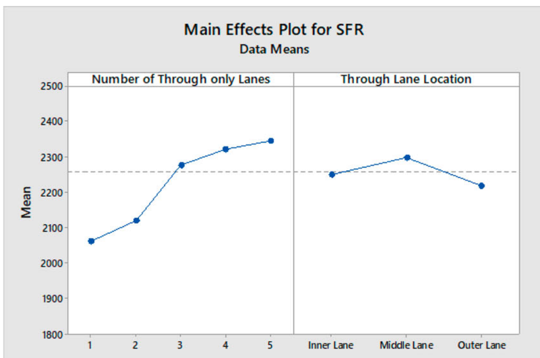
**Table 2.** Descriptive statistics of observed BSFR data based on number of through lanes at approaches.

| Number of through lanes at the approach | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Number of Cycles | 38 | 267 | 1375 | 128 | 81 |
| Mean of SFR | 2062 | 2120 | 2278 | 2322 | 2345 |
| StDev | 324 | 318 | 224 | 229 | 209 |

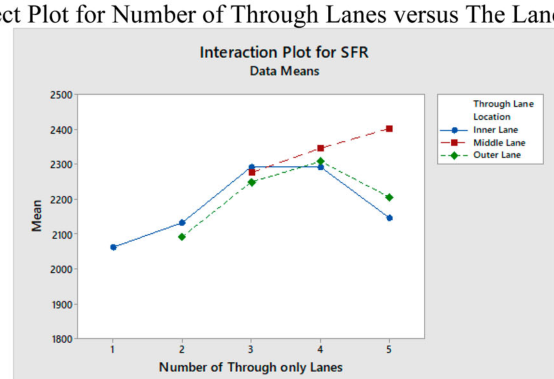
**Table 3.** Comparison of SFR with other countries.

| Source | City/Country | Lane Movement* | SFR (veh/hr/ln) |
|---|---|---|---|
| Hamad and Abuhamda (2015) | Doha, Qatar | TH | 2323 |
| Al-Ghamdi (1999) | Riyadh, Saudi Arabia | TH | 2195–2293 |
| Gao and Alam (2014) | Makkah, Saudi Arabia | TH | 2500 |
| Al-Omari and Musa (2020) | Jordan | TH | 2050 |
| | Kuwait | | 2100 |
| Mohseni and Mirza Boroujerdian (2018) | Tehran, Iran | TH | 1905 |
| Dündar and Öğüt (2018) | Istanbul, Turkey | TH | 1894 |
| Stanić, Tubić, and Čelar (2011) | Belgrade, Serbia | TH | 2120–2209 |
| Rahman, Ahmed, and Hassan (2015) | Dhaka, Bangladesh | TH | 2006–2091 |
| | Yokohama, Japan | | 1636–2093 |
| Mukwaya and Mwesige (2011) | Kampala, Uganda | TH | 1470–1774 |
| Shawky, Al-Ghafli, and Al-Harthi (2017) | Malaysia | TH | 1945 |
| Hussayin and Shoukry (1986) | Cairo, Egypt | TH | 1617 |
| Coeymas and Meely (1988) | Santiago, Chile | TH | 1603 |
| Lee and Do (2002) | South Korea | TH | 1978 |
| De Andrade (1988) | Brazil | TH | 1660 |
| Bruwer, Bester, and Viljoen (2019) | South Africa | TH & RT | 1711–2370 |
| Chand, Gupta, and Velmurugan (2017) | India | TH & RT | 1869–2083 |

Note: TH refers to exclusive through lanes, LT refers to the exclusive left-turning lanes, RT refers to right turning lanes and LUT refers to shared left-turning & u-turning lanes.
Source: Table 1 from Abuhijleh et al. (2020).

