Simulation Analysis of Entry Capacity at Single-lane Roundabout Considering Pedestrian Impact

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Abstract: Serving as a basic parameter for performance evaluation, entry capacity estimation is of top importance at roundabout. In addition to circulating flow, pedestrians are the main conflicting stream to entry vehicles before entering roundabout. In the Japanese case, due to the relatively high pedestrian volume pedestrian impact needs to be carefully considered in capacity estimation. Moreover, less insight has been provided upon the influence of pedestrian approach sides and geometric characteristics (e.g., physical splitter island and crosswalk position). In order to qualitatively analyze pedestrian impact under various influencing factors, microscopic simulation is employed in this study. Under the condition of no physical splitter island, far-side approaching pedestrians lead to entry capacity decrease more significantly than near-side. The installation of physical splitter island was found to be able to improve entry capacity to some extent. In addition, entry capacity has a better performance when the distance between yield line and crosswalk became larger.

Keywords: Roundabout, capacity, pedestrian impact, geometric characteristics, microscopic simulation

1. INTRODUCTION

Roundabout, as one type of unsignalized intersection, is defined as “intersections with a general circular shape, characterized by yield on entry and circulation around a central island” according to Highway Capacity Manual (2010). The modern roundabout was developed in United Kingdom in 1960s, which entering traffic must always yield to traffic already in the circle. In this study, note that roundabout means modern roundabout. Compared to other types of intersections, roundabouts have relatively better performance for vehicle traffic under the condition of low demand. It can be characterized by shorter delay, fewer conflict points and lower entering and turning speed.

Serving as a basic parameter for performance evaluation, entry capacity estimation is of top importance at roundabout. Entry capacity is generally considered as the maximum entry flow that can be expected to traverse yield line during a certain period. In addition to circulating vehicles, pedestrian is another key factor that may block entry flow at crosswalk and impact entry capacity. This pedestrian impact will become stronger when the volume is higher.

Roundabouts existing in Japan have several representative characteristics. First, due to the limitation of space almost all roundabouts existing in Japan are single-lane roundabouts and physical splitter island cannot always be installed. Moreover, stop control is applied at entry approaches. Another operational characteristic of roundabout is that these roundabouts are likely to be located in the areas which have high pedestrian flow. Thus, the pedestrian impact needs to be carefully considered in capacity estimation.

The existing methods, e.g., HCM (2010) quantify the pedestrian impact on entry capacity by using adjustment factor. The empirical approach has shortcomings to reflect the interactive impact of both pedestrians and circulating flow on entry vehicles. In addition, less insight has been provided upon the influence of pedestrian approach sides and geometric characteristics (e.g., physical splitter island and crosswalk position).

In order to qualitatively analyze pedestrian impact, microscopic simulation is employed in this study to examine roundabout entry capacity under various influencing factors, e.g., pedestrian flow, pedestrian approach sides, physical splitter island and crosswalk position. The remainder of the paper is organized as follows. After literature review is presented, the simulation experiments in VISSIM are explained in detail. Then, the results and discussions are given regarding the identified influencing factors on entry capacity estimation. Finally, it concludes this study and provides future works.

2. LITERATURE REVIEW

The existing estimation methods calculated roundabout entry capacity dependent on circulating flow from macroscopic and microscopic viewpoints. Regarding macroscopic methods, regression models are utilized to model the relationship between entry capacity and circulating flow. Kimber (1980) developed a linear regression model considering roundabout geometry based on data from 86 sites in the United Kingdom. After that, an exponential regression model was developed in Germany (Brilon *et al*., 1997; Brilon, 1991). Due to the limitation of study sites in many countries, microscopic methods were also developed.

The existing microscopic estimation methods are based on gap acceptance behavior towards circulating flow. In practice, entry vehicles need to merge into circulating flow by selecting acceptable gaps. Therefore, the estimation of roundabout entry capacity is largely dependent on how many acceptable gaps are provided by circulating flow during certain time and how many vehicles can enter in one acceptable gap. The acceptable gaps distribution of circulating flow relates to arrival pattern of circulating vehicles. Poisson arrival pattern and bunching arrival pattern were proposed in gap distribution calculation by Brown (1972) and by Cowan (1974), respectively. Regarding the maximum number of vehicles entering in one acceptable gap, two types of models have been developed, continuous model and step model. Continuous model was proposed by Siegloch (1973) and McDonald and Armitage (1978). Then, step model was proposed by several researchers (Tanner, 1967; Harders, 1976; Troutbeck, 1990). In these models, two key parameters are concluded. One is critical gap t_c which is defined in HCM 2010 as the minimum headway in the major traffic stream that allows the entry of one minor-street vehicle. The other is follow-up time t_f which is described in HCM 2010 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. Table 1 shows the equations for entry capacity estimation in guidelines from several countries.

