Estimation of Roundabout Entry Capacity under Autonomous Vehicle Mixed Flows through a Traffic Simulator

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Abstract: In recent years, increasing number of roundabouts has been implemented in Japan due to their good performance on both safety and efficiency. To evaluate their efficiency, entry capacity is one of the most important indices. The appearance of autonomous vehicles (AVs) will lead to a mixed flow condition with human driven vehicles (HDVs) which is suspected to have significant impact on roundabout entry capacity. This study aims at analyzing the influence of AVs on the entry capacity through traffic simulator. For classifying impacts of AVs, different aggressiveness levels and penetration rates of AVs mixed flows are discussed. It was found that, with increasing penetration rate of AVs, the entry capacity with aggressive AVs will increase, while the capacity with discreet AVs will decrease. Moreover, models of adjustment factors for AVs are estimated to generalize the impact of AVs mixed flows on roundabout entry capacity.

Keywords: Roundabout, Entry Capacity, Autonomous Vehicle Mixed Flows, Traffic Simulator

1. INTRODUCTION

Roundabouts have been an increasing presence on roadways all around Japan, even the whole world, since they can allow drivers to cross the intersection without the need for a complete stop, and have been verified to have the fewer number of conflict points and less possibilities of severe crashes compared to ordinary intersections. With the great development of science and technology in recent decades, the introduction of autonomous vehicles (AVs) can be expected to bring capacity benefits and improve safety in the traffic system due to their potentiality of smoother and wiser maneuvers. Moreover, there are only merging and diverging behaviors in roundabouts, which can be easier to apply AVs comparing to ordinary intersections since AVs only need to select a gap when entering the roundabout.

However, the occupancy of AVs will not reach 100% within a short time due to the limitation of science and technology in current step, even in near future. Thus, it is necessary to forecast the influence of AVs and human driven vehicles (HDVs) mixed flow on roundabout entry capacity. Specifically, the performance of AVs depends on their performance parameters which are set by human beings. Usually, headways, reaction time, desired speed, maximum acceleration and deceleration etc., are considered as important parameters of AVs. Among those, headways are critical parameters in roundabout entry capacity estimation. Through adjusting these parameters, different types of AVs can be defined. In this study, three headway parameters and speed distributions are considered to distinguish between different types of vehicles. To be specific, aggressive AVs (aAVs) are assumed to have shorter headways and higher speed compared to HDVs, while discreet AVs (dAVs) are assumed to have longer headways and lower speed.

Besides, due to the limitation of technology, the introduction of AVs into the real world is still at an early stage, and this study mainly focuses on the influences of penetration rates of AVs on the roundabout entry capacity. Thus, information exchanges and communications among vehicles or with any other infrastructures are not considered or discussed in this study.

Therefore, the aim of this research is to estimate roundabout entry capacity under AVs mixed flow with different AVs' penetration rates and types of AVs through a traffic simulator; meanwhile, models of adjustment factors of AVs are also developed to generalize their impacts on roundabout entry capacity.

2. LITERATURE REVIEW

Since continuous and stable AVs mixed flow in real world has not been realized yet, it is difficult to obtain empirical data and utilize it to estimate the capacity. Instead, there are the following two methods to consider AVs' impact on roundabout entry capacity: one is to adjust headway parameters of different types of AVs in the existing entry capacity equation based on gap acceptance theory; the other is to use microscopic traffic simulation model to evaluate various scenarios. It is common for both of them that AV parameters must be reasonably assumed for the evaluation.

The existing roundabout entry capacity equation in Japan Roundabout Manual (JRM, 2016), as shown in equation (1), is based on the German formula (FGSV, 2001). Gap acceptance model was adopted that the driver on the entering stream is required to select an acceptable gap on the circulating stream to perform the desired maneuver. The existing equation assumed that headways in circulatory roadway follow the negative exponential distribution and their values are constant. However, the assumptions made the equation only reliable under low to medium traffic volumes, and the influences of different geometry designs of roundabout cannot be reflected with constant headway values, not to mention the appearance of AVs in roundabouts.

$$c_i = \frac{3600}{t_f}\left(1 - \tau\frac{Q_{cir}}{3600}\right) \times exp\left[-\frac{Q_{cir}}{3600}\left(t_c - \frac{t_f}{2} - \tau\right)\right] \quad (1)$$

Where,

c_i: entry capacity of entry i in the unit of pcu/h

Q_{cir}: circulating flow at the entry i in the unit of pcu/h

t_c: critical gap in the unit of s

t_f: follow-up time of entry vehicle in the unit of s,

τ: minimum headway of circulating flow in the unit of s.