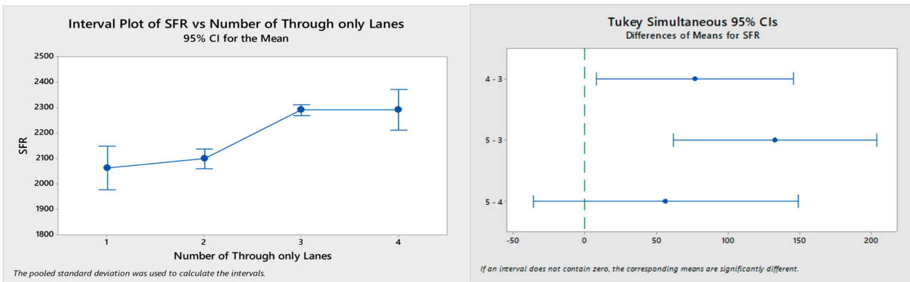



(a) Main Effect Plot for Number of Through Lanes versus The Lane Location Effect

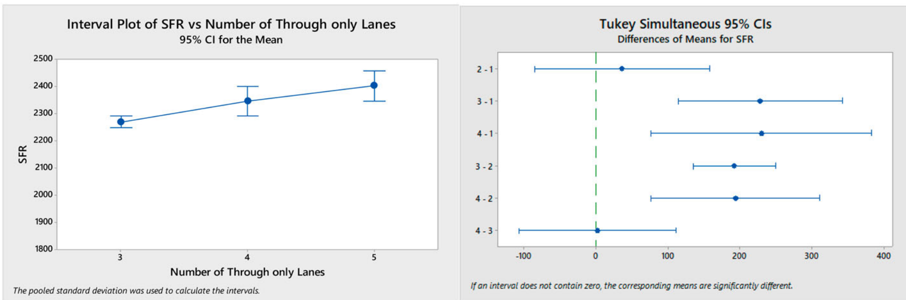



(b) Interaction Plot for Number of Through Lanes and The Lane Location Effect on SFR

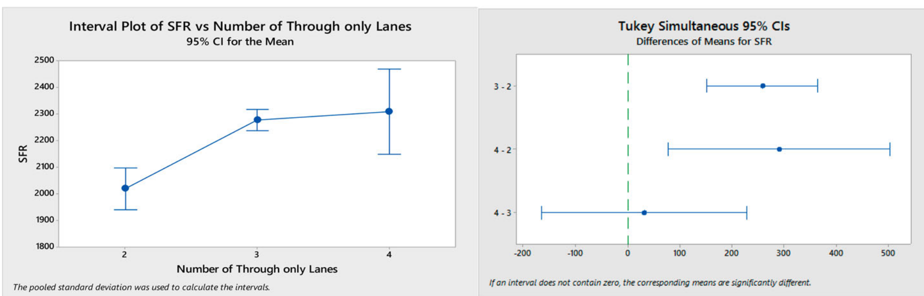
**Figure 2.** Main effect and interaction plot based on two-way ANOVA test for SFR and both number of lanes and lane location factors.




a)BSFR at Inner Lane




b) BSFR at Middle Lane




c)BSFR at Outer Lane

**Figure 3.** Interval plots and tukey comparison results at 95% confidence level.

low (9 and 12 cycles); therefore, they were removed when this test was conducted, as shown in Figure 3.

### 4.3. Interaction effects of lane configuration and traffic composition on SFR

To understand the effect of heavy vehicles, and the number of lanes on SFR, the Pearson correlation test was conducted at a 0.05 significance level. The Pearson correlation of SFR and the number of through-only Lanes was 0.361, which has a positive effect on SFR. However, the number of through-only Lanes factor was found to be significant ($p$-value $< 0.05$).

The factorial design of the experiment was used to test the interaction effect of number through lanes and heavy vehicles proportion on SFR. The standardized effect is used to test the null hypothesis that the factor has no significant effect on the response as shown in Figure S5, which is the SFR in this case. The results showed that the proportion of heavy vehicles has the highest negative effect on the SFR. Therefore, an increase in the proportion of heavy vehicles significantly reduces the SFR. Similarly, the interaction between the number of lanes and the proportion of heavy vehicles showed a significantly negative effect on the SFR.

The effect of the interaction between the number of lanes and the proportion of heavy vehicles can be further illustrated in Figure 4 that shows the contour plots of the number of lanes versus the proportion of heavy vehicles to predict the SFR. The heavy vehicles effect on SFR increases when the number of through lanes is less.

### 4.4. Regression model for estimating HV impact on SFR

Based on previous sections, it was statistically evident that the number of lanes and the HV% affect SFR value which the Highway Capacity Manual (HCM 6th Edition 2016) (Transportation Research Board 2016) does not consider. It was also evident that the SFR is significantly different when the through lanes are less or more than two lanes. Therefore, to further estimate the effect of the heavy vehicles on SFR with respect to the number of through lanes, the data were divided into two groups (number of through lanes $\leq$ 2 Lanes and > 2 Lanes). The SFR data for each group were analyzed for model estimation using linear and non-linear regression and compared to HCM 6th Edition (2016) model shown in Equation (2). The normality and outlier tests were conducted before regression analysis for the two above-described groups. Outlier tests had $p$-values greater than 0.05, indicating that there were no outliers at the 5% significance level. It was found that the negative exponential function, which provides a similar SFR pattern when compared to HCM 6th Edition (2016), yielded to the best fitting results.

