Impact of Pedestrians on the Left-turn Lane Capacity of Signalized Intersections under Autonomous Vehicle Mixed Flows

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Pedestrians have a significant impact on capacities of turning movements at signalized intersections, especially for the left-turning movements which commonly share the same phase with pedestrians. Recent technological developments have brought the autonomous vehicle (AV) era closer to reality. AVs will face the same problems with human driven vehicles (HDVs) in road traffic, and capacity will be significantly influenced by the interaction between left-turning vehicles and pedestrians. Thus, this study aims to estimate capacity of the left-turn lane under AV mixed flows by using the traffic simulator, considering AV penetration rates, pedestrian flow and crosswalk length. The impact of AV mixed flow on capacity is analyzed by giving different settings of vehicle's desired speed and the critical gap of pedestrians between AVs and HDVs. The results show that capacity will increase when the desired speed of AV is higher than HDV. It is obvious that if AV will completely follow the traffic law, the capacity of left-turn lane sharply decreases, especially the case of long crosswalks.

Key Words: *autonomous vehicle, mixed flows, pedestrian, capacity, left-turn lane*

1. INTRODUCTION

Intersections are the key components of road network and the places where the paths of various movements from different directions cross each other. The capacities of the turning movements in signalized intersections are highly influenced by the conflicts between turning movements and pedestrians since they will share the same space and signal phase. In case of the two-phase control, both left-turning vehicles (LTVs) and right-turning vehicles will have the conflicts with pedestrians. Since the conflict between LTVs and pedestrians is more common and has a greater impact on the capacity, this study focuses on the capacity of the left-turn lane.

Autonomous vehicles (AVs) are expected to be a reality in the near future and have the potential to reduce congestion, improve safety and operational performance of future road traffic systems. However, under the influence of conflicts, it is not sure whether AV mixed flows with different settings will increase or decrease the capacity.

Additionally, the mixed impact of crosswalk geometry and pedestrian volume with various settings of AV may also affect the capacity of left-turning lane.

Thus, the objective of this study is to estimate the capacity of the left-turning lane at signalized intersections under AV mixed flows considering AV penetration rates, pedestrian flow and crosswalk length. Since this level of impact has not been confirmed yet due to lack of data, this study developed AV mixed traffic flow and reproduced the conflicts between pedestrians and LTVs in simulation software VISSIM 11.0[1].

This paper is organized as follows: In the next section, existing literature on gap acceptance models as well as the capacity of left-turn lane and its differences from this study are presented. Then, the vehicle types and road users' behaviors considered in this study are introduced in section 3. In section 4, a description of the signalized intersection is drawn in VISSIM and the parameter settings are explained. The fifth section of this paper presents the results obtained from simulation. Finally, the last section summarizes this study's conclusions and proposes future directions for AV simulation research.

2. LITERARURE REVIEW

In order to estimate the capacity of left-turn lanes, it is important to gain better insight into the method of analyzing the interaction between pedestrians and vehicles and calculating capacity. There are two parts of this section; studies on gap acceptance models and those related to capacity of left-turn lane.

(1) Gap acceptance models

Alhajyaseen, et al.[2] analyzed the lag/gap acceptance behavior of LTVs considering pedestrian movements at signalized crosswalks. It is assumed that pedestrian movements have their origins at either the near-side (the side of the exiting vehicular traffic) or far-side of the crosswalk. Accepted/rejected lags and gaps are extracted, classified depending on the direction of pedestrian movement, and modeled by using the cumulative Weibull distribution function.

Chen, et al.[3] developed a gap acceptance model which was used for the capacity estimation of right-turning movements (right-hand traffic system) at signalized intersections. These models are based on the deterministic critical gap approach, and they do not consider the effect of pedestrian movement characteristics on driver decisions.

