An Empirical Analysis on Critical Gap and Follow-up Time at Roundabout Considering Geometry Effect

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Microscopic methodology for estimating roundabout entry capacity is based on the gap provided by circulating traffic and the maximum numbers of vehicles entering the roundabout in one given gap. Critical gap and follow-up time are essential parameters to be applied in this microscopic methodology. Regarding influencing factors of roundabout entry capacity, many analyses suggested that roundabout geometry significantly impact entry capacity. However, microscopic estimation methods weakly reflect this effect; since parameters (critical gap and follow-up time) applied in most of the existing researches don't reflect the roundabout geometry. This study aims to find a relationship between parameters (critical gap and follow-up time) and the roundabout geometry, in order to improve the estimation method of entry capacity to reflect the geometry. Through empirical analyses on the field observation data in Iida City Japan, several geometric influencing factors such as pavement marking, entry angle, physical curb and distance between stop line and yield line are identified to have significant effect on parameters.

Key Words: *Entry capacity estimation, critical gap, follow-up time, roundabout geometry*

1. INTRDUCTION

Roundabout entry capacity which is estimated as the maximum entry flow is a necessary index for roundabout operational performance assessment. The estimation method of roundabout entry capacity is classified into macroscopic and microscopic approaches.

The macroscopic methodology proposes regression models which are the functions of the circulating flow rate as well as the roundabout geometry. The regression model needs sufficient observed data with various geometry patterns, which is difficult to be obtained in the countries like Japan, where few roundabouts are practically installed.

The microscopic methodology has a capability to describe the entry capacity by analyzing detailed driver behavior even though the number of sites is limited. This approach is based on the headway distribution of the circulating traffic and the number of entry vehicles which can enter within a certain headway (which is called as gap from entry vehicle's viewpoint). Headway distribution is dependent on the arrival pattern of circulating traffic; the number of entry vehicles is dependent on critical gap and follow-up time. Therefore, critical gap and follow-up time are essential parameters applied in microscopic methodology.

Although macroscopic estimation methods suggest that roundabout entry capacity is significantly affected by roundabout geometry, it is not reflected in the parameters of microscopic methods. This study aims to find the relationship between these parameters (critical gap and follow-up time) and the roundabout geometry for improving microscopic estimation methodology.

2. LITERATURE REVIEW

Roundabout entry capacity is dependent on the gaps provided by the circulating traffic flow and the maximum number of entry vehicles in the given gap. Based on this concept, the entry capacity can be estimated by **Equation (1)**.

$$c_e = q_c \int_0^{\infty} h(t)E(t)dt \quad (1)$$

where c_e is the estimated roundabout entry capacity (veh/h); q_c is the circulating flow rate (veh/h); $h(t)$ is the probability density function of headway distribution when headway is over than t and $E(t)$ represents the number of entry vehicles in a given headway t.

(1) Headway distribution *H*(*t*)

$h(t)$ is dependent on the cumulative function of headway distribution $H(t)$, which can be obtained from assumed arrival patterns of the circulating traffic. Until now three types of headway distributions under different assumptions of arrival pattern have been applied in the existing estimation methods as shown in **Table 1**.

$H_1(t)$ shown in **Equation (2)** follows exponential distribution under the assumption of vehicle arrival as Poisson distribution pattern which means all arriving circulating vehicles are free flow vehicles.

$$H_1(t) = 1 - e^{-\lambda t}\ (h > t), \lambda = q_c \qquad (2)$$

$H_2(t)$ in **Equation (3)** is shifted exponential distribution by assuming one part of intra-bunched vehicles with the minimum headway τ and other vehicles are free flow vehicles.

$$H_2(t) = 1 - e^{-\lambda(t-\tau)}\ (t > \tau), \lambda = \frac{q_c}{1 - \tau q_c} \qquad (3)$$

$H_3(t)$ is proposed by Cowan[2], which the circulating vehicles are assumed to arrive as two patterns. One is free flow vehicles with the proportion α; the other one is bunching vehicles with the proportion 1-α. $H_3(t)$ under this situation follows shifted exponential distribution as shown in **Equation (4)**.

$$H_3(t) = 1 - \alpha e^{-\lambda(t-\tau)}\ (t > \tau), \lambda = \frac{\alpha q_c}{1 - \tau q_c} \qquad (4)$$

(2) Maximum number of entry vehicles *E*(*t*)

$E(t)$ is the combination of the first entry vehicle and the following entry vehicles in a waiting queue, which has different characteristics when entering. The first vehicle should judge the gap of circulating vehicles for entering. Thus, critical gap (t_c) which is defined as the minimum gap can be accepted by entry vehicles is utilized to estimate the entering behavior. However, the number of following vehicles which can enter is dependent on the headway of these entry vehicles which is called follow-up time (t_f).