Due to the limitations of the equation, traffic simulators have been widely used to discuss the impact of AVs mixed flows and the AVs settings. Patcharinee *et al.* (2011) and Shi *et al.* (2016) estimated the highway capacity could be increased exponentially with an increase in the AVs penetration rate due to the shortened average headway. However, this study was not considering roundabout entry capacity and only one type of AVs was involved. Bailey (2016) investigated a simple simulation network with an isolated roundabout and observed that an increase in AVs percentage corresponded with an increase in entry capacity, while this research was also based on the assumption that AVs were set to have better performance compared to HDVs. Friedrich (2016) developed a microscopic traffic flow model and found that two factors are responsible for the increase in capacity under AVs mixed flow conditions at traditional intersections; one factor is the shortening of headways between AVs, the other is the speed of vehicle group. Although this study does not include the situation in roundabout, these conclusions are quite inspiring for setting the AVs in this paper. Besides, Pan *et al.* (2020) also defined three types of AVs and analyze related parameters of each of them in a simulation of efficiency and safety of signalized intersections under AVs mixed flow. However, roundabout entry capacity under AVs mixed flow was not discussed in this research. Moreover, Kang *et al.* (2020) also defined two types of AVs and figured out their influences on roundabout entry capacity through using a traffic simulator, which is very inspiring for this study. However, the three headway parameters of AVs in their study were roughly assumed just as a larger or smaller value according to the type of AVs compared to the observed headway data of HDVs, which are lack of reliability.

Thus, this study applies the simulation method to estimate roundabout entry capacity under AVs mixed flows by calibrating headways of HDVs and AVs based on the observed data in VISSIM. Meanwhile, various types of AVs should also be considered to intensively analyze their impacts on the entry capacity.

3. METHODOLOGY

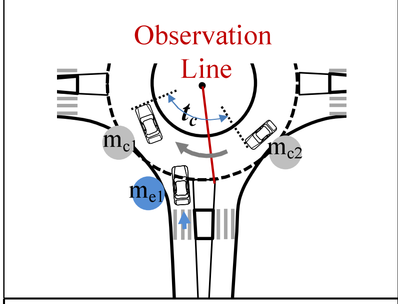
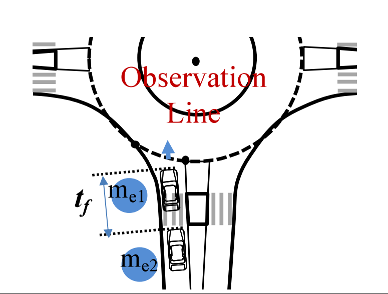
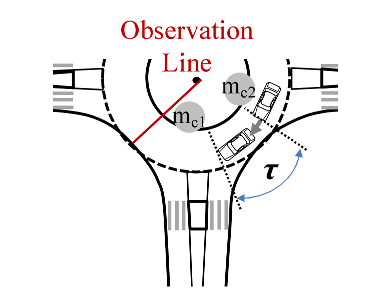
3.1 Description of vehicle types

In this study, three headway parameters and speed distributions are utilized to distinguish HDVs and two types of AVs. The aggressive AVs (aAVs) are expected to have more aggressive behaviors compared to HDVs. As mentioned earlier, shorter headways and higher desired speed are set for aAVs; oppositely, discreet AVs (dAVs) are defined to have more conservative behaviors compared to which of HDVs, as a result, longer headways and lower desired speed are given to dAVs. Furthermore, in order to present the stable performance and less stochastic behaviors of AVs, the range of desired speed distribution of both types of AVs are set narrower than HDVs.

3.2 Headway parameters in roundabout

Entry capacity is the maximum number of vehicles that are expected to enter roundabout from one approach during a certain period. The Japan Roundabout Manual (2016) estimates the entry capacity which is based on the gap acceptance theory by defining three gap parameters in circulating and entry flows. The illustrations of the three headway parameters are shown in Table 1.

Table 1. Discriptions of the three headway parameters

		
(a) critical headway t_c	(b) follow-up time t_f	(c) minimum headway τ

Critical headway t_c is defined as the minimum acceptable headway between two circulating vehicles (m_{c1}, m_{c2}) at the observed line where the gap is judged by entering vehicle (m_{e1}) to accept or reject. Follow-up time t_f and minimum headway τ on circulatory roadway are headways between continuous leading vehicle and following vehicle of entry approach (m_{e1}, m_{e2}) and circulatory roadway (m_{c1}, m_{c2}), respectively.

In this paper, a common 4-leg roundabout with a diameter of 27m is hypothesized. As illustrated in Figure 1, the Moriyama roundabout in Shiga Prefecture, Japan is selected (Kanbe *et, al* , 2019) to collect the three headway parameters for HDVs. The parameters of AVs are also assumed based on HDVs' data observed in this roundabout, since it has the similar geometry to the hypothesized roundabout. aAVs are assumed to have more aggressive behaviors than HDVs, thus smaller headway parameters are set for them. Oppositely, larger values are set for dAVs due to more conservative behaviors. The detailed values of the three headway parameters for each type of vehicle are illustrated in Figure 2 and summarized in Table 2.

