Estimation of Roundabout Entry Capacity Considering Impact of Pedestrians by Applying Microscopic Simulation

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Roundabout entry capacity is one of the most important indices for performance evaluation of roundabout. In addition to circulating flow, pedestrians are another conflicting stream for entry vehicles before entering roundabout. However in the existing methods, roundabout entry capacity is estimated dependent on circulating flow without considering pedestrian impact. In the Japanese case, due to the relatively high pedestrian volume, pedestrian impact needs to be carefully considered in capacity estimation. Moreover, entry capacity can also be affected by pedestrian approaching sides and geometric characteristics (i.e., physical splitter island and crosswalk position). Therefore, this study aims to analyze pedestrian impact on entry capacity under various influencing factors by applying microscopic simulation. Under the condition without physical splitter island, pedestrians from far side only lead to decrease entry capacity more significantly than near-side pattern. It was found that the installation of physical splitter island improves entry capacity to some extent. In addition, entry capacity increases when the distance between the yield line and crosswalk is long enough for accommodating the vehicle waiting for acceptable gap.

Key Words: *Roundabout, capacity, pedestrian impact, geometric characteristics, microscopic simulation*

1. INTRDUCTION

Highway Capacity Manual (HCM) 2010[1)] shows that the capacity of an approach at roundabout decreases as the conflicting flow increases. In general, the primary conflicting flow is the circulating flow that passes directly in front of the subject entry. In existing methods circulating flow is incorporated in entry capacity estimation as the most important variable. However, in addition to circulating flow, pedestrian at crosswalk is another key factor that may block entry flow and significantly impact entry capacity.

Existing roundabouts in Japan have several representative characteristics. First, stop control is applied at entry approaches. And physical splitter islands at entry/exit cannot always be installed due to the limitation of space. Moreover, these roundabouts are likely to be located in the areas which have high pedestrian demand. Thus, in order to well introduce roundabouts in Japan, an appropriate method for entry capacity estimation by carefully considering pedestrian impact is needed.

The pedestrian impact on entry capacity in existing method, i.e. HCM 2010[1)], is considered by using adjustment factors. However, the empirical approach has shortcomings to reflect the compound impact of both pedestrian and circulating flow on entry capacity. On the other hand, pedestrian approaching sides and geometric characteristics (i.e., physical splitter island and crosswalk position) which potentially affect entry capacity have not been identified.

Therefore, an appropriate estimation method on roundabout entry capacity considering the Japanese situations of high pedestrian demand is needed. This study aims to analyze pedestrian impact on entry capacity under various influencing factors, i.e., pedestrian approaching sides, physical splitter island

and crosswalk position by applying microscopic simulation.

2. LITERATURE REVIEW

In the existing estimation methods, roundabout entry capacity is calculated by incorporating circulating flow. Both macroscopic and microscopic methods have been developed for entry capacity estimation.

(1) Macroscopic methods

Regarding macroscopic methods, regression models were developed to establish the relationship between entry capacity and circulating flow in two forms, linear and exponential regression model by Kimber[2] and Brilon *et al*.[3], respectively. They are given by **Equations (1)** and **(2)**.

$$c_e=A-B\cdot q_c \tag{1}$$

$$c_e=C\cdot exp(D\cdot q_c) \tag{2}$$

where, c_e is entry capacity (veh/h), q_c is circulating flow (veh/h) and A, B,C and D are parameters.

a) Linear regression model

Kimber[2] developed the model considering roundabout geometry based on data from 86 sites in the United Kingdom. This linear regression model is shown by **Equation (3)** which is applied in U.K. guideline.

$$c_e=k\cdot(F-f_c\cdot q_c) \tag{3}$$

$$k=1-0.00347(\varphi-30)-0.978(1/r-0.05)$$

$$F=303x_2 \text{ (veh/h)}$$

$$f_c=0.21T_D(1+0.2x_2)$$

$$x_2=v+(e-v)/(1+2S)$$

$$T_D=1+0.5/\{1+\exp[(D-60)/10]\}$$

$$S=(e-v)/l'$$

where, e is entry width (m), v is approach half-width (m), l' is effective flare length (m), r is entry radius (m), φ is entry angle (degree), S is measure of degree of the flaring and D is inscribed circle diameter (m).