(2) Capacity of left-turn lane

The existing guidelines or manuals consider the influence of pedestrian flows for estimating turning vehicle capacity. For instance, Highway Capacity Manual (HCM)[4] (2016) and a Planning and Design of at-grade Intersections - Basic Edition; Guide for Planning, Design and Traffic Signal Control of Japan (Hereafter, JSTE manual)[5] (2018) considered the influence of pedestrians for estimating capacity of turning lanes.

Liu, et al.[6] established a capacity model of dedicated right-turn lanes (right-hand traffic system) at signalized intersections under the influence of pedestrians. Besides, the influence of pedestrians on vehicles is considered into the calculation method of intersection capacity.

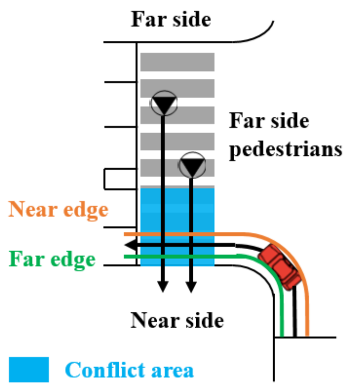


Fig.1 Definition of lags/gaps

Ecem, et al.[7] concluded that autonomous vehicles might not have a significant effect under low traffic flow conditions, but when their percentage in traffic flow increases and under relatively heavy flow conditions, they may improve intersections' capacity and performance.

Wanibe, et al.[8] developed a simulation model. The conclusion is that when changing AV penetration rate and AV's setting, the efficiency of the through movement in signalized intersections will be influenced.

However, in these studies, they did not consider the impact of pedestrians when they interact with AVs. Moreover, AVs will also encounter similar problems with HDV, but research in this field is still very limited, and the impact of AV on the capacity of left-turn lanes under different settings is unknown.

3. METHODOLOGY

The estimation of capacity in this study is conducted on a signalized intersection designed in VISSIM 11.0. This section describes the basic definitions of terminology, vehicle types, road user behaviors and calibration methods used in this study,

(1) Definition

In general, lag is the time that a subject needs to reach a specific position while gap is the time difference between two successive subjects arriving at the same position[2]. In this research, the gap which is shown in **Fig.1** is the time difference between the first pedestrian crossing the far edge of the vehicle trajectory and the second pedestrian crossing the near edge of the vehicle trajectory.

Near-side pedestrians are those pedestrians who start crossing from the side of the crosswalk which is close to the existing left-turning vehicles while far-side pedestrians are those pedestrians who start crossing from the side of the crosswalk which is close to the entering traffic.

The vehicle edge which a pedestrian meets earlier while crossing is called near edge, while the opposite edge is called far edge. It is important to note that the near edge and the far edge of the vehicle for near side and far side pedestrians are opposite.

Conflict point is defined as the point where the trajectories of two users intersect. Regarding the conflict between LTVs and pedestrians, pedestrian will have the conflict point with near edge of LTV.

Conflict area is defined as the area of crosswalk length where LTV will have conflict with pedestrians (blue-colored area in **Fig.1**).

(2) Lag/Gap acceptance behaviors

The lags/gaps are classified into five different types depending on the pedestrians' direction of movement as shown in **Fig.2**.

Type A: includes the lags of pedestrians from the near side of the crosswalk,

Type B: includes the lags of pedestrians from the far side of the crosswalk,

Type C: includes the gaps between two pedestrians from the near side of the crosswalk,

Type D: includes the gaps between two pedestrians from the far side of the crosswalk, and

Type E: includes the gaps between one pedestrian from the near side of the crosswalk and another one from the far side of the crosswalk.

Due to the limitation of VISSIM 11.0, we only consider the type A (Near lag) and type B (Far lag) in this study, since the function priority rules cannot be used to calibrate the other three types of lags/gaps.

