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Analyzing the Impact of Geometric Design on Heavy Vehicles' Behavior at Roundabouts

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This study examines the impact of geometric design of roundabouts on heavy vehicles' behavior. In previous research, it was indicated that heavy vehicles have significant impact on gap parameters which are critical gap, follow-up time and minimum headway of circulatory roadway, and then affect the entry capacity of roundabouts. Meanwhile, it is found that heavy vehicles' behavior is affected by geometric design of roundabout, such as entry angle and inscribed circle diameter. This study compares the impact of heavy vehicles on gap parameters in several roundabouts with different geometric layout, and discusses geometric parameters to be considered when estimating passenger car equivalent for heavy vehicles.

Key Words: *roundabout, gap parameter, geometric design, heavy vehicles*

1. INTRODUCTION

Roundabout was first defined and prescribed by Road Traffic Law of Japan in June 2013, which took effect in September 2014. For the introduction of roundabout into Japan traffic system, analyzing entry capacity is indispensable. According to Roundabout Manual[1)] in Japan published in 2016, entry capacity can be estimated by equation (1).

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

Where, c_i: entry capacity of entry i(veh/h), Q_{ci}: circulating flow for i(veh/h), t_c: critical gap(sec), t_f: follow-up time of entry vehicle(sec), τ: minimum headway of circulating flow(sec). Here, 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. However, the impact of geometry and heavy vehicles are not considered in equation (1), although they would significantly influence on driver's behavior.

In previous studies[2)3)], the impact of geometric design on passenger vehicles and the impact of heavy vehicles on the three gap parameters were analyzed. However the impact of geometric design on heavy vehicles' behavior was not taken into account.

Thus, this study aims to examine the impact of geometric design on the three gap parameters considering the influence of heavy vehicles, and to discuss which geometric parameters should be considered when estimating passenger car equivalent for heavy vehicles, based on empirical data of Japan.

2. LITERATURE REVIEW

Three gap parameters introduced in Chapter 1 are the most important variables that reflect drivers' behavior for entry capacity estimation. In previous research in Japan, Kanbe and Nakamura[2)] 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 make it easier for entry vehicles to merge into circulating flow. Regarding follow-up time, it is easier for following vehicles to follow the leading ones and improve the induction effect for the entry vehicles. For minimum headway of circulating roadway, larger inscribed circle diameter and/or merging angle make vehicles on the circulating roadway easier to travel. However, heavy vehicles are not considered in this research.

Mashima et al.[3] analyzed the three gap parameters as well, and estimated the passenger car equivalent for heavy vehicles at the standard roundabout entry and circulatory roadway. It was evaluated that the difference of each headway parameter depends on vehicle composition.

Dahl et al.[4] also analyzed the three gap parameters considering the effect of heavy vehicles, and tried to estimate entry capacity by using the existing capacity models with the adjusted gap acceptance parameters.

In the previous research, there is still a lack of the further analysis on the relationship between heavy vehicles and geometric parameters deeply, particularly in Japan. Therefore, it is necessary to analyze by combining the heavy vehicles' behavior and geometric parameter and to find the relationship between them.

3. DATA COLLECTION AND PROCESSING

In order to analyze the relationship between geometric elements and gap parameters, video data was collected at six roundabouts (RABs) in Japan; i.e. Moriyama RAB in Shiga Prefecture, Karuizawa RAB in Nagano Prefecture, Hitachitaga RAB in Ibaraki Prefecture, Towacho RAB in Nagano Prefecture, Itoman RAB in Okinawa Prefecture and Azuma RAB in Nagano Prefecture (**Fig.1**). The trajectories of vehicles are extracted from videos by using the image processing system TrafficAnalyzer (Suzuki and Nakamura, 2006)[5].