Kimber's model estimated entry capacity by incorporating circulating flow and various geometric factors. However, impact of pedestrians and splitter island which will significantly affect entry capacity have not been considered.

b) Exponential regression model

Brilon *et al*.[3] developed the exponential model dependent on data observed in Germany. Parameters included in **Equation (2)** are estimated dependent on the number of entry lanes and circulating lanes. The parameter values of this model are summarized in **Table 1**.

Table 1 Parameter values of the German model[3]

Number of lanes		C	D
Entry	Circulating road		
1	1	1089	7.42
2-3	1	1200	7.30
2	2	1553	6.69
3	2	2018	6.68

Impacts of pedestrians and geometric factors have not been considered in this model.

Since regression models need the sufficient number of samples as database, this approach cannot be used in the countries which have limited number of roundabouts, e.g., Japan.

(2) Microscopic methods

Focusing on behavior of individual vehicle, entry vehicles merge into circulating flow by utilizing acceptable gaps of circulating vehicles.

a) Theoretical models

Microscopic methods were developed by focusing on these individual vehicle maneuvers. Entry capacity is heavily dependent on how many acceptable gaps are provided by circulating flow during a certain time period and how many vehicles can enter in one acceptable gap under a certain level of circulating flow. The formula of microscopic estimation is shown by **Equation (4)**.

$$c_e = q_c\int_0^\infty h(t)\cdot E(t)dt \tag{4}$$

where, $h(t)$ represents the probability density function of gap distribution of circulating flow and $E(t)$ represents the maximum number of vehicles entering one acceptable gap.

The gap distribution of circulating flow is determined by arrival pattern of circulating vehicles. Brown[4] first developed $h(t)$ model dependent on Poisson arrival pattern. Cowan[5] then introduced bunching arrival pattern into $h(t)$ model.

Regarding the maximum number of vehicles entering one acceptable gap, several studies developed models for representing this as by Troutbeck[6] and Siegloch[7]. In these models, two key parameters are included; critical gap t_c which is defined as the minimum headway in the major traffic stream that allows the entry of one minor-street vehicle and follow up time t_f which is defined as the time between the departure of one vehicle from the minor street and the departure of the next vehicle using the same major-street headway under a condition of continuous queuing on the minor street described in HCM 2010[1].

Several countries applied microscopic methods and the estimation equations in several guidelines are shown in **Table 2**.

Table 2 Estimation equations of entry capacity

FGSV[8]	$c_e = \frac{1}{t_f}\alpha\exp[-\lambda\left(t_c - \frac{t_f}{2} - \tau\right)]$
NCHRP 572[9]	$c_e = \frac{1}{t_f}\exp[-\lambda\left(t_c - \frac{t_f}{2}\right)]$
HCM 2010[1]	$c_e = 1130 \cdot \exp(-0.0010 \cdot q_c)$
AUSTROAD[10]	$c_e = \frac{\alpha q_c e^{-\lambda(t_c-\tau)}}{1-e^{-\lambda t_f}}$

where, α: free flow ratio of circulating flow, λ: vehicles arrival rate, τ: minimum headway in circulating flow

Pedestrian impact on roundabout entry capacity is considered through an adjustment factor, f_{ped} in HCM 2010. Entry capacity under pedestrian impact is estimated by the maximum entry flow only considering circulating flow c_e multiplying the adjustment factor as shown by **Equation (5)**.

$$c_{e,ped}=f_{ped}\cdot c_e \tag{5}$$

where $c_{e,ped}$ is roundabout entry capacity considering pedestrian impact.

f_{ped} is modeled under various levels of circulating and pedestrian flows as shown in **Table 3**. **Fig.1** illustrates the adjustment factors f_{ped} according to the equations in **Table 3**. The range of circulating flow and pedestrian flow are set to be 0~1000pc/h and 0~400ped/h, respectively.

The f_{ped} model was developed based on empirical data. In the Japanese situations, the classifications of pedestrian impact based on circulating and pedestrian flows need to be carefully considered. It is a complicated situation in real world when both circulating and pedestrian flows are in high levels. Circulating and pedestrian flows will have a compound impact on entry capacity. However, this compound impact has not been described in the method. Additionally, no geometric factor is included in any existing theoretical model.

b) Microscopic simulation

Other than the theoretical capacity estimation models, microscopic simulation has also been utilized for roundabout capacity estimation because it can help conduct quantitative analysis and simulate