Table 1 Estimation equations of entry capacity applied in guidelines

Country (guideline)	Vehicles arrival pattern	Function for number of entering vehicles	Equation
U.S. (NCHRP 572)	Poisson	Continuous	$c_e = \frac{1}{t_f}\exp[-\lambda\left(t_c - \frac{t_f}{2}\right)]$ (1)
German (FGSV)	Bunching	Continuous	$c_e = \frac{1}{t_f}\alpha\exp[-\lambda\left(t_c - \frac{t_f}{2} - \tau\right)]$ (2)
Australia (AUSTROADS)	Bunching	Step	$c_e = \frac{\alpha q_c e^{-\lambda(t_c-\tau)}}{1-e^{-\lambda t_f}}$ (3)

λ: vehicles arrival rate, τ: minimum headway in circulating flow

Besides circulating flow, crossing pedestrians are found to have significant impact on roundabout entry capacity. In general, entry capacity decreases with the increase in pedestrian volume at crosswalk. HCM 2010 quantifies the impact of pedestrians on entry capacity through an adjustment factor, f_{ped}. Thus, the entry capacity is estimated by the maximum entry flow only considering circulating flow $c_{e,cir}$ multiplying this adjustment factor as shown in Equation (1),

$$c_e = f_{ped} * c_{e,cir} \tag{4}$$

where

$c_{e,}$: roundabout entry capacity.

f_{ped} is modeled under various levels of circulating and pedestrian flows shown in Table 2. Figure 1 illustrates the adjustment factors f_{ped} according to the equations shown in Table 2.

Table 2 Pedestrian adjustment factor in HCM 2010

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

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

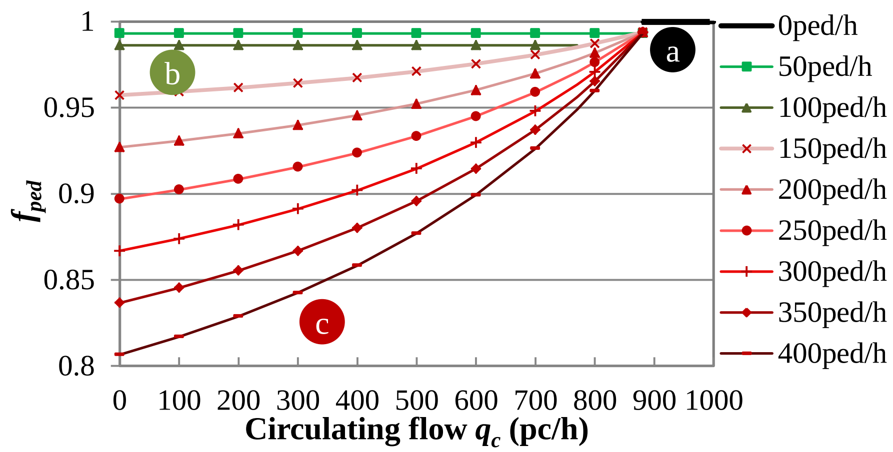


Figure 1. The adjustment factor f_{ped} by pedestrian demand in HCM 2010

The range of circulating flow and pedestrian flow are set 0~1000 pc/h and 0~400ped/h, respectively. It shows that

(a) when circulating flow q_c is higher than 881pc/h, f_{ped} equals 1 which means that pedestrian impact is negligible. In such a case, entry queue is generated due to high level of circulating flow. Pedestrians typically pass between queued vehicles on entry approach and thus have negligible impact on entry capacity;

(b) then, if circulating flow is lower than 881pc/h and pedestrian flow is lower than 101p/h, ($n_{ped} \leq 101$), f_{ped} changes only dependent on pedestrian flow with a decreasing tendency. For certain pedestrian flow, it is a constant value as circulating flow changing;

(c) when circulating flow is lower than 881pc/h and pedestrian flow is higher than 101p/h, pedestrian impact significantly increases with pedestrian flow increase. However, at the same level of pedestrian flow, the impact decreases with the increase of circulating flow.

The classifications of pedestrian impact based on circulating and pedestrian flows should be carefully reconsidered dependent on Japanese situations. Moreover, pedestrian impact is only considered as an adjustment factor in the method above. As mentioned previously, when pedestrian flow is in high level, circulating vehicles and pedestrians will interactively impact on entry capacity.

Microscopic simulation is often utilized for roundabout capacity issue recently because it can help conduct quantitative analysis and simulate complicated situations which are likely to be observed in real world. Moreover, simulation can provide better visualization for prediction. Carlos and Ruey (2011) utilized microscopic simulation VISSIM to estimate pedestrian impact on two-lane roundabout entry capacity considering crosswalk position. The position of crosswalk was set 3 patterns so that the distance between crosswalk and yield line can store 1, 2 and 3 vehicles. Different levels of pedestrian flows were assumed to examine the entry capacity. Although this analysis estimated entry capacity considering pedestrian with crosswalk position, it is for two-lane roundabout and questionable whether the same conclusion can also be obtained for single-lane roundabout as well.

