Analysis on start-up lost time at closely spaced signalized intersections

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Start-up lost time (SLT, hereinafter) serves as one of the important parameters in the performance of signalized intersections. In the area where traffic demand is higher and intersections are closely spaced, the drivers' desire for quick speed up is demotivated by negative downstream conditions, such as long queue, limited available storage length, and poorly coordinated traffic signals, which leads to the growth in the SLT of upstream lane groups. In this paper, the influence of downstream conditions over upstream SLT is analyzed. Result indicates that the distance to the last vehicle in downstream queue and last moving vehicle are two main downstream factors influencing the SLT at subject intersections. Short downstream segment length and inappropriate offset settings will lead to a high SLT value as well.

Key Words: *Signalized intersection, start-up lost time, downstream conditions.*

1. INTRODUCTION

Signalized intersection is the fundamental component of the urban transportation system and appropriate treatments for intersection-related congestion and issues are increasingly growing in importance. On the other hand, longer spaces are required to accommodate a departing flow with higher traffic demands in the downstream segment. However, the presence of long 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 platoons will reach the maximal departure flow rate after a few seconds. During this time, the green time is underutilized and it is generally regarded as Star-up Lost Time (SLT).

However, if the queue in the downstream segment is still waiting for the traffic signal to turn to 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 traffic signals). Thus, the SLT at the subject intersection approach is expected to be significantly affected by the downstream conditions.

SLT is defined as the additional time consumed by first few vehicles in a queue at a signalized intersection above and beyond the saturation headway because of the need to react to the initiation of the green phase and to accelerate[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 performance. This study is designed to analyze the influence of downstream conditions over upstream SLT.

2. LITERATURE REVIEW AND HYPOTHESIS

(1) Literature Review

Start-up lost time denotes the underutilized time due to platoon accelerating process[2)]. It is often defined as the total time difference between the first four headways and the 4 times saturation headway. Generally, in signal timing, the SLT is measured by field survey or set as 3 seconds. Until now, many efforts have been done to reveal the relevance of SLT and other traffic parameters through empirical studies at isolated intersections. In 2003, Minh C.C. and

Sano K. pointed that the start-up lost time consists of start reaction time part and vehicle acceleration part[3]. In 2016, Çalışkanelli S.P. et al. proposed an empirical model for estimating the start response time of drivers in leading position and pointed out that SLT is related to lane width, bus percentage and queue length[4)5)].

On the other hand, it has also been proved that the performance of intersections could be influenced by downstream traffic. As the earliest researcher in this field, in 1992, Rouphail and Akcelik found that downstream queues could affect the capacity, delay, and queue length of subject intersection[6]. In 2005, Ahmed and Abu-Lebdeh estimated the delay in a system consisting of two closely spaced signalized intersections and found that delay caused by the downstream conditions can be reduced by adjusting offsets and green splits[7]. In 2017, Hashemi et al. revealed that as the available space behind the queue in the downstream segment at the onset of green becomes smaller, the saturation flow rate (SFR, hereinafter) at the subject intersection approach tends to decrease[8].

Nowadays, traffic demand is growing rapidly and traffic congestion happens frequently in the urban area. It is more meaningful to research non-isolated intersections than isolated intersections. However, as an important parameter for estimating intersection capacity, the downstream impact over SLT haven't been studied yet.

(2) Hypothesis

It is difficult to know how the SLT influenced by downstream conditions through observation. But it is obvious that if drivers know that they have to stop or decelerate in a short distance, they will not accelerate as quickly as a free start. Both the smaller space available in the downstream segment and red signal at the downstream intersection will demotivate their desire for quick to accelerate. According to the inference above, it can be assumed that the longer the downstream queue is, the greater such an impact becomes. In addition, if at the onset of green at the subject intersection, the signal light at the downstream intersection is red, vehicles approaching the downstream segment will be further demotivated by viewing the stationary queue and the red signal light, resulting in a higher SLT.

