Evaluation of Randomness of Shared Left-turn Lane at Signalized Intersections

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Managing signalized intersection is always one of the issues in urban transportation planning, design and operation. It is important to evaluate expected performance of each lane group, when designing geometric layout and determining signal phase and timing. On shared left-turn lane at signalized intersections, left-turners often disturbs through vehicles, because they have to yield for crossing pedestrian in many cases. Even there is only one left-turner, if it is at the head of the queue, it might block all the following vehicles by facing to heavy pedestrian flow. In contrast, many vehicles can depart if the left-turner is queued at the very last position. Thus, the performance of shared lane may have significant fluctuations due to a random nature of the number and order of left-turners by cycle. Although many efforts have been made on reasonably estimating capacity of shared lanes in previous studies, which cannot fully account for such a random nature, it may sometimes result in unexpectedly low performance even demand does not exceed the planned capacity. To address this problem, a Monte Carlo simulation is conducted under the consideration of the order and number of left-turners as random. Result showed that left-turn proportion and blockage time have significant influence on the standard deviation of departed number in a cycle. Also, the randomness is shown to be significant to congestions even under lower demand than the capacity in terms of its mean value.

Key Words : *signalized intersection, shared left-turn lane, capacity, evaluation of randomness*

1. INTRODUCTION

Managing signalized intersection is always one of the issues in urban transportation planning, design and operation. It is important to evaluate expected performance of each lane group, when designing geometric layout and determining signal phase and timing. Performance of shared left-turn lane is one of the critical topics because of its unstableness.

Shared left-turn lanes accommodate both through and left-turn movements in one lane. Although only one more movement is added, the performance still contains quite unpredictable characteristics. It is because left-turners often disturbs through vehicles, because they have to yield for crossing pedestrian in many cases especially under heavy pedestrian flow.

Fig.1 shows an example of such unstable characteristics of shared left-turn lane. Assume that 10 vehicles including only one left-turners are departing from the shared left-turn lane, green time is 45 seconds, but pedestrians block the crosswalk at the exit of left-turn for 30 seconds. Three lines show the cumulative departed number of vehicles by time, while setting the order of the left-turner as the 1st, 5th, and the 10th position. It clearly tells that simply changing the order of the left-turner causes significant difference in the results. Therefore, even the demand flow does not exceed the designed capacity, congestion may still occur. Under such consideration, the performance of shared lane may have significant fluctuations which are affected by the order and number of left-turners.

So far, many studies have been conducted in order to obtain more precise estimation on capacity of shared left-turn lanes. However, the focus is only on its expected value during a period of time, and its fluctuation due to the randomness was not fully investigated. To address this problem, this study aims

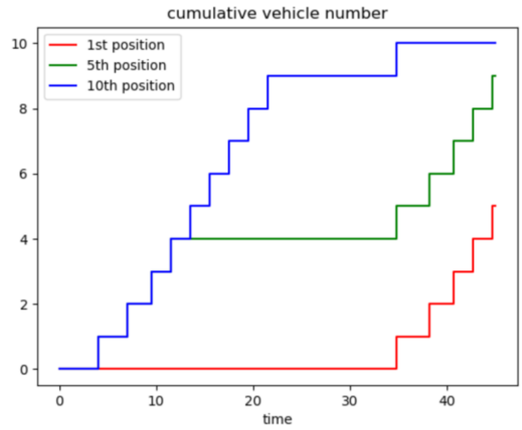


Fig.1 The performance of the cycle when the left-turner is located at the 1st, 5th , and 10th position

to evaluate the randomness of shared left-turn lane performance, and eventually provide insight into design and managing shared left-turn lanes at signalized intersections.

2. LITERATURE REVIEW

Capacity of shared lanes have been investigated over time to evaluate performance of shared left-turn lane (in the case of left-hand traffic; equivalent to shared right-turn lane in the case of right-hand traffic). In both Highway Capacity Manual[1] (hereafter, "HCM") and Japanese manual[2] (hereafter, "JSTE Manual"), the capacity of shared left/right-turn lane is calculated as equation (1).

$$C_s = S_s \times \frac{G}{C} \tag{1}$$

Where, C_s: capacity of shared lane, S_s: saturation flow rate (hereafter, "SFR") of shared lane, G: effective green time for shared lane, and C: cycle length. Thus, effect of left/right-turners is included in the calculation of SFR.