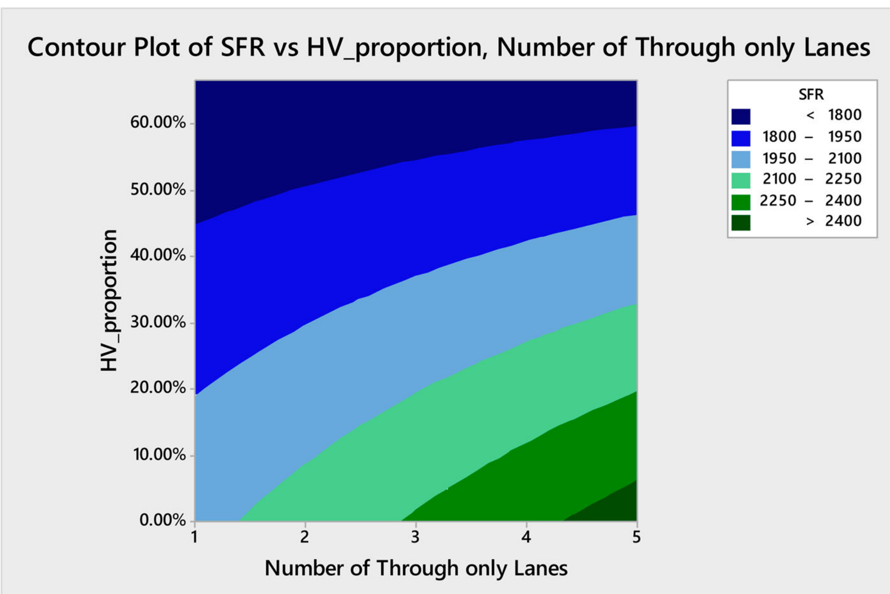
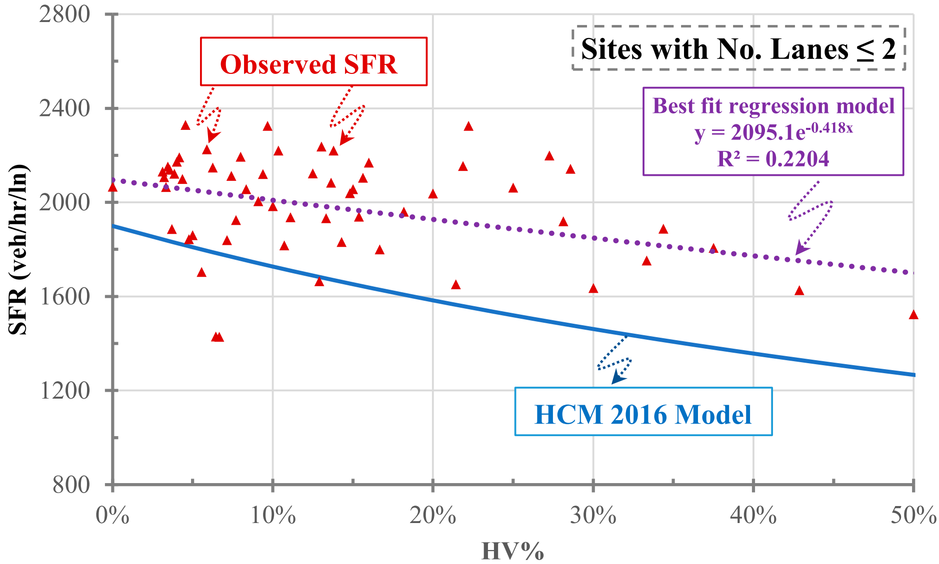
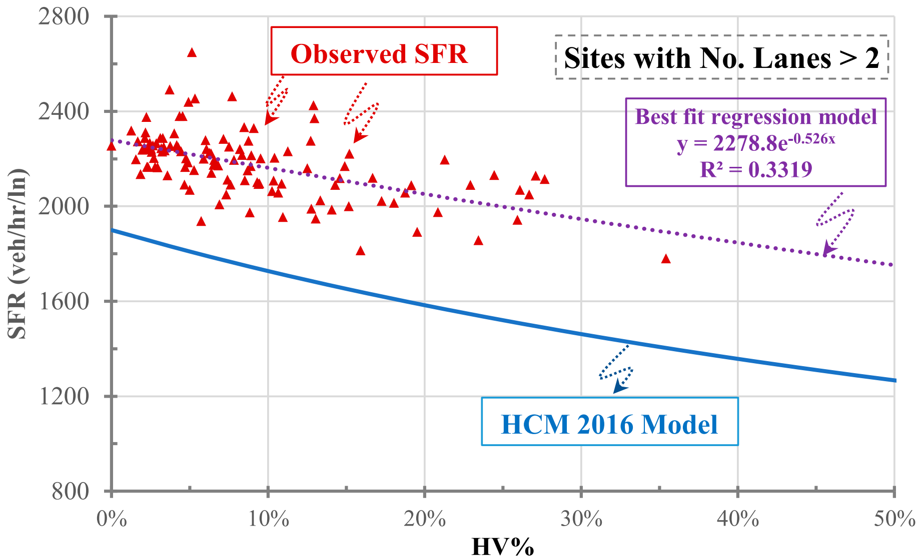