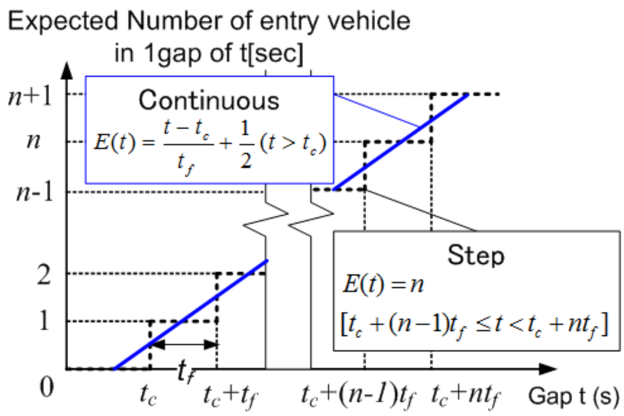


Fig.1 Functions of maximum number of entry vehicles E(t)

Many researchers conducted observations and found that number of entry vehicles in one given gap increased with the increase of the gap. Therefore the step function was developed to try to fit the observed data. Tanner[4], Harders[5] and Troutbeck[6] conducted analysis for this step function. On the other hand, in order to simplify the step function, continuous linear function was developed through using the average gap in each step. This continuous linear function reflects the assumptions of continuous queue in minor street made by Siegloch[3] and McDonald and Armitage[7]. The step and continuous linear functions are shown in **Fig.1**.

The manuals on highway capacity in U.S., Germany and Australia utilize microscopic method for roundabout entry capacity estimation. Each country chose different functions of $h(t)$ and $E(t)$ dependent on their situations. **Table 1** shows the options of $h(t)$ and $E(t)$ and the estimation function c_e of each country. The assumed values of t_c and t_f are shown in **Table 1** as well.

Different from the other two countries, manual in Australia utilizes regression model for t_f, then t_c is dependent on t_f considering roundabout geometry. However, only entry width, inscribed diameter, number of circulating lanes and entry lanes are considered. Regarding other important geometry factors such as entry angle and entry radius, they say that these factors do not significantly relate to entry capacity while having effect on delay[8].

Table 1 Estimation function utilized by each country (for single line roundabout) and value of t_c, t_f and τ

Country	$H(t)$		$E(t)$			c_e
	Function	τ(sec)	Function	t_c(sec)	t_f (sec)	
U.S.(NCHRP)	$H_1(t)$	/	Continuous	4.1~4.6	2.6~3.1	$c_e = \frac{1}{t_f}\exp[-\lambda\left(t_c - \frac{t_f}{2}\right)]$
German (FGSV)	$H_3(t)$	2.1	Continuous	4.1	2.9	$c_e = \frac{1}{t_f}\alpha\exp[-\lambda\left(t_c - \frac{t_f}{2} - \tau\right)]$
Australia (AUSTROADS)	$H_3(t)$	2	Step	Regression model relating to roundabout geometry		$c_e = \frac{\alpha q_c e^{-\lambda(t_c - \tau)}}{1 - e^{-\lambda t_f}}$

3. HYPOTHESES

Some geometry factors have been applied in the existing estimation methods such as the number of entry lanes, circulating lanes and entry width. Besides these, other geometry factors such as pavement marking, entry angle, physical curb and distance between stop line and yield line may affect entry capacity.

(1) Critical gap

Pavement marking and entry angle are considered to affect critical gap.

Yield line marking in the roundabout may decrease the critical gap, since without yield line marking entry drivers may feel confused to decide where to stop. Thus drivers are expected to choose the place far from the circulating road for avoiding the conflict with circulating vehicles, and which may cause the critical gap to be longer.

Truck apron marking is utilized for heavy vehicles to smoothly turn in roundabout. Without truck apron marking, the circulating road width becomes wider, which increases the probability of parallel travelling of the circulating vehicle. Under this condition, gap judgment for entry drivers may become difficult. As a result, short gaps are rejected, leading to increased critical gap.