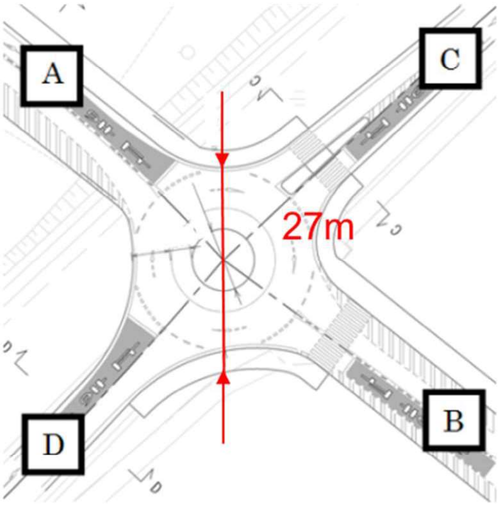
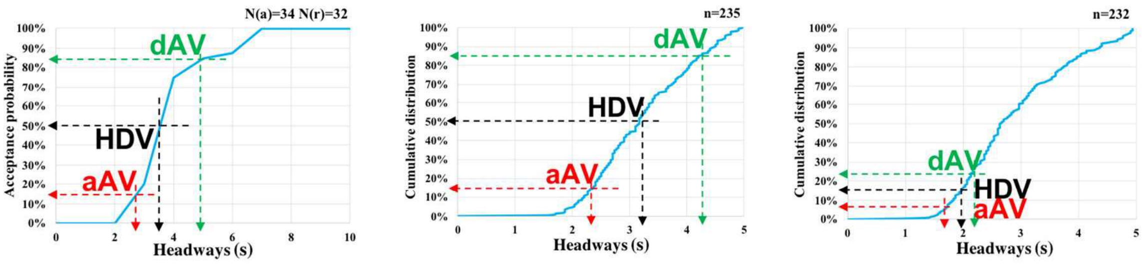


Figure 1 Layout of the Moriyama roundabout



critical headway t_c follow-up time t_f minimum headway τ

Figure 2 Observed three headway parameters in Moriyama roundabout

Table 2 Values of three headway parameters for each type of vehicle

Type	t_c (s)	t_f (s)	τ (s)
aAVs	2.9 (15 percentile)	2.4 (15 percentile)	1.7 (5 percentile)
HDV	3.6 (50 percentile)	3.2 (50 percentile)	2.0 (15 percentile)
dAVs	4.8 (85 percentile)	4.2 (85 percentile)	2.2 (25 percentile)

3.3 Calibrations and settings in VISSIM

In this study, traffic simulator VISSIM 7 is utilized to conduct a simulation. The hypothesized standard 4-leg roundabout with a diameter of 27m is established in the simulator as illustrated in Figure 3. Since there is no attribute which can be directly used to adjust the three headway parameters in VISSIM, *Driving Behaviors* is used for calibrating t_f and τ, and *Priority rules* is used for calibrating t_c instead as summarized in Table 3. Within *Driving Behaviors*, parameters of car following model "Wiedemann 74" model, average standstill distance (ax), additive part of safety distance (bx) and multipic part of safety distance(mult), are adjusted for follow-up times of vehicles in circulatory roadway and entry approach, respectively. Within *Priority rules*, minimum gap time (min.gap), minimum headway (min.hdwy) and maximum speed (max. spd) are calibrated to adjust t_c. Then, driving behaviors of both HDVs and two types of AVs are assigned to *Link Behavior* by *Vehicle Class* for certain link. Thus, the behavior type can be chosen in the link, for representing the car following behavior of mixture flow of HDVs and AVs.

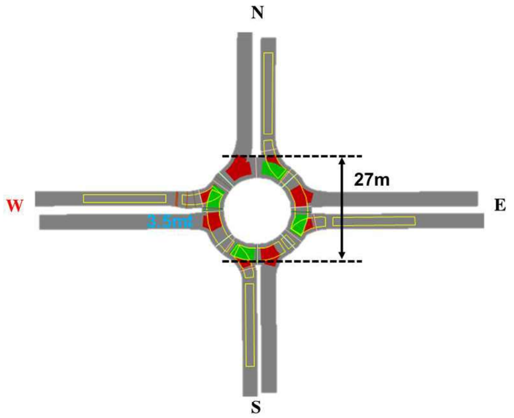


Figure 3 Layout of roundabout in VISSIM 7

To figure out the influence of each attribute in VISSIM on entry capacity, sensitivity analyses of related parameters in VISSIM are conducted. Besides the parameters mentioned above, it is found that speed distribution can also influence entry capacity in VISSIM. In order to investigate the impact of speed, two cases with differenct speed distributions of AVs; identical-speed case and different-speed case are defined. In the identical-speed case, all the three types of vehicles are assumed to share the same speed distribution, ranging from 20km/h to 30km/h; however, in the different-speed case, the speed distribution for aAVs has higher average speed and ranges from 27.5km/h to 32.5km/h, while for dAVs, lower averge speed and ranging from 17.5km/h~22.5km/h were given. All the speed distributions in both cases are assumed to follow normal distribution. The details of speed values are shown in Table 3 and speed distribution for both cases are illustrated as Figure 4.

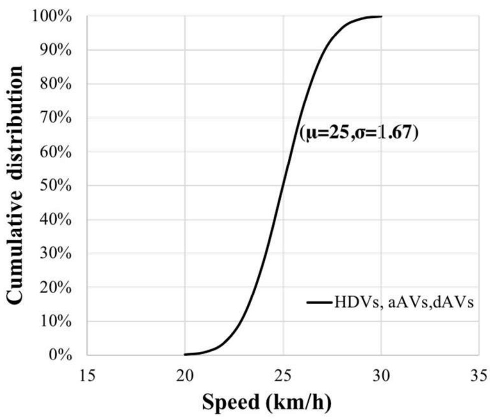
The three headway parameter values were calibrated to be the same for both cases, and the following scenarios were estimated in each case:

