ESTIMATION OF ROUNDABOUT ENTRY CAPACITY UNDER AUTONOMOUS VEHICLES MIXED FLOW

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In recent years, increasing number of roundabouts has been implemented in Japan due to their good performance on both safety and efficiency. To evaluate the roundabout operational performance, entry capacity is one of the most important indices. While with the development of vehicular technologies, the appearance of autonomous vehicles will lead to a mixed flow condition which is suspected to have significant impact on roundabout entry capacity. Therefore, this paper aims to examine the influence of autonomous vehicles on the entry capacity through adjusting headway parameters in the roundabout entry capacity equation. In order to clearly classify the impacts of autonomous vehicles, different aggressiveness levels and the percentage of autonomous vehicles included in traffic flows are considered in this paper.

Key Words : *roundabout, entry capacity, autonomous vehicle mixed flows*

1. INTRODUCTION

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. 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 fewer number of conflict points and less possibilities of severe crashes. Based on the development of AVs technology, merging behavior at roundabout can be automatically conducted which can be expected for the improvement of safety.

However, the impact of AVs on roundabout entry capacity is fully dependent on the setings of AVs performance, particularly under mixed flow conditions with conventional vehicles. The occupancy of AVs cannot be expected to become 100% within a short period due to various technology limitations and necessity of adaptations, even in the near future. Thus, it is necessary to estimate the influence of AVs and human driven vehicles (HDVs) mixed flow on roundabout entry capacity.

The performance of AVs depends on the paremeters which are set by human beings. Usually, headways, reaction time, desired speed, maximum acclearation and deceleration etc. are considered as important parameters of AVs. Among those, headways are critical parameters in roundabout entry capacity estimation[1)]. Through adjusting these parameters, different types of AVs can be defined, such as aggressive AVs (aAVs), discreet AVs (dAVs) and normal AVs (nAVs), which will also result in different performance of roundabout.

Therefore, the aim of this research is to estimate roundabout entry capacity under autonomous vehicles mixed flow with different AVs' percentage and different types of AVs. Note that mixture of AVs of different performance mentioned above is not considered in this study.

2. LITERATURE REVIEW

The entry capacity is the maximum number of vehicles that are expected to enter roundabout from one entry during a certain period. The Japan Roundabout Manual (JRM)[1] estimates the entry capacity based on the gap acceptance theory by defining three headway parameters in entry and circulatory flows.

Since continuous and stable AVs mixed flow in the real world has not been realized yet, it is difficult to obtain empirical data and utilize them 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 exsiting entry capacity equation based on the gap acceptance theory; the other is to use microscopic traffic simulation software to evaluate various scenarios. Nevertheless, it is common for both of them that AVs parameters must be reasonably assumed for the evaluation.

Kanbe, et al.[2] developed a methodology to consider the influence of geometric design of roundabout on entry capacity by empirically modeling the three headway parameters based on headway data collected at eight roundabouts in Japan. Fang, et al.[3] proposed a procedure to estimate impact of large vehicles on roundabout entry capacity by considering probability of combinations different types of vehiclses forming headways in traffic flows.

Bokui, et al.[4] investigated a traffic system with mixed flows of AVs and HDVs at intersections and found that the critical vehicle density and the maximum average flow are the critical factors for measuring capacity. However, they did not mentioned about parameter settings assumed for AVs themselves nor discussed traffic flows in roundabouts.

Pan, et al.[5] analyzed the impact of AVs mixed flow on the capacity of signalized intersections and safety of gap acceptance behaviors of right-turn vehicles by defining three types of AVs.

Bierstedt, et al.[6] estimated roundabout entry capacity under different AVs mixed flows by utilizing a traffic simulator. They considered two types of AVs, which are aAVs and dAVs by assuming different speeds, accelerations, decelerations and other operational parameters. It was found that the entry capacity will only arise when at least 75% of the vehicles are AVs, and the settings should not be extremely aggressive or discreet values compared with which of the normal HDVs. However, in this research, the three headway parameters were not intensively discussed.

Bailey[7] investigated a simple road network with an isolated roundabout and obserbveed that an increase in AVs percantage corresponds with an increase in entry capacity. However, only aAVs were considered in this research, the impact of dAVs and nAVs were not discussed.

