Empirical Analysis of Saturation Flow Rate by Considering the Downstream Conditions

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Saturation flow rate (SFR, hereinafter) serves as the most important parameter in the analysis of a signalized intersection. Due to higher traffic demand rates the queues present at the intersection approaches tend to become longer, which leads to deteriorate the performance of the vehicles approaching from the upstream intersection. Such a phenomenon is frequently observed in large urban areas where the traffic volume is heavy, intersection spacing is short and cycle length is long. In this paper, analysis of the SFR and the downstream conditions reveals that as the space available behind the queue in the downstream segment at the onset of green becomes smaller, the SFR at the subject intersection approach tends to deteriorate.

Key Words: *Signalized intersection, saturation flow rate, downstream conditions, available queue storage length.*

1. INTRODUCTION

Signalized intersection forms a fundamental component of an urban transportation system and appropriate treatments for intersection related congestion and issues are increasingly growing in importance. Recent research indicates that for a variety of reasons such as population, economic and car ownership growth, increasing traffic demand can quickly exceed the capacity of urban intersections during peak periods, resulting in longer queues at an intersection approach. On the other hand, longer spaces are required to accommodate a departing flow with higher traffic demands in the downstream segment. However, the availability of longer queues in the downstream segment will diminish the performance of the subject intersection approach. This phenomenon is frequently observed in large urban areas where the traffic volume is heavy, intersection spacing is short and cycle length is long.

At any typical signalized intersection, vehicles would arrive during the red time and wait in the queue, as the signal display turns green, the vehicles will depart the intersection with a certain flow rate, which is generally regarded as Saturation Flow Rate (SFR). However, if the queue in the downstream segment is still waiting for the traffic signal to turn green or the space available behind the queue in the downstream segment is smaller the drivers departing from subject intersection approach would be discouraged to accelerate to discharge. It is expected that the longer the downstream queue, the greater such an impact becomes (e.g. peak hour, or poorly coordinated intersections). Thus, the SFR at the subject intersection approach is expected to be significantly affected by the downstream conditions. SFR is defined as, the equivalent hourly rate at which previously queued vehicles can traverse an intersection approach under prevailing conditions, assuming that the green signal is available at all times and no lost

times are experienced[1)]. It is important in transportation engineering because it serves as the basis for setting traffic signal timings, estimating the capacity of signalized intersections and evaluating the mobility performance.

This study is designed to provide a practical model that evaluates the interactions between the downstream conditions and SFR of the subject intersection approach. The model could be used to assist the traffic engineers to determine the deterioration rate in the value of SFR due to the influence of downstream conditions.

2. LITERATURE REVIEW AND HYPOTHESIS

(1) Literature Review

A review of the literature regarding the influence of downstream conditions over SFR yielded a limited number of publications. *The Traffic Timing Manual*[4] recommends that the performance measures of intersection treatments should include queue lengths.

The latest version of Highway Capacity Manual (HCM 6th Edition)[1] explains the procedure to calculate the SFR by using the following equation:

$$s = s_0\, f_w\, f_{HVg}\, f_p\, f_{bb}\, f_a\, f_{LU}\, f_{LT}\, f_{RT}\, f_{Lpb}\, f_{Rpb}\, f_{wz}\, f_{ms}\, f_{sp} \quad (1)$$

Where SFR (s) is calculated by adjusting the base SFR (s_0) by different geometric and traffic flow adjustment factors (f_{xx}). Among all the adjustment factors, adjustment factor for downstream mid segment lane blockage (f_{ms}) and adjustment factor for sustained spillback (f_{sp}) represents the adjustment for the downstream conditions. f_{ms} discusses the effect of lane blockage only due to construction work or due to the occurrence of special event, like accident, etc.

Whereas, f_{sp} discusses the effect of downstream conditions as a result of sustained spillback. HCM categorizes the queue spillback as one of the two cases; cyclic or sustained. Cyclic spillback occurs on short street segments with relatively longer signal cycle lengths and sustained spillback is a result of oversaturation (i.e. more vehicles discharging from the subject intersection than can be served at the downstream intersection). As shown in Equation (2) f_{sp} depends upon the volume-to-capacity ratio of the subject intersection and f_{ms}, which means that f_{sp} shows the reduction in the SFR of the subject intersection approach due to mid-segment lane blockage only, but it does not include the effect of queuing from the downstream intersection, which could happen due to increase in the traffic demand or due to oversaturation.