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), merging angle φ_m(deg) and entry angle φ_e(deg), which were defined by Kimber[6]. Definitions of these parameters are illustrated in **Fig.2**. 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_m is the angle between midline of entry lane and tangent of the yield line; and φ_e is half of the angle between midline of entry lane and midline of next outflow

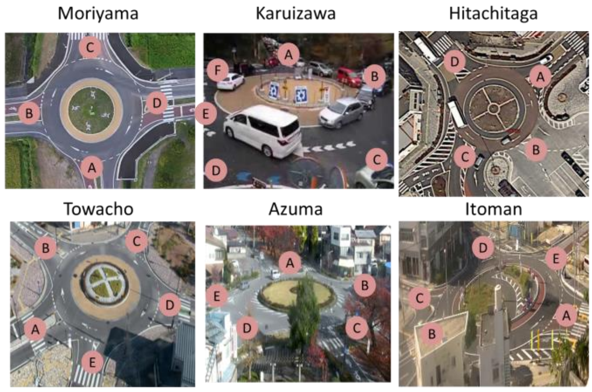

Fig.1 Roundabouts studied in this research

Table 1 Geometric parameters of each roundabout

RAB	Approach	W_e(m)	W(m)	D(m)	R(m)	l(m)	φ_e	φ_m
Moriyama (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
Moriyama (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
Karuizawa	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
Hitachitaga	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
Towacho	N	4.49	3.00	30.0	13.0	10.2	53.5	67.0
	NW	3.42	2.75		6.50	10.2	61.5	63.0
	S	3.89	3.33		13.5	10.6	45.0	61.0
	E	4.46	2.92		13.5	10.1	47.5	66.0
	W	4.99	3.43		13.5	10.3	35.0	90.0
Azuma	N	6.11	3.00	39.0	15.0	11.7	57.0	78.0
	E	4.60	3.36		9.22	7.75	26.0	27.0
	S	5.42	3.02		16.5	8.58	48.0	67.0
	SW	4.79	3.35		18.9	0.977	48.5	61.0
	W	3.98	2.82		8.19	0.897	44.0	59.0
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

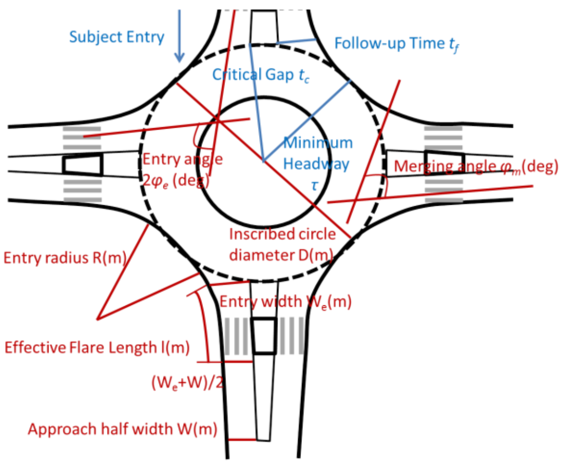

Fig.2 Definition of geometric parameters and cross-sections for measuring gap parameters.

approach. Measured values of those variables at the subject roundabouts are summarized in **Table 1**.

Gap parameters are extracted from the video recordings of the roundabouts. **Fig.2** shows the cross-section (blue 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. Including heavy vehicles, each gap can be formed be several combinations of vehicle types, as shown in **Fig.3**. Although in some cases there could be two or more heavy vehicles involved, such situation would be too rare to be included in this study.

In this analysis critical gap t_c is determined by the intersecting point of the cumulative distribution of the accepted and rejected gap by following the definition of Raff Method[7]. The gaps 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 15 percentile value of the headway distributions of entry and circulatory roadway that is shorter than 5 seconds.

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.

4. ANALYSIS HYPOTHESIS

The results of previous research[2] show that when heavy vehicles are not included, critical gap t_c is influenced by entry width and entry radius, as they make the entry curve smoother and vehicles can merge with circulating flow easier. For follow-up time t_f, it is influenced by entry width, entry radius and approach half width. When approach half width is shorter, speed of entry vehicle is limited, and it causes t_f becomes smaller. For minimum headway of circulating flow, inscribed circle diameter and merging angle show the most significant influence. Because smaller inscribed circle diameter causes vehicles harder to drive along the circulating roadway and results in τ becomes larger.

The purpose of this paper is to understand the impact of geometric parameter on the three gap parameters considering heavy vehicles, and the difference among different combinations.