3. METHODOLOGY AND DATA COLLECTION

(1) Estimation of SLT

Theoretically, as **Fig. 1** shows, departure headways decrease sequentially with respect to vehicle queue

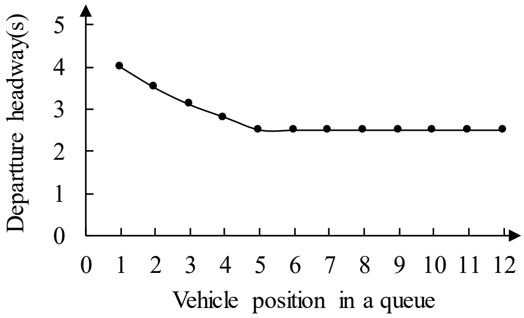


Fig. 1 Theoretical headway distribution

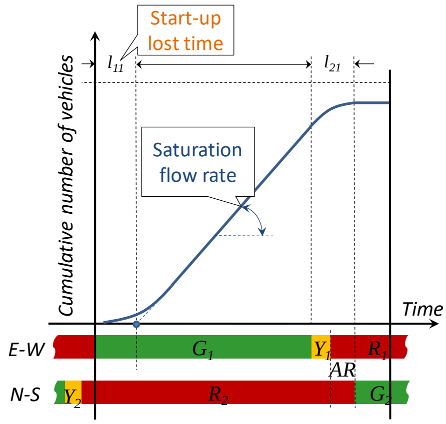


Fig. 2 SLT measurement method

positions, because the first few departure headways include driver reaction time and vehicle acceleration time. Conventionally, the saturation departure headway is assumed to be reached when the fifth vehicle crosses the stop line[1]. Accordingly, the observed SLT is calculated considering the total time difference between the saturation headway and the first four headways as the following formula.

$$t_s = \sum_{i=4}^{4} (h_i - h_s) \tag{1}$$

$$h_s = \frac{T_{n_i} - T_{4_i}}{n_i - 4} \tag{2}$$

Where,

s_i : SFR for cycle i [veh/h/ln],
i : position of the vehicle in a queue,
h_i: queue discharge headway of i^{th} vehicle (s),
h_s: saturation headway (s),
T_{n_i}: discharge time of n^{th} queued vehicle during cycle i (s),
T_{4_i}: discharge time of 4th queued vehicle during cycle i (s),
n_i: number of queued vehicles observed during cycle i.

This method is based on the assumption that the headways will be stable after the fourth vehicle. In reality, the headway distribution varies in different

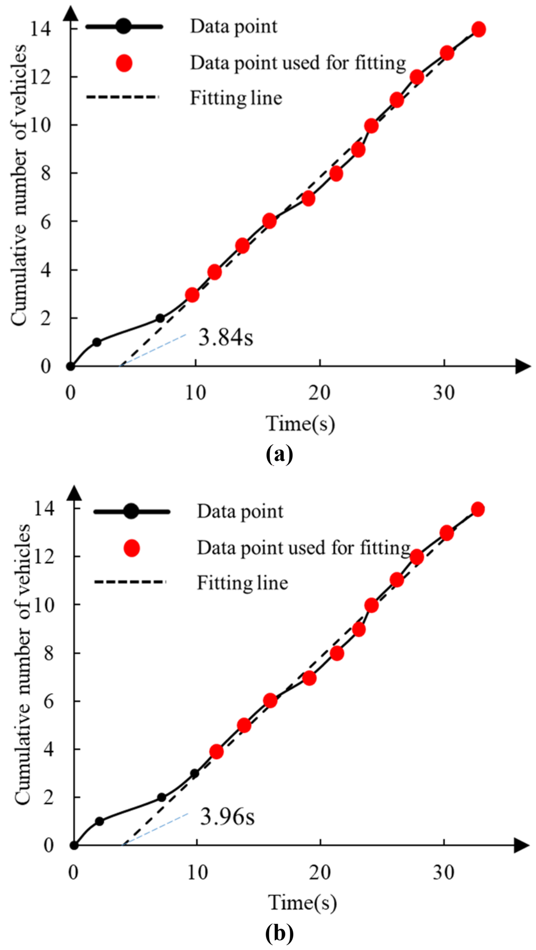


Fig. 3 Example of measuring SLT

cycles, sometimes the headway reduction ends before the fourth vehicle but sometimes after the fourth vehicle. Even in some cycles, the discharge headways fluctuate irregularly. In these cases, this method will no longer be appropriate. Considering this problem, a traditional method is introduced to measure SLT[9]. This method is to analyze the curve of the cumulative number of discharged vehicles and elapsed green time as **Fig. 2** shows. By extending the part of the straight line and solving its x-intercept, the value of start-up lost time can be determined.

In practice, fluctuation of real data makes it difficult for us to identify the straight part of the curve. Instead, the fitting line for whole data points is solved by the least square method and remove the point starting from the first point gradually until the result meets the following requirements.

a. The value of SLT should be larger than zero.

b. The difference ratio of two values obtained from three successive calculation should be less than 5%.