As shown above, most of previous studies only considered either AVs' performance in traditional intersections or the impact of headway parameters of HDVs on roundabout capacity, and there is no research focusing on AVs' headway parameter settings on capacity. Thus, this study can be positioned as a significant one which fills out this missing gap.

Table 1 Definitions of the three headway parameters

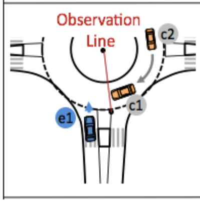
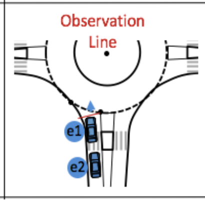
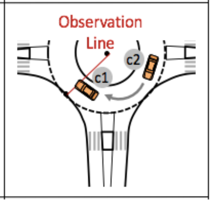
Critical headway t_c	Follow-up time t_f	Minimum headway τ
		

Table 2 values of three headway parameters

Type	t_c (s)	t_f (s)	τ (s)
Default values in JRM	4.1	2.9	2.1
HDV/nAV	3.6	3.2	2.0
aAV	2.9	2.4	1.7
dAV	5.0	4.2	2.2

3. METHODOLOGY

(1) Entry capacity equation

Equation (1) is indicated in Japan Roundbout Manual[1] (JRM) for estimating roundabout entry capacity.

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

Where, c_j: entry capacity of entry j in the unit of pcu/h, Q_r: circulating flow at the entry j in the unit of pcu/h. The three headway parameters t_c, t_f, and τ are the critical gap, the follow-up time of entering vehicle and the minimum headway of circulating flow, in the unit of s, respectively.

2) Definition of three headway parameters

The definitions and measurement methods of three headway parameters are illustrated in **Table 1**.

(a) Critical gap t_c

The critical gap in Equation of JRM is defined as the minimum acceptable gap between two circulating vehicles where the gap is judged by entering vehicle to accept or reject. Since the vehicle size is not considered in this research and headway is more easier to collect, headway is usually observed and utilized for the calculation for convenience. Therefore, this paper substitute critical headway for critical gap.

(b) Follow-up time t_f

The follow-up time is headway between consecutive leading vehicle and following vehicle in entry approach.

(c) Minimum headway τ

The minimum headway is headway between consecutive leading vehicle and following vehicle on circulatory roadway.

The reference values of three headway parameters given in JRM are shown in **Table 2**.

3) Hypothesis for each type of vehicles

In this research, four types of vehicles are considered; HDVs and three types of AVs (aAVs, dAVs and nAVs). To define AVs, a great number of parameters need to be discussed. For example, the reaction time, maximum acceleration, maximum deceleration, desired speed, and so on. Since headway parameters are critical for estimating entry capacity based on the equation in JRM, as the first step, only the settings of three headway parameters are assumed to define different types of AVs in this research. Thus, for HDVs, three headway parameters are selected based on empirical data. For aAVs, t_c, t_f, τ are assumed to be shorter compared to which of HDVs due to its definition. Similarly, t_c, t_f, τ for dAVs are assumed to be longer than HDVs. For nAVs, the reaction time and other parameters as mentioned above may be different from other types of AVs, however, in terms of the three headway parameters, they are assumed to be the same values as HDVs.

(4) Estimation methods for the three headway parameters of each type of vehicles

Although empirical data of AVs flow is not available, the headway data of HDVs flow can be utilized as a reference. To be specific, the three headway parameters of each type of AVs can be assumed within the ranges of observed headways. In this paper, a common 4-leg roundabout with a diameter of 27m is hypothesized. Empirical data which was observed at Moriyama roundabout in Shiga Prefecture, Japan is selected, since it has the similar geometry to the hypothesized roundabout[1]. The three headway parameters for each type of vehicles are set based on this empirical data.

a) Estimation of t_c

In the case of t_c, only the headways up to 10s were collected. The headway acceptance probability method is utilized to estimate the representative value of t_c for each type of vehicles. The probability of ac-