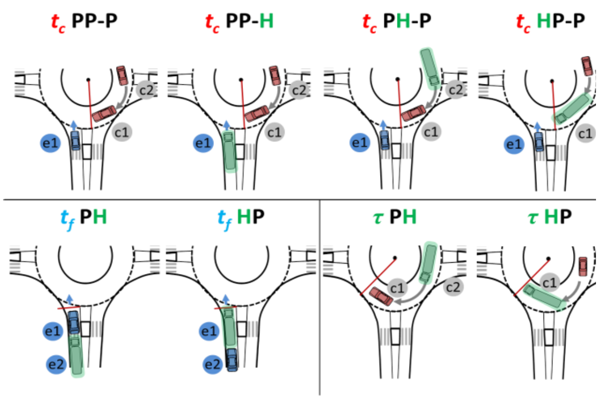

Fig.3 Combinations of vehicle types forming gaps

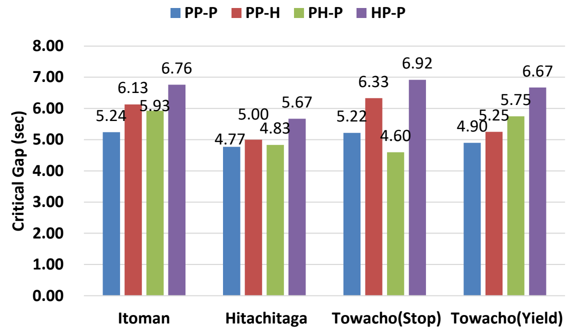

Fig.4 Average critical gap t_c by vehicle type combination

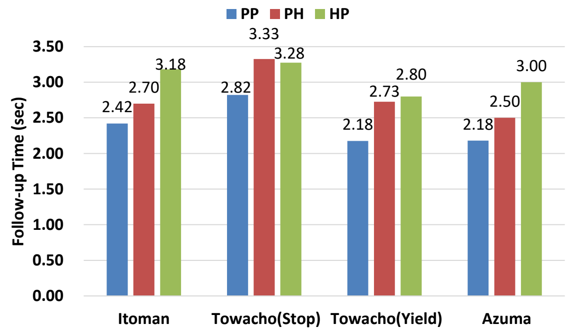

Fig.5 Average follow-up time t_f by vehicle type combination

For that first, the average critical gap are shown in **Fig.4**, it is found that PP-P < PH-P < PP-H < HP-P. For PH-P, the influence of heavy vehicle is the least out of the three combinations. As well as in the hypothesis, the influence of geometric parameter on PH-P may be similar with that on PP-P. For PP-H, the geometric parameters that may influence entry vehicles, like entry width, should show more significant influence when the entry vehicle is heavy vehicle. For HP-P, the physical length of leading heavy vehicle on circulating roadway may block the sight of entry vehicle. When entry angle is smaller, it is easier for entry vehicle to check out the following vehicle behind the heavy vehicle, results in t_c becomes smaller.

Second, for follow-up time as **Fig.5** shows: PP < PH < HP. For PH, the follow-up time depends on the speed of following vehicles, which would be influenced by entry width and approach half width.

For HP, it depends on leading heavy vehicles' behavior and judgment, which can be influenced by entry angle.

Finally, for minimum headway of circulating flow as **Fig.6** shows: PP < PH < HP. For minimum headway, the geometric parameter with the most significant influence is found as inscribed circle diameter. When the inscribed circle diameter D is larger, it is easier for vehicles running. As hypothesis, the result of PH should be more significant than that of HP, due to the fact that when heavy vehicle is the leading vehicle, its physical size can cause to need longer time to turn around in the circulating roadway, and thus results in longer τ.

In order to verify the hypothesis above, multiple linear models shown by equations (2) to (4) are developed for each combination of vehicle types for the three gap parameters.

$$t_c = \alpha_0 + \alpha_1 x_1 + \cdots + \alpha_7 x_7 + \alpha_8 d_1 + \cdots + \alpha_{10} d_3 \quad (2)$$

$$t_f = \beta_0 + \beta_1 x_1 + \cdots + \beta_7 x_7 + \beta_8 d_1 + \cdots + \beta_{10} d_3 \quad (3)$$

$$\tau = \gamma_0 + \gamma_1 x_1 + \cdots + \gamma_7 x_7 + \gamma_8 d_1 + \cdots + \gamma_{10} d_3 \quad (4)$$

Where, α_0-α_{10}, β_0-β_{10}, γ_0-γ_{10} are coefficients, x_1-x_7 are the geometric element parameters and d_1-d_3 are dummy variables.