Table 3 Pedestrian adjustment factor in HCM 2010

Case	f_{ped}	
q_c>881	f_{ped}=1	(a)
q_c≤881and n_{ped}<101	f_{ped}=1-0.000137n_{ped}	(b)
q_c≤881and n_{ped}≥101	$f_{ped} = \frac{1119.5 - 0.715q_c - 0.644n_{ped} + 0.00073q_c n_{ped}}{1068.6 - 0.654q_c}$	(c)

where n_{ped}: number of pedestrians per hour (ped/h), q_c: circulating flow (pc/h)

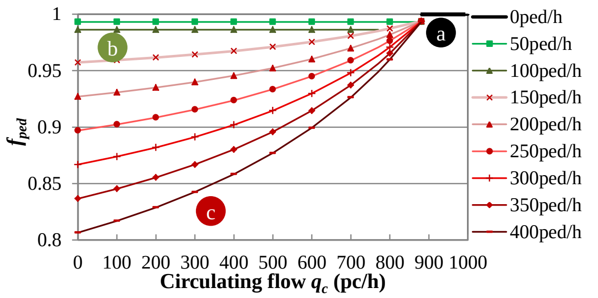


Fig.1 The adjustment factor f_{ped} by pedestrian demand in HCM 2010

complicated situations which are likely to be observed in real world. Carlos and Ruey[11] identified the influence of crosswalk position on entry capacity at two-lane roundabout. However, it is questionable whether the same conclusion can be obtained for single-lane roundabout as well.

Thus, no existing methods can appropriately estimate the entry capacity considering pedestrian impact for the Japanese case. Moreover, many other factors which potentially have significant impact on entry capacity have not been identified. Therefore, this study aims to analyze the impact of various influencing factors on entry capacity, namely, pedestrian approaching sides, physical splitter island and waiting position of entry vehicles.

3. METHODOLOGY

(1) Roundabout simulation

Micro-simulation software VISSIM 5.40[9] is utilized for this analysis. The study site is Azuma-cho roundabout, located in Iida City, Nagano, Japan. **Fig.2** shows the geometry layout of the studied roundabout. It is a five-leg roundabout with the diameter of 40m. The midblock boulevards at the North and South approaches perform the function of splitter islands. However at other approaches, no splitter islands is available.