1) mixed flow types: aAVs mixed flow and dAVs mixed flow
2) penetration rate of aAVs or dAVs in circulatory roadway ($\%aAV_c$ or $\%dAV_c$): from 0 to 100% in the gradient of 20%
3) penetration rate of aAVs or dAVs in entry approach ($\%aAV_e$ or $\%dAV_e$): from 0 to 100% in the gradient of 20%
4) circulating flow (Q_{cir}): from 0 to 1000veh/h in the gradient of 200veh/h

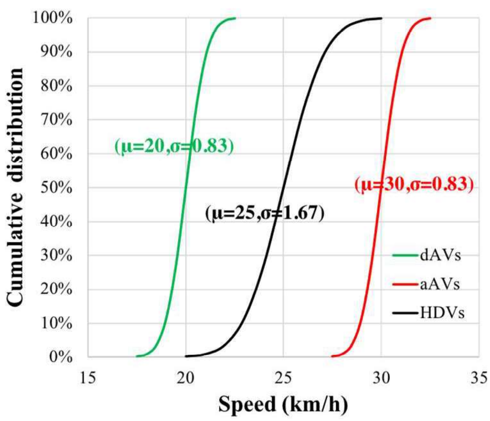
All simulation experiments were made for the analysis period of 3,600 sec with a warmup period of 1,200 sec. Because of the stochastic nature of micro-simulation, five runs with different seed numbers were performed for each scenario to obtain reliable outputs.

Table 3 Two cases of comparisons

Case name	Type	Driving behaviors & Priority rule			Speed Distribution (km/h)	t_c / t_f / τ (s)
		Entry (ax/bx/mult)	Circulating (ax/bx/mult)	(min.gap/min. hdwy/max.spd)		
Identical-speed case	HDVs	2/3.3/3.3	0.5/1.1/1.1	1.4/4/30	20~30	3.6/3.2/2.0
	aAVs	1.6/2.2/2.2	0.3/0.7/0.7	0/5/30		2.9/2.4/1.7
	dAVs	3/5/5	0.9/1.3/1.3	3/4.5/30		4.8/4.2/2.2
Different - speed case	HDVs	2/3.3/3.3	0.5/1.1/1.1	1.4/4/30	20~30	3.6/3.2/2.0
	aAVs	1.8/2.3/2.3	0.3/0.7/0.7	0/5/30	27.5~32.5	2.9/2.4/1.7
	dAVs	3/4.9/4.9	0.9/1.3/1.3	2.5/4.5/30	17.5~22.5	4.8/4.2/2.2



(a) Identical-speed case



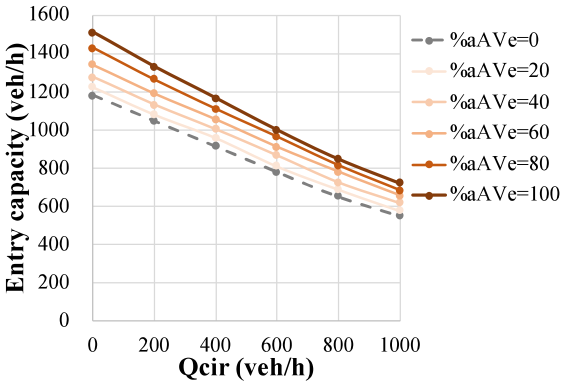
(b) Different speed case

Figure 4 Speed distributions of each case

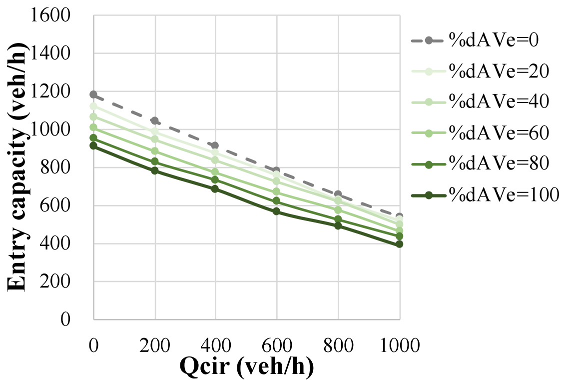
4 ESTIMATING ENTRY CAPACITY UNDER AVs MIXED FLOW

Figure 5 shows the entry capacity in each case when the penetation rate of AVs in circulatory roadway (%aAVc and %dAVc) is fixed at 40%. Both cases have the same tendency that with circulating flow increasing, entry capacity decreases accordingly. For aAV mixed flow (a)(c), entry capacity increases with the penetration rate of aAVs increasing due to smaller headways and higher average speed can be held by aAVs. Oppositely, for dAVs mixed flows(b)(d), all the cases indicate that entry capacity decreases with the penetration rate of dAVs increasing because larger headways and lower average speed were set for dAVs.

Specifically, for aAVs mixed flow, if took the curves of %aAV$_e$=0 and %aAV$_e$=100 as the boundaries as illustrated in (e)(f), it can be found that the curve of %aAV$_e$=0 in different-speed case is higher than which in identical-speed case, while the curve of %aAV$_e$=100% is lower. This is because in different-speed case, higher averge speed and narrower range of speed distribution lead to smaller and relatively constant headway size for aAVs. Thus, when the penetration rate of aAVs in entry approach is low, the relatively constant headway size has main influences which allows more vehicles to enter the roundabout. Oppositely, when the penetration rate of aAVs in entry approach is high, the smaller headway size has the main influence which leads to the situation that the smaller gaps cannot be accepted by entry vehicles. The same reasons can also apply to the dAVs mixed flow conditions.