Table 3 Vehicle compositions

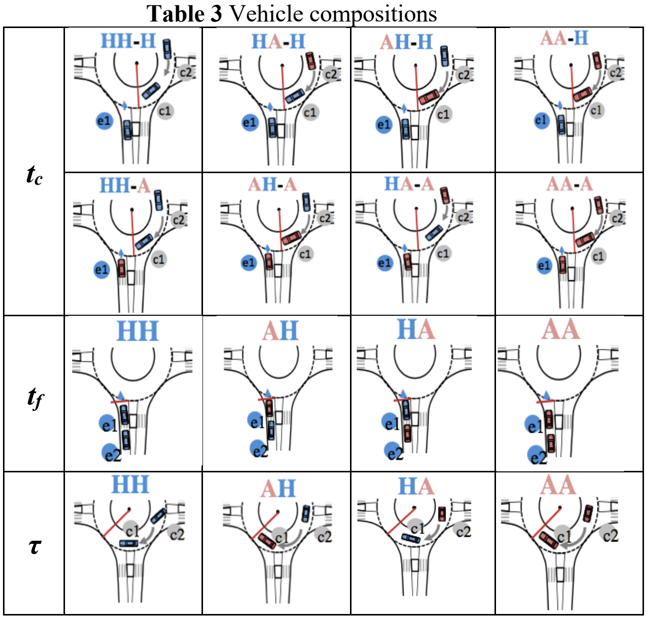


Table 4 Headway parameters for AVs mixed compositions

aAV	t_c (s)	HH-H	HA-H	AH-H	AA-H
		3.6	3.6	3.6	3.6
		HH-A	AH-A	HA-A	AA-A
		2.9	2.9	2.9	2.9
	t_f (s)	HH	AH	HA	AA
		3.2	3.2	2.6	2.6
	τ (s)	HH	AH	HA	AA
		2.0	2.0	1.7	1.7
dAV	t_c (s)	HH-H	HA-H	AH-H	AA-H
		3.6	3.6	3.6	3.6
		HH-A	AH-A	HA-A	AA-A
		5.0	5.0	5.0	5.0
	t_f (s)	HH	AH	HA	AA
		3.2	3.2	4.2	4.2
	τ (s)	HH	AH	HA	AA
		2.0	2.0	2.1	2.1

cepted headways is calculated by the number of accepted headways devided by the number of all headways as **Equation (2)**, and the 50 percentile value is defined as the critical headway since it can reflect the average performance. **Figure 1(a)** shows the acceptance probability curve. One second is defined as a time interval. The 50 percentile value is defined as the critical headway for HDVs and nAVs; then the 15 percentile value and 85 percentile value are defined as the critical headway for aAVs and dAVs, respectively. The accurate values of t_c for each type of vehicle is shown in **Table 2**.

$$P(a) = \frac{n(a)}{n(a) + n(r)} \tag{2}$$

Where, $P(a)$: the headway acceptance probability; $n(a)$: the number of accepted headways; $n(r)$: the number of rejected headways.

b) Estimation of t_f

In this case, only the headways smaller than 5s were collected and then the 50 percentile value of the cumulative distribution curve is defined as a representative value of t_f for HDVs and nAVs as shown in **Figure 1(b)**. The 15 percentile value and 85 percentile value are defined as the representative values of t_f for aAVs and dAVs, respectively.

c) Estimation of τ

Similarly, only the headways smaller than 5s were collected. However, different from t_c and t_f, the 15 percentile value of the cumulative distribution curve as shown in **Figure 1(c)** is defined as the representative value of τ for HDVs and nAVs, since the definition of τ is the minimum headway in circulatory roadway, and the 15 percentile value is close to the recommended value in JRM. Then, the 5 percentile value and 25 percentile value of the curve are defined as the representative value of τ for aAVs and dAVs, respectively.

(5) Vehicle compositions

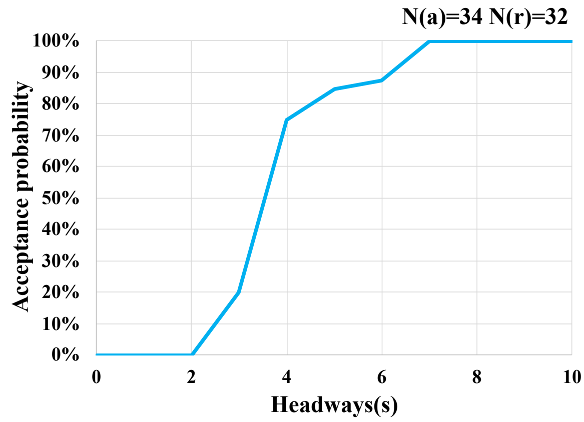
To estimate the entry capacity under AVs mixed flow, AVs' position in consecutive vehicles need to be carefully considered. Regardless of the types of AVs, there are eight compositions for t_c, four compositions for t_f and four compositions for τ, as summarized in **Table 3**, where H and A represent for HDVs and AVs, respectively. Meanwhile, e_1, e_2, c_1 and c_2 represent leading entering vehicle, following entering vehicle, leading circulating vehicle and following circulating vehicle, respectively.