Due to the situations in Japan, the existing methods may not appropriately estimate the entry capacity considering pedestrian impact. Moreover, many 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, e.g., pedestrian approach side, physical splitter island and waiting position of entry vehicles.

3. METHODOLOGY

3.1 Roundabout Simulation

VISSIM 5.40 is employed for this analysis. The study site is Azuma-cho roundabout, located in Iida City, Nagano, Japan. Figure 2 shows the coded roundabout in VISSIM with blue and pink lines separately representing links and connectors. Arrows in Figure 2 show the direction of vehicle flow.

At roundabout, entry capacity is dependent on gap acceptance behavior toward circulating flow. The gap acceptance behavior is controlled by two functions in VISSIM 5.40, namely “conflict area” and “priority rule”. The “conflict area” is an overlap area of different links and connectors as shown in Figure 2. Green polygons represent major roads which are assigned priority whereas red polygons represent minor roads. They were set in circulating roads in front of each entrance to control the conflict between entry vehicles and circulating vehicles. On the other hand, “priority rule” is another way to assign priorities on roads. As shown in Figure 2, green and red markers were drawn on the crosswalk and the stop line. Meanings of colors are the same as in “conflict area”. Pedestrians are assigned priority at crosswalk in the simulation. The “stop sign control” was applied at the stop line to realize the characteristic of stop control.

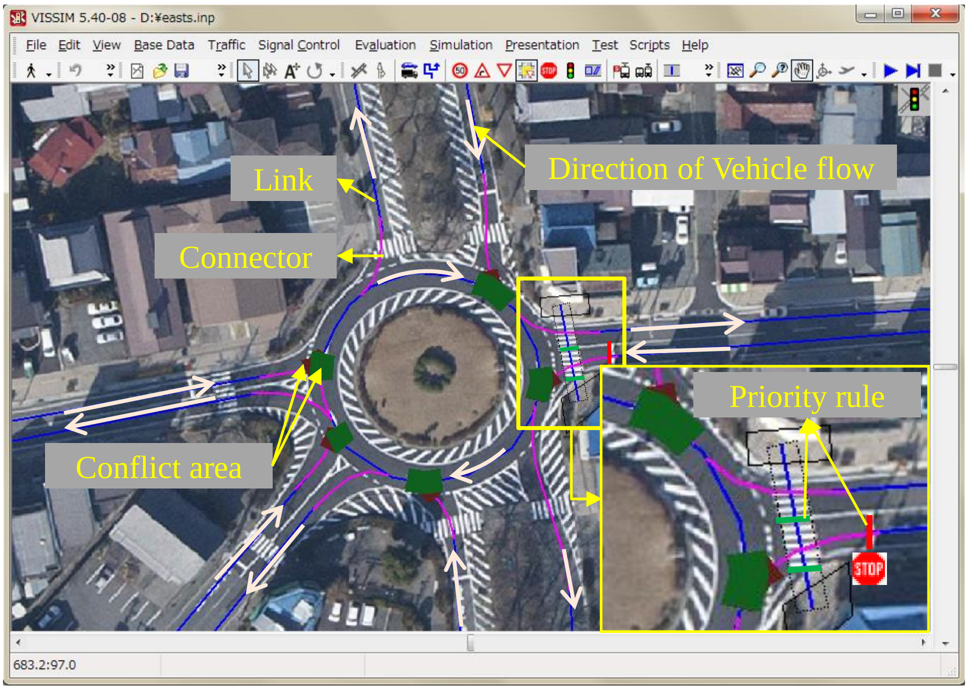


Figure 2. Illustrations of conflict area and priority rule in coded roundabout

Parameters applied in “conflict area” and “priority rule” control the performance of gap acceptance behavior. The “conflict area” includes four main parameters, “visibility”, “front gap”, “rear gap” and “safety distance factor”. The “visibility” is applied to interpret the sight distance. The “front gap” refers to the elapsed time of the vehicle on the major approach that has just passed the vehicle searching a gap in the minor approach. The “rear gap” refers to the time gap between the vehicle in the minor approach and the oncoming vehicle in the major approach. The front and rear gaps affect crossing conflicts. The “safety distance factor” is related to the merging maneuver. The values of parameters after calibration were set as follows, visibility =100m, front gap=1.0s, rear gap=2.5s, safety distance factor=1.0.

On the other hand, two parameters are included in the “priority rule”, which are “minimum headway” (distance) and “minimum gap time”. By assigning the different values to these two parameters, identifications of pedestrian approaching sides can be realized. Pedestrian approaching sides are classified as near side, far side and both sides from the viewpoint of entry vehicles. Near side is the walk side near to entry vehicles whereas far side is the walk side far from entry vehicles. The illustration is shown in Figure 3.