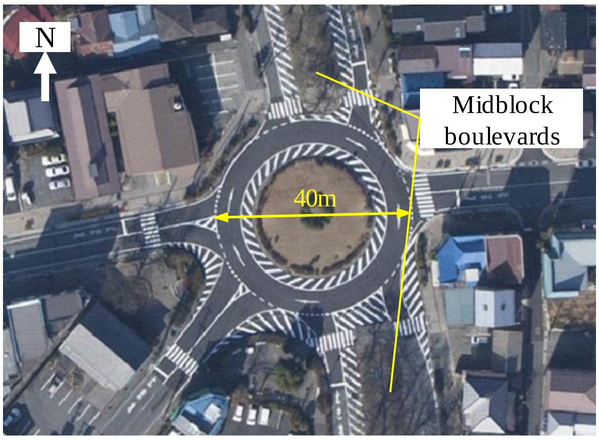


Fig.2 Geometry layout of subject roundabout

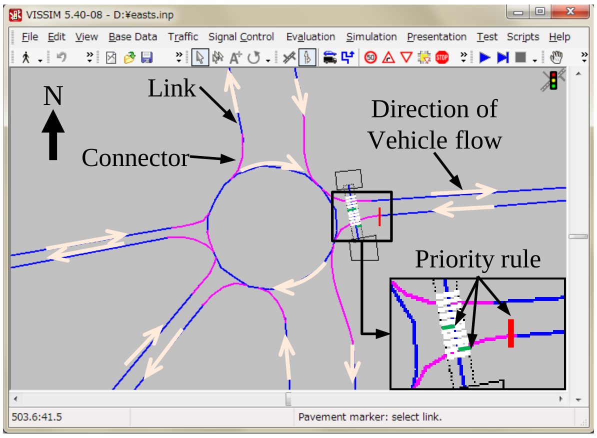


Fig.3 Illustrations of coding in VISSIM

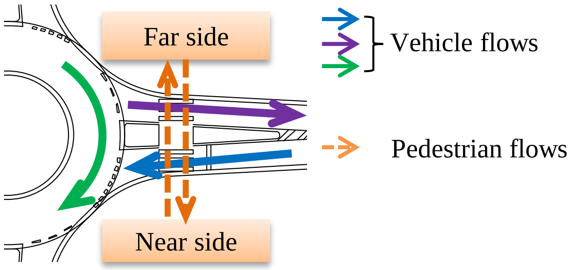


Fig.4 Illustration of pedestrian approaching sides

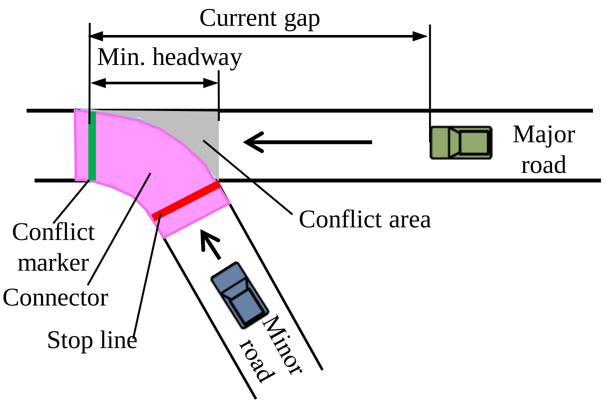


Fig.5 Illustration of minimum headway and current gap

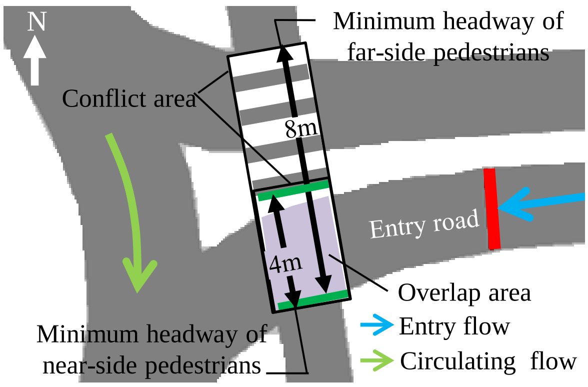


Fig.6 Illustration of minimum headway for pedestrian from near/far side

Fig.3 shows the subject roundabout coded in VISSIM with blue and pink lines representing links and connectors, respectively. The arrows in **Fig.3** show the directions of vehicle flows. The function "priority rule" applied in VISSIM is utilized to control gap acceptance behavior of entry vehicles to pedestrians, which are shown as red and green lines in **Fig.3**. The roads in green and red lines represent major roads and minor roads, respectively. In this analysis, pedestrians are set to have priority on crosswalk.

Pedestrian approaching sides are classified into three patterns; near-side only, far-side only and both sides from the viewpoint of entry vehicles. Near-side is the walkway side close to entry vehicles whereas far-side is the walk side far from entry vehicles, as illustrated in **Fig.4**.

The pedestrian approaching sides are realized in VISSIM through adjusting the parameter "minimum headway" (distance) and "minimum gap time", which are included in "priority rule". The "minimum headway" is defined as the length of the conflict area[12]. The current gap is determined by current speed and the distance between current space point and the ending edge of conflict area[12]. The illustrations of minimum headway and current gap are shown in **Fig.5**.

When minor-road subject arrives at the stop line, current gap of major-road subject is calculated. The principle of the priority rule is at this moment either the current gap of major-road subject is smaller than minimum gap time or the major-road subject is in conflict area, the minor-road subject should wait at the stop line until major-road subject completely leaving the conflict area. The length of conflict area is controlled by minimum headway.

East approach of the studied roundabout is chosen to identify the impact of splitter island and crosswalk position. Entry vehicles are assumed to stop at the stop line when pedestrians are about to cross regardless of approaching sides and wait until pedestrians complete crossing the overlap area of crosswalk and entry road which is shown as purple polygon in **Fig.6**. Thus, conflict areas for near and far side pedestrians are defined on crosswalk with different lengths. Depending on the definition of "minimum headway", the values for far-side and near-side pedestrians were set to 8m and 4m as illustrated in **Fig.6**.

(2) Experimental design

Five input conditions are set in simulation. Here an equal ratio is assumed for pedestrian demands from both sides. The basic input condition settings are shown as follows:

- Circulating flow: 0 to 1600 pc/h in increment of 100pc/h
- Pedestrian flow: 50 to 500ped/h in increment of 50ped/h
- Pedestrian approaching side: near-side, far-side and both sides
- Physical splitter island: with/without
- Crosswalk position: distance between yield line and crosswalk: 2m, 5m

For every combination of input conditions, the VISSIM model was run for 10 times with a unique random number seed. Thus, in total 20,400 combinations were computed and each of them was run for one simulation hour. Performance statistics were measured at 15min intervals. The measured entry flow (pc/h) was averaged based on 10 simulation runs. **Fig.7** shows a screenshot of the VISSIM model during a simulation run.

