INVESTIGATING THE IMPACTS OF GEOMETRIC LAYOUT AND HEAVY VEHICLES ON ROUNDABOUT ENTRY CAPACITY

Yujia ZHAO[1], Xin ZHANG[2], Wael K.M. ALHAJYASEEN[3], Hideki NAKAMURA[4]

[1] Student member of JSCE, Master Course Student, Graduate School of Environmental Studies, Nagoya University
(Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan)
E-mail: yiling1211zhao@gmail.com
[2] Member of JSCE, Research Fellow, Dr.-Eng, Department of Civil and Environmental Engineering, Nagoya University
Email: zhang@genv.nagoya-u.ac.jp
[3] Member of JSCE, Assistant Professor, Dr.-Eng, Qatar Transportation and Traffic Safety Center, Qatar University
International Visiting Faculty, Department of Civil and Environmental Engineering, Nagoya University
Email: wyaseen@qu.edu.qa
[4] Fellow member of JSCE, Professor, Graduate School of Environmental Studies, Nagoya University
E-mail: nakamura@genv.nagoya-u.ac.jp

Entry capacity is one of the most important indices for evaluating roundabout performance and it is usually estimated using gap theory by defining three different gap parameters: critical gap, follow-up time and minimum headway of circulating roadway. These parameters are affected by the composition of vehicle types and geometric layout of roundabouts. However, the impact of these elements is still unclear and not considered in current methodologies. In this research, gap parameters were empirically analyzed and modeled considering the influence of heavy vehicle ratio and geometric elements. Then it is used to assess the impacts on entry capacity. In conclusion, this study confirms the significant impact of geometric layout of roundabouts on its entry capacity. Furthermore, it was found that entry capacity is positively correlated with inscribed circle diameter, while it is negatively affect by heavy vehicles.

Key Words: *roundabout, gap parameter, geometric layout, heavy vehicles, entry capacity*

1. INTRODUCTION

Roundabouts are popular control type at intersections in many counties worldwide due to their proven safer operation. However, in terms of their operational efficiency, they are usually advantageous at medium vehicle demand levels with balanced flows in the major and minor approaches. In Japan, roundabouts were first defined and prescribed by Road Traffic Law of Japan in June 2013. After the partial revision of Road Traffic Law in 2014 in which the operational procedures and priority rules of roundabouts were clearly defined, the number of roundabouts start increasing rapidly. In the planning stage, entry capacity is one of the most important indices used to predict the operational performance of roundabouts by investigating whether it can accommodate the expected traffic demand or not.

In the Japan Roundabout Manual JRM[1)] (2016) as well as the Highway Capacity Manual HCM[2)] (2016), a procedure is proposed to estimate entry capacity based on the gap acceptance theory. In this approach, entry capacity is mainly dependent on the settings of the gap parameters in circulating and entry flows. These gap parameters are: follow-up time (t_f), minimum headway of circulating flow (τ), and critical gap (t_c). Few recent studies[3)4)] concluded that these gap parameters are affected by vehicle type and roundabout geometry. However, these manuals propose fixed gap parameter values independent of vehicle type or the geometric layout of the roundabout. The presence of heavy vehicles on the circulatory roadway or at the entry approach will significantly and differently affect the entry capacity. HCM[2)] and JRM[1)] propose Passenger Car Equivalent (PCE) factor, which is defined based on the reduction on entry capacity caused by heavy vehicles, to convert heavy vehicle demand to equivalent number of passenger cars without considering their impact on gap parameters. They recommend a constant value of

2.0 to be used for PCE although recent studies[4)7)] show that PCE value is not constant but rather changes with percentage of heavy vehicles.

On the other side, we can observe that roundabouts are being constructed with different dimensions since existing design manuals does not provide strict specifications for their layout. Such different layouts may significantly affect driver behavior and as a result, it may yield to significantly different entry capacities. Thus, this study aims to investigate the potential impacts of geometric layout and heavy vehicle ratio on the entry capacity of roundabouts through empirical observations. Furthermore, this study proposes a methodology to quantify the impacts of roundabout geometry and heavy vehicle ratio on the gap parameters.