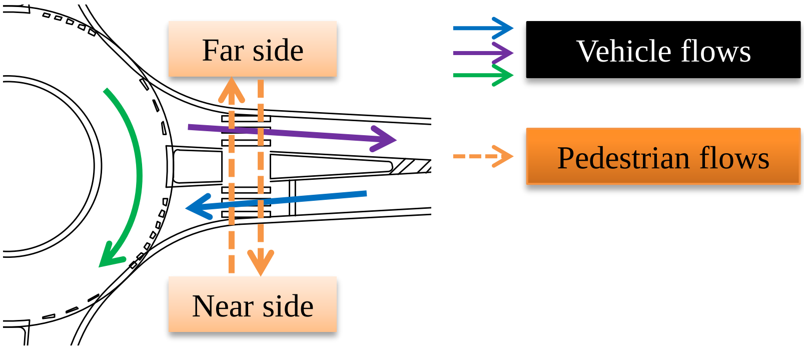


Figure 3. Illustration of pedestrian approaching sides

For near-side pedestrians, the parameters in the "priority rule" were set as minimum headway=4m, minimum gap time=3s. For far-side pedestrians, they were set as minimum headway=8m, minimum gap time=6s.

3.2 Experimental Design

Subsequently, simulation experiments were conducted at the roundabout as shown in Figure 2. Five scenarios are set in simulation. Here equal ratio is assumed for pedestrian demands from both sides, i.e., 1:1. The basic scenario settings are shown as follows:

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

For each combination of scenarios the VISSIM model was run for 10 times with a unique random number seed. In total 20,400 simulation runs were conducted. Each combination is run for one simulation hour. Performance statistics were measured at 15min intervals. The measured entry flow (pc/h) were averaged based on 10 simulation runs. Figure 4 shows a screenshot of the VISSIM model during a simulation run.

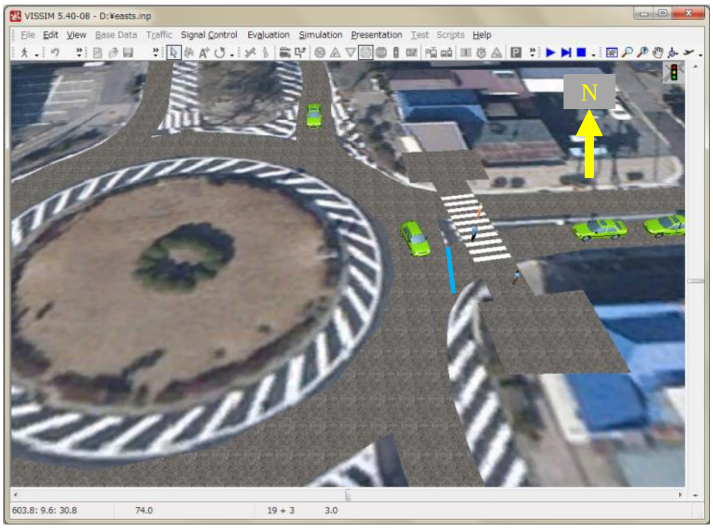


Figure 4. Screenshot of the VISSIM model

Entry flow in East approach was observed. In order to create the saturated condition, the entry volume was set to be 1600pc/h. Then, to simplify the compositions of circulating flow and present conflict flow to entry vehicles in East approach, all the circulating vehicles were set to enter the roundabout from the North approach and exit the South approach. To measure the entry capacity, "data collection point" was placed at the yield line in the East approach as shown the blue line in Figure 4.

4. RESULTS AND DISCUSSIONS

4.1 Entry capacity without crossing pedestrian

Figure 5 shows the estimation results of entry capacity c_e by simulation and those calculated by various formulas shown in Table 1 with no impact of crossing pedestrians. Critical gap t_c and follow-up time t_f are estimated from empirical data, t_c=3.5s, t_f=3.0s. The minimum headway τ of circulating vehicles is 2s.

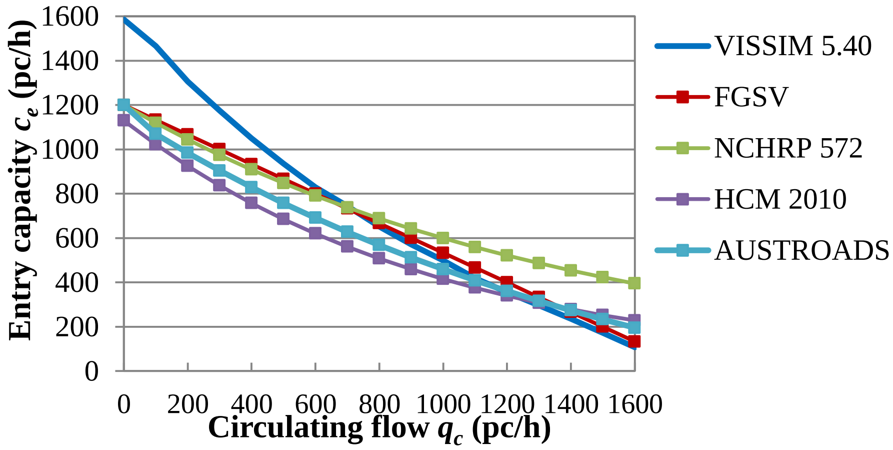


Figure 5. Comparison of estimated entry capacity by simulation and the existing methods