Entry flow in East approach was observed. In order to create the saturated condition, the entry volume was set to be 1600pc/h. The compositions of circulating flow were simplified to give from North to South for clearly identifying the impact of splitter island and crosswalk. "Data collection point" was placed at the yield line to measure the entry capacity in the East approach, as shown by the blue line in **Fig.7**.

4. RESULTS AND DISCUSSIONS

(1) Entry capacity without pedestrian impact

Fig.8 shows the estimation results of entry capacity c_e by simulation and those calculated by various estimation equations shown in **Table 1** and **Equation (3)** without impact of crossing pedestrians. Critical gap t_c, follow-up time t_f and minimum headway τ of circulating vehicles are estimated from empirical data; t_c=3.5s, t_f=2.25s and τ=1.5s. The geometric factors of studied roundabout are input in Kimber's model.

It is found that the initial values when q_c=0 of HCM 2010 and Kimber's model are lower than others. Based on the estimated equation shown in **Table 2**, HCM 2010 gives the stable initial value 1130veh/h.

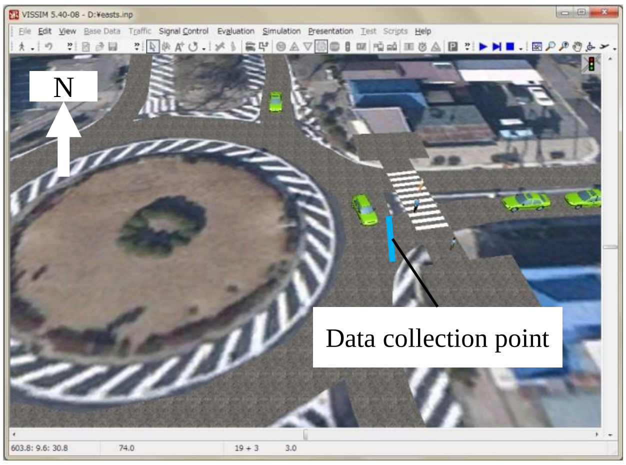


Fig.7 Screenshot of the VISSIM model

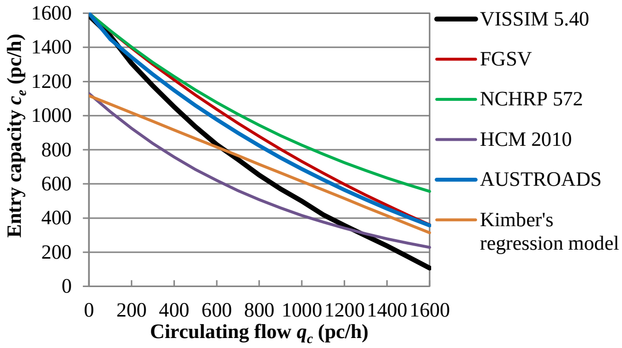


Fig.8 Comparison of estimated entry capacity by simulation and the existing methods

However, in other models, the initial values are changed dependent on t_f. Kimber's model includes geometric factors, which are not considered in other estimation models. This causes the different performance between Kimber's model and others. The other three existing models show the same initial value as simulation output since input value t_f is same. Note that in simulation, circulating flow in front of the East approach was set only from north to south. In the real world the arrival pattern of circulating vehicles is different from the simple case set in simulation. However, this difference does not have significant impact on following analyses.