2. LITERATURE REVIEW

The three gap parameters used in the estimation of entry capacity are the most important variables that reflect drivers' behavior. In previous research, Kanbe and Nakamura[3)] attempted to analyze the impact of geometric elements on gap parameters, and developed a model between them. It was found that critical gap is influenced by entry width and effective flare length, as these parameters facilitate the merging of entry vehicles into circulating flow. Furthermore, it was found that minimum headway of circulating roadway is significantly affected by inscribed circle diameter and merging angle. However, heavy vehicles are not considered in this research.

Goto et al.[4)] analyzed the three gap parameters as well, and estimated the passenger car equivalent for heavy vehicles at the standard roundabout entry and circulatory roadway and normalized the values of gap parameters for each vehicle composition based on the case have passenger car only as shown in **Table 1**. A microscopic traffic simulator was adopted for obtaining entry capacity under various heavy vehicle percentages in either enter and circulating flow. Then PCE was evaluated that the difference of each headway parameter depends on vehicle composition.

Dahl et al.[5)] also analyzed the gap parameters considering the effect of heavy vehicles, and tried to estimate entry capacity by using the existing capacity models[1)2)] with the adjusted gap acceptance parameters.

Chris Lee[6)] estimated PCE for heavy vehicle by adjusting the headway parameters based on empirical data, such as critical gap and follow-up time collected in United States. It is determined that the accuracy of capacity prediction can be improved by PCE for heavy vehicles. However the PCE for heavy vehicles is different depending on maximum size of heavy vehicles and their performance. However, they did not consider the impact of roundabout geometry.

Table 1 Normalized Value

t_c	PP-P	PP-H	HP-P	PH-P
	1.0	1.3	1.2	1.1
	HH-P	HP-H	PH-H	HH-H
	1.3	1.6	1.4	1.7
t_f	PP	PH	HP	HH
	1.0	1.2	1.4	1.4
τ	PP	PH	HP	HH
	1.0	1.1	1.4	1.9

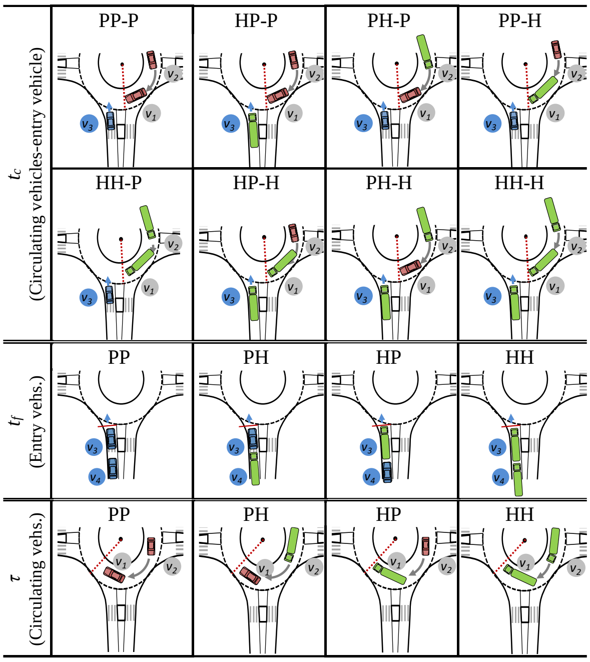

Fig.1 Compositions for each gap parameter

As shown in the previous summary, there is still a lack of the further analysis on the relationship between heavy vehicles and geometric parameters and entry capacity, particularly in Japan. Thus, this study aims at analyzing these relationships through empirical data.

3. METHODOLOGY

According to Roundabout Manual[1)] (2016) in Japan, entry capacity can be estimated using equation (1).

$$c_i = \frac{3600}{t_f}\left(1-\tau\cdot\frac{Q_{ci}}{3600}\right)\cdot\exp\left\{-\frac{Q_{ci}}{3600}\cdot\left(t_c-\frac{t_f}{2}-\tau\right)\right\} \qquad (1)$$

Where, c_i: entry capacity of entry i(pcu/h), Q_{ci}: circulating flow for i(pcu/h), t_c: critical gap(sec), t_f: follow-up time of entry vehicle(sec), τ: minimum headway of circulating flow(sec). There three parameters: t_c, t_f, and τ are defined as "gap parameters" and recognized as the most important variable that represent driver's gap acceptance behavior and they significantly affect the estimation of c_i.