In HCM, SFR of shared right-turn lane is estimated by multiplying several adjustment factors with the base SFR, and then consider the impact of left-turn proportion and pedestrians.

$$S_s = \frac{S_T}{1 + P_R(\frac{E_R}{f_{Rpb}} - 1)} \tag{2}$$

Where, S_T: base SFR for exclusive through lane adjusted by several factors, P_R: proportion of right-turn vehicles, E_R: equivalent number of through vehicles for a protected right-turning vehicle, usually 1.18, f_{Rpb}: the pedestrian-bicycle adjustment factor which is obtained by estimating the pedestrian and bicycle occupancy from their flow rate.

Similarly, JSTE Manual introduces the estimation method of SFR as follows.

$$S_S = S_B A \alpha_{LT} \tag{3}$$

Where S_B: base SFR, A: product of several adjustment factors, α_{LT}: adjustment factor of left-turn movement which is calculated as:

$$\alpha_{LT} = \frac{100}{(100 - P_L) + E_{LT} P_L} \tag{4}$$

Where P_L: left-turn proportion (%), and E_{LT}: equivalent number of through vehicles for a protected left-turning vehicle, which is obtained by dividing the capacity of exclusive through lane by the capacity of exclusive left-turn lane. The probability of left-turners utilizing available gaps is considered in the capacity of exclusive left-turn lane in terms of cycle length, crosswalk length, and pedestrian flow.

Bonneson[3] proposed a model that first calculated the proportion of left or right turn vehicles in the left or right-most lane. Then, the lane change probability is incorporated and the SFR of shared lane is obtained. His study also included the sensitivity analysis of left- and right-turn proportion on SFR.

Chen, at al.[4] examined the precision of the methods estimating SFR in HCM (2000) and JSTE Manual (2007). The result shows that both manuals tend to overestimate the SFR, and a binary regression model is proposed to show that several factors are related to the shared lane blockage probability. To study the usage of shared lanes, Chen et al.[5] proposed a four-step procedure and incorporated it into his simulation. Case study showed that the proposed method provides better representation than that of HCM, as well as the JSTE. Such four-step procedure reproduced a rather realistic situation and thus outperformed the methods from HCM and JSTE Manual. Chen et al.[6] then used the four-step procedure to discover the factors that affects the SFR on shared right-turn lane (shared left-turn in Japan), such as right-turn proportion, pedestrian flow, crosswalk length, and storage capacity.

To further study how turning movements disturb through movement, researchers also studies the blockage probability on shared lanes. Wu[7] developed a model through a mathematical procedure that quantifies the influence of turning vehicles in both right-turn and left-turn shared lanes. The blockage probability and capacity of shared lanes can be calculated straightly through his model.

Although many efforts have been made on reasonably estimating capacity of shared lanes in previous studies, most of them do not consider the impact of the order of left-turners in the queue. Therefore, only the expected value, a kind of average capacity is used for planning and designing intersection layout and signal timing while its variation is not well understood, which may

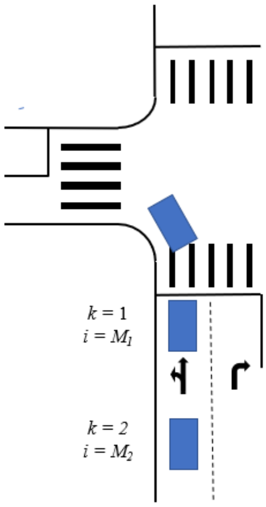


Fig.2 Intersection layout assumed for the simulation

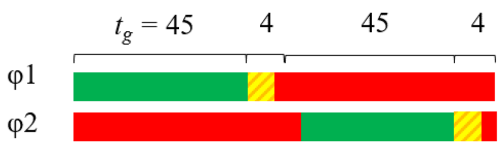


Fig.3 Signal phase assumed for the simulation

sometimes result in unexpectedly low performance even demand does not exceed the planned capacity.