(3) Vehicle types

In this study, except for HDV, five types of AV are defined. The aggressive autonomous vehicles (aAV) means AV maneuver is more aggressive than HDV when it faces the pedestrian's lag or gap to choose the smaller lag or gap to cross the conflict area. Conversely, the discreet autonomous vehicle (dAV) is more conservative than HDV to wait for the more considerable lag or gap of pedestrian and cross. It is noticeable that we consider three types of dAV in this study. When dAV decides whether it will turn indirectly based on gap acceptance behavior, we defined it as $\mathrm{dAV_g}$.

However, according to the *Road Traffic Act*[9] in Japan, when approaching a crosswalk, vehicle must proceed at a speed that will enable it to stop immediately in front of the pedestrian ahead of the vehicle and cannot pass in front of pedestrians. In order to ensure the pedestrian safety and improve the reliability of AVs, the engineers will give the settings

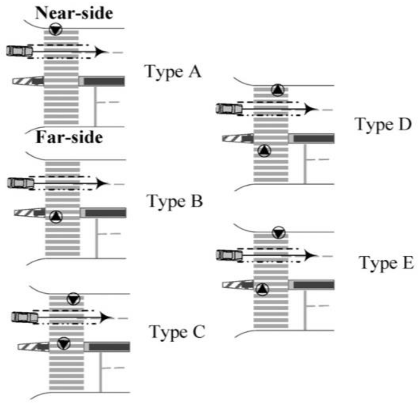


Fig.2 Types of lags/gaps (Alhajyaseen, et al.[2],2012)

of AV strictly. Therefore, it is assumed that $d\mathrm{AV}_{cw}$ is based on this rule. AVs will stop immediately when encounter a pedestrian on the crosswalk.

Usually, on some relatively long crosswalks, refuge islands are set up to ensure the safety of pedestrians. In this paper, it is also considered that the left-turning vehicle only needs to determine whether there is a pedestrian passing in the conflict area. $d\mathrm{AV}_{ca}$ is set according to this situation.

In this regard, L_d is defined as the crosswalk length of driver's decision making. More specifically, it means the length of the section in crosswalk where driver will obey the traffic laws. For example, when the compliance rate of *Road Traffic Act*[9] reaches 100%, L_d is the length of the entire crosswalk. When a refuge island is set in the middle, L_d is the length of the conflict area.

(4) Method of calibration

In this study, there are two parts of calibration; average headway and critical lags/gaps. This section introduces the method of these works.

a) Method of average headway calibration

In VISSIM 11.00, a psycho-physical car following model- Wiedemann 74 car following model (1974) is used for the urban roads.

The equation of Wiedemann 74 car-following model is shown by **Eq. (1)** and **(2)**.

$$d = ax + bx \quad (1)$$

$$bx = (bxadd + bxmult * z) * \sqrt{v} \quad (2)$$

where d is the distance between two vehicles; ax is the average standstill distance; bx_add is the additive part of desired safety distance; and bx_mult is the multiple part of desired safety distance.

By adjusting these three parameters of ax, bx_add and bx_mult, we can calibrate the average headway.

b) Method of critical gap calibration

In order to calibrate the critical gap, we can use the function *Priority Rules* in VISSIM 11.0. **Fig.3** presents the definition of *Priority Rules*.

The *Priority Rules* includes one *stop line* (second stop line in red color) and one or more *conflict markers* associated with the stop line. According to the current road conditions at the *conflict marker*, the *stop line* controls whether the vehicle passes or not.

The two main constrains at the *conflict marker* include *minimum headway* which means the minimum headway distance and *minimum gap time*. The larger one of them will play a decisive role.

For dAV_{ca} and dAV_{cw}, the *minimum headway* is the main factor of calibration since it is larger than the *minimum gap time*. When any part of the pedestrian is above the conflict marker, the current headway is 0 meter. If the current headway distance is less than the *minimum headway*, all vehicles approaching the conflict area must stop at the second stop line (equivalent to a red light).