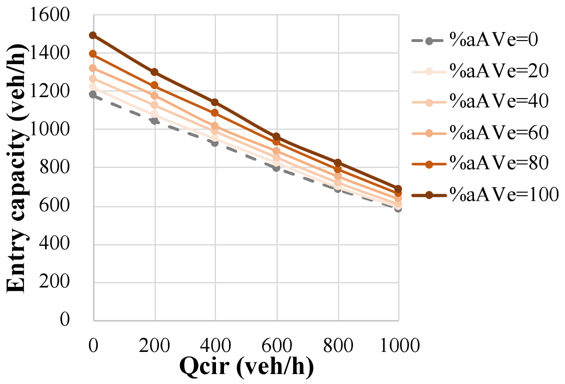


(a) aAVs mixed flow

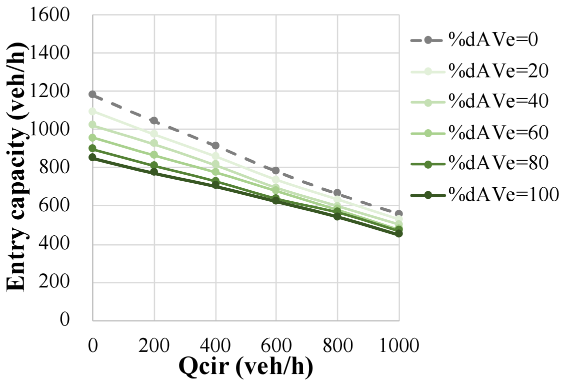


(b) dAVs mixed flow

(i) Entry capacity of the identical-speed case

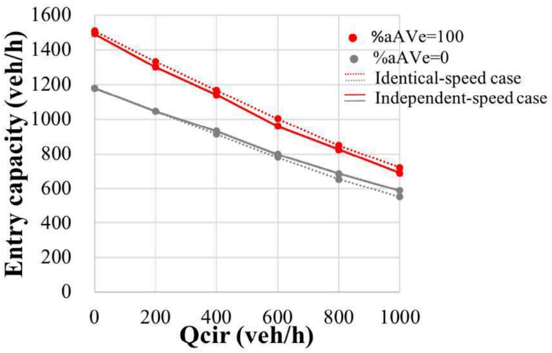


(c) aAVs mixed flow

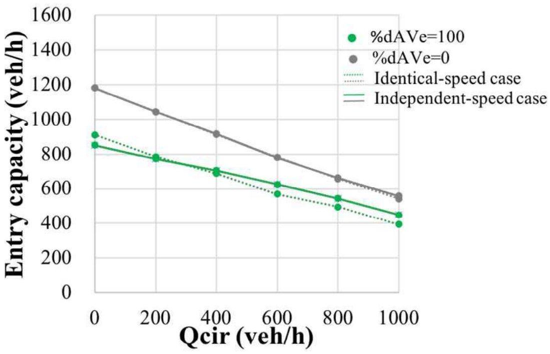


(d) dAVs mixed flow

(ii) Entry capacity of the different-speed case



(e) aAVs mixed flow

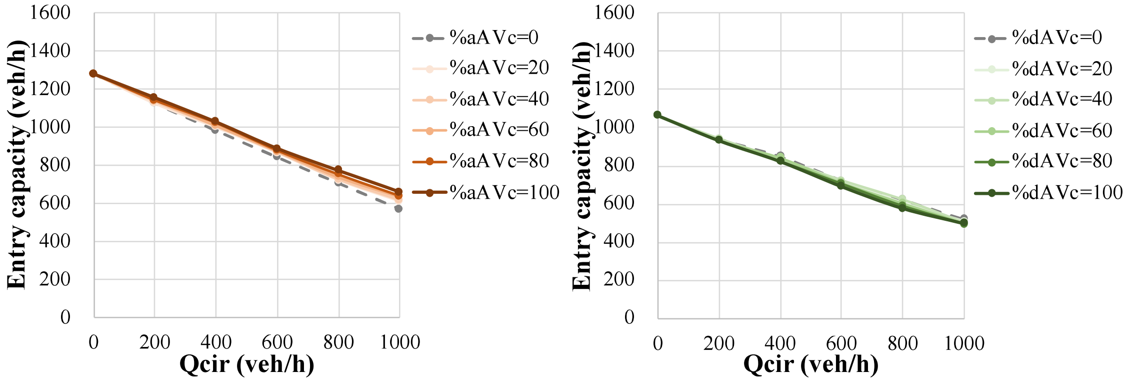


(f) dAVs mixed flow

(iii) Comparisons of two cases

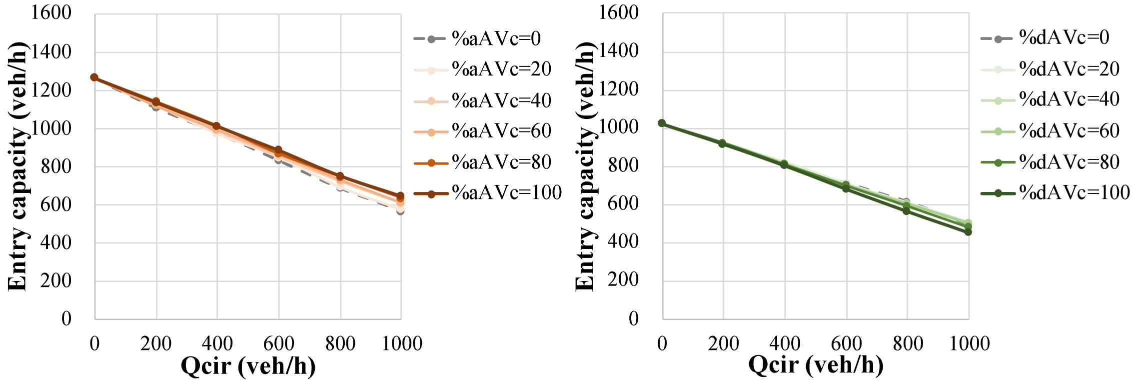
Figure 5 Entry capacity under AVs mixed flows (%AV_c=40)

Figure 6 shows the entry capacity in each case when penetation rate of AVs in entry approach is fixed at 40%. For both aAVs and dAVs mixed flows, both cases show that entry capacity decreases with the increase in circulating flows. However, the entry capacity changes very insignificantly with the increase in $\%aAV_c$ or $\%dAV_c$. This phenomenon indicates that AVs penetration rate in entry approach mainly influences the entry capacity while AVs penetration rate in circulatory roadway has minor impacts on roundabout entry capacity.



(a) aAVs mixed flow (b) dAVs mixed flow

(i) Entry capacity of the identical-speed case