It is found that the initial value by simulation when circulating flow is 0 is higher than the estimates given by the existing methods. Under this situation, except HCM 2010 with a given initial value of 1130pc/h, other methods are dependent on the follow-up time t_f. As a result, it equals to 1200pc/h=3600/3.0. When circulating flow is at a lower level, entry capacity is mainly dependent on t_f, instead of the circulating flow . However, with increasing circulating flow, entry capacity is primarily dependent on critical gap t_c. The value t_c is set identical in simulation and other estimation methods, t_c=3.5s. As a result, estimated values are close to each other with the increasing circulating flow.

4.2 Pedestrian approach sides

Figure 6 plots the entry capacity against circulating flow under different levels of pedestrian flow. Because different pedestrian approaching sides show the similar tendency of the analysis results, only the case of pedestrians from near side is shown for example.

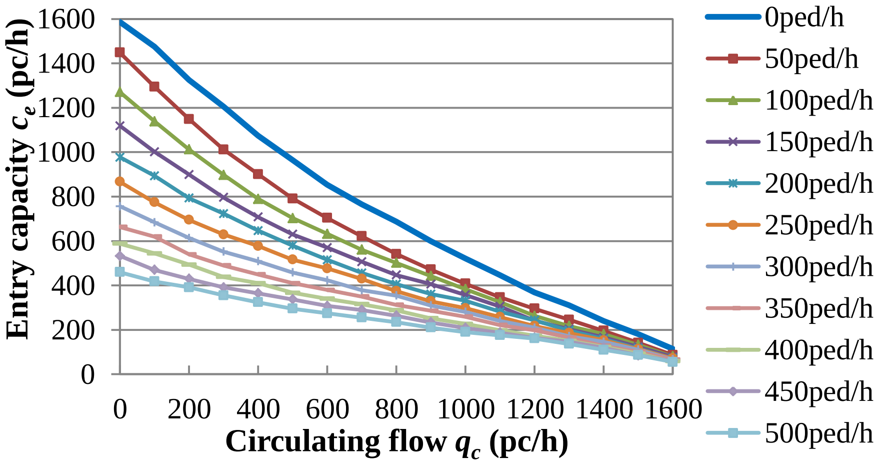
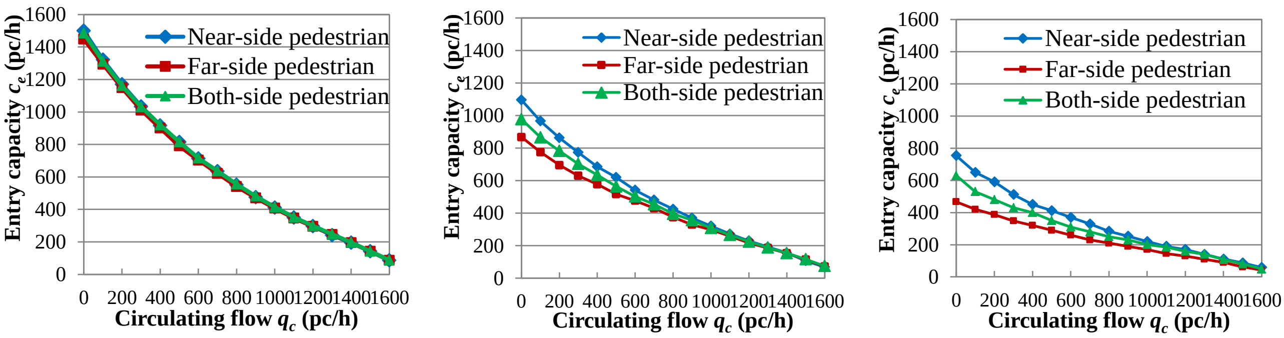


Figure 6. Entry capacity under different levels of circulating and near-side approaching pedestrian flow

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.

Figures 7(a)~(c) show the entry capacity against circulating flow under different pedestrian approach sides and flow rates (i.e., 50ped/h, 250ped/h and 500ped/h).