(6) Estimating the three headway parameters for AVs mixed compositions

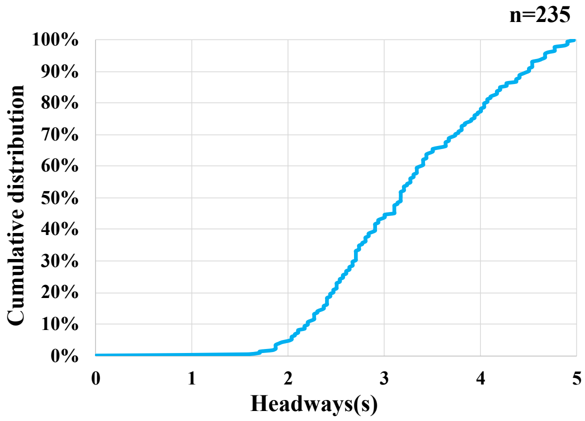
The three headway parameters estimated for each type of vehicles above work only when 100% of vehicles are AVs or HDVs in traffic flows. To estimate the headway parameters when compositions including both HDVs and AVs, several assumptions are made.

For t_c, assumption is that t_c is only decided by the the type of entry vehicle regardless of the vehicle types of leading vehicle and following vehicle in circulatory roadway. This is because of the hypothesis that the drivers in entry vehicles cannot distinguish the types of the oncoming vehicle on circulatory roadway and they will judge whether to accept only based on the size of the headway itself. As a result, t_c of composition AH-A, HA-A, HH-A will be just same as the value of composition AA-A, since the entry vehicles in each of them are all AVs. Similarly, t_c of composition AH-H, HA-H, AA-H will be just the same as the value of composition HH-H for the same reason. The result is summarized in **Table 4**.

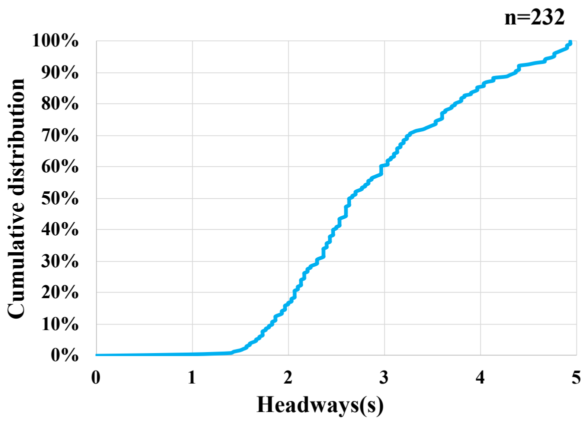
For t_f and τ, assumptions are that the values of t_f and τ are only decided by the type of following vehicle in entry approach and circulatory roadway, respectively, regardless of the type of leading vehicle. The same reason as t_c is considered that headway is only dependent on the following vehicles. For instance, in the case of t_f, the composition AA and HA will share the same t_f value since they have same type of following vehicles.



(a) t_c



(b) t_f



(c) τ

Fig.1 Measurements of the three headway parameters

(7) Estimating the three headway parameters for AVs mixed flow

In this paper, only the equation in JRM from macroscopic scope is selected to analyze the influence of different settings of AVs on rounabout entry capacity. However, only one value of three headway parameters can be inputted in the equation and it can only estimate for the 100% of AVs and HDVs conditions, but not of HDVs and AVs mixed flow considitions. Here, the weighted average of headway parameters is calculated based on the probabilities of each composition and headway parameters. If the type of AVs and the percentage of AVs in entry approach and circulatory roadway can be determined, **Equation (3)~(8)** can be utilized to calculate the three headway parameters for the specific scenarios:

t_c: $Pc1c2-e1 = Pc1 \times Pc2 \times Pe1$ (3)

t_f: $Pe1e2 = Pe1 \times Pe2$ (4)