As one of few example which considers the order of turning vehicle in the queue, Yoshitane, et al.[8] attempted to estimate capacity of single lane approach with all through, left- and right-turn vehicles, taking into account of the order of right-turners which have to stop for opposing through traffic by theoretical approach. However, their focus is still on the expected value, not its variation. Therefore, this study highlights the effect brought by the order and number of left-turners in the queue by focusing on the variation of departed numbers of each cycle in shared left-turn lanes.

3. METHODOLOGY

In order to assess the randomness of shared left-turn lane, we developed a Monte Carlo simulation to represent the impact of left-turners on departure during green time in a microscopic way. It enables us to evaluate not only average but also variation of the departed number of vehicles in each cycle. Here, it should be mentioned that the term of SFR is not used in this paper, regarding the fact that departure on shared left-turn lane cannot always be stable.

(1) Basic assumption

A two-lane four-way signalized intersection with exclusive right-turn lane was assumed for the simulation in this paper, as the simplest but also one of the typical geometric layouts of the intersection with shared left-turn lane. Since right-turn movement is completely separated, only shared left-turn lane of one subject approach was focused in the simulation, as illustrated in **Fig.2**. As there is only one shared lane, it needs to serve all of the through and left-turn traffic demand on the subject approach.

Table 1 Assumption on headways h_{ij}

i (Leader) / *j* (Follower)	*L* (Left)	*T* (Through)
L (Left)	3.0 sec	2.8 sec
T (Through)	2.4 sec	2.0 sec

Because the simulation is conducted only for the subject shared left-turn lane under the given demand, only green time t_g for that lane was actually the necessary parameter for the signal timing. This time, green time t_g was set as 45 seconds, assuming the simple two-phase signal control such as **Fig.3** which is typically installed in small intersections in Japan.

(2) Core ideas of the simulation

In order to reproduce the influence on departed number of vehicles in a green time t_g brought by the random order and number of left-turners which may be blocked by pedestrian, followings are the core ideas of the simulation in this study.

a) Traffic demand

For the traffic demand of each green time t_g, a platoon of through and left-turners is generated. Note that this process forms a platoon of vehicles that are ready to depart when its leading vehicle is departing, no matter whether it arrives during red or green. It does not consider the case that the succeeding vehicle has not yet arrived when its leading vehicle is departing.

The total number of vehicles in the platoon A is determined either as fixed or a value following Poisson distribution with a mean value λ. Here, each vehicle in the platoon is assigned as either through or left-turner randomly based on the given left-turn proportion P_L.

b) Blockage of left-turners by pedestrian

In order to simplify the occurrence of blockage of left-turners by pedestrian, green time is divided into three stages as illustrated in **Fig.4**:

- Stage 1: pedestrian flow completely blocks the way of left-turners, which means that left-turners cannot depart the intersection. Accordingly, once a left-turner is the head of the queue, departed number of vehicles on shared left-turn lane does not increase. This interval continues until blockage time t_{block}.
- Stage 2: most of the pedestrians left but few are still on the crosswalk, enabling left-turners to utilize available gaps to left-turn. This