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

Figure 7. Entry capacity under different pedestrian approach sides and flow rates

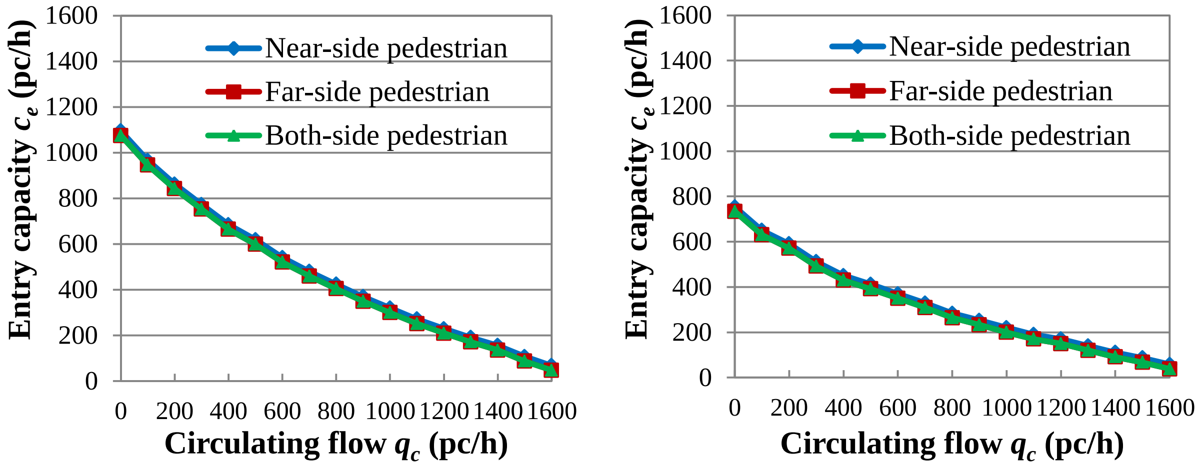
In each figure, by comparing the entry capacity under different pedestrian approaching sides, far-side approaching pedestrians are found to have the most significant impact on entry capacity decrease. In simulation, pedestrians are set to be reacted by vehicles from the moment when entering the crosswalk. Entry vehicles have to wait longer time for far-side pedestrians than near-side pedestrians. The longer waiting time results in the lower entry capacity.

Comparing the margin of performance in c_e at different levels of pedestrian flow, it is found that pedestrian approach sides have more significant impact under the high level of pedestrian flow (e.g., 500ped/h) than under the low level (e.g., 50ped/h). In reality, when pedestrian flow is at a lower level, entry vehicles are seldom blocked by pedestrians. Thus, the different approaching sides are assumed not to significantly affect entry capacity. However, with increasing pedestrian flow, the probability of entry vehicles getting blocked by pedestrians becomes higher, which leads to decreased entry capacity. It demonstrates that pedestrian approaching sides can significantly affect entry capacity. Far-side pedestrians have much stronger impact on entry capacity than near-side pedestrians. Furthermore, higher pedestrian volume shows more distinct variations between three curves as in Figure 7.

4.3 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. For pedestrians, physical splitter islands improve safety performance during crossing. On the other hand, for entry vehicles, physical splitter islands are assumed to provide better performance on entry capacity. Far-side pedestrian is assumed to be judged from the moment when leaving the island. The waiting time for far-side pedestrian may be shortened. As a result, entry capacity under the impact of far-side pedestrian is expected to be improved.

In order to realize physical splitter island in simulation, the parameters of “minimum headway” and “minimum gap time” of far-side pedestrians were accordingly changed. Assuming that at single-lane roundabout entry vehicles travel in the central of road, the distance from physical splitter island to the right side of vehicle (far-side pedestrians) equals to the distance from the edge of crosswalk to the left side of vehicle (near-side pedestrians). Thus, the value of “minimum headway” and “minimum gap time” for far-side pedestrians are set to be the same as near-side pedestrian. The results calculated for 250ped/h and 500ped/h are shown in Figure 8.



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

Figure 8. Estimated entry capacity by pedestrian approach sides with physical splitter island

It shows that there is no significant difference of entry capacity between the far-side and near-side pedestrian with physical splitter island. It implies that physical splitter island can decrease the reduction of entry capacity due to far-side pedestrians by shortening waiting time of entry vehicles for far-side pedestrians by comparing the results of Figure 8 with Figure 7.

4.4 Crosswalk position, distance between yield line and downstream edge of crosswalk

Distance between yield line and downstream edge of crosswalk decides the position of entry drivers judging circulating vehicles.

Figure 9 shows the illustration of different distances. Right upper one shows the simulation environment coded according to the real geometry condition. Note that the distance between yield line and downstream edge of crosswalk on the East approach is only 2m, shorter than one-vehicle length 5m. It means that this space cannot be utilized as waiting space for entry vehicles after passing pedestrian flow. Right bottom one shows the case after extending the space between yield line and downstream edge of crosswalk to one-vehicle length 5m. Entry vehicles in this situation can wait in this space and judge circulating vehicles without getting influence from crossing pedestrians.