When analyzing the HDV, aAV and dAV_g, the situation is opposite which means we only consider the *minimum gap time* and the *minimum headway* is set as 3.5m. The current gap time depends on the time required for the pedestrian approaching the conflict area to reach the *conflict marker* assuming that the pedestrian is walking at the current speed. If the current gap time is less than the *minimum gap time*, all vehicles approaching the conflict area must stop at the second stop line (equivalent to a red light).

4. SIMULATION

(1) Basic conditions

This study assumes two intersections with different lengths of crosswalk: two typical multilane signalized four-leg intersections with shared/ exclusive left-turn lane and are drawn in VISSIM 11.00. The geometric design of the four approaches is point symmetric. As shown in **Fig.4**, the lane width is set as 3.5m. The length of the crosswalk is set as 20m while 25m in another intersection. The pedestrian waiting area is both set as 5.0m*5.0m.

(2) Parameter settings of AVs

Because of the difference between machinery and humans, AVs will have a smaller range of speed variations than HDVs. Therefore, there are two settings of desired speed and in this paper only AVs have different desired speed with HDVs. *Desired speed*, *Average vehicle length*, *Max acceleration* and *deceleration* are shown in **Table 1**.

(3) Calibration of headway

In VISSIM 11.00, the function *Driving Behaviors* includes ax, bx_add, $\_mult$. Thus, we can change the value of these three parameters to calibrate the

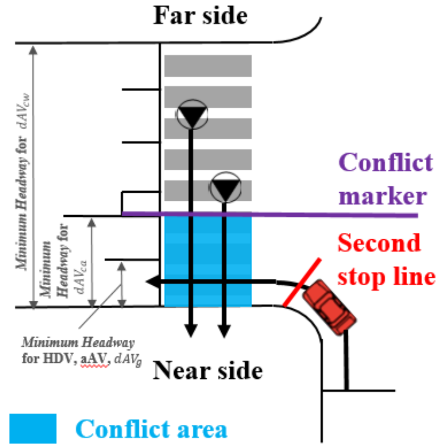


Fig.3 Definition of *Priority Rules* between near-side pedestrian and LTV

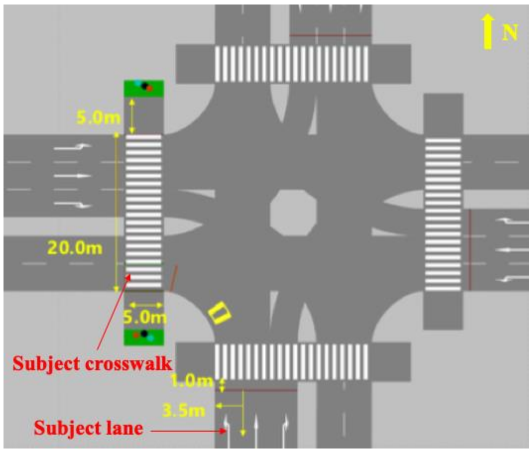


Fig.4 Geometric design of the intersection in VISSIM

Table 1 Parameters settings of vehicles

Parameter	Value
Desired speed *v* (km/h)	Same speed case: HDV, aAV, dAV_g, ,dAV_{ca},dAV_{cw}: 45~55; Different speed case: aAV:52.5~57.5
Average vehicle length *l* (m)	4.6
Max acceleration *a* (m/s^2)	2.0
Max deceleration *b* (m/s^2)	-3.0

average headway of the through vehicles.

In this study, it is assumed that LTVs have the same driving behaviors as the through vehicles due to the limitation of VISSIM 11.00.

Empirical data which is observed on Ueda signalized intersection, Nagoya City, Japan is utilized because of the similar geometry design. The *Driving Behaviors* parameter settings of through vehicles are as follows: average standstill distance (ax) is adjusted to 3; additive part of safety distance (bx_add) is set to

3; multiple part of safety distance (bx_mult) is changed to 4.15. In this study, it is assumed that the vehicles have the same average headway no matter what the types of vehicles they are.