(2) Pedestrian approaching sides

Fig.9 plots the entry capacity versus circulating

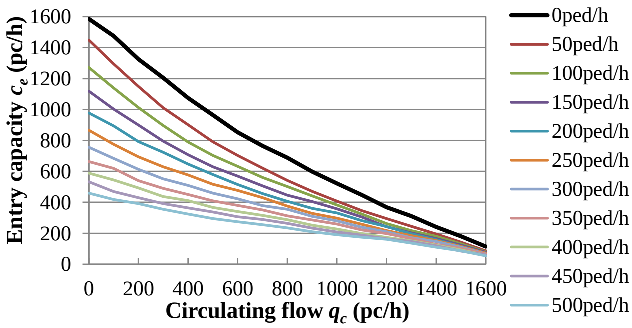
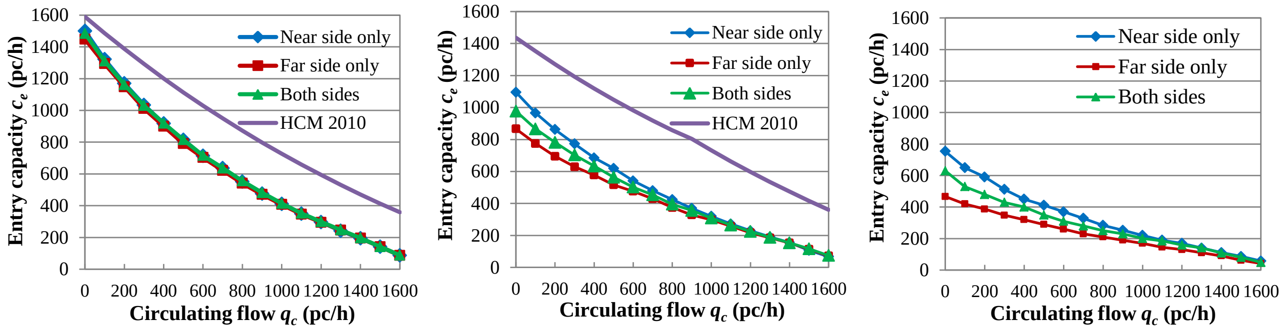


Fig.9 Entry capacity under different levels of circulating and near-side approaching pedestrian flows



(a) Pedestrian flow of 50ped/h (b) Pedestrian flow of 250ped/h (c) Pedestrian flow of 500ped/h

Fig.10 Entry capacity under different pedestrian approaching sides and flow rates

flow under different levels of pedestrian flow for the case of pedestrians from near side only. It shows that at the same level of pedestrian flow, entry capacity is reduced with the increase of circulating flow. When the circulating flow is kept at the same level, entry capacity decreases with the increase of pedestrian flow. Since the cases of pedestrians from far side only and both sides show the same decreasing tendency, the case of pedestrians from near side only is shown as example here.

Based on this, **Fig.10(a)~(c)** show the entry capacity under different pedestrian approaching sides. Pedestrian flows of 50ped/h, 250ped/h and 500ped/h are selected for analysis. When pedestrian flows are 50ped/h and 250ped/h, the estimated results by applying adjustment factor f_{ped} in HCM 2010 are also shown in **Fig.10(a)** and **(b)**. Since pedestrian flow 500ped/h is out of range defined in HCM 2010, the curve is not shown in **Fig.10(c)**.

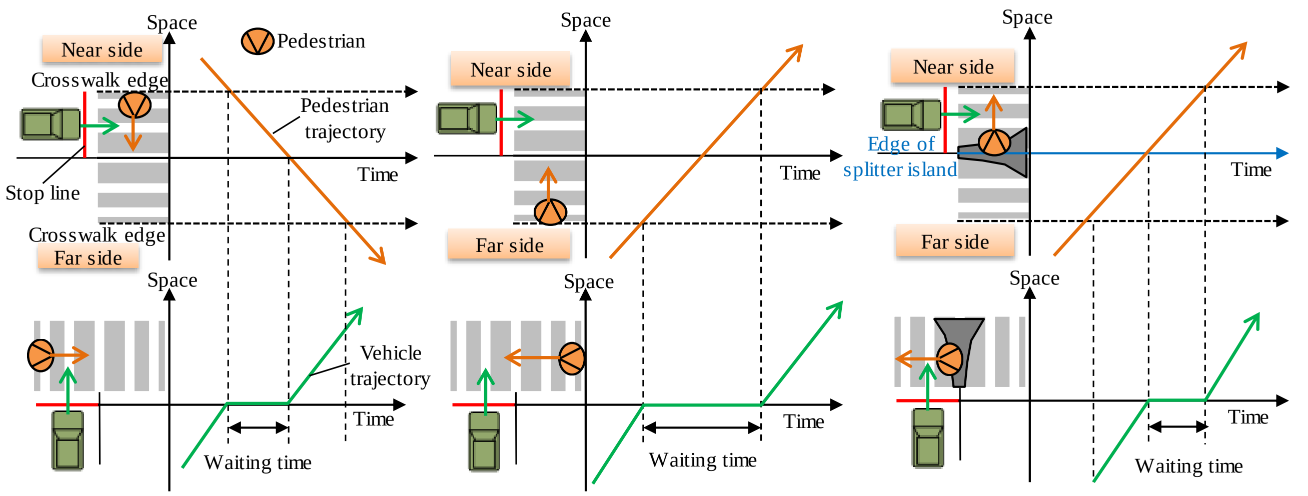
In each figure, at the same level of circulating flow, entry capacity decreases most under the condition of pedestrian from far side only. Under condition without splitter island, conflict area for far-side pedestrian is longer than that for near-side pedestrian, which results in longer waiting time of entry vehicles. The longer waiting time leads to larger delay, then lower entry capacity.