τ: $Pc1c2 = Pc1 \times Pc2$ (5)

If $ci = AV, Pci = PAVi$

Otherwise, $Pci = 1 - PAVi$

Also, if $ei = AV, Pei = PAVi$

Otherwise, $Pei = 1 - PAVi$

Then, $t_{ci}=\sum_{i=0}^{8}(Pi \times t_{ci})$ (6)

$t_{fi}=\sum_{i=0}^{4}(Pi \times t_{fi})$ (7)

$\tau_i=\sum_{i=0}^{4}(Pi \times \tau_i)$ (8)

Where, e_1, e_2, c_1 and c_2 represent leading entering vehicle, following entering vehicle, leading circulating vehicle and following circulating vehicle, respectively. Thus, c_i and e_i represent for the types of vehicle in circulatory roadway and entry approach, respectively. $P_{c1c2-e1}$, P_{e1e2} and P_{c1c1} represent for the probability of each composition of t_c, t_f and τ, respectively. t_{ci}, t_{fi} and τ_i represent for t_c, t_f and τ value of the composition, respectively.

Giving an example that *Pdc*=0.2, *Pde*=0.3, where *P* stands for the percentage of the target vehicles; *d* denotes dAVs; if it is the case of aAVs, *a* is utilized to denote aAVs. *c* and *e* stand for circulatory roadway and entry approach, respectively. Therefore, *Pdc*=0.2 can be explained as the percentage of dAVs in circulatory roadway is 0.3. Then the detailed calculation process of t_c under this premise is given below:

P_{HH-H}= (1-0.2) × (1-0.2) × (1-0.3)=0.448

P_{AH-H}= (1-0.8) × (1-0.2) × (1-0.3)=0.112

Besides, since the t_c values of each of these compositions are already known, the weighted average t_c value for all the compositions can be calculated as:

$t_c = P_{HH-H}\times t_c(HH\text{-}H) + P_{AH-H}\times t_c(AH\text{-}H) + P_{HA-H}\times t_c(HA\text{-}H) + P_{HH-A}\times t_c(HH\text{-}A) + P_{AA-H}\times t_c(AA\text{-}H) + P_{AH-A}\times t_c(AH\text{-}A) + P_{HA-A}\times t_c(HA\text{-}A) + P_{AA-A}\times t_c(AA\text{-}A)$

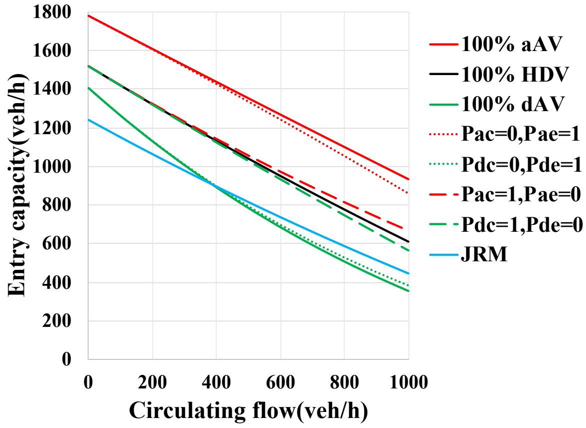
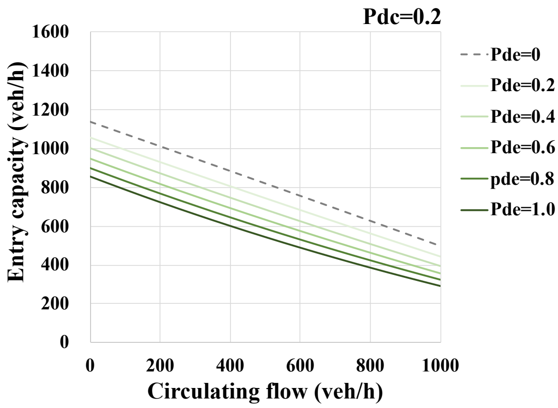
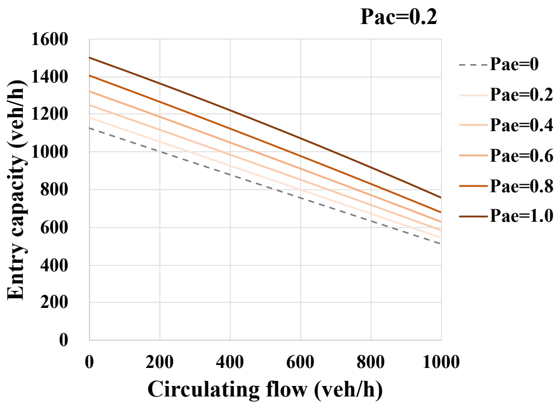