The function *Reduced Speed Area* is used to calibrate the average headway of LTVs. The parameter settings of this function are as follows: the length of this area is set to 2 m; the location as well as the deceleration is adjusted to 3 m/s^2; the desired speed is changed to 26.3~31.3m/s. **Table 2** shows the observed average headways of the through vehicles, the LTVs and the calibrated results.

(4) Calibration of critical gap

Lag acceptance of each type of vehicle is expressed by using the function of *Priority Rules*. In the LTV-pedestrian conflict, the pedestrian always has priority. Parameters of *Minimum gap time* and *Minimum headway* are adjusted for lag acceptance behavior. The lag value cannot be output directly, however, it can be obtained by using the vehicle's simulation time of passing the conflict point and pedestrian's simulation time of passing the conflict point. In this study, only the lags under 10 seconds are collected. Raff's method (1950) is utilized to estimate the value of critical lag for each type of vehicle, which defines critical lag as the intersecting point of the cumulative distributions of accepted lags and rejected lags. **Table 3** shows the *Priority Rules* parameter settings in VISSIM 11.00 (under the intersection with 25m of crosswalk).

(5) Signal timing

In VISSM 11.00, pedestrian flashing green (PFG) time has no impact on the speed of pedestrian and pedestrian cross-stop decision. Pedestrians may still enter the crosswalk until the onset of the pedestrian red interval. It means that PFG interval does not have any effects of clearing the pedestrian already present in the crosswalk in VISSIM 11.00. In the basic signal timing, there is a ten-second long PFG interval for 20m crosswalk while a twelve-second long PFG interval for 25m crosswalk. Thus, it will be replaced by the pedestrian red interval in VISSIM. The signal timing setting in VISSIM 11.00 is shown in **Table 4**.

(6) Scenario setting

The variation of capacity due to AVs was calculated using VISSIM 11.0 as described in the methodology section of this paper. The scenario settings with the cases are shown in **Table 5**. Case 1 and case 2 are designed for analyzing the influence of aAVs desired speed by giving aAV with same and different speed with HDV, respectively. Case 3 is set under dAV_{ca} mixed flow and case 4 is under dAV_{cw} mixed flow. For each penetration rate scenario, 10 simulation runs were performed with different random seeds. The simulation time period is 7200s with the first 3600s as warm-up time. In this study, capacity is estimated by calculating the maximum number of LTVs within one hour.

Table 2 Calibration of average headways

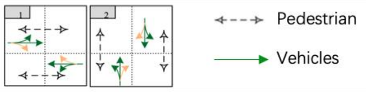
		Observed data (Target)	Simulation average	Difference
Through vehicle	Average headway(s)	2.14	2.15	-0.01
	SFR(pcu/h/ln)	1682	1678	4
LTV	Average headway(s)	2.47	2.47	0
	SFR(pcu/h/ln)	1457	1459	-2

Table 3 *Priority Rules* parameter settings

Lag type	Vehicle type	Same speed case		Different speed case	
		Min. gap (s)	*Min. headway* (m)	*Min. gap* (s)	*Min. Headway* (m)
Near lag	aAV	6.9	3.5	5.7	3.5
	HDV	7.1	3.5	7.1	3.5
	dAV_g	9.6	3.5	10.1	3.5
	dAV_{ca}	9.6	10.5	10.1	10.5
	dAV_{cw}	9.6	25.0	10.1	25.0
Far lag	aAV	7.2	3.5	6.5	3.5
	HDV	7.9	3.5	7.9	3.5
	dAV_g	8.5	3.5	7.5	3.5
	dAV_{ca}	8.5	10.5	7.5	10.5
	dAV_{cw}	8.5	25.0	7.5	25.0