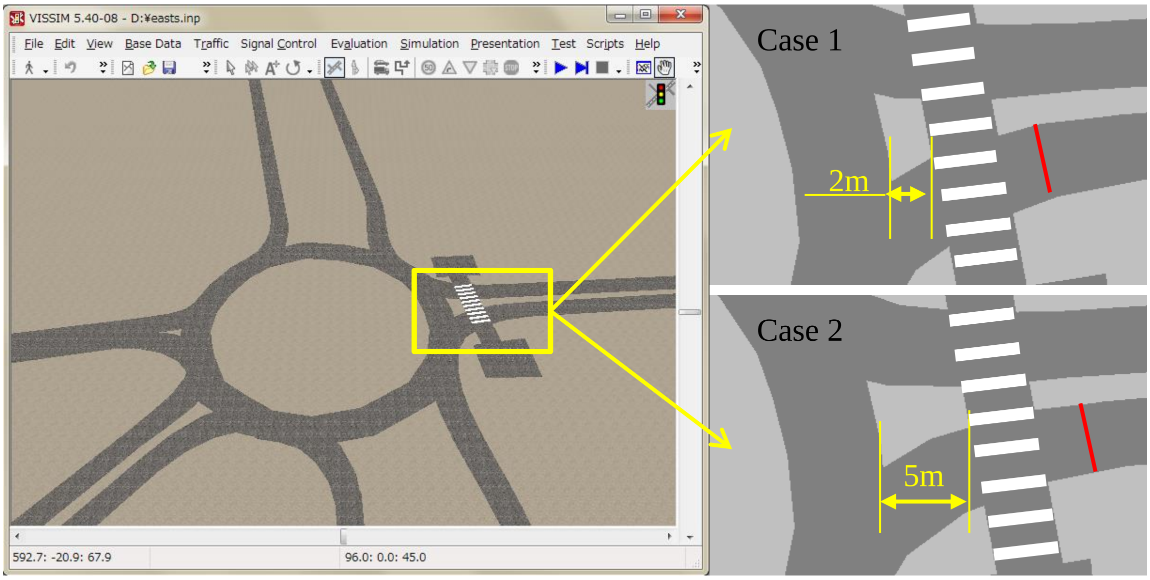
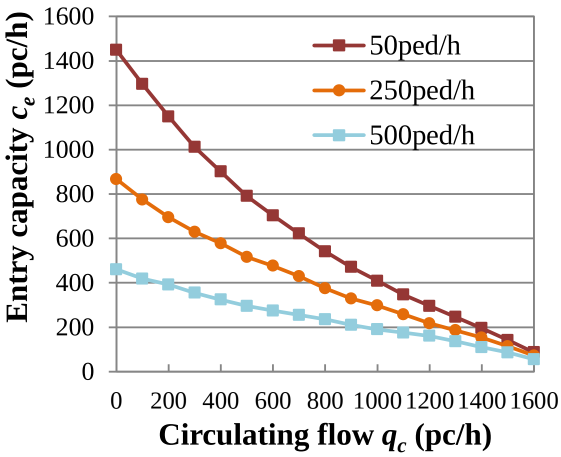
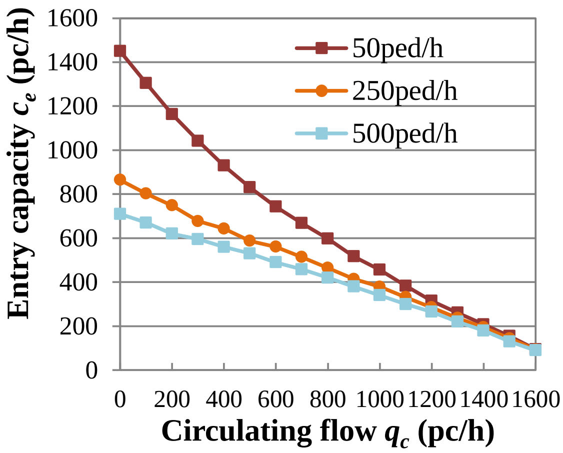


Figure 9. Illustration of distance between yield line and crosswalk



(a)Case 1: Distance of 2m



(b)Case 2: Distance of 5m

Figure 10. Estimated entry capacity in the case of different distance between yield line and downstream crosswalk

Figures 10(a) and (b) show the results of different cases of distance between yield line and downstream edge of crosswalk. It is found that at each level of pedestrian flow, entry capacity under the condition of small space performs lower values than that under the condition of great space. The entry capacity reduction becomes more significant when increasing pedestrian flow. In the case of 2m, because the distance is too short, entry drivers cannot enter this area. As a result, they have to judge circulating vehicles at the stop line. When pedestrians and circulating vehicles exist simultaneously, entry drivers have to judge both of them. Under this situation, if there are no available gaps in pedestrian flow, although circulating vehicles provide acceptable gaps, they cannot be utilized. Therefore, acceptable gaps of circulating flows are neglected so that entry capacity is reduced. When pedestrian flow is in low level, it seldom happens because entry drivers have low opportunity to be in the situation of acceptable gaps from circulating vehicles whereas no available gaps provided by pedestrians. However, this happens much more frequently when increasing pedestrian flow. This is the reason why entry capacity drops more when increases pedestrian flow. The changing tendency is same as the analysis of Carlos and Ruey (2011) which was conducted at two-lane roundabout.