$$f_{sp,i,l} = \left(\frac{dv_{u,i}}{c_{u,i}}\right)^{0.5} \times f_{ms,i} \times f_{sp,i,l-1} \quad (2)$$

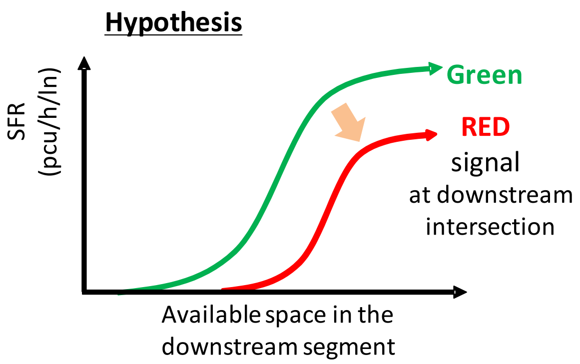


Fig. 1 Expected result due to the influence of downstream conditions

Where,

$f_{sp,i,l}$: adjustment factor for spillback for upstream movement i for Iteration l,

$dv_{u,i}$: maximum discharge rate of upstream movement i [veh/h],

$c_{u,i}$: capacity at the upstream intersection for movement i [veh/h], and

$f_{ms,i}$: adjustment factor for downstream lane blockage for movement i.

(2) Hypothesis

Generally, when the vehicles are departing from the subject intersection their flow rate is not only affected by the downstream spillback but also when the space available in the downstream segment is smaller and the departing drivers are demotivated to accelerate which leads to affect the SFR at the subject intersection. **Fig.1** shows the expected results due to the influence of downstream conditions over SFR. It is expected that the longer the downstream queue is, the greater such an impact becomes (i.e. peak hour, or poorly coordinated intersections). In addition, if at the onset of green at the subject intersection, the signal light at the downstream intersection is red, vehicles approaching the down-stream segment by viewing the stationary queue and the red signal light will be further demotivated to accelerate, resulting in a further deterioration in the value of SFR.

3. METHODOLOGY AND DATA COLLECTION

(1) Estimation of SFR

In order to consider the influence of downstream conditions, two different types of SFRs are considered; adjusted SFR and observed SFR. Adjusted SFR is calculated by the adjustment of base SFR using different geometric and traffic flow adjustment factors, based upon the methodology prescribed in the *Manual on Traffic Signal control*[3].

Observed SFR is calculated for each cycle by considering the average headway of the 4th until the last vehicle in the queue, termed as saturation headway calculated by using Equations (3) and (4).

$$s_i = \frac{3600}{h_i} \tag{3}$$

$$h_i = \frac{Tn_i - T4_i}{n_i - 4} \tag{4}$$

Where,

s_i : SFR for cycle i [veh/h/ln],

h_i : average saturation headway for cycle i [s],

Tn_i : discharge time of nth queued vehicle during cycle i [s],

$T4_i$: discharge time of 4th queued vehicle during cycle i [s], and

n_i : number of queued vehicles observed during cycle i

An analysis on the trajectories of all the vehicles involved in between two intersections (subject and downstream intersections) reveals that, longer queues in the downstream segment tend to affect the headways of the departing vehicles from the subject intersection. **Fig. 2** shows an example of the trajectories of the vehicles departing from the subject intersection during one cycle. Where the black dotted line indicates the end of the queue in the downstream segment. By the time the departing vehicles from subject intersection reaches the queue in the downstream segment they tend to reduce their speed, which produces a backward shockwave. The red dotted circle indicates the propagation of the shockwave until it results in the increase in the headways of the departing vehicles. Therefore, it is necessary to consider some analysis of parameters which could define the presence of the queue and increase in the headways of the departing vehicles.

(2) Definition of Influencing Parameters

Fig. 3 shows the definition of downstream parameters necessary for the analysis, measured at the onset of green. In order to fully explain the downstream conditions, the vehicles availability is categorized into two cases, vehicles in the queue (stationary or moving) and the moving vehicles behind the queue which are still trying to reach the queue. The influence of the vehicles in the queue is illustrated by the value of L_a, and the influence of the moving vehicles behind the queue is defined by their density (k).