In **Fig.10(a)** and **(b)**, estimated results by applying f_{ped} in HCM 2010 is obviously higher than that of simulation output. It implies that HCM 2010 insufficiently considered the compound impact of circulating and pedestrian flows on entry capacity.

Comparing the margin of c_e estimates at each levels of pedestrian flow, it is found that pedestrian approaching sides more significantly impact on entry capacity under the high level of pedestrian flow (i.e., 500ped/h) than under the low level (i.e., 50ped/h). This can be explained that the probability of notice by drivers is higher under the condition of high pedestrian flow than that of low pedestrian flow, which reduces entry capacity.

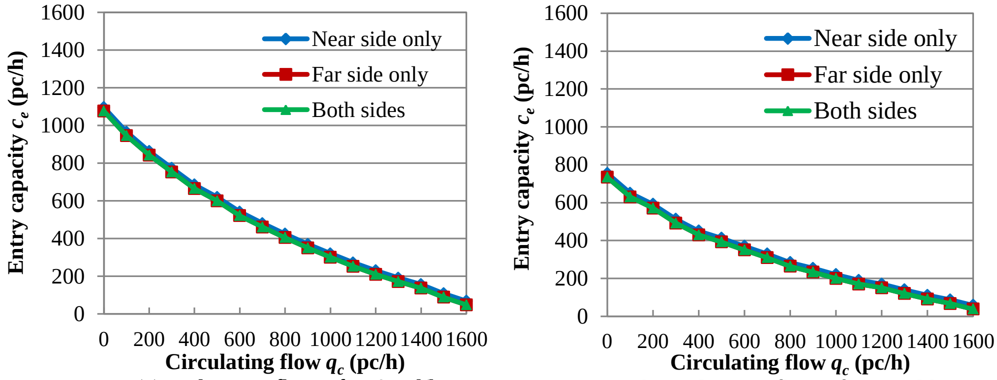
(3) Physical splitter island

Physical splitter islands provide waiting space to crossing pedestrians. Due to the existence of physical splitter island, pedestrian crossing can be separated into two parts; conflicting to entry vehicles only and conflicting to exit vehicles only. Under this condition entry vehicles are assumed to react far-side pedestrians from the moment when leaving the island.



(a) Pedestrians from near side (b) Pedestrian from far side without splitter island (c) Pedestrian from far side with splitter island

Fig.11 Illustration of waiting time under different assumed conditions of pedestrian approaching sides and splitter island



(a) Pedestrian flow of 250ped/h (b) Pedestrian flow of 500ped/h

Fig.12 Estimated entry capacity by pedestrian approach sides with physical splitter island

Thus, the conflict area is shortened. Accordingly, waiting time for far-side pedestrian is shortened. The waiting times under conditions without/with splitter island are illustrated in **Fig.11**. It can be found that waiting time for far-side pedestrian without splitter island is longest.

The results calculated for 250ped/h and 500ped/h are shown in **Fig.12**. It is found that there is no significant difference of entry capacity between the far-side and near-side pedestrian under the condition of with physical splitter island. Note that entry capacity for near-side pedestrian effect under this condition is same as in the case of no splitter island.

(4) Crosswalk position and the distance between yield line and edge of crosswalk

Case 1 in **Fig.13** shows the simulation environment coded according to the real geometry condition. Note that the distance on the East approach is 2m only, shorter than the ordinary vehicle length 5m. It means that this distance is not large enough for accommodating the vehicle waiting for acceptable gap of circulating vehicles after passing pedestrian flow. Case 2 in **Fig.13** shows the case after extending the distance to 5m. Entry vehicles in this situation are assumed to judge circulating vehicles at the yield line without getting influence from crossing pedestrians.