Fig.3 is an example of a cycle with 15 data points. Plot **(a)** shows that by fitting 4^{th} to 15^{th} data points the x-intercept value of the fitting line is 3.84s. Then the 4^{th} data point is removed, as the plot **(b)** shows, the x-intercept value of newly obtained fitting line (for 5^{th} to 15^{th} data points) is 3.96. The changing rate is

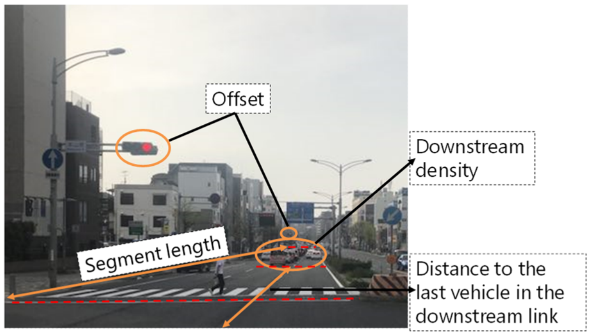
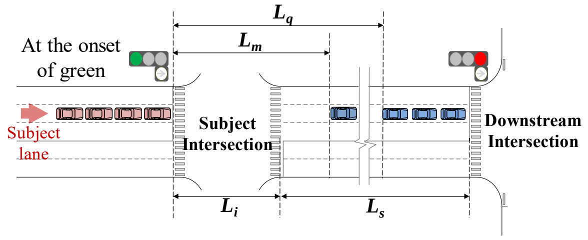


Fig. 4 Driver's perspective



Where,

L_s : length of downstream segment (m),
L_i : length of subject intersection (m),
L_q : distance to the last vehicle in downstream queue (m),
L_m: distance from upstream stop line to the rear bumper of last moving vehicle in the downstream segment,
Offset: time difference between the downstream and subject intersection green indication (s).

Fig. 5 Definitions of analysis parameters

(3.96-3.84)/3.96≈ 3%< 5%. Thus, the SLT value in this example is 3.84.

(2) Definitions of Influencing Parameters

In this study, all downstream parameters are extracted considering drivers' perspective. **Fig. 4** shows what drivers can see when they are waiting for discharge and the information they can know from the image. **Fig. 5** shows the detailed definition of downstream parameters and all parameters are measured at the onset of green.

(3) Data Collection

Fig. 6 and **Fig. 7** provide a description of the surveyed sites and the approach numbers. The approach 1-5 is located on Yasukuni-Dori in Tokyo. They are Jimbocho WB approach, Jimbocho EB approach, Sendaimae WB approach, Sendaimae EB approach, and Matsubara EB approach separately. A video survey was conducted on Tuesday, January 31 and Wednesday, February 1, 2017, along an urban arterial corridor (Yasukuni-Dori) including five approaches of three different intersections in the metropolitan area of Tokyo. Around 235 cycles were recorded on two consecutive sunny days. The distance between the intersections varies between

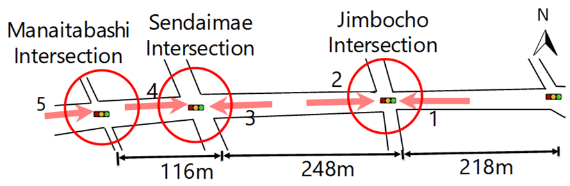


Fig. 6 Site description - Yasukuni-Dori, Tokyo

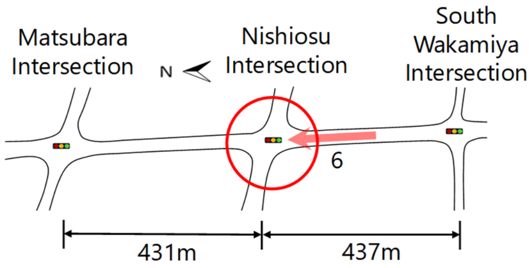


Fig. 7 Site description - Nishiosu intersection, Nagoya

116 m to 248 m. Each approach consists of an exclusive right turning, two through and a shared through and left turning lanes.

As a comparison, the Nishiosu intersection in Nagoya is selected as the base intersection without downstream influence. The video survey was carried out on Tuesday, January 31, 2008, and around 235 cycles were recorded covering both the morning and evening peak hours. After checking the video, only the Northbound approach is selected and numbered as approach 6. This approach consists of an exclusive right turning, two through and an exclusive left-turn lane and the distance to downstream intersections is 431m.

An image processing software[10] is used to extract data from the videos. In order to neglect the effect of turning vehicles only the one exclusive through lane for each approach was selected. For obtaining valid data, only those signal cycles with sufficient queue lengths (more than 8 vehicles) were selected. With the consideration of available samples, the queues which are built up by less than a heavy vehicle and the first 6 vehicles are all small vehicles were chosen for the analysis. The heavy vehicle effect was eliminated by removing their headways and the vehicle behind them from the queue. Also, extremely large headways caused by vehicle breakdowns and spillback at the observed lanes were excluded to ensure the validity of samples.