(3) Data Collection

A video survey was conducted on Tuesday, January 31 and Wednesday, February 1, 2017, along an urban arterial corridor (Yasukuni-dori) including five

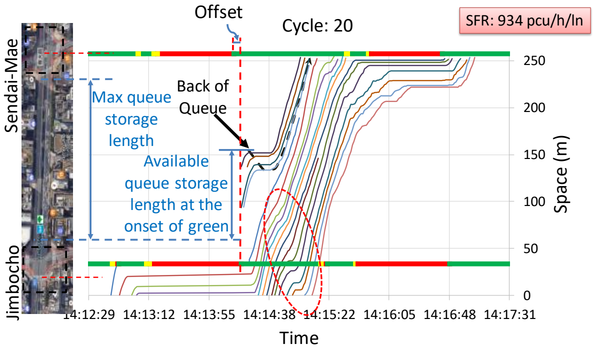
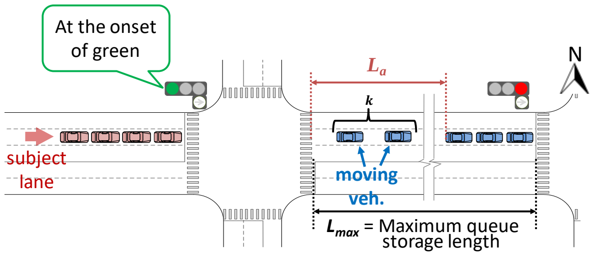


Fig. 2 Trajectories of the vehicles



Where,

L_a : available queue storage length in the downstream segment [m],

k : density of the moving vehicles behind the queue in the downstream segment [veh/km], and

Offset : time difference between the downstream and subject intersection green indication [s].

Fig. 3 Definition of analysis parameters

approaches of three different intersections, including a key intersection (Jimbocho) in the metropolitan area of Tokyo. Around 235 cycles were recorded on two consecutive sunny days, covering both the morning and evening peak hours for the major through eastbound (EB) and westbound (WB) approaches. Each approach consists of an exclusive right turning, two through and a shared through and left turning lanes. An image processing software is used to extract the data from the videos.

Distance between the intersections (segment length) is varying in between 116 m to 248 m. In order to neglect the effect of turning vehicles only the outer exclusive through lane is considered for the analysis in this paper. The traffic signal timing is actuated and the length of green signal changes cycle by cycle. The heavy vehicle effect is eliminated by removing their headways and the vehicle behind them from the queue. Thus, only the cycles having more than 8 vehicles (only PCs) are analyzed in the following section.

4. DATA ANALYSIS AND DISCUSSION

(1) Average SFR for each appraoch

The adjusted SFR is calculated by considering the base SFR as 2,000 pcu/h/ln[2)] adjusted by two adjustment factors (lane width and approach gradient), resulting as 1,900 pcu/h/ln for all the five approaches, because of almost the same geometric characteristics.

On the other hand, the average observed SFRs for all the five approaches are estimated by using the *average headway method*[4]. In this method, the average SFR is obtained by the averaging of h_i from all the cycles and dividing it into 3,600.

The data is categorized based upon the value of L_a, because after viewing the situation on the site it was revealed that "$L_a = 0.6L_{max}$" acted as a threshold value in between the cycles affected and not affected by the downstream conditions. **Fig. 4** shows three different SFR values for all the five approaches. The adjusted SFR value is the same (1,900 pcu/h/ln) for all the five approaches. "$L_a \geq 0.6L_{max}$" represents the observed SFR of the cycles which are not affected by the downstream conditions, "$L_a < 0.6L_{max}$" repersents the observed SFR of the cycles which are affected by the donwstream conditions.

The difference between the adjusted SFR and "$L_a \geq 0.6L_{max}$ SFR" indicates the drawbacks of the existing methodology, which means that the existing method-ology could not fully explain the real conditions. And the difference between the "$L_a < 0.6L_{max}$ SFR" and "$L_a \geq 0.6L_{max}$ SFR" indicates that it is quite necessary to include the influence of downstream conditions while calculating the value of SFR. By corporating the affect of downstream conditions in the existing methodology the difference could be reduced.

Comparing the reducing trend of the "$L_a < 0.6L_{max}$ SFR" from the "$L_a \geq 0.6L_{max}$ SFR" and adjusted SFRs, is quite higher in the last two approaches with compare to the first three approaches, that is because of the availability of the bottle-neck (key intersection) in the downstream as shown in **Fig. 5**, and also the 5th approach has the highest reduction in SFR among all the approaches, which is because of the smaller segment length (116 m).

(2) Impact of downstream conditions over SFR

While analyzing the data, three different cases of downstream conditions were observed. The proportion of the occurance for each of the cases is shown in **Fig. 6**.

Case (i) Only queue available in the downstream segment

Case (ii) Queue plus moving vehicles available behind the queue in the downstream segment

Case (iii) The first two cases plus red signal indication at the downstream intersection.