**Figure 4.** Contour plot of SFR versus heavy vehicle proportion and number of lanes.




a) When Number of Lanes at Upstream Approach ≤ 2




b) When Number of Lanes at Upstream Approach > 2

**Figure 5.** Observed VS regression models for SFR considering HV impact.

Figure 5 presents the relationship between observed SFR as a function of HV% from the observed data as well as the HCM 6th Edition (2016) Model. Figure 5 also illustrates a scattered plot for HV Impact on SFR value for the observed versus the proposed model based on the number of lanes at the upstream approach. The graphical representation in Figure 5 clearly indicates that the current SFR models in HCM 6th Edition (2016) to represent HV impact have more effect on SFR than the proposed model. The proposed model provides the SFR value under different traffic or HV conditions but is dependent on the number of lanes at the upstream approach. The SFR values are higher for approaches with more than two lanes, but it drops faster compared to the SFR of approaches with two lanes or less, as illustrated in Figure 6. However, both models show less HV impact on SFR than the HCM 6th Edition (2016) model.

## 5. Implications

The SFR model developed in this study indicates that BSFR and the impact of HV on SFR can be better explained considering the number of lanes at the upstream approach and the driving conditions in Qatar. In addition, the outcomes of this study help improve the adjustment factors in SFR multiplicative model proposed in HCM 6th Edition (2016) method. Figure 5 provides a comparison between the SFR estimation using HCM 6th Edition (2016) models and this study to predict the effect of heavy vehicles proportion on SFR based on the number of lanes for through movements.

It is evident that BSFR in the HCM 6th Edition (2016) method is underestimated by at least 150–400 veh/hr/ln compared to BSFR indicated in Table 2. At the same time, the effect of heavy vehicles on SFR in HCM 6th Edition (2016) is overestimated almost twice compared to SFR models developed in this research. This would lead to an over-design of signalized intersection infrastructure, i.e. the number of lanes and improper allocation of signal phases. The findings of this study can be used by planners and designers in Qatar to analyze and amend current standards for SFR parameters included in Qatar's Guidelines and Procedures for Transport Studies (QGPTS) since SFR is the primary input during traffic signal design. QGPTS is currently using SFR values and functions recommended by HCM 6th Edition (2016). Thus, adopting the outcomes of