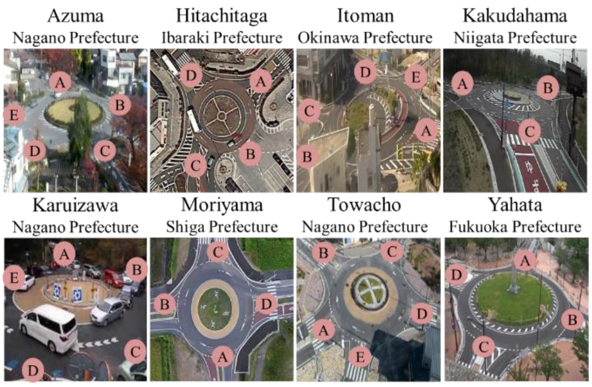

Fig.2 Roundabouts studied in this research

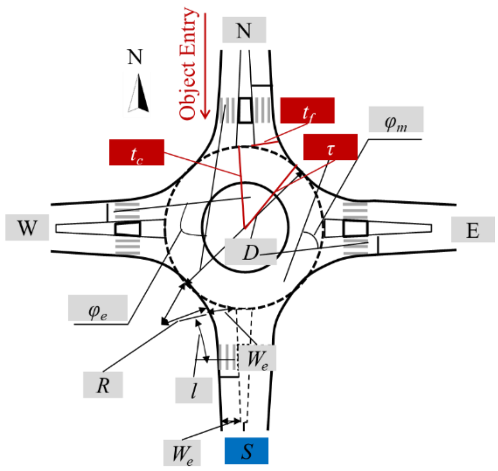

Fig.3 Definition of geometric parameters and cross-sections for measuring gap parameters

Meanwhile, these three gap parameters are also influenced by geometric layout of roundabouts. For example, circulating vehicles can run more smoothly in a larger inscribed circle diameter. Vehicle type also influences gap parameters due to the large size and low speed of heavy vehicle. When considering heavy vehicles at roundabout, each parameter can be categorized into several compositions depending on the position of heavy vehicles as shown in **Fig.1**. Regarding t_c, it has 8 different compositions while t_f, and τ have only 4 compositions.

Behavior of heavy vehicles is also influenced by geometric layout. With different composition of gap parameter, the influencing geometric layout parameters might be different. To investigate these relationships, empirical data is collected at several sites.

The modified $\overline{t_c}$, $\overline{t_f}$,and $\overline{\tau}$ considering the heavy vehicle percentage of enter and circulating road way (*He*% and *Hr*%) can be calculated by Equation (2)-(4).

$$\overline{t_c} = \sum_{n=1}^{8} t_{c,v_{1n}v_{2n}-v_{3n}} \times P_{v_{1n}v_{2n}-v_{3n}} \quad (2)$$

Table 2 Geometric elements of each roundabout

RAB		W_e (m)	W (m)	D (m)	R (m)	l (m)	φ_e (deg)	φ_m (deg)
Itoman	A	4.15	3.00	39.0	21.5	7.17	43.0	15.0
	B	3.87	3.00		23.5	4.95	40.0	39.5
	C	3.26	3.00		6.00	2.42	45.0	37.0
	D	3.99	3.00		21.5	4.68	37.0	26.5
	F	3.74	3.00		39.0	7.61	33.0	28.5
Hitachi -taga	A	4.70	3.25	28.0	11.0	4.44	32.0	34.0
	C	4.44	3.00		5.50	11.5	56.0	11.5
	D	5.35	3.25		13.0	5.03	26.0	14.0
Towa -cho (Stop)	A	4.49	3.00	30.0	13.0	10.2	53.5	67.0
	B	3.42	2.75		6.50	10.2	61.5	63.0
	C	3.89	3.33		13.5	10.6	45.0	61.0
	D	4.46	2.92		13.5	10.1	47.5	66.0
	E	4.99	3.43		13.5	10.3	35.0	90.0
Azuma	A	6.11	3.00	39.0	15.0	11.7	57.0	78.0
	B	4.60	3.36		9.22	7.75	26.0	27.0
	C	5.42	3.02		16.5	8.58	48.0	67.0
	D	4.79	3.35		18.9	23.7	48.5	61.0
	E	3.98	2.82		8.19	17.8	44.0	59.0
Mori -yama (Case1)	A	4.88	2.75	27.0	22.0	3.00	35.0	17.5
	B	4.85	2.75		22.0	2.92	40.0	27.5
	C	4.94	2.75		22.0	2.56	41.0	33.5
	D	5.03	2.75		22.0	3.38	43.0	23.5
Mori -yama (Case2)	A	3.71	2.75	27.0	30.0	2.74	19.0	21.0
	B	3.49	2.75		30.0	2.22	16.0	22.0
	C	3.92	2.75		30.0	3.09	21.0	24.0
	D	3.55	2.75		30.0	2.33	17.0	21.5
Karui -zawa	A	3.00	2.90	27.0	6.00	2.90	55.0	57.5
	C	3.50	2.90		6.00	0.30	65.0	57.0
	D	4.10	2.50		3.00	1.60	77.0	65.0
Kakuda -hama	1	4.38	2.94	30.0	27.4	4.85	20.0	57.0
	2	4.79	2.79		28.5	5.06	15.5	50.0
	3	4.63	2.76		26.7	5.44	25.0	49.0
Yahata	1	3.09	3.09	44.0	12.4	10.0	21.6	39.0
	2	3.09	3.09		10.0	10.0	41.3	37.2
	3	3.09	3.09		10.0	10.8	44.4	44.6
	4	3.09	2.32		10.0	11.6	48.0	38.4