Entry angle is the crossing angle of the entry direction and the assumed circulating vehicle path which corresponds to the central line of circulating roadway. Larger entry angle provides better visibility for entry drivers, which makes drivers' gap judgment easier. Therefore shorter critical gap may occur.

(2) Follow-up time

Follow-up time is the headway of entry vehicles which has significant relationship to entry speed. Entry speed may be affected by physical curb and distance between stop line and yield line.

Physical curb at the roundabout entry is supposed to force drivers to reduce entry speed, since the physical curb would limit drivers' activity. Therefore, follow-up time is increased.

Distance between stop line and yield line may affect the entry speed, since longer distance causes higher probability for entry drivers to accelerate until arriving at the yield line. This leads to higher entry speed. Therefore, follow-up time may become shorter under this condition.

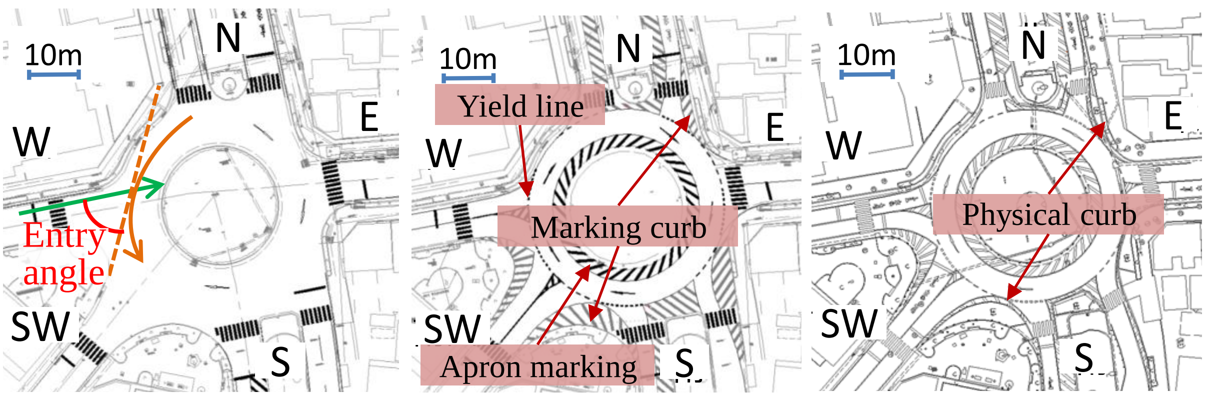
4. OBSERVATION AND DATA PROCESSING

(1) Information of observed field

The roundabout located in Iida City, Nagano Prefecture in Japan is observed for this study. Physical improvements were conducted at this roundabout in 2010 and 2011. Three times of video surveys were conducted before physical improvements (survey A, 09/28/2010-Tue, 6:00~10:00), after the first improvement (survey B, 01/12/2010-Wed, 6:00~10:00) and after the second improvement (survey C, 27/10/2011-Thu, 6:00~10:00). **Fig.2(a)-(c)** shows the geometric condition at each survey. **Fig.2(a)** shows the situation before physical improvements, which is no marking for yield line and truck apron in the roundabout. Besides this, the shape of the roundabout is rather the ellipse than the circle. **Fig.2(b)** shows the situation after the first physical improvement. Markings were drawn and the roundabout was changed to be a circle. **Fig.2(c)** shows the situation after the second physical improvement. Marking curb has been changed to the physical curb at North and South approaches. Physical information of each survey is shown in **Table 2**. Data collection was conducted for each approach.

(2) Data processing

The trajectory of both entry and circulating vehi-



(a)Survey A (b) Survey B (c) Survey C

Fig.2 Geometry in each survey

Table 2 Physical improvement of the roundabout at Iida City

Approach	Survey	Entry angle (degree)	Existence of yield line and circulating line	Physical curb	Distance from yield line to stop line(m)
N	A	18	No	No	/
	B	61	Yes		13
	C			Yes	10
S	A	65	No	No	/
	B		Yes		15
	C			Yes	10
SW	A	48	No	No	/
	B	55	Yes		25
	C			Yes	25
E	A	80	No	No	/
	B	75	Yes		10
	C			Yes	10
W	A	75	No	No	/
	B	65	Yes		20
	C			Yes	18

/: not available due to no yield line marking

cles are extracted by using video image processing system TrafficAnalyzer[9]. The positions were extracted every 0.5 second and then their video coordinates are converted to the global coordinates by projective transformation. The point where the right-front wheel is touching the ground is the reference observation point for all subject vehicles. By considering the dimension of each turning vehicle, the observed trajectories based on the right-front wheel are transformed to the trajectories which correspond to the center-front of the vehicles. The transformed trajectories are smoothened by Kalman smoothing method.