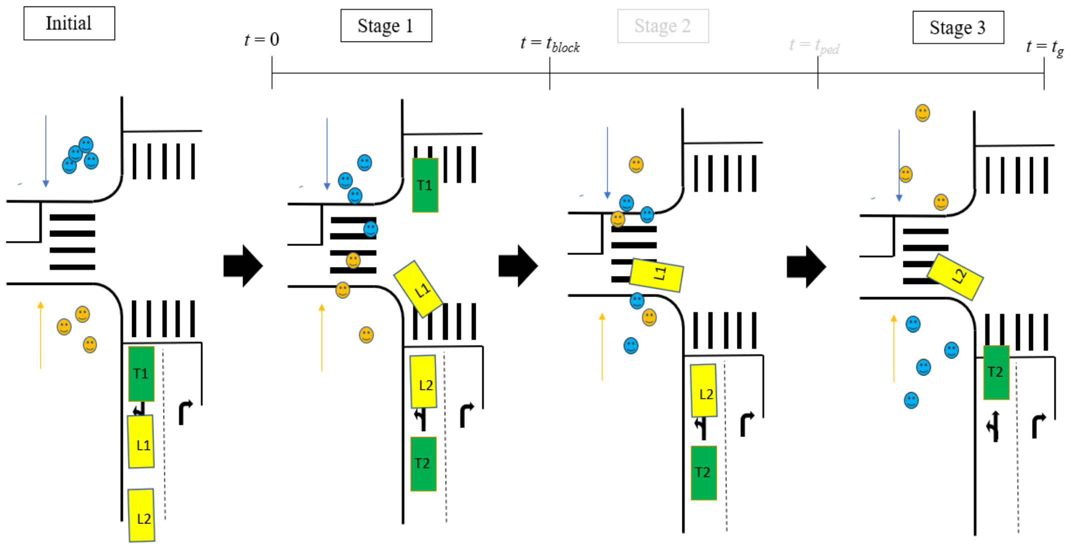


Fig.4 Three stages of a cycle

interval continues until time t comes to t_{ped}. In this paper, this stage is not considered for simplicity and left for the future work.

- Stage 3: there is no crossing pedestrian, and thus left-turners can depart freely until the end of the green time t_g.

c) Headway of through and left-turners

Although there is no pedestrian effect and vehicles can freely depart, headways of left-turners cannot be the same as that of through vehicles, because left-turners have to decelerate for turning movement when approaching to the stop line, especially in a small intersection. This emphasizes the blockage effect caused by left-turners.

Therefore, headway h_{ij} is assumed to be different by the movement (T: through or L: left-turn) of leader i and follower j in this simulation. **Table 1** shows an assumption of headways for that. So far, these values are determined based on assumptions only, and to be updated based on the empirical observations and statistical analysis in the future. In addition, start-up loss time is considered, because it happens not only after the onset of green but also after each stop of left-turner blocked by pedestrians on shared left-turn lanes. Under a rough assumption by referring to Tan, et al. [9] and Jin, et al. [10], 2 seconds, 1 second, and 0.5 second are added to the headways for the 1st, 2nd, and the 3rd vehicles after a stop. In the current simulation with only stage 1 and 3, this start-up effect occurs at most two times. It will be more significant if stage 2 is taken into account, because more frequent stops may happen due to gap acceptance.

(3) Simulation Process

a) Computation of discharge during green time

Integrating the above-mentioned ideas, **Fig.5** describes a flowchart of the simulation process, where k denotes the order of vehicles in the platoon, M_k is the movement of the kth vehicle, either through (denoted as "T") or left-turn ("L"). Each cycle starts with time $t = 0$, and ends at the end of the green time $t = t_g$. Note that at the initial setting, the leader i is set as a "T" movement, because the 1st vehicle can depart without any influence of the "L" leader, which is the same situation as having a "T" leader in this simulation.

At stage 1, through vehicles can depart freely. Here, time t increases with h_{ij} for each departed through vehicles. However, once a left-turner becomes the head of the queue (j = "L"), it blocks following vehicles and the departed number does not increase until $t = t_{block}$, thus process goes to stage 3.

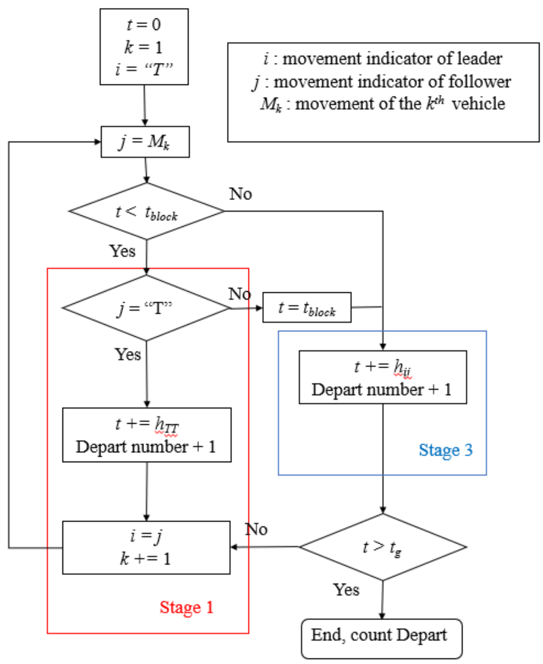


Fig.5 Flow chart of the simulation process

At stage 3, all vehicles depart freely while the increment of time t is either of h_{TT}, h_{LT}, h_{TL}, or h_{LL}, depending of the movement of leader and follower.