(c) aAVs mixed flow (d) dAVs mixed flow

(ii) Entry capacity of the different-speed case

Figure 6 Entry capacity under AVs mixed flows ($\%AV_e$=40)

5. ESTIMATING ADJUSTMENT FACTOR MODEL FOR AVs

For evaluating the impact of AVs on the entry capacity estimation, an adjustment factor for AVs (f_{AV}) is calculated through Equation (2).

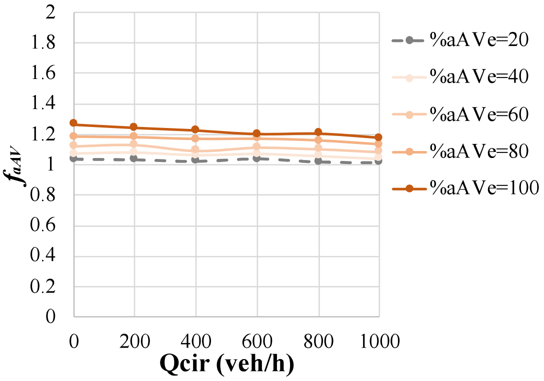
$$f_{AV} = \frac{C_e(\%AV_e, \%AV_c, Q_{cir})}{C_e(0,0,Q_{cir})} \tag{2}$$

where,

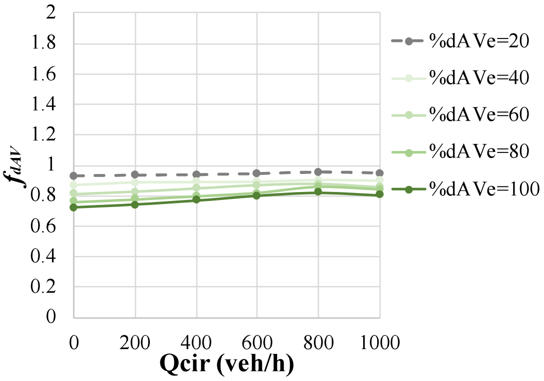
$C_e(\%AV_e, \%AV_c, Q_{cir})$: the entry capacity for circulating flow when AVs penetration rate at both entry approach and circulatory roadway are $\%AV_e$ and $\%AV_c$, respectively.

$C_e(0,0,Q_{cir})$: the entry capacity for circulating flow when AVs penetration rate at both entry approach and circulatory roadway are 0.

Since the adjustment factors for AVs have a positive correlation with entry capacity under both cases, f_{AV} under identical-speed case is given as examples for discussion. f_{aAV} and f_{dAV} stand for f_{AV} of aAVs and dAVs, respectively.

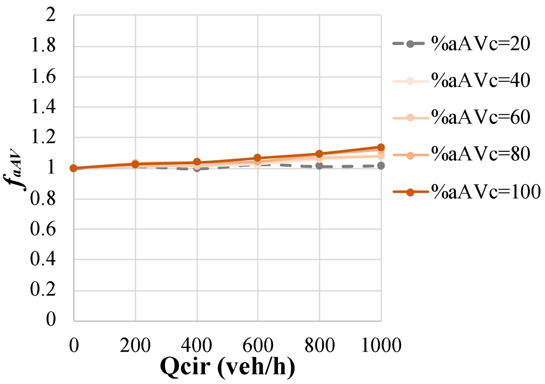


(a) aAVs mixed flow

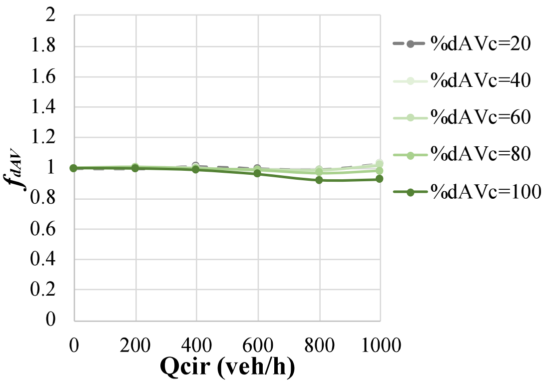


(b) dAVs mixed flow

(i) f_{aAV} and f_{dAV} (%AV_c=40)