Fig.2 Entry capacity under non-mixed flow



(a) dAVs mixed flow



(b) aAVs mixed flow

Fig.3 Entry capacity under AVs mixed flow

$= 0.448\times3.6 + 0.112\times3.6 + 0.112\times3.6 + 0.192\times5.0 + 0.028\times3.6 + 0.048\times5.0 + 0.048\times5.0 + 0.012\times5.0 = 4.02s.$

Through the similar process, t_f and τ can also be calculated under the premise that *Pdc*=0.2, *Pde*=0.3.

In order to figure out the impact of the appearance of AVs on roundabout entry capacity, the percentage of AVs in both entry approach and circulatory roadway is gradually increasing from 0 to 100% in the gradient of 20% to observe the changes in entry capacity.

4. ESTIMATING ROUNDABOUT ENTRY CAPACITY OF AV MIXED FLOWS

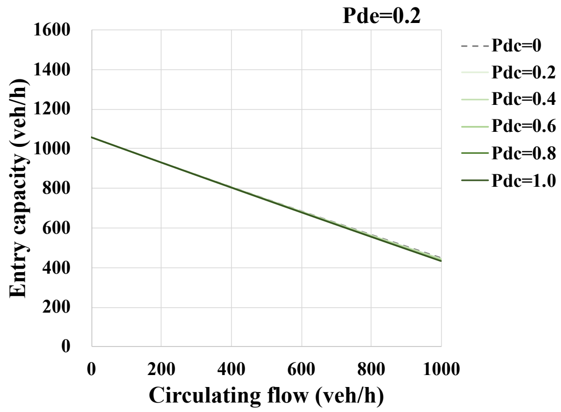
Three types of AVs are assumed in this research which are aAVs, nAVs and dAVs. However, since the three headway pamameters for nAVs are set just the same as HDVs, there is no any impact on entry capacity by changing the percentage of nAVs in roundabout through the capacity equation. Thus, only aAVs and dAVs mixed flow will be discussed here.

(1) Non-mixed flow in entry and circulating road way

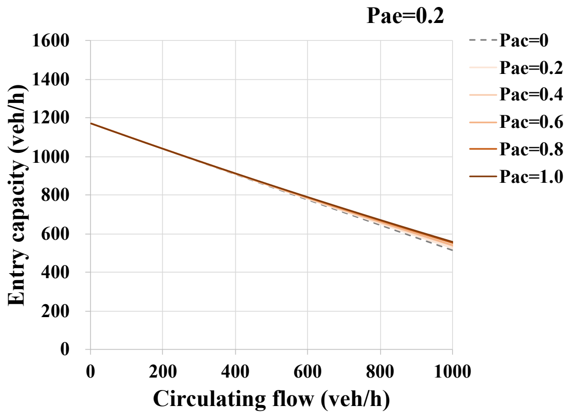
Figure 2 shows the entry capacity under non-mixed flow conditions, which are 1) both entry approach and circulatory roadway are occupied by 100% AVs; 2) only entry approach is occupied by 100% AVs; 3) only circulatory roadway is occupied by 100% AVs. Meanwhile, curves for 0% AVs are also drawn, the black line is based on the observed data of the three headway parameters, and the blue line is based on the recommended value from JRM. With the circulating flow increasing, the entry capacities decrease under each of these scenarios. Putting the JRM curve aside provisionally, the 100% aAVs curve and 100% dAVs curve denote the largest entry capacity and lowest entry capacity, respectively. They consist of two boundary lines, and the 100% HDVs curve denotes the averge level of entry capacity.