5. ANALYSIS RESULT

5.1 Critical Gap t_c

The model is developed for each combination of critical gap as shown in **Table 2**.

Firstly, regarding PP-P combination, it is found that critical gap is influenced by W_e and l. Larger W_e and longer l tend to make entry vehicles easier to accelerate and enter the circulating flow, result in shorter t_c.

Secondly, regarding PP-H combination, critical gap is mainly influenced by W_e and D. The result of W_e shows more significant influence than PP-P as hypothesis. It is because that heavy vehicle needs larger entry width than passenger car does. When D is larger, then the speed of circulating flow is faster. It would be more difficult for entry vehicle to find the accepted gap to enter the circulating flow, and result in longer t_c.

Thirdly, regarding PH-P combination, W_e, D, R, l and φ_e have the significant relationship with critical gap. It becomes difficult for entry vehicle to choose the accepted gap to enter the circulating flow when D becomes larger. When W_e, and R are larger and l is shorter, the entry curve turns into longer and easier for entry vehicles to accelerate, result in

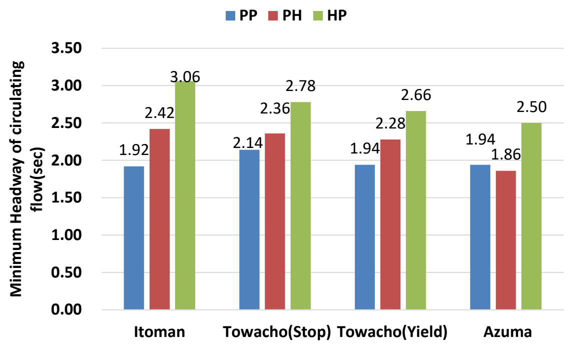

Fig.6 Average minimum headway of circulating flow τ by vehicle type combination

Table 2 Model for the four combinations of critical gaps

Model	PP-P Coef. (t-value)	PP-H Coef. (t-value)	PH-P Coef. (t-value)	HP-P Coef. (t-value)
Intercept	5.21 (14.3**)	5.59 (3.59**)	-30.9 (-5.98**)	5.17 (6.57**)
W_e	0.0954 (1.2)	-0.477 (-2.33*)	4.19 (6.28**)	-
D	-	0.0593 (1.81)	0.44 (6.91**)	-
R	-0.0138 (-1.74+)	-	-0.0793 (-3.10+)	-
l	-	-	-0.291 (-4.71*)	-0.181 (2.35*)
φ_e	-	-	0.157 (6.25**)	0.0439 (2.07+)
φ_m	-	-	-	0.0205 (2.81*)
d_{op}	-0.672 (4.66**)	-	-	-
d_{st}	0.135 (1.23)	1.1 (2.97*)	-	-
R_2	0.418	0.650	0.915	0.510
Approach	40	13	9	14

+: Significant Level < 10%

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

shorter t_c. Compared with the coefficients of W_e, the sign of PP-P, PH-P and PP-H are opposite, and further study is necessary.

Finally, HP-P combination is only influenced by l, φ_e and φ_m. When l is shorter, the acceleration of entry vehicle may reduce and the speed when entry vehicle enters the circulating flow becomes slower. It causes that t_c becomes longer. When φ_e and φ_m are large, it is difficult for entry vehicle to turn into the circulating roadway, results in longer t_c.

The three dummy variables also show influence on critical gap. When the d_{op} is longer, drivers become more familiar with the roundabout, and the gap becomes shorter, particularly for PP-P and PH-P. It is because that the increase of passenger cars' speed is higher than speed of heavy vehicles after experienced. And stop control have a positive relationship with t_f, particularly for PP-H, since heavy vehicle needs more time to start-up.

5.2 Follow-up Time t_f

The model is developed for each combination of follow-up time as shown in **Table 3**.

First, for PP combination, it is influenced by *W*. When *W* is shorter, it is more difficult for entry vehicle to accelerate, results in longer t_f. The other influencing parameter is φ_m. When it is larger, it is harder for entry vehicle to merge into circulating flow, causes longer t_f.

Next, for PH combination, it is influenced by W_e and *W*, as well as *D*. When *D* is larger, the speed of circulating flow becomes faster. It is harder for entry vehicle merge into circulating flow, especially for following heavy vehicles to choose the accepted gap, then it may cause longer t_f.