Table 4 Basic signal timing

	Signal phasing length (sec)										Cycle length (sec)
	φ1				φ2	φ3				φ4	
	1	2	3	4	5	8	9	10	11	12	
WE Vehicle											
WE Pedestrian											
NS Vehicle											
NS Pedestrian											
20m crosswalk	43	10	1	3	3	43	10	1	3	3	120
25m crosswalk	40	13	1	3	3	40	13	1	3	3	120



Green |||| Pedestrian flashing green Amber Red

Table 5 Scenario setting

	Value
AV penetration rate (%)	0,20,40,60,80,100
Desired speed of AVs	aAV is different from HDV (case1) aAV is the same as HDV (case2)
Crosswalk length *L* (m)	20,25
Crosswalk length for driver decision L_d (m) / Crosswalk length *L* (m)	dAV_{ca}: 7/20, 10.5/25 (case3) dAV_{cw}: 20/20, 25/25 (case4)
Pedestrian volume (ped/h)	150,300,600
Critical lag (s)	Near-side: HDV:2.87, aAV:2.30, dAV:3.31 Far-side: HDV:4.08, aAV:3.46, dAV:4.50

5. CAPACITY ESTIMATION RESULTS

(1) Sensitivity analysis of AVs' desired speed

The trends of the left-turn lane capacity changing with different penetration rate of AVs (AV%) are shown in **Fig.5** which has different pedestrian volumes. In this study, only the aAVs with different speeds are considered as an example. It can be found that when AV% gradually increases, the effect of AVs on capacity is more significant, especially for case2. A possible explanation is that since the aAV's setting is more aggressive which has higher average desired speed and smaller speed range in this study, the lost time causing by low vehicles in case1 is more than in case2. Therefore, the increment of capacity is more obvious.

(2) Reduction of capacity under dAV$_{ca}$ and dAV$_{cw}$ mixed flows

Fig.6 and **Fig.7** show the influence of dAV_{ca} and dAV_{cw} with different AV% on the capacity under different pedestrian volume. In these two figures, the scenario with 100%HDV are regarded as a reference line. It can be found that compared with HDV, it has a greater impact on capacity. When the pedestrian flow is 600 ped/h, the reduction percentage even reaches 39.25%. Therefore, if the compliance rate of LTV to *Road Traffic Act* reaches 100%, the capacity of the left-turning lane will be significantly reduced, affecting vehicles behind, and even blocking the signalized intersections. In addition, when pedestrian volume increases, there are decreasing trends of the differences between 100% of HDV case and dAV cases with different penetration rate on capacity. The reason is considered that HDV is also difficult to pass when there are a lot of pedestrians.

(3) The impact of geometric designs on capacity

Fig.8 compares the impact on the capacities when crosswalk length are 20m and 25m under different pedestrian volumes, respectively. Among them, it should be noted that the figure only includes the situation when the penetration rate of dAV_{ca} and dAV_{cw} are 100%. It can be found that when value of L_d is getting larger, the more significant the influence of the penetration rate of dAV_{ca} and dAV_{cw} on capacity. Especially when L_d is 10~20m, the capacity of the left-turn lane is significantly reduced. For instance, in case3 which the length of conflict area equals to the length of a half of crosswalk (L_d=7m, 10.5m), the capacity slightly reduced. It is because that there may be some gaps between the arriving time to conflict area of near-side and far-side pedestrians. For case4 with L_d=20m, 25m, compared to case3 capacity of the left-turn lane reduced significantly.

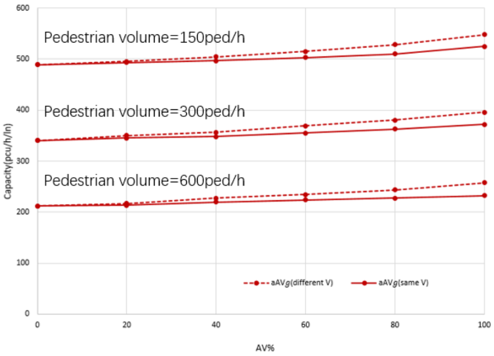


Fig.5 The relationship between aAVs' speed and capacity (case1 and case2)