4. DATA ANALYSIS AND DISCUSSION

(1) Average SLT for each approach

After data screening, a total of 180 samples are extracted from 281 recorded cycles and the methodology mentioned in Chapter 3 are used to calculate the SLT of each cycle. The data is further

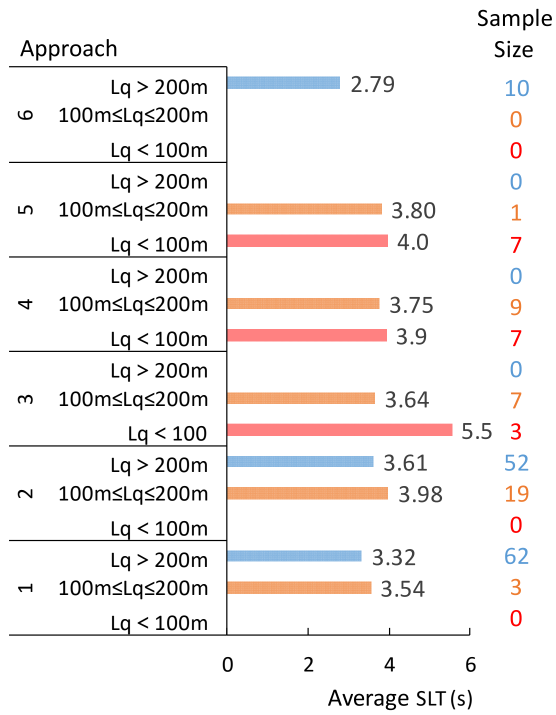


Fig. 8 Average SLTs for different approaches

categorized based on the value of L_q. By watching the recorderd video combining with actual driving experience, it is found that the available space to the last vehicle in the downstream queue has a great influence on drivers' behavior. When L_q is less than 100m, drivers will accelerate slowly and the SLT is extremely higher than the average value. Also, when L_q is longer than 200m, this effect will be significantly weakened and SLT is lower than the sample average value. Thus, "L_q=100m" and "L_q=200m" are selected as two thresholds. **Fig. 8** shows three different SLT values for all the six approaches. "L_q>200m" represents the SLT of the cycles which are less affected by downstream conditions. "L_q<100m" represents the SLT of the cycles which are greatly affected by downstream conditions. "200m≥L_q≥100m" represents the transitional part between them.

The difference between the average SLT of approach 6 and approach 1-5 indicates that the SLT of closely spaced intersections is higher than isolated intersections. Also, the decreasing trend of SLT in groups "L_q>200m", "200m≥L_q≥100m" and "L_q<100m" indicates that the downstream conditions do affect upstream SLT and it is quite necessary to consider the downstream influence while estimating SLT. Meanwhile, **Fig. 7** shows the information about downstream segment length and intersection length of each approach. The L_s+L_i of approach 1 and 2 is longer than 3 and 4. The absence of data group "L_q<100m" in approach 1 and 2 means that longer downstream segments could avoid the happening of shorter L_q and mitigate the downstream influence.

(2) Impact of downstream conditions over SLT

While processing the data, samples are further categorized into two different cases. The proportion of the occurrence for each cases is shown in **Fig. 9**.

Case (i) Positive offset, at the onset of green, the downstream signal is red;

Case (ii) Negative offset, at the onset of green, the downstream signal is green;

Fig. 10 and **Fig. 11** shows the result of the relationship between SLT, L_a and L_m for the two cases. Where the two different colors represent the two cases: red and blue for cases (i) and (ii). Also, the five different symbols indicate five different approaches separately.

With the decrease of L_q and L_m, the SLT becomes larger. This decreasing trend on L_q is more obvious than it on L_m, it can be inferred that the L_q have greater influence than L_m. Although the moving vehicles in the downstream link do impact upstream drivers' judgment, drivers consider more about the queuing vehicles than the moving vehicles. Also, the **Fig. 10** indicated that the SLT in case (i) is higher than case (ii) and as the L_q decreases, the difference between the case (i) and case (ii) becomes larger. This supports the assumption made in chapter 2 that positive offset could further demotivate drivers' desire for quick acceleration leading to a higher SLT.