(3) Data calculation

The gap of circulating vehicles is defined as the time difference when the circulating vehicles passing the conflict point (C.P.), which is defined as the crossing point of entry and circulating vehicle trajectories. Since vehicle size couldn't be ignored, conflict point in this study is defined as the crossing point of the right side trajectory of entry vehicle and the left side trajectory of circulating vehicle as **Fig.3** shown. Based on the drivers' decision, gaps can be classified into either accepted or rejected as **Fig.4** shown. Gaps are only collected for entry leading vehicles which have no other vehicles ahead from the stop line to the yield line.

Critical gap can be calculated based on two measurements. One is the cumulative distributions of accepted gap and rejected gap; critical gap is the gap when the accepted gap and rejected gap has the same percentage as **Fig.5(a)** shown. The other one is probability of accepted gap which is calculated by **Equation (5)**.

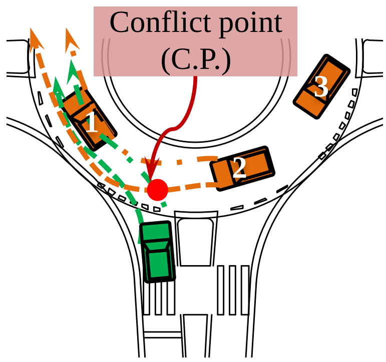


Fig.3 Definition of conflict point

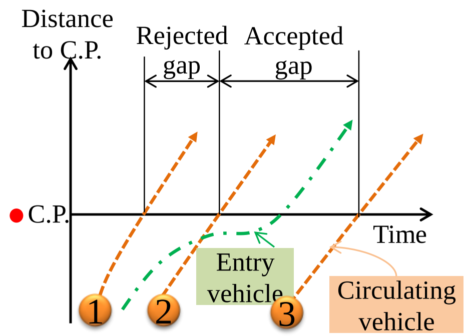


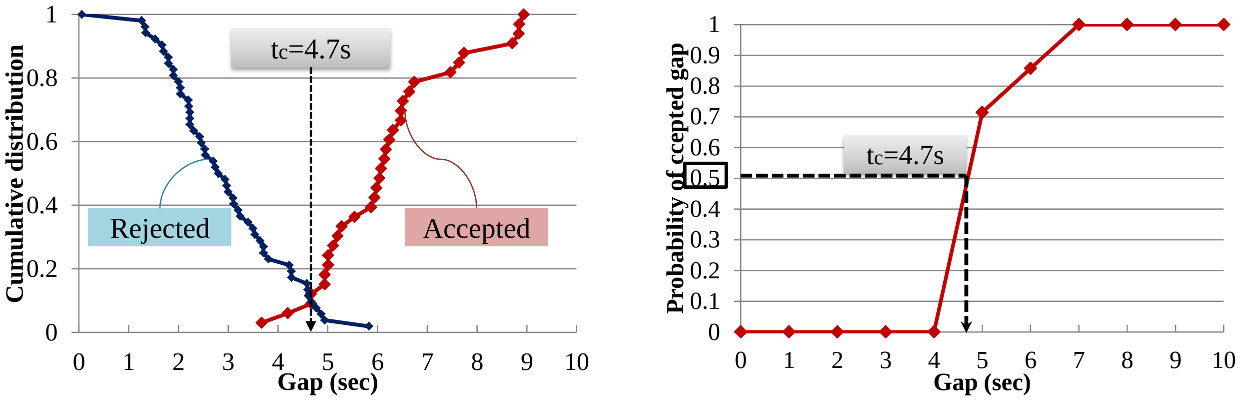
Fig.4 Calculation of accepted and rejected gap

$$P = \frac{(No. of\ accepted\ gap)_i}{(No. of\ accepted\ gap + No. of\ rejected\ gap)_i} \quad (5)$$

where P is the probability of accepted gap. In this approach, critical gap is the gap when the probability of accepted gap achieves 50% as shown in **Fig.5(b)**. In this study, the cumulative distribution measurement is applied.