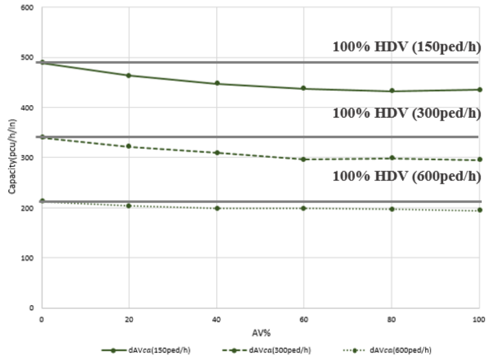


Fig.6 The reduction of capacity under dAV_{ca} mixed flow (case3) compared to 100%HDV case

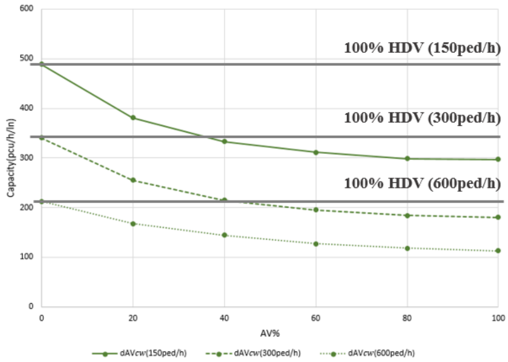


Fig.7 The reduction of capacity under dAV_{cw} mixed flow (case4) compared to 100%HDV case

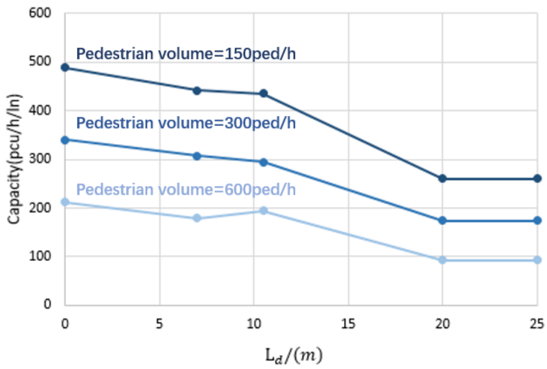


Fig.8 The relationship between capacity and L_d under different level of pedestrian volume

6. CONCLUSIONS AND FUTURE WORKS

This study analyzed the impact of AVs' speed changes, lag/gap acceptance behavior, and geometric design on the capacity of left-turn lanes at signalized intersection under AV mixed flow conditions.

First of all, for the speed change of AV, since aAVs react faster than humans, different speeds and smaller ranges are set for aAVs. Through simulation, it is concluded that when the speed of AV is different from that of HDV, the increase in capacity is greater.

Secondly, with regard to the impact of lag/gap acceptance behavior on the capacity, this study considers not only the behavior of selecting gaps when a LTV passes through an intersection in the actual situation, but also the impact of driving behavior in accordance with Japanese law on the capacity. If Japanese law is strictly complied by AVs, the capacity of the left-turn lane will drop by nearly 40%. In addition, the impact of refuge islands on capacity when the crosswalk is long is also studied. In this case, the capacity of the left-turn lane will also decrease. The two-stage crossing can be also considered as a meaningful solution for AV mixed flow in the future.

Finally, this study puts forward the concept of L_d, and summarizes the impact of this distance on capacity. When L_d is 10 to 20m, the capacity of the left-turn lane will decrease significantly.

However, this research does not consider the signal timing changes after the refuge island is set up. When the crosswalk is very long, signal lights can be set separately to improve the capacity. In future research, we can study how to set signal timing to achieve a balance of traffic efficiency between pedestrians and left-turning vehicles.

In addition, due to the limitation of VISSIM, the compliance rate of LTV at signalized crosswalks could not be set. In the future work, some field surveys can be conducted to obtain the compliance rate in the real world for this study.

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