This procedure outputs the departed number of vehicles in one cycle. By repeating this procedure abundant times, mean and standard deviation of the departed number of vehicles are calculated for analysis.

b) Accumulation of randomness effect by successive cycles

Even on exclusive lane under unsaturated period, not all arrived vehicles can depart in one cycle due to the randomness of arrival by cycle. In the case of shared left-turn lane, because not only arrival side but also departure side has variation, such phenomenon is more likely to happen. The randomness effect is analyzed in terms of the number of uncleared cycles during a period of time.

Here, a series of 40 successive cycles is used to simulate approximately one peak hour to find out how many cycles cannot be cleared according to different mean value λ of vehicles in the platoon in one cycle. For each cycle, if the departed number is less than the number of vehicles in the platoon, A, that cycle is counted as an uncleared cycle. In addition, the vehicles left become the leading vehicles of the platoon in the next cycle.

This procedure is then repeated abundant times. As a result, average number of uncleared cycles can be obtained for evaluating how many unexpected congestion happened due to the randomness.

c) Effect of storage space for left-turners

In **Fig.**5, it is assumed that once a left-turner becomes the head of the queue (j = "L"), it blocks following vehicles in order to evaluate the simplest and severe condition at first. However, many intersections have a space to accommodate one left-turner in front of crosswalk. The effect of such storage space can be reflected by inserting additional judgment for the occupation of the storage space after j is judged as an "L". If another "L" arrives at stage 1 while the storage space is occupied, the simulation proceeds to step 3. Such effect will be discussed in the next section.

4. RESULT

(1) Variation in the departed number of vehicles

Fig.6 shows change of the departed number of vehicles in a single cycle by left-turn proportion P_{LT}, assuming blockage time t_{block} = 30 (sec). Blue line with plots show the average (μ), with the area of STD (σ). Here, demand is given as fixed, the maximum available number of 20.

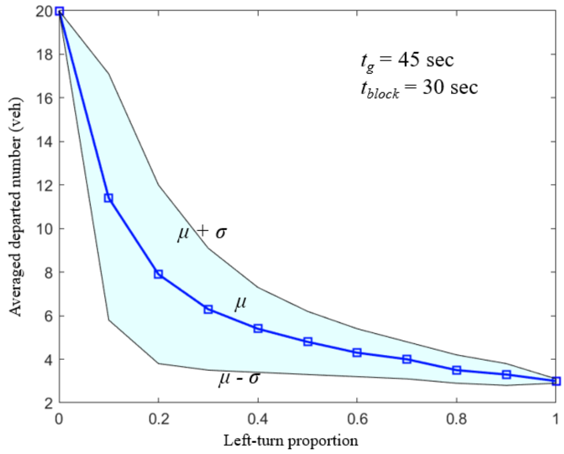


Fig.6 Averaged number of departed vehicles for each left-turn proportion

As same as known in general, sharp decrease of the average of departed number with the increase of left-turn proportion can be observed also from **Fig.6**. In addition, the figure shows that there is a large variation in the departed number under the mixture of through and left-turners (0 < left-turn proportion < 1), especially when left-turn proportion is small.

The influence of left-turn proportion P_{LT} on STD was further investigated by changing blockage time t_{block}. **Fig.7** shows STD under different left-turn proportion and blockage time with different colors. Here, blockage time t_{block} is set in terms of the percentage of green time t_g.