(c) aAVs mixed flow



(d) dAVs mixed flow

(ii) f_{aAV} and f_{dAV} (%AV_e=40)

Figure 7 f_{AV} in identical-speed case

Figure 7 shows f_{aAV} and f_{dAV} calculated from the entry capacity in the identical-speed case. It can be found that f_{aAV} is larger than 1, for aAVs bring positive impact on entry capacity, while f_{dAV} is smaller than 1 because dAVs would decrease the entry capacity. Specifically, when %aAV_c and %dAV_c are fixed at 40%, respectively, f_{aAV} increases with increasing %aAV_e, because the entry capacity under aAVs mixed flows also increases with larger %aAV_e; f_{dAV} decreases with increasing %dAV_e because the entry capacity under dAVs mixed flows also decreases with larger %dAV_e. On the other hand, when %aAV_e and %dAV_e are fixed at 40%, respectively, the change of %aAV_c and %dAV_c has insignificant impacts on the values of f_{aAV} and f_{dAV}, for %aAV_c and %dAV_c also have minor influence on entry capacity. Same conclusions can be found in different speed case as well.

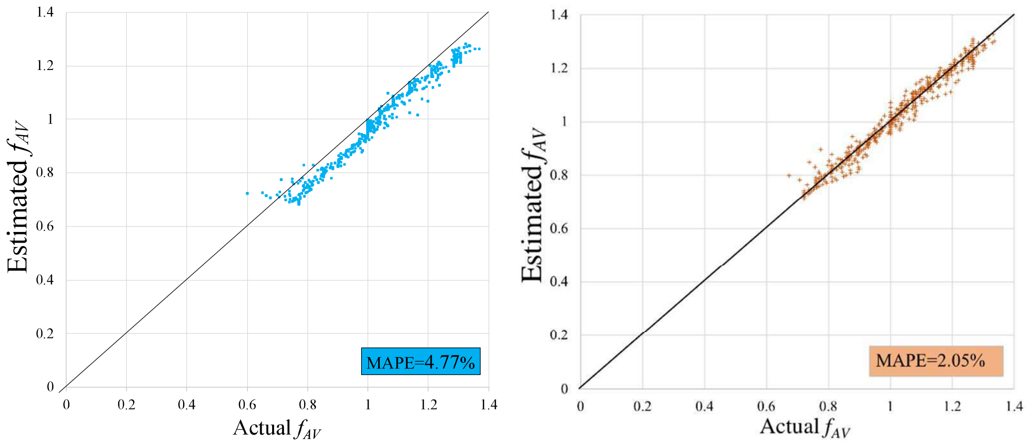
So far, it is clear that %aAV_c, %aAV_e, %dAV_c, %dAV_e and Q_{cir} can influence f_{AV}. Thus, it is possible to establish a model to estimate f_{AV} considering these factors for each case. A linear regression model with respect to f_{AV} is put forward as Equation (3):

$$f_{AV} = a + k1 * \%aAV_c + k2 * \%dAV_c + k3 * \%aAV_e + k4 * \%dAV_e + \frac{k5}{1000} * Q_{cir} \quad (3)$$

Table 4 shows the linear regression model for f_{AV} under the identical-speed case and the different-speed case, respectively. It can be found that models under the both cases are strongly related to %aAV$_c$, %dAV$_c$, %aAV$_e$, %dAV$_e$ and Q_{cir}, for the significant level for each variable is above 99%. Besides, Figure 8 illustrates the comparison between actual f_{AV} and estimated f_{AV} through the linear regression models, and the result indicates that the model fits the actual f_{AV} very well, for the MAPE is only 4.77% and 2.05% for the identical-speed case and the different-speed case, respectively, thus it can be said that both models are very reliable.

Table 4 Three headway parameters of Moriyama roundabout

Variables	Coef. (t-value)	
Case name	Identical-speed case	Different-speed case
Intercept	1.001(271.3)	0.9841(264.9)
aAV$_c$(%)	0.02892(5.778)	0.04018(7.974)
aAV$_e$(%)	0.2563(51.21)	0.2164(42.95)
dAV$_c$(%)	-0.01314(-2.625)	-0.03172(-6.097)
dAV$_e$(%)	-0.2589(-51.74)	-0.2424(-48.11)
Q_{cir} (veh/h)/1000	0.04127(10.41)	0.08823(18.74)
R^2	0.9723	0.9690
Number of samples	432	432



(a) Identical-speed case (b) Different-speed case

Figure 8 Comparisons between estimated f_{av} and actual f_{av}

6. CASE STUDY

A standard 4-leg roundabout located in Moriyama City of Japan is selected for the case study of this paper. Yield control is being applied and there are no crosswalks or splitter islands in this roundabout. The model of the different-speed case is utilized.

In this case study, entry D is chosen as the target entry to estimate the entry capacity under AVs mixed flows. The observed critical headway, follow-up time and minimum headway of the entry D were 4.37s, 3.30s and 2.64s, respectively. VISSIM 7 traffic simulation software is utilized for calibration and validation. The three headway parameters of entry D were calibrated, meanwhile entry capacity under 100% HDVs condition was simulated. Then capacity under AVs mixed flow can be estimated through multiplying f_{AV} with capacity under 100% HDVs flows.