In addition to the importance of space availibility in the downstream segment, the third case also reflects the importance of proper coordination

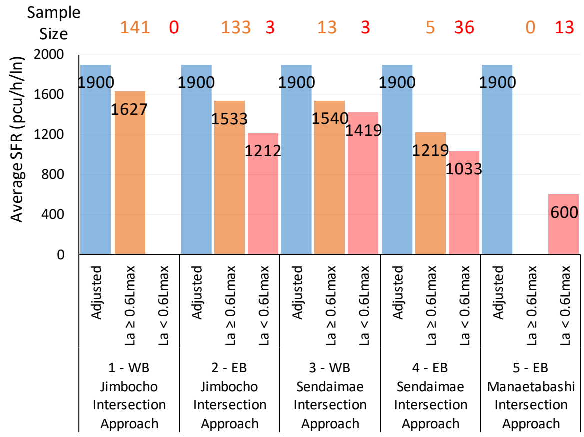


Fig. 4 Average SFRs for different approaches

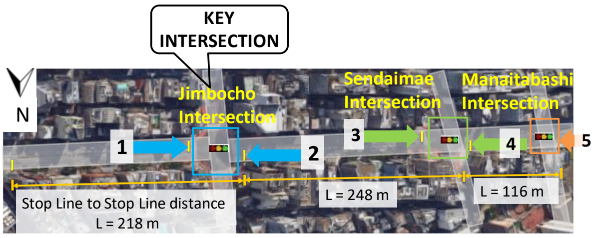


Fig. 5 Site description

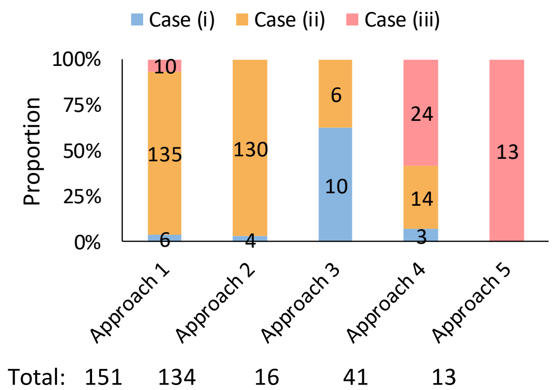


Fig. 6 Proportion of the values in three cases

between two intersections. **Fig. 7** shows the result of the relationship between SFR and L_a for the three cases. Where the three different colors indicate the three cases; blue, orange and red for cases (i), (ii) and (iii), respectively. And the five different symbols represents five different approaches.

As the percentage of space available in the downstream segment tends to reduce, the SFR becomes smaller. This reducing trend depends upon the available different conditions at each approach. Aproaches **1**, **2** and **3** are not affected by the downstream conditions, because for all the data set L_a value is more than $0.6L_{max}$ (except three values for approach **3**), which is due to the proper offset setting between these intersections. Even for approach **1** few cycles exists, where the downstream intersection is red at the onset of green at the subject intersection (negative offset), but the value of SFR is not affected, which is because the negative offset value is not very high which leads the spillback to occur or cause the vehicles to fully occupy the downstream segment, and also because the segment length is long enough (246 m) to accomodate the existing and approaching vehicles into the downstream segment.

On the other hand, approaches **4** and **5** are highly affected by the downstream conditions, because the key intersection (Jimbocho intersection) exists at their downstream, where due to the longer queue at the key intersection approach leads to smaller L_a values. Improper offset settings at these two approaches leads to higher traffic volumes, hence greatly affecting the flow rate. In addition, approach **5**, exists with shorter segment length (143 m), which frequently leads to spillback.

Generally, the reduction in the value of SFR for each intersection approach could be due to the the following reasons:

1. Small available queue storage length (L_a)
2. Negative signal offset setting
3. Key intersection in the downstream
4. Smaller segment length
5. Higher traffic volume

As a result the downstream conditions has the least effect over the SFR of the subject intersection approach in the first case and the highest effect in the third case.

(3) Model Development:

Three different non-linear regression models are developed for each case, as defined in section **4(2)**. The following model is considered:

$$SFR = a\ln(bL_a + c) + d \quad (5)$$

Fig. 8 shows the validation of the model with the model estimation results shown in **Table 1.**
For case (i), where the constant c is zero therefore L_a should be always more than zero. For the lower values of L_a it results in a higher SFR value with compare to the other two cases, because of the unavailability of the affect of the moving vehicles behind the queue.