The result shows that STD increases with increasing blockage time, but only at lower left-turn proportions. Higher STDs appear at rather low left-turn proportion and longer blockage times. This is because at lower left-turn proportions, whether a left-turner arrives at early period of green time or not significantly affects the departed number of that cycle. This phenomenon will become severer when blockage time is longer, because that means the left-turner affects the cycle much longer. However, when

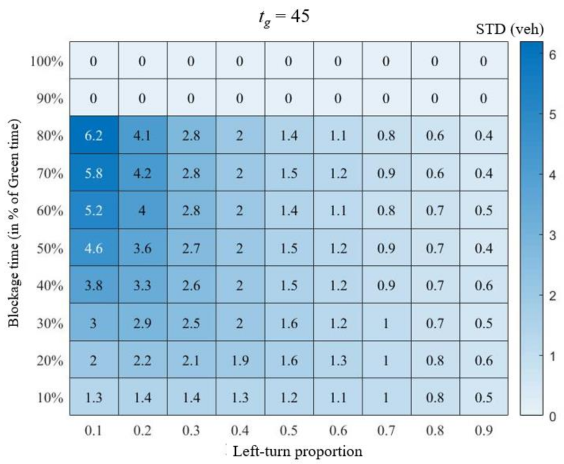


Fig.7 STD - Blockage time – Left-turn proportion

blockage time comes to be over 90%, only one or no vehicles can depart no matter if it is through or left-turner. Therefore, STDs remain 0.

(2) Effect of Random Arrival

Fig.8 shows the number of uncleared cycles with two different blockage time t_g. Lower left-turn proportion and lower blockage time can accept higher λ. Also, these curves show the effect of random arrival. If A is fixed, no uncleared cycle will exist until A exceeds the available number under each blockage time. For example, the minimum available number for t_{block} = 30% case is,

$$\frac{t_g * (1 - 0.3) - t_{start}}{h_{TT}} = \frac{45 * 0.7 - 3.5}{3} = 9 \quad (5)$$

Where t_{start} is the start-up loss time. If A is fixed, then no uncleared cycle will occur before A = 10. However, all cycles become uncleared when λ = 9. For the de facto exclusive lanes, the number of uncleared cycle reaches maximum when λ is approaching their maximum performance. Here, the curve with P_L = 0 can be explained to be purely affected by the random arrival, and it becomes steeper with the increasing random left-turn effect.

This result proves that even the average arrival is lower than the expected departed number, congestion still occurs due to the randomness on shared left-turn lane.

(3) Effect of storage space

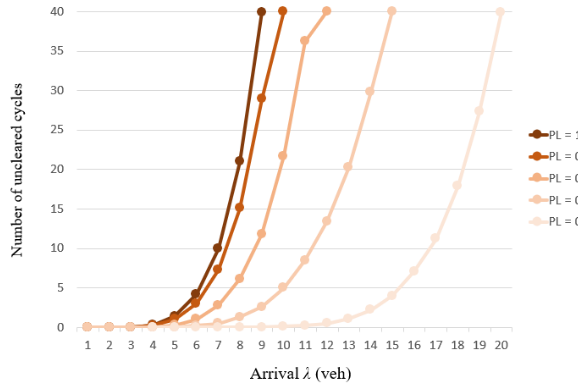
Additionally, in **Fig. 9**, average and STD of the departed numbers are compared with (c_{stor} = 1) and without (c_{stor} = 0, same as **Fig.6**) storage space in front of the crosswalk for a left-turner. It shows a right-shift in the averaged departed number from c_{stor} = 0 to 1, which means that the shared lane averagely performs better with a storage space. However, STDs remain almost the same. That means the performance does not become steadier due to the storage capacity. At stage 1, such storage space allows the through vehicles queueing between the first and second left-turners to depart. Thus, especially with relatively high left-turn proportion, such effect does not improve the steadiness of the performance so much.

5. CONCLUSION

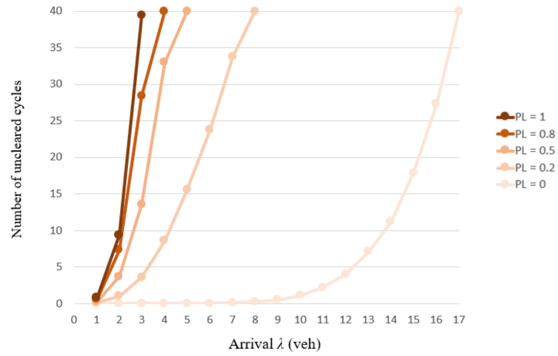
In this study, the randomness of left-turn movement on shared left-turn lane is evaluated by calculating STD of the departed number of vehicles and number of uncleared cycles from a microscopic viewpoint. The simulation considered the effect of left-turners in the platoon by setting their order and number as random.