Follow-up time is calculated as the time difference of following entry vehicle at the yield line under the condition of no circulating vehicles in upstream of one quarter of roundabout as **Fig.6** shows.

Sample size and values of critical gap and fol-



(a)Calculation from cumulative distribution (b)Calculation from probaiblity of accepted gap

Fig.5 Examples of two measurements of critical gap

low-up time are summarized in **Table 3** and **Table 4**.

Cumulative distribution of critical gap was drawn respectively at each survey in order to compare the difference before and after pavement marking improvements. In order to identify the effect of physical curb and distance between stop line and yield line, cumulative distributions of follow-up time and entry speed are calculated at North and South approach in each survey. Finally, the estimated entry capacity at each approach of each survey was calculated by applying the observed critical gap and follow-up time into German function (**Table 2**, τ=2.1sec).

5. RESULTS AND DISCUSSIONS

(1) Critical gap

Fig.7 shows the cumulative distribution of critical gap at each survey. There is no yield line and truck apron marking in survey A while marking has been drawn in survey B and C. Comparing the result of survey A and survey B, it is found that the critical gap became shorter after drawing the pavement marking. This is because entry drivers may feel difficult to decide the waiting place for judging gap without yield line marking. Thus, in order to avoid the conflict with circulating vehicles, entry drivers may choose the far place from the yield line to wait for the acceptable gap. As a result, they need longer time to reach the conflict point, which makes the longer critical gap. Secondly, wider circulating road makes entry drivers hesitate to entry due to the high probability of travelling in parallel in circulating road, which makes gap judgment become difficult.

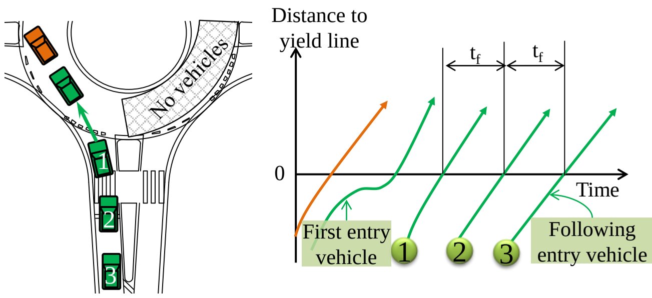


Fig.6 Calculation of follow-up time

Table 3 Sample size and value of critical gap, t_c

	Survey A			Survey B			Survey C		
	No. of samples		t_c(sec)	No. of samples		t_c(sec)	No. of samples		t_c(sec)
	Accepted	Rejected		Accepted	Rejected		Accepted	Rejected	
N	31	35	4.7	33	52	4.5	21	32	3.6
S	25	59	4.6	35	49	4.4	25	54	3.8
SW	27	27	4.3	26	32	4.2	35	49	4.0
E	32	49	4.3	43	51	4.1	25	54	3.5
W	27	33	4.8	35	39	4.5	30	30	3.9

Table 4 Sample size and statistic value of follow-up time, t_f

	Survey A				Survey B				Survey C			
	No. of samples	Max (sec)	Min (sec)	Mean (sec)	No. of samples	Max (sec)	Min (sec)	Mean (sec)	No. of samples	Max (sec)	Min (sec)	Mean (sec)
N	27	5.9	1.6	3.5	44	6.0	1.4	3.3	59	6.7	1.3	3.8
S	31	5.9	1.8	3.2	35	6.6	1.7	3.2	29	5.9	1.9	3.7
SW	34	5.0	1.0	2.8	22	5.8	1.5	2.8	50	5.0	1.6	2.6
E	38	5.4	2.1	3.3	38	5.5	1.6	3.2	30	5.9	1.6	3.2
W	22	5.5	2.2	3.4	24	4.2	1.7	2.8	20	4.5	1.7	2.8