$$\overline{t_f} = \sum_{n=1}^{4} t_{f v_{3n} v_{4n}} \times P_{v_{3n} v_{4n}} \quad (3)$$

$$\overline{\tau} = \sum_{n=1}^{4} \tau_{v_{1n} v_{2n}} \times P_{v_{1n} v_{2n}} \quad (4)$$

Where, $t_{c,v1nv2n\text{-}v3n}$, tf_{v3nv4n} and τ_{v1nv2n} are gap parameters of vehicle composition n and their probability are defined as $P_{v1nv2n\text{-}v3n}$, P_{v3nv4n} and P_{v1nv2n}.

It is important to highlights, that by using the methodology proposed by the Roundabout Manual and the empirically modeled gap parameters in this study, the impact on entry capacity is assessed.

However, it is very difficult to assume heavy vehicles in the circulating roadway while estimating the entry capacity since the circulating flow (pcu/hr) can not be defined in that case. Therefore, thus study assumes that heavy vehicles are present only at the entry approach while the circulating flow is only composed from passenger cars.

4. DATA COLLECTION AND PROCESSING

In order to analyze the relationship between geometric elements and gap parameters, video data was collected at eight roundabouts (RABs) in Japan as shown in **Fig.2**. The trajectories of vehicles are extracted from videos by using the image processing system TrafficAnalyzer (Suzuki and Nakamura, 2006)[8].

In this research, seven geometric elements are used for the analysis, entry width W_e(m), approach half width W(m), inscribed circle diameter D(m), entry radius R(m), effective flare length l(m) and entry angle φ_e(deg), which were defined by Kimber[9]; and merging angle φ_m(deg), which were defined to estimate the behavior of entry vehicle more easily. Definitions of these parameters are illustrated in **Fig.3**. W_e is the length of a line perpendicular to the midline of approach; W is the width of entry lane; D is the diameter of inscribed circle; R is the radius of the arc which connects entry approach with circulating roadway; l is the distance from the entry to the halfway point in the approach; φ_e is half of the angle between midline of entry lane and midline of next outflow approach; and φ_m is the angle between midline of entry lane and tangent of the yield line. Geometric elements at the subject roundabouts are summarized in **Table 2**.

Gap parameters are extracted from the video recordings of the roundabouts. **Fig.3** shows the cross-section (red lines) defined for measuring the three gap parameters. t_c is the time interval between two vehicles on circulating roadway pass the cross section. τ is the time between two vehicles on circulating roadway pass the cross section. If an entry vehicle enters the circulating roadway, it is defined as accepted gap, if not then it is a rejected gap. t_f is the time interval between two following entry vehicles passing the relevant cross-section.

In this study, critical gap t_c is determined by the intersecting point of the cumulative distribution of the accepted and rejected gap according to the Raff Method[10]. t_c shorter than 10 seconds are collected for the analysis. Follow-up time t_f and minimum headway of circulating flow τ are defined as the 50 percentile value of the headway distributions of entry and circulatory roadway that is shorter than 5 seconds.