From the viewpoint of different types of AVs, for aAVs involved flow, if *Pae*=1, the entry capacity curve is still very close to the 100% aAVs curve, that is because only τ changed and τ has little impact on the roundabout entry capacity. On the contrary, if *Pac*=1, the entry capacity decreases sharply and the curve moves close to the 100% HDVs curve. This can be explained that in this case, both t_c and t_f changed to the settings of HDVs, and meanwhile these two parameters have great effect on entry capacity. Similarly, for dAV included flow, for all the same reasons, if *Pde*=1, the capacity curve is still close to the curve under 100% dAVs; while if *Pdc*=1, the capacity decreases sharply and the curve gets close to the lower side of 100% HDVs curve.

From the viewpoint of different flows, if AVs only occupy the entry approach, the capacity curves for aAVs and dAVs are drawn close to 100% aAVs and 100% dAVs curves, respectively, since only τ changed compared to 100% AVs curves, and this parameter matters least for the entry capacity. On the contrary, if AVs only occupies the circulatory roadway, the capacity curves are lying close to each side of 100% HDVs curve since both t_c and t_f changed to



(a) dAVs mixed flow



(b) aAVs mixed flow

Fig.4 Entry capacity under AVs mixed flow

the settings of HDVs and these two parameters influence entry capacity greatly.

Entry capacity curves under 100% HDVs are also drawn through observed data and values in JRM, respectively. The capacity under JRM values is much smaller compared to the capacity curve drawn according to observed data, this is because JRM gives quite conservative values to ensure safety.

(2) Mixed flow in entry and circulating road way

Figure 3 shows the results of entry capacity when AVs percentage in circulatory roadway is fixed as 20%. With the circulating flow increasing, roundabout entry capacity decreases at the same time.

However, for dAVs, **Figure 3(a)** shows that with increasing percentage of dAVs changing from 0 to 100% in entry approach, the capacity decreases correspondingly since headways will increase with larger percentage of dAVs. On the contrary, for aAVs mixed flow, the capacity increases with the increasing percentage of aAVs as illustrated in **Figure 3(b)** since shorter headways can be remained by aAVs.

Figure 4(a) and **(b)** show results of entry capacity when AVs percentage in entry approach is fixed as 20%. Similarly, with the circulating flow increasing, roundabout entry capacity decreases at the same time.

However, by changing the AVs percentage in circulatory roadway from 0 to 100%, the roundabout entry capacity does not change so much under both aAVs mixed flow and dAVs mixed flow. This result indicates that τ has less influence on the entry capacity compared to t_c and t_f.

4. CONCLUSIONS AND FUTURE WORK

In this study, the roundabout entry capacities were discussed under AVs mixed flow conditions with different AVs' percentage of each of the three AVs types. The headways observed from field data is used to set the headway parameters for three types of AVs, and the roundabout entry capacity equation is also flexibly utilized for AVs mixed flows conditions through estimating headway values by considering percentage of AVs.

Through this study, it was found that firstly, aAVs mixed flows provide positive impact on entry capacity since smaller t_c and t_f are set. On the contrary, dAVs mixed flows put negative impact on entry capacity since they will not enter the roundabout unless the headways are large enough; meanwhile, they tend to keep longer headways from leading vehicles so that the efficiency of roundabout will decrease.

Secondly, with the increasing percentage of aAVs in both circulatory and entry flows, the entry capacity will increase accordingly. This is because with the increasing occupancy of aAVs, the headways become shorter compared to which of 0% aAVs flow; when aAVs reaches 100%, the entry capacity will be the largest. For the same reason, with the increasing percentage of dAVs in both circulatory roadway and entry approach, the entry capacity will decrease at the same time, and when dAVs reached 100%, entry capacity will be the smallest.

Thirdly, in terms of the three headway parameters, it's t_c and t_f that mainly influence the entry capacity while τ has little effect on it. As a result, efforts should be put on decreasing critical headways and follow-up headways in roundabout in the premise of safety to improve roundabout entry capacity.

In this study, since the entry capacity equation cannot reflect the impact of reaction time, the influence of nAVs cannot be considered in this study. Thus, in future, simulation will also be applied for nAVs and other parameters of vehicles, such as desired speed, reaction time, maximum acceleration and deceleration and so on, to make the result more reliable.

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