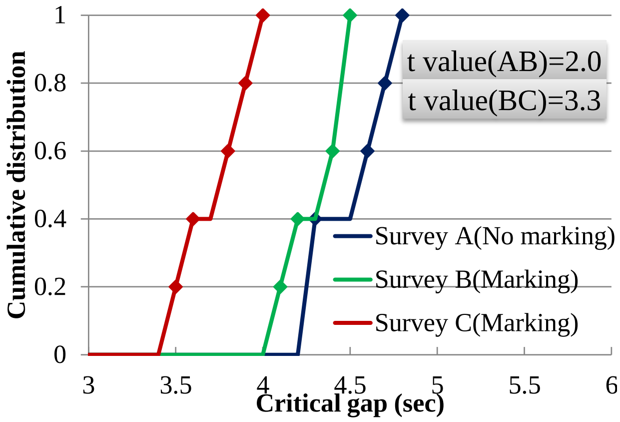


Fig.7 Comparison of critical gap in each survey

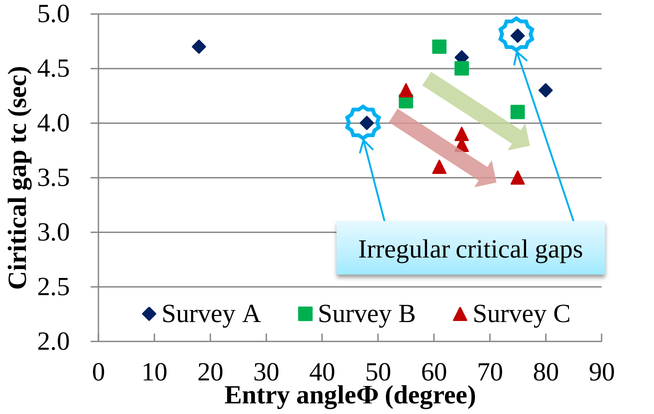


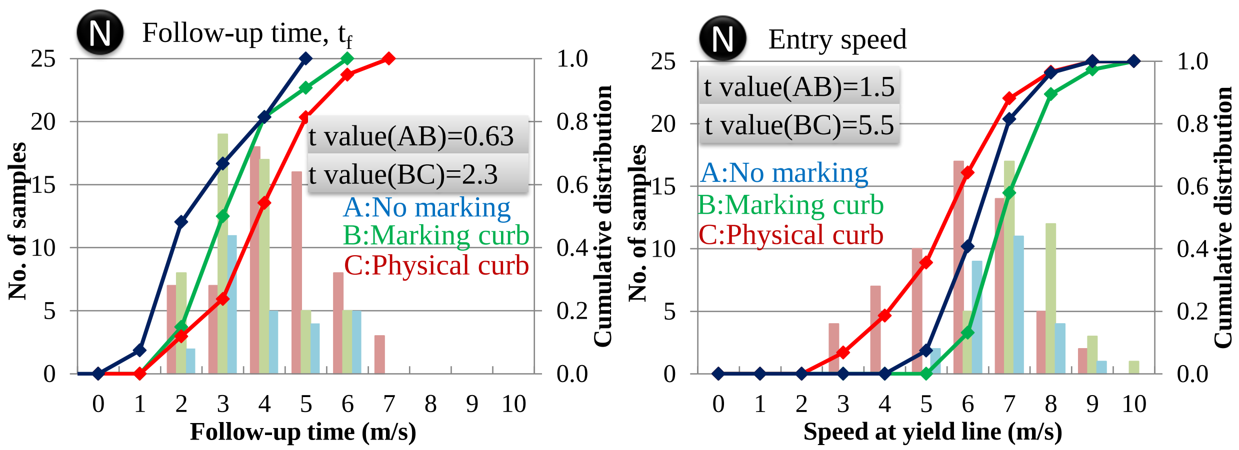
Fig.8 Comparison of critical gap under different entry angle

Therefore, longer gaps are accepted, and critical gap becomes longer.

Comparing result of survey B and C, it is found that the critical gap becomes shorter in survey C since entry drivers are familiar with the pavement marking.