Table 3 Sample size for each composition

	Sample Size			
t_c	PP-P	PP-H	HP-P	PH-P
	46	14	14	-
	HH-P	HP-H	PH-H	HH-H
	-	-	-	-
t_f	PP	PH	HP	HH
	1185	167	276	-
τ	PP	PH	HP	HH
	1858	514	878	-

Table 4 Model for t_c

	PP-P	**PP-H**	**HP-P**
	Coef. (t-value)	Coef. (t-value)	Coef. (t-value)
Intercept	6.21 (14.5***)	3.40 (2.98***)	5.17 (6.57***)
D	-0.0349 (-2.89***)	0.0599 (2.35**)	-
l	-	-	-0.181 (2.35***)
φ_e	-	-	0.0439 (2.07**)
φ_m	0.00548 (1.61*)	-	0.0205 (2.81***)
d_1	-0.593 (-3.41***)	-	-
d_3	-	1.14(2.66**)	-
R^2	**0.239**	**0.426**	**0.510**
N	46	14	14

*: Significant Level < 10%
: Significant Level < 5% *: Significant Level < 1%

Considering some possibility that other parameters can influence on vehicles' behavior, three dummy parameters are used for analyzing the data. They are, opening period dummy d_{op}, which is 0 if a period since the opening is less than three months, 1 otherwise; splitter island dummy d_{se}; and stop control dummy d_{st}, which is 1 if stop-controlled, 0 yield control.

Sample size of each composition is shown in **Table 3** Due to the limitation of sample size, model is only developed for the compositions which have enough data.

5. MODEL DEVELOPMENT

5.1 Critical Gap t_c

The model is developed for each combination of critical gap as shown in **Table 4**.

Firstly, both PP-P and PP-H are significantly influenced by D, but the results shows that the impact is totally opposite. This is because when D increases, the speed of circulating vehicle also increases which yields to longer distances between circulating

Table 5 Model for t_f and τ

		PP	PH	HP	PP	PH	HP
		Coef.(t-value)	**Coef.(t-value)**	**Coef.(t-value)**	**Coef.(t-value)**	**Coef.(t-value)**	**Coef.(t-value)**
		t_f	τ	t_f	t_f	τ	t_f
α	D	-	-2.16×10^{-2} (-2.69^{***})	-	$-4.13*10^{-2}$ (-2.29^{**})	-	-
	d_1	$0.585(3.78^{***})$	-	$-2.56(-2.78^{***})$	-	$-2.37(-2.63^{***})$	$-1.42(-4.28^{***})$
	Cons.	$2.22(13.7^{***})$	$2.98(10.6^{***})$	$4.95(5.24^{***})$	$3.85(5.67^{***})$	$6.30(4.90^{***})$	$5.06(9.96^{***})$
β	D	-	$-2.29\times10^{-2}(-4.61^{***})$	-	$-0.019(-1.72^{*})$	-	$-1.73*10^{-2}$ (-2.39^{**})
	φ_e	$-6.18\times10^{-3}(-2.77^{***})$	-	-	-	-	-
	d_1	$0.322(3.79^{***})$	-	$-0.79(-3.31^{***})$	-	$-0.365(-2.43^{**})$	$-0.465(-5.28^{***})$
	Cons.	$2.21(16.1^{***})$	$2.93(16.9^{***})$	$2.94(10.6^{***})$	$2.95(6.80^{***})$	$3.23(6.76^{***})$	$3.96(10.4^{***})$
γ	D	-	-	$0.0575(3.49^{***})$	-	$0.0217(1.81^{*})$	-
	R	$0.0186(4.66^{***})$	-	-	-	-	-
	d_3				-0.234 (-2.26^{**})	-	$-0.136(-1.92^{*})$
	Cons.				$-1.38(-26.6^{***})$	$-1.53(-2.44^{**})$	$-0.779(-3.35^{***})$
Prob>χ^2		0.0002	0.0071	0.0055	0.0222	0.0086	0.0000
N		1185	1858	167	514	276	878

*: Significant Level < 10%

: Significant Level < 5% *: Significant Level < 1%

vehicles. For passenger car, long distance between two circulating vehicle will encourage them to accept shorter gaps. However for heavy vehicle, even the distance is long, they tend to be conservative because of the high speed on circulating roadway.