Result showed that both left-turn proportion and length of blockage time have considerable influence on variation of departed number of vehicles. A scenario of successive cycles demonstrated that even the average arrival is lower than the expected departed number, congestion still occurs due to the randomness of arrived number and order of left-turners.

The impact of storage space is also considered in



(a) t_{block}/t_g = 30%



(b) t_{block}/t_g = 70%

Fig.8 Number of uncleared cycles

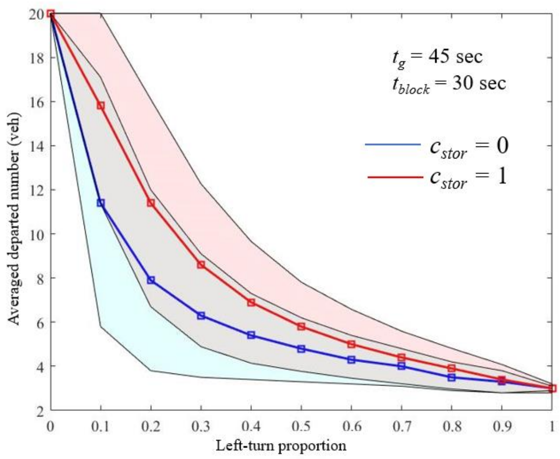


Fig. 9 Effect of storage space

this study. Although the average performance has an overall improvement, the variation does not seem to be alleviated by the storage space.

Different cycle length will be examined in further studies along with the delay experienced by the vehicles. It will also be necessary to incorporate stage 2 into the simulation to include the effect of gap acceptance on the randomness of shared lane performance. Furthermore, shared left-turn with exclusive through lane, and exclusive turning lane with exclusive through lane will be compared to study the difference between the performance of two designs. With such improvement, this study is expected to provide an insight into actual performance of shared lane, which may be helpful in managing and designing intersections.

REFERENCES

1) Transportation Research Board: Highway Capacity Manual 6th Edition, 2016.
2) Japan Society of Traffic Engineers (JSTE): Basic Manual on Planning, Design and Traffic Signal Control of At-Grade Intersection, 2018.
3) Bonneson, J., A. : Lane volume and saturation flow rate for multilane intersection approach, *Journal of Transportation Engineering,* Vol. 124. No. 3, pp. 240-255, 1998.
4) Chen, P., Nakamura, H., Asano, M. : Saturation flow rate analysis for shared left-turn lane at signalized intersections in Japan, *Procedia-Social Behavioral Sciences,* Vol. 16, pp. 548-559, 2011.
5) Chen, P., Nakamura, H., Asano, M. : Lane utilization of shared left-turn lane based on saturation flow rate modeling, *Procedia-Social Behavioral Sciences,* Vol. 43, pp. 178-191, 2012.
6) Chen, P., Qi, H., Sun, J. : Investigation of saturation flow rate on shared right-turn lane at signalized intersection, *Transportation Research Record: Journal of the Transportation Research Board,* No. 2461, Transportation Research Board of the National Academies, Washington D.C., 2014, pp. 66–75.
7) Wu, N. :Modeling blockage probability and capacity of share lanes at signalized intersections, *Procedia-Social Behavioral Sciences,* Vol. 16, pp. 481-491, 2011
8) Yoshitane, K., Tanaka, S., Nakamura, F., Ariyoshi, R. and Miura, S.: A study about construction of intersection capacity calculation formula in four-leg signalized intersections with single-lane approaches, Proceedings of the Conference on Infrastructure Planning and Management, Japan Society of Civil Engineers, Vol.58, 4pages, 2018.
9) Tan, J., Li, L., Li, Z., Zhang, Y. : Distribution models for start-up lost time and effective departure flow rate, *Transportation Research, Part A, Policy and Practice,* Vol. 51 (3), pp.1–11, 2013.
10) Jin, X., Zhang, Y., Wang, F., Li, L., Yao, D., Su, Y., Wei, Z.: Departure headways at signalized intersections: a log-normal distribution model approach, *Transportation Research, Part C, Emerging Technologies,* Vol. 17 (3), pp.318–327, 2009.