Finally, for the HP combination, it is only influenced by φ_e. When leading vehicle is heavy vehicle, the physical length of the vehicle causes longer t_f. When φ_e is larger, it is harder for entry vehicle to merge into the circulating flow, then it results in longer t_f.

d_{op} and d_{st} also show a significant relationship with follow-up time. The latter is more significant, as stop control makes entry vehicle taking more time to accelerate and causes longer t_f.

5.3 Minimum Headway of Circulating Flow τ

For minimum headway of circulating flow, the most related geometric parameter is *D*, as shown in **Table 4**. It is because larger *D* is easier for vehicles travel on circulating roadway. Among these three combinations, PH shows the most significant result. Because the improvement of easiness to drive a heavy vehicle is more significant than passenger car in a larger inscribed circle diameter, when heavy vehicle is following vehicle, the decrease of τ is more significant than PP.

Effective flare length *l* also shows a significant relationship with PP and PH. Longer effective flare length makes vehicles easier to accelerate when entering the circulating flow and result in smaller minimum headway in circulating roadway.

For dummy variables, opening period dummy shows a significant relationship with PH and HP combination. The reason can be considered that heavy vehicles need more experience to get accustomed to traveling on the circulating roadway.

Table 3 Model for three combinations of follow-up time

Model	PP	PH	HP
	Coef. (t-value)	Coef. (t-value)	Coef. (t-value)
Intercept	2.27 (12.8**)	-7.56 (-1.51)	2.73 (5.40**)
W_e	-	-0.395 (-2.28*)	-
W	-0.05 (-1.43)	-0.824 (-1.33)	-
D	-	0.489 (2.10+)	-
φ_e	-	-	0.013 (1.39)
φ_m	0.0061 (2.28*)	-	-
d_{op}	-0.108 (-1.19)	-4.27 (-1.92+)	-0.466 (-1.89+)
d_{st}	0.348 (4.24**)	0.6 (1.39)	0.332 (1.66)
R_2	0.528	0.542	0.533
Approach	45	16	17

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

Table 4 Model for three combinations of minimum headway

Model	PP	PH	HP
	Coef. (t-value)	Coef. (t-value)	Coef. (t-value)
Intercept	2.35 (13.3**)	4.72 (14.3**)	4.01 (8.93**)
D	-0.0186 (-3.49**)	-0.0573 (-7.61**)	-0.0244 (-2.16*)
l	-0.0106 (-1.51)	-0.0129 (-1.37)	-
φ_e	0.0084 (4.75**)	-	-
d_{op}	-	-0.552 (-8.76**)	-0.56 (-4.76**)
R_2	0.504	0.86	0.577
Approach	45	20	20

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

6. CONCLUSIONS

This paper analyzed the impact of geometric elements of roundabouts on heavy vehicles' behavior, based on the three gap parameters. Through the analysis, major findings are as follows:

Regarding critical gap, PP-P is influenced by W_e and *R*, which makes the entry curve easy for entry vehicle to enter the circulating roadway. PP-H is also influenced by W_e, and when *D* is smaller, it is easier for heavy vehicle to accept a gap. PH-P is also influenced by W_e, *D* and *R*. *l* and φ_e also show a significant result. For HP-P, as the leading vehicle on circulatory roadway can hinder the sight of entry vehicle, when φ_e is smaller, it is easier for entry vehicle to check out the circulatory roadway and causes shorter t_c.

Regarding follow-up time, PP and PH are influenced by W_e and *W*, when the width of entry lane is shorter, the speed of entry vehicle is smaller and results in longer t_f. PH also has positive relationship with *D*. When *D* is larger, it is more difficult for entry vehicle to accept a gap, and it causes longer t_f. It is indicated that opening period and stop control also have some significant impacts on t_f other than geometric parameters.

Regarding minimum headway of circulating flow, all the combinations are influenced by *D*. It is because that larger *D* is easier for vehicles to travel on circulatory roadway. PP and PH are also influenced by *l*. When *l* is shorter, entry vehicles have lower speed when entering circulatory roadway, and it results in shorter τ.

This study compared the impact of heavy vehicles on gap parameters and discussed which geometric elements show significant relationship with three gap parameters. The results still have limitations and further study is necessary, such as some contradictory result of t_c. More sample size is necessary, and other non-linear regression model can be considered. 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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