Next, for HP-P, the influencing geometric elements are very different with PP-P and PP-H. This is because when heavy vehicle is the leading vehicle on the circulating roadway, its large size affects the visibility of the entry vehicle. This is the reason why on the geometric parameters that influences the speed and entry behavior of entry vehicle were found significant. Longer l make it easier for entry vehicle to accelerate, and smaller φ_e and φ_m make it easier to turn. They all reduce the impact of leading heavy vehicle on circulating roadway.

Finally, regarding to dummy variables, PP-P reduces when it is 3 months after opening, which is because drivers become more familiar with roundabout and choosing accepted gap. Stop control only shows significant negative influence on PP-H, which is because heavy vehicle needs more time to accelerate under stop control.

5.2 Follow-up Time t_f

Since the sample size is big enough, the distributions of t_f and τ gap parameters are modeled using Weibull distribution as equation (5). The parameters of the distribution α, β, γ are fitted using linear regression as functions of geometric layout parameters. The models for t_f and τ are shown in **Table 5**.

$$\mathrm{F}(t)=\frac{\alpha}{\beta}\left(\frac{t-\gamma}{\beta}\right)^{\alpha-1}e^{-\left(\frac{t-\gamma}{\beta}\right)^{\alpha}} \qquad (5)$$

Table 3 shows that the follow-up time of $t_{f,PP}$ decreases when entry radius increases. When entry radius is larger, the entry curve becomes smoother, thus it is easier for vehicle at the entry approach to turn into the circulating roadway. For $t_{f,HP}$ case, entry radius does not show significant impact. It is because the movement for heavy vehicle merging into the circulating roadway is more sensitive to the geometry of entry curve. Inscribed circle diameter also shows influence on $t_{f,HP}$ where it decreases with the increase in D.

The result of $t_{f,PH}$ is similar to $t_{f,HP}$. However D shows more significant result with $t_{f,PH}$. This can be explained that the leading heavy vehicle might block the view of the following vehicle, which makes it difficult for the following vehicle to observe the available gaps in the circulatory roadway.

The opening period dummy (d_{op}) and stop control dummy (d_{st}) also show significant influence on t_f. The impact of d_{op} in in $t_{f,PP}$ model is opposite to that of $t_{f,HP}$ model. This is because of the behavior change of entry vehicles. During the first three months after opening the roundabout, drivers are not familiar with the priority rule of roundabouts since they are not common intersection types in Japan. Thus they may ignore the priority of vehicles on circulating roadway. This is reflected in the estimated longer follow up time after the three months period since drivers start to understand and apply the priority rules. However for heavy vehicles including buses, considering the size of their vehicles, they tend to be more conservative in the first three months after opening the roundabout since they are not familiar with its operation. However after they got accustom with roundabout priority rule, they tend to become less conservative and accept shorter gaps.

Stop control dummy is also a significant influencing variable for t_f. When the type of control is stop control, entry vehicles need longer time to accelerate than yield control. However, this tendency is not observed in the $t_{f,HP}$ model that's because heavy vehicles usually slow down significantly and stop in both stop or yield control situations forcing the following vehicle to follow its speed reduction.

5.3 Minimum Headway of Circulating Flow τ

The developed empirical models for τ is presented in **Table 5**. In all developed models for the three compositions of τ, it can be found that only D shows significant negative influence on τ. When D increases, minimum headway of circulating decreases. Regarding τ_{PH}, due to the following heavy vehicle, the gap between the two vehicles will be large because of the slower movement of the heavy vehicle. Thus, the influence of D in τ_{PH} is lower than τ_{PP} model.

Opening period dummy and stop control dummy also have significant impact on τ models. First, for opening period, the influence on τ_{HP} is much larger than it on τ_{PP}. It is because with more experience of driving in the roundabout, the increase of speed for heavy vehicle is more significant than passenger car. Although, stop control dummy shows an opposite result compare to opening period dummy. The influence of stop control on τ_{HP} is the smallest and on τ_{PP} is the largest.

6. IMPACT OF GEOMETRIC ELEMENTS AND HEAVY VEHICLE ON ENTRY CAPACITY

To modify three gap parameters, values of all compositions are necessary. For the compositions which models cannot be developed, normalized value which defined by Kang et al. (2016)[4)5)] is used, as shown in **Table 1**.