For case (ii) and case (iii) where, the constant $c \neq 0$, resulting in SFR values of 870 and 450 pcu/h/ln, respectively at L_a= 0. In case (ii) where in addition to the queue some moving vehicles also exist behind the queue, therefore the influence over SFR is larger than case (i). Lastly case (iii) has the highest influence over SFR, because of the negative offset setting.

In reality all the three cases should result in some value of SFR at L_a=0, because beyond L_a=0 intersection width can accomudate some vehicles. But in case (i) due the small number of sample size the result could not be of satisfactory.

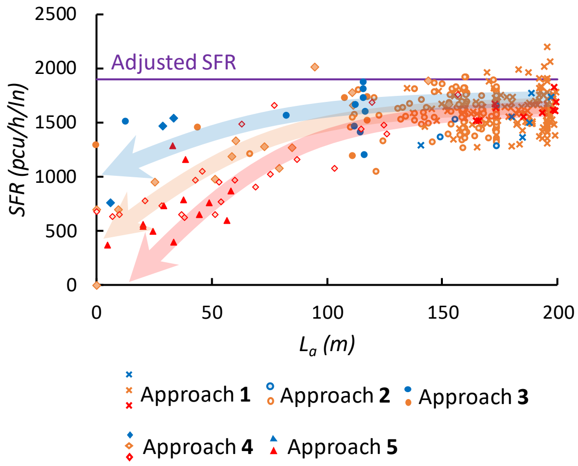


Fig. 7 Relationship between SFR and L_a

Table 1 Model Estimation Results

	Case (i) *t-stat*	Case (ii) *t-stat*	Case (iii) *t-stat*
a	126.1 *2.490*	307.2 *3.730*	1243 *1.700*
b	0.01000 *2.810*	57.87 *1.070*	0.01286 *0.8800*
c	0.00 -	987.6 -	1.436 *6.380*
d	1509 -	-1248 *-2.330*	0.00 -
R-square	0.2277	0.2329	0.9691
Sample size	23	285	47

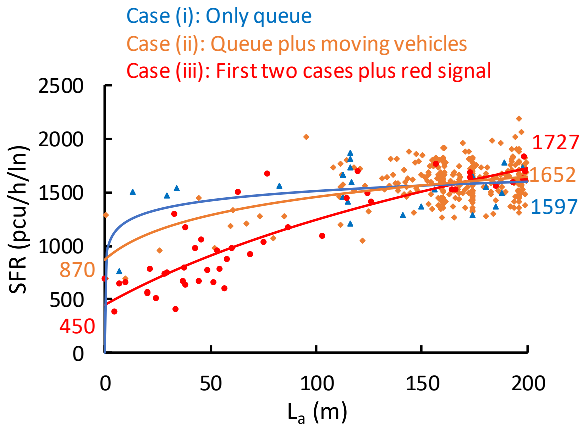


Fig. 8 Model Validation

On the other hand, the maximum value for all the three cases are expected to converge at a constant maximum value of base SFR, but due to the large variation in the data set at the higher values of L_a, which is due to more freedom of driver behavior but not due to the impact of downstream conditions, some fluctuation is observed.

Among all the three cases, case (iii) reduction is more sharp, which is because of the red signal in the downstream intersection. The difference between the case (ii) and case (iii) tend to become larger as it reaches the minimum value of L_a, which means that with poor coordination in between two intersections, a small increment in the queue length in the downstream segment could result in a larger reduction in the value of SFR. Such conditions are more likely to occur in the peak hours.

5. CONCLUSION AND FUTURE WORK

In large urban areas where the traffic volume is heavy, intersection spacing is short and cycle length is long, frequent diminishing in the performance of upstream departing flow is expected. In order to eliminate the effect of the downstream conditions, it is necessary to exactly quantify its effect by considering all the possible parameters. Among all the downstream variables available queue storage length (L_a) results to be the most influencing variable. In the third case where in addition to L_a, offset is also necessary to be considered. Under higher traffic flow conditions, the queue lengths in the downstream segment becomes longer and reduces the SFR at the subject intersection. Therefore, firstly it is necessary to consider the downstream conditions while estimating the SFR and not only when spillback condition occurs, but all the other downstream conditions should also be considered.

In the above mentioned research work, intersections located in smaller distance are highly affected by the downstream conditions, but due to only 5 sample of approaches it could not be considered as an influencing variable in modelling, therefore it is necessary to increase the number of sites. Furthermore, it is necessary to consider the variation in SFR due to the fluctuation in traffic demand.

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