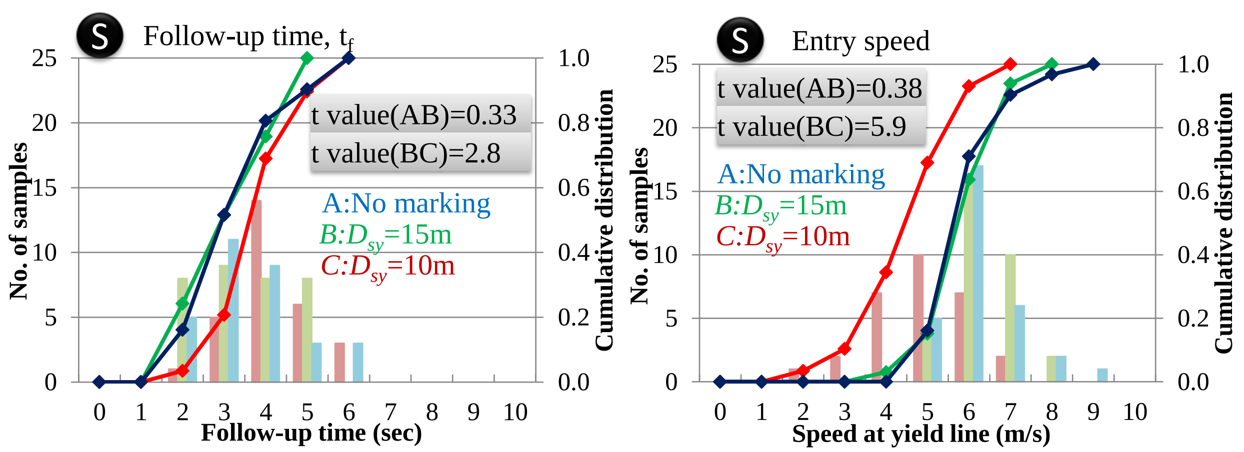
It can be concluded that standard pavement marking can reduce the critical gap comparing to no-marking condition.

Fig.8 shows the critical gap changing with the entry angle in each survey. The critical gaps in survey B and C decrease with the increasing entry angle. This is because larger entry angle provides better visibility to entry drivers, and which make gap judgment become more easily. Therefore short gaps may be accepted and the critical gap becomes shorter. However, in survey A the tendency of the critical gap is not clear, since the pavement markings don't exist and the shape of the roundabout is not regular. All of these may make the critical gap anomalistic.



(a) (b)

Fig.9 Comparison of follow-up time and entry speed at yield line under different curb conditions



(a) (b)

Fig.10 Comparison of follow-up time and entry speed at yield line under different distance between stop line and yield line(D_{sy})

(2) Follow-up time

Fig.9 shows the comparison results of follow-up time and entry speed at North approach in each survey. Comparing survey A and survey B, it is found that there is no significant difference on the follow up time and entry speed after adding the marking curb. Since the follow-up time is calculated from the circulating vehicles under the condition of without circulating vehicle, it is implied that marking curb does not affect the following driver behavior. However, comparing the results in survey B and survey C, it is found that follow-up time increases after changing the physical curb in survey C. Simultaneously, the entry speed in survey C is decreased, comparing to the condition of marking curb in survey B. it is interpreted that physical curb prevents drivers accelerating when entering the roundabout. As a result of the reduction of entry speed, follow-up time becomes longer.

Fig. 10 shows the comparison results of follow-up time and entry speed with different distance between stop line and yield line. Comparing the results in survey A and survey B, it is found that neither the follow-up time nor the speed changes significantly. Since follow-up time is calculated from following vehicle, it is implied that yield line marking do not have significant effect on following driver behavior. Comparing the results in survey B and survey C, it is found that follow-up time becomes shorter with the increase of distance between stop line and yield line while entry speed increased. It is because that longer distance between stop line and yield line increases entry speed therefore follow-up time becomes shorter. Through this analysis, the hypotheses regarding the effect of physical curb and distance between stop line and yield line are verified.

(3)Estimated entry capacity

Fig.11 shows the results of entry capacity estimation for each approach calculated by applying the observed critical gap and follow-up time into German function. It is found that the estimated entry capacity increased after physical improvement conducting. Therefore, it is proved that roundabout geometry had significant effect on entry capacity. In other words standard geometry design can improve the entry capacity.

6. CONCLUSION

In order to improve the microscopic methodology of roundabout entry capacity estimation, this study aims to find the relationship between estimation parameters (critical gap and follow-up time) and roundabout geometry. Empirical analyses were conducted by utilizing observed data from the practical roundabout in Iida City, Japan.

It was found that the existence of yield line and truck apron marking reduced the critical gap, since it could provide clear position for entry drivers to judge the gaps. In addition, the critical gap decreased with the increase of entry angle, since larger entry angle could provide better visibility to entry drivers so that shorter gap could be accepted.