5. CONCLUSIONS

This study estimated roundabout entry capacity considering various influencing factors. Microscopic simulation VISSIM 5.40 was applied in this study. Influences of pedestrian volume, pedestrian approach side, physical splitter island and distance between yield line and downstream edge of crosswalk on entry capacity were identified.

Pedestrian volume was found to decrease roundabout entry capacity by increasing the volume. However, different performances in entry capacity were identified when changed pedestrian approach sides. Under the same level of circulating flow, entry capacity was reduced more if pedestrians were from far side because entry drivers had to wait longer time for far-side pedestrians under the condition of without physical splitter island.

After assuming installing physical splitter island, a better performance in entry capacity of far-side pedestrians was shown. This can be explained that under the condition of with physical splitter island, far-side pedestrians were judged from leaving the island so that the waiting time of entry driver was shortened. As a result, entry capacity was relatively improved. This result implied that physical splitter island was necessary to be installed not only from safety considerations, but also important for operational performance.

The influence of distance between yield line and downstream edge of crosswalk was demonstrated at single-lane roundabout. The results showed that under a certain level of pedestrian flow, the case of longer distance had a better performance on entry capacity than that of short distance. It can be contributed to that sufficient space, at least more than one-vehicle length allowed entry drivers to separately judge pedestrians and circulating vehicles before entering roundabout. This can increase the utilization of acceptable gaps of circulating vehicles so that improve entry capacity. However, in practice, it should also be noted that the longer the distance between the circulatory roadway and the downstream crosswalk becomes, the greater the vehicle speed becomes.

The results of simulation provide direct expressions of the impacts of various influencing factors on roundabout entry capacity. Furthermore, they also will be utilized as initial effort for developing analytical models in the future. The influencing factors examined in this study will be considered in the analytical model.

REFERENCES

AUSTROADS (1993): Guide to Traffic Engineering Practice, Part 6-Roundabouts. Sydney, Australia.

Brilon, W., Wu, N. and Bondzio, L. (1997) Unsignalized Intersection in Germany - A State of the Art 1997, Proceedings of the Third International Symposium on Intersections Without Traffic Signals, Portland, Oregon, USA, pp. 61-70.

Brilon, W. (1991) Intersections Without Traffic Signals, Springer-Verlage, Vol. II, Berlin.

Brown M. (1972) Low density traffic streams. Adv. Appl. Prob. 4,177-192.

Carlos, D. and Ruey, L.C. (2011) Effect of crosswalk location and pedestrian volume on entry capacity of roundabouts. Presented at the 91st Annual Meeting of the Transportation Research Board.

Cowan, R. J. (1974) Useful headway models, Transportation Research, 9(6), pp. 371-375.

FGSV(Forschungsgesellschaft für Straßen- und Verkehrswesen) (2006): Merkblatt für die Anglage von Kreisverkehren (Guideline for the design of roundabouts).

Harders, J. (1976) Die Leistungsfähigkeit nicht Signalgeregelter städtischer Verkehrsknoten (The capacity of unsignalized urban intersections), Schriftenreihe Strassenbau und Strassenverkehrstechnik., Vol. 216.

Highway Capacity Manual (2010).

Kimber, R. (1980) Traffic Capacity of Roundabouts, Transportation and Research Laboratory, Laboratory Report LR942, Crawthorne, Berkshire, U.K..

McDonald, M. and D.J. Armitage (1978) The capacity of roundabouts, Traffic Engineering & Control, Vol. 19(10), pp. 447-450.

NCHRP (National Cooperative Highway Research Program) (2007): NCHRP Report 572 Roundabouts in the United States.

Siegloch, W. (1973) Die Leistungsermittlung an Knotenpunktem Ohne Lichtsignalsteuerung (Capacity calculations for unsignalized Intersections), Schriftenreihe Strassenbau und Strassenverkehrstechnik, Vo. 154.

Tanner, J. C. (1967) The capacity of an uncontrolled intersection, Biometrica, 54(3 and 4), pp.657-658.

Troutbeck, R. J. (1990) Roundabout capacity and associated delay, Transportation and Traffic Theory, Proceedings of the11th International Symposium on Transportation and Traffic Theory, in Yokohama, Japan.

VISSIM Vision 5.40 User Manual (2012), Planung Transport Verkehr AG, Karlsruhe, Germany.