Fig.14 shows the estimated entry capacity under the condition of the two distances. Groups of dotted line and solid line represent the cases of 2m and 5m, respectively. It is found that at each level of pedestrian flow, entry capacity under the condition of 2m performs lower values than that under the condition of 5m. Moreover, the entry capacity decreases more significantly with the increasing pedestrian flow. In the case of 2m, because the distance is insufficient to accommodate one vehicle, entry drivers have to judge circulating vehicles at the stop line (red line in **Fig.13**). When pedestrians and circulating vehicles exist simultaneously, entry drivers have to judge both of them. Under this situation, if there are no acceptable gaps in pedestrian flow, acceptable gaps

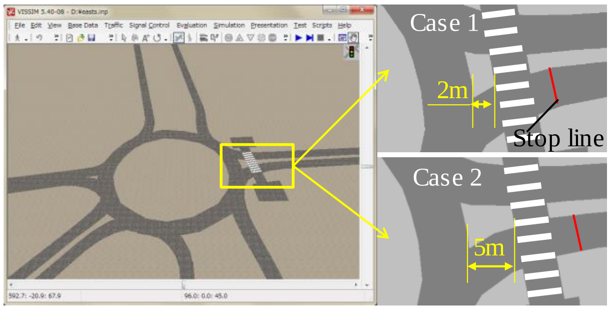


Fig.13 Illustration of distance between yield line and crosswalk

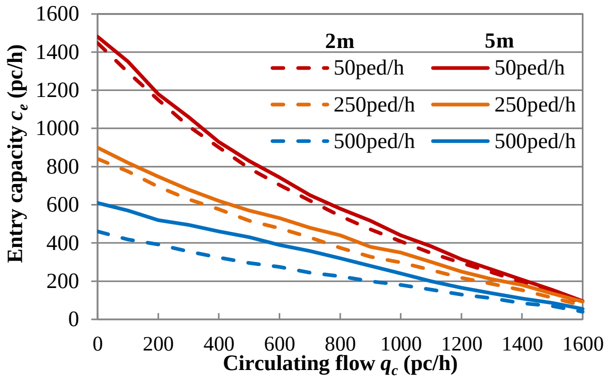


Fig.14 Estimated entry capacity in the case of different distance between yield line and downstream crosswalk

provided by circulating flows cannot be utilized. This reduces entry capacity. When pedestrian flow is at a low level, the difference in two cases is not significant because the probability of getting blocked by pedestrians is lower comparing to the case with high-level pedestrian flow. The similar tendency was found by Carlos and Ruey[11] which focused on two-lane roundabout.

5. CONCLUSIONS

In this study, roundabout entry capacity considering various influencing factors was estimated by applying microscopic simulation VISSIM 5.40. The results can be concluded as follows.

Increasing pedestrian volume was found to decrease roundabout entry capacity. However, variations of entry capacity were identified for different pedestrian approaching sides without physical splitter island. Under the same level of circulating flow, entry capacity was reduced more significantly for far-side approaching pedestrians because entry vehicles had to wait longer time for far-side pedestrians than near-side pedestrians. Another finding is f_{ped} in HCM 2010 cannot reflect the compound impact of circulating and pedestrian flows on entry capacity.

The difference between far-side and near-side pedestrians was not significant after installing of physical splitter island since far-side pedestrians were reacted by entry vehicles from the moment when leaving splitter island. Thus, the waiting time of entry vehicles are shortened and accordingly entry capacity gets improved. This result demonstrated that physical splitter island was necessary to be installed not only from safety considerations, but also for operational performance.

In addition, entry capacity increases when the distance between the yield line and crosswalk is long enough for accommodating the vehicle waiting for acceptable gap. However, in practice, it should be noted that the longer the distance between the circulatory roadway and the downstream crosswalk becomes, the greater the vehicle speed becomes, which may be more dangerous for pedestrians. Therefore, this distance should be carefully designed considering both entry capacity and pedestrian safety.

Note that in simulation experiment, circulating flow was only assigned by one direction from north to south and the entry vehicles were set to stop once pedestrians entered on crosswalk. In real world, circulating flow is composited by the flows from several approaches. Therefore, the arrival pattern of circulating vehicles is different from the simple case set in simulation. On the other hand, the judgments to pedestrians are flexible in practice. Entry vehicles do not stop exactly at the moment when pedestrians are about to cross. Therefore, all these input conditions should be carefully considered in future to make the simulation experiment be as realistic as possible.

In summary, the results of simulation provide direct expressions of the impacts of various influencing factors on roundabout entry capacity. This study demonstrated that in addition to pedestrian volume, several other influencing factors, i.e., pedestrian approaching side, physical splitter island and distance between yield line and crosswalk, should also be incorporated in the estimation of roundabout entry capacity.

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