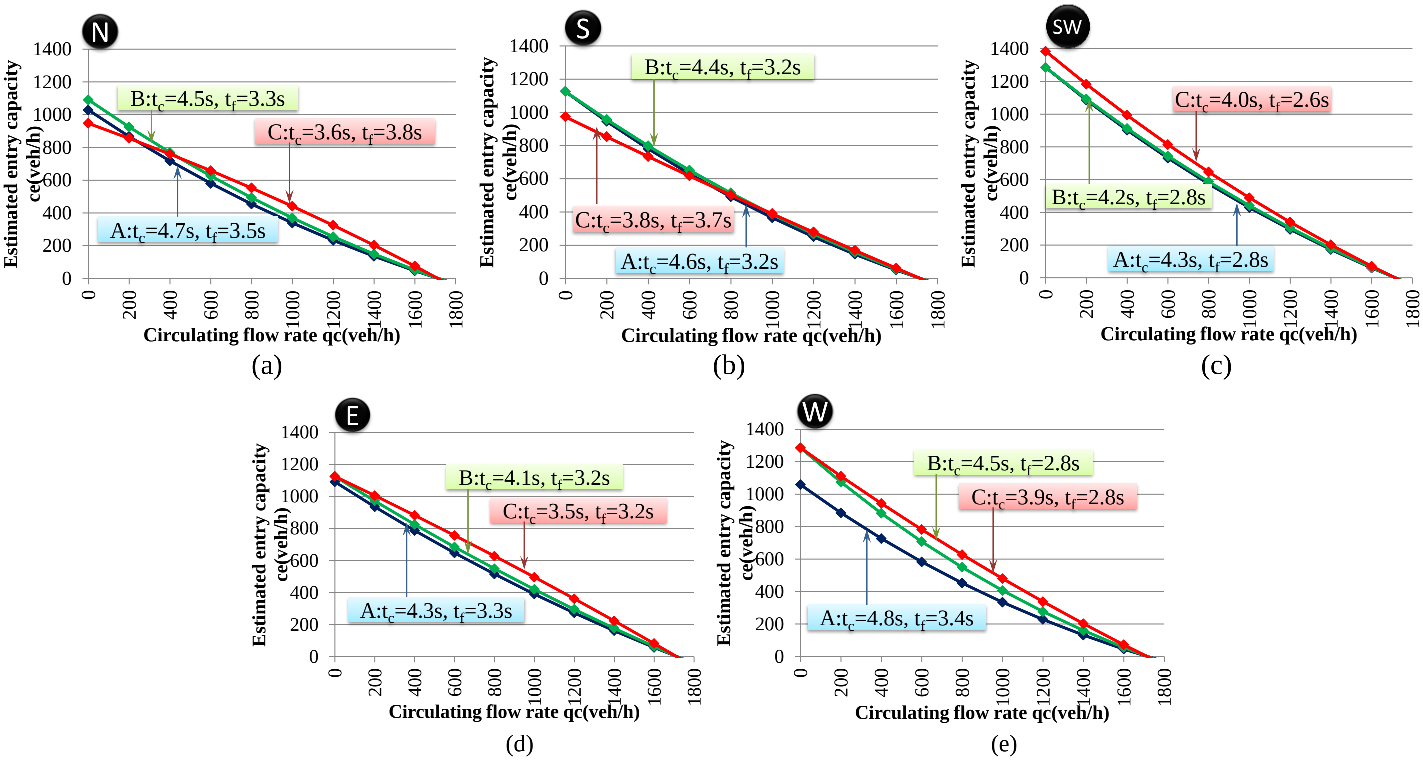


Fig.11 Comparison of estimated entry capacity in each survy under different critical gap, t_c and follow-up time, t_f

Follow-up time was found to be affected by physical curb and distance between stop line and yield line. Follow-up time was increased under the condition of physical curb, compared to the marking curb. It could be explained that physical curb had stronger effect on driver behavior especially reducing entry speed which may cause longer follow-up time. Not only the physical curb but also distance between stop line and yield line could influence entry speed. Longer distance caused higher entry speed, thus shorter follow-up time occurred.

After applying the observed critical gap and follow-up time into German function, it is found that estimated entry capacity increased after physical improvement.

Through analyzing the observed data, geometry factors such as pavement marking, entry angle, physical curb and distance between yield line and stop line were verified as the influencing factors for developing the model of critical gap and follow-up time. However, several factors such as entry radius, inscribed diameter, entry width and circulating road width which are also assumed to have effects on roundabout entry capacity haven't been considered in this analysis due to the limited sample size. In the future, these potential factors should be analyzed at first through adding sample numbers. Critical gap and follow-up time model will be developed afterwards for improving entry capacity estimation method.

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