Five geometric elements influence three gap parameters of roundabout. In order to verify the influence of geometric elements on entry capacity, a basic common geometry layout of hypothetical entry is used as a reference as shown in **Table 5**. Also hypothesis this roundabout has opened over 3 months and under yield control.

Regarding the models developed in this study, D is found to be the most significant value of five geometric elements, because it influences all three gap parameters. So only the influence of D on entry capacity is estimated as shown in **Fig.4** and **Fig.5**.

When D is 27 meters (**Fig.4**), entry capacity decreases when H_{entry} increases. It is because heavy vehicle's large body and low speed will affect entry passenger cars' behavior. When circulating flow is low, behavior of entry heavy vehicle mostly depends on its behavior and the impact of heavy vehicle is more significant.

As D increases, entry capacity under different percentage of H_{entry} become higher, as shown in **Fig.5**. The reason can be considered that when D increases, the circulating flow rate also increases. The change ratio of percentage of H_{entry} will also increases, especially when circulating flow is high. This is because when D increases, the difference of speed between passenger car and heavy vehicle also increases, and then the impact of heavy vehicle increased.

Table 6 Layout of hypothetical entry

Geometric Elements				
D(m)	R(m)	l(m)	φ_e(deg)	φ_m(deg)
27	15	11	25	30

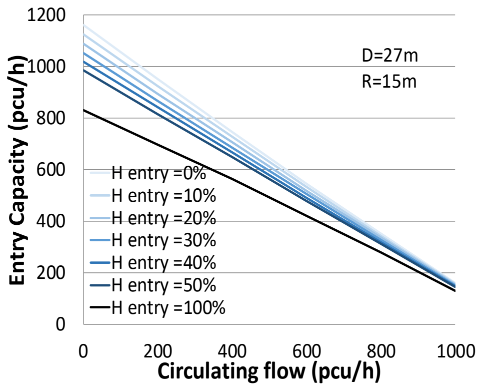

Fig.4 Impact of D and H_{entry} on entry capacity (D=27m)

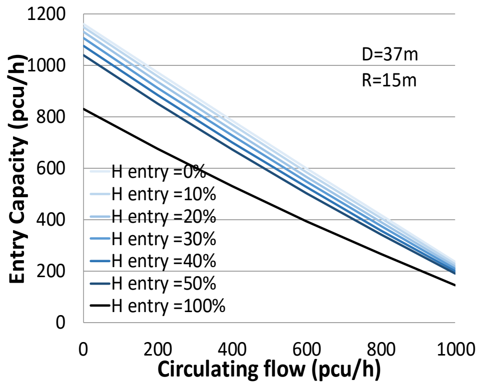

Fig.5 Impact of D and H_{entry} on entry capacity (D=37m)

7. CONCLUSIONS

This paper analyzed the impact of geometric elements and vehicle type on entry capacity. Through the analysis, major findings are as follows:

Regarding t_c, impact of D is significant but opposite for $t_{c,PP-P}$ and $t_{c,PP-H}$. This is because that passenger car can choose a small accepted gap although there are high vehicle speeds on circulating roadway. However heavy vehicle needs to find a greater and safer accepted gap. For $t_{c,HP\text{-}P}$, geometric elements which will affect turning behavior of entry vehicle, shows significant impact.

Regarding t_f, impact of D is also significant. With a larger D, following circulating vehicle is more far from entry approach, so it is easy for following vehicle at entry approach to follow. Stop control is also an important variable for t_f.

In regard to τ, all the combinations are influenced by D. It is because that larger D is easier for vehicles to travel on circulatory roadway.

D is a significant influencing factor for all three gap parameters, and the impact on entry capacity is most significant. At the roundabout with the same D, it is found that when percentage of H_{entry} increases, entry capacity decreased. When D increases, entry capacity also increases. The changing ratio of high circulating flow also increases, and the reason can be considered as the difference of speed between passenger and heavy vehicles become larger with a larger D.

This study estimated the impact of geometric elements and vehicle type on entry capacity. The result is still limited, and models of three gap parameters are still incomplete, because of small sample size. The results still have limitations and further study is necessary. After a further analysis of the relationship between geometric elements and three gap parameters, it is an important task to estimate passenger car equivalent for heavy vehicles.

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