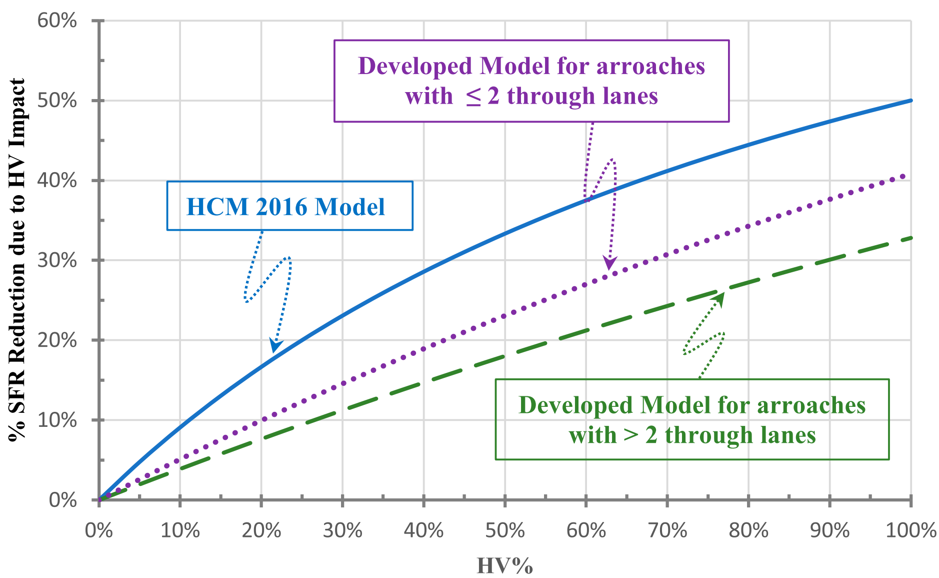



Figure 6. Comparison of HV% impact on SFR between new estimated model and HCM model.

this study by the responsible transport authority in Qatar (i.e. MOTC) will improve the planning, design, and operation of signalized intersections.

Furthermore, Ashghal (the responsible agency for operating roads in Qatar) would benefit from the outcomes of this study. A possible implication could be to reduce the volume-to-capacity ratio (V/C) when defining the traffic signal timing and phasing plans at the operation phase of fixed-time signals and setting the maximum and minimum green for actuated signals. This would lead to less green time allocation to through movement, which can be relocated to other critical turning movements to improve overall intersection quality of service. These improvements could potentially reduce unutilized green time and average delay per vehicle. In the long run, such policy-driven optimization would reduce traffic congestion and resulting emissions.

Consequently, the infrastructure or operation savings from optimized intersections can be utilized by Qatar's governments or policymakers to enhance and develop roads in other areas or even reallocate budget savings for developing sustainable transport facilities such as e-vehicles charging stations and public transport services, and active transport facilities. Moreover, other countries with similar driving and road conditions could also adopt the finding of this research. Ultimately, embracing the SFR models offered in this research would help in achieving more optimal infrastructure and more robust operation for road networks in Qatar and similar countries.

## 6. Conclusions and recommendations

HCM 6th Edition (2016) defines the BSFR as a constant value regardless of the number of lanes at the upstream approach. To verify this hypothesis, the collected data were put into groups based on the number of lanes at the upstream approach (1, 2, 3, 4, and 5 lanes). Tukey comparison and one-way analysis of variance (ANOVA) were used to test if the number of lanes at the upstream approach would affect the BSFR. In addition, ANOVA and Tukey multiple comparison tests were used to see if there is any evidence that the groups' means are statistically different and find out which of the means is different. It was found that the mean of BSFR for through movement steadily increases from 2062 Veh/hr/ln for a single-lane approach to 2345 Veh/hr/ln for five lanes through movement approach, and there is a significant difference in SFR when the number of through lanes is more than two lanes. This is mainly due to the effect of middle lane SFRs'.

The measured SFRs were analyzed to account for the effect of the number of through lanes and heavy vehicles proportion and their interaction effect, which was studied for the first time in this research to the best of our knowledge. Regression analysis was used to estimate the SFR adjustment factors for the heavy vehicle percentages and the number of lanes for through movements. It is expected that the proposed model in this study would decrease the SFR estimation error. The adjustment factor for heavy vehicles is not independent and is significantly affected by the interaction between the number of lanes and heavy vehicles proportion. Moreover, the interaction between the number of lanes and the proportion of heavy vehicles showed a significantly negative effect on the SFR, which increases when the number of through lanes is more. The proposed model to predict the effect of heavy vehicles proportion on SFR based on the number of lanes for through movement showed that heavy vehicles have a higher effect on the BSFR when the number of through lanes is more than two lanes which has a similar trend in HCM 6th Edition (2016) when through lanes are more than two lanes.

The significance of this finding would help professionals with concrete SFR values to be adopted during intersection design and operation, considering the combined effects of heavy vehicles and the number of lanes for through movement. In addition, this supports the need to review and update current guidelines and standards for planning and developing transportation infrastructure to achieve more optimal infrastructure and more robust operation. Such policy-driven optimization is intended to minimize traffic, energy needs, and emissions in the long run.

The combined effects of the number of lanes and the proportion of heavy vehicles on SFR for Left-Turn and U-Turn or shared lanes were not investigated in this research. Future research is recommended to explore the interaction effect of other adjustment factors in the HCM 6th Edition (2016) method using more global data. The calibrated SFR values can be validated in such future research by comparing observed and calculated queue lengths, which were a limitation in our study due to the absence of measured queue length. Also, the empirical estimation for SFR during the nighttime condition and rural areas were not examined. These are important factors to be further studied in the future.

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