This reducing trend depends on conditions of different approaches. Approaches 1 and 2 are not affected by the downstream conditions greatly, which is due to longer downstream link and lower traffic demand. Although some cycles of approach 1 are positive offset, the value of SLT is not affected. It is because that the offset values are not high enough for queue growing to influence SLT. It also because that its downstream segment length (246 m) is long enough to accommodate queueing vehicles. On the contrary, approach 4 is highly affected by the downstream conditions, because the cycle length of downstream intersection (Jimbocho intersection) is long and traffic demand is higher. Queueing vehicle accumulate in the downstream link which leads to the lower value of L_q. In addition, the distances to downstream stop line (L_s+L_i) of approach 3 (143m) and approach 5 (116m) are relatively short. Even few vehicles may result in a lower L_q resulting in a higher value of SLT in approach 3 and 5.

The reduction in the value of SLT for each intersection approach could be summarized into the following 5 reasons:

1. Long queue and a shorter distance to the last vehicle in the downstream queue (L_q);
2. Inappropriate signal offset setting;
3. The long cycle length of downstream intersection;

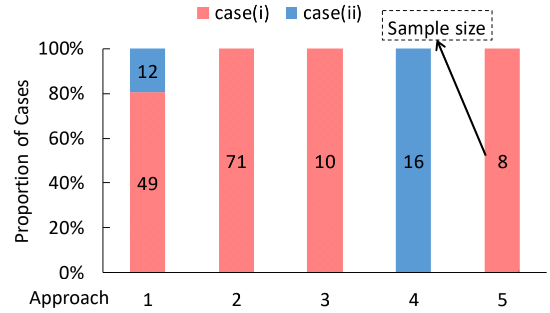


Fig. 9 Proportion of the values in two cases

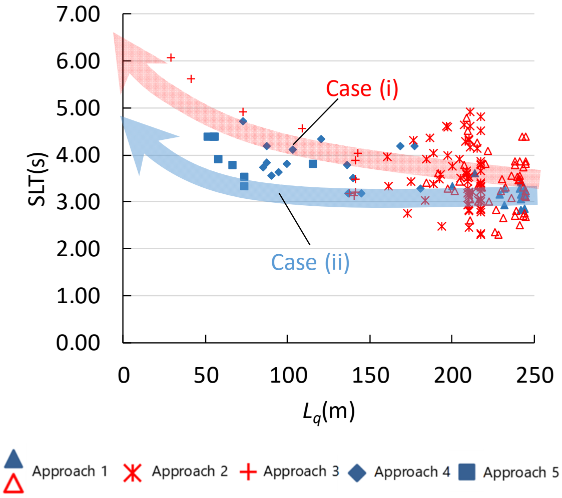


Fig. 10 Relationship between SLT and L_q

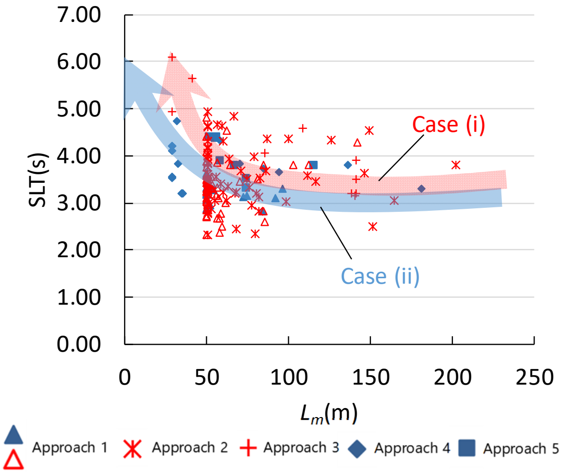


Fig. 11 Relationship between SLT and L_m

4. Smaller segment length (L_s) and smaller size intersection (L_i);
5. High traffic demand.

5. CONCLUSION AND FUTURE WORK

Analysis results revealed that among all the downstream variables, distance to the last vehicle in the downstream queue (L_q) and offset play an important role in impacting SLT. With the increase of traffic demand, the queue length in the downstream segment becomes longer resulting in a higher SLT at the subject intersection. This phenomenon happens frequently in the urban area where the intersection are closely spaced and segment length between intersections is short. Therefore, when estimating the SLT, the downstream influence should be highly considered.

In the above-mentioned research work, it has been proved that intersections located closely are highly affected by the downstream conditions, but only samples from 6 approaches are not enough to know the detailed changing rule, therefore increasing the number of sites is an inevitable requirement for future works.

Furthermore, SFR, SLT and clearance lost time (CLT, hereinafter) are three main parameters for estimating capacity. It has already been proved that negative downstream conditions could lead to a higher SLT and a lower SFR. For the future research it is necessary to continue to study the influenced CLT and build a mathematical model for the capacity at signalized intersections considering downstream impacts.

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