Figure 9 shows the capacity results of target entry D. The black dashed curve is estimated through VISSIM, then capacity under AVs mixed flows are estimated through calculating f_{AV} by using the linear regression model. It can be found that large $\%AV_e$ will greatly increase or decrease the entry capacity, while large $\%AV_c$ has minor influence on the entry capacity, which are consistent with the findings in the previous discussions. Besides, the capacities estimatied through the model and VISSIM are compared as illustrated in Figure 10. When %aAVe is fixed at 40%, entry capacity under %aAVc=0 and %aAVc=100 through both methods are compared. It can be found that the model fits the actual capacity very well, especially under high aAVs penetration rate.

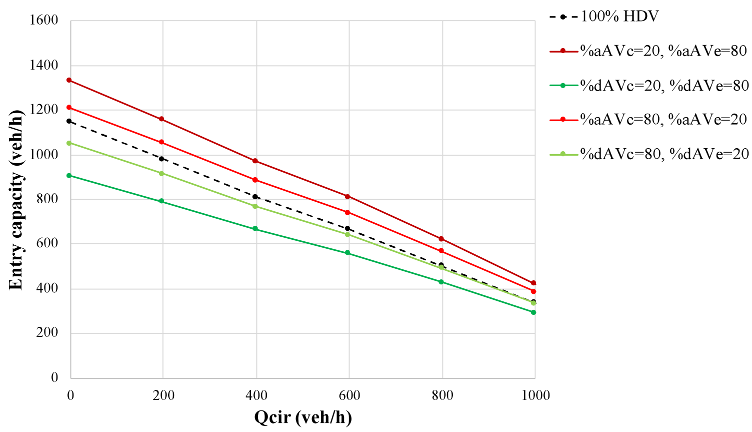


Figure 9 Entry D capacity under AVs mixed flows

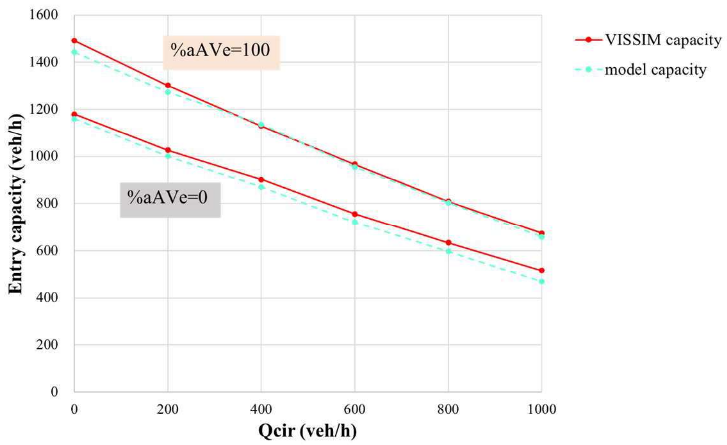


Figure 10 Comparison between entry capacity estimated through model and VISSIM($\%aAV_c$=60%)

7. CONCLUSIONS AND FUTURE WORK

In this study, a traffic simulator VISSIM was utilized to estimate a common 4-leg roundabout entry capacity under AVs mixed flows. Linear regression models for f_{AV} were also put forward to generalize the results. Conclusions of this study are summarized as follows.

Firstly, the capacity results indicate that AVs mixed flows put positive impact on entry capacity since smaller headway parameters are set. On the contrary, dAVs mixed flows give negative impact on entry capacity since they will not enter the roundabout unless the headways are large enough; meanwhile, they tend to keep longer gaps from leading vehicles so that the efficiency of roundabout will decrease.

Secondly, with the increasing penetration rate of aAVs in entry approach, the entry capacity will increase accordingly. Oppositely, with the increasing percentage of dAVs in entry approach, the entry capacity will decrease at the same time. Same conclusions can be summarized from the penetration rate of AVs in circulatory approach, however, their impacts on entry capacity are much less significant.

Thirdly, excepting the three headway parameters, it is also found that the desired speed of vehicles have impact on the entry capacity through simulation results. Flows sharing same headway parameters do not have same entry capacity if different speed distribution are given in VISSIM 7. Sepecifically, when circulating flow is large, both aAVs and dAVs mixed flows in different speed case have greater capacity under low AVs penetration rate while smaller capacity under high AVs penetration rate.

Finally, the modeling of f_{AV} helps generalize the results when AVs are introduced into roundabout. It can be found in both model that fa_{AV} indicates aAVs can improve the capacity performance in roundabout while fd_{AV} indicates that dAVs can decrease the capacity.

Since aAVs and dAVs mixed flows were separately analyzed in this study, the mixed flow of aAVs, dAVs and HDVs are also to be considered in a future work. Besides, the influence of pedestrian was not discussed in this study, however, it should be evaluated as well. What's more, f_{AV} models in this study are separately established according to speed distributions due to the limited numbers of different speed cases. In the next step, with greater number of experiments with various speed distributions, f_{AV} models can be summaried into a generalized one. Moreover, V2V and V2I communications which are expected to improve the efficiency and safety of roundabout, are also considered in the next step of this study.

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