Estimation of Influencing Factors on Roundabout Capacity at Entry with Crosswalk

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Pedestrian flow is the typical conflicting stream which has significant impact on entry capacity. In existing method, pedestrian impact is estimated through an adjustment factor based on empirical data obtained from roundabouts with standard design[1)]. However some elements of the standard design, e.g. physical splitter island, cannot be always satisfied due to space limitation, especially in Japan. In addition, several factors, i.e. pedestrian approaching side and far-side pedestrian recognition rate (FPRR) are also considered to have impact on entry capacity through influencing pedestrian behavior. This study aims to estimate entry capacity considering pedestrian impact through examining impacts of several influencing factors. Through the simulation study, it was found that entry capacity was reduced more under the condition without physical splitter island and more pedestrians from far-side of the crosswalk whereas it relatively increased with decreasing FPRR.

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

1. INTRDUCTION

At roundabout, circulating vehicles and pedestrians are two conflict flows to entry vehicles. Entry capacity c_{cir} in existing methods is generally estimated by only considering circulating flow based on gap acceptance behavior as shown in **Equation (1)**, which was originally developed for estimating the capacity of minor road stream at unsignalized intersection[2)]. This estimation method is from the view point of microscopic approach and widely applied in several guidelines, e.g., HCM 2010[3)], FGSV[4)] and AUSTROAD[5)].

$$c_{cir} = q_{cir} \int_0^\infty h(t)E(t)dt \qquad (1)$$

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 of size t.

Pedestrian impact on entry capacity is estimated through an adjustment factor f_{ped} which was developed by Brilon, W. et al[1)] and applied in HCM 2010 (named f_{ped} model thereafter). The f_{ped} model was developed dependent on circulating flow q_{cir} and number of pedestrians n_{ped}, and the concept of f_{ped} is described as follows.

- q_{cir}≥881veh/h, f_{ped}=1
- q_{cir}<881veh/h and n_{ped}≤101ped/h, f_{ped} is represented in **Equation (2)**.

$$f_{ped}=1-0.000137n_{ped} \qquad (2)$$

- Else if q_{cir}<881veh/h and n_{ped}>101ped/h, f_{ped} is described by **Equation (3)**.

$$f_{ped} = \frac{1119.5 - 0.715q_{cir} - 0.644n_{ped} + 0.00073q_{cir}n_{ped}}{1068.6 - 0.654q_{cir}} \qquad (3)$$

Accordingly, entry capacity with pedestrian impact c_{RAB} is estimated by **Equation (4)**.

$$c_{RAB}=c_{cir} \cdot f_{ped} \qquad (4)$$

The existing f_{ped} model was developed based on the roundabouts which are under the conditions of single-lane approach with physical splitter island at entry/exit, crosswalk and one-vehicle length between crosswalk and yield line. However, in places with the problem of space limitation, e.g., Japan, some conditions such as physical splitter island cannot be satisfied, so that the f_{ped} model may not be appropriate to apply. Moreover, under the condition without physical splitter island, several influencing factors, i.e. far-side pedestrian directional ratio r_{far}, far-side pedestrian recognition rate FPRR are also considered to have impact on pedestrian behavior further influence entry capacity, however not reflected in the existing estimation method. Therefore, the objective of this study is to examine impact of the influencing factors, i.e. physical splitter island, r_{far}, FPRR and pedestrians across downstream exits on entry capacity considering Japanese situations. Since it is not realistic to collect entry capacity data considering various conditions at a limit number of roundabouts in Japan, microscopic simulation is adopted as the analysis tool for this study.

2. LITERATURE REVIEW

Tollazzi et al[6] estimated entry capacity considering pedestrian flow at downstream exits. Entry capacity was found to be reduced when motorized vehicles are disturbed by pedestrian and cyclist flow. Duran and Cheu[7] identified the influence of crosswalk position on entry capacity at two-lane roundabout and found that entry capacity was reduced when decreases the distance between downstream edge of crosswalk and yield line. However, none of these studies considering impacts of pedestrian approaching side and with/without physical splitter island which may have significant impact on entry capacity.

3. SIMULATION ANALYSIS

(1) Layout of example roundabout

Microscopic simulation software VISSIM 5.40[8] is utilized for this study. The simulation analysis is conducted at a four-lag roundabout with crosswalk at each entry. The diameter is assumed to be 27m which is the minimum standard value for four-leg roundabout and trucks are allowed to travel smoothly under such condition. As shown in **Fig.1**, Entry S is selected as the subject entry to observe entry capacity. In order to examine the impact of physical splitter island, it is assumed that the physical splitter island is uninstalled only at Entry S whereas it is installed at other entries. In addition, 5m, which is equal to one-vehicle length, is given between crosswalk and yield line at each entry.

(2) Input parameters

a) Speed

Vehicle speed and pedestrian speed are set to be 20km/h and 4km/h, respectively.

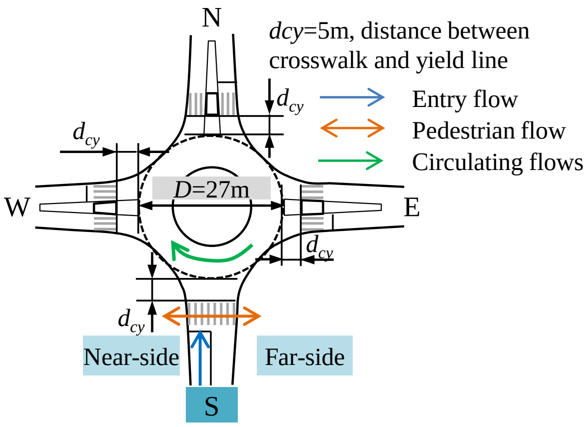


Fig.1 Assumed roundabout in VISSIM

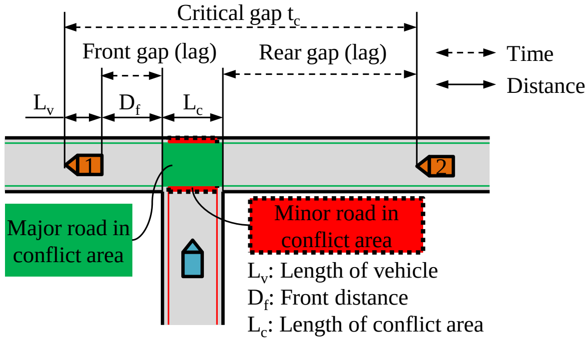


Fig.2 Relationship of critical gap and "front gap" and "rear gap" in the function of "conflict area"

b) Gap acceptance behavior

Entry vehicles are assumed to cross pedestrian flow by utilizing available gaps of pedestrians, which is similar to merging into circulating flow. Thus, the impact of pedestrians and circulating vehicles on entry capacity is estimated by gap acceptance theory. In gap acceptance theory, critical gap, follow-up time and minimum headway are importance parameters for estimating entry capacity. Critical gap is the parameter reflecting the driver's judgment to conflict flow, which is realized by the function of "conflict area" in VISSIM 5.40. While, the parameters of follow-up time and minimum headway which is related to car-following behavior are expressed by the functions of driving behavior in VISSIM 5.40.

i) Conflict area

Conflict area is defined as the overlap area of major road and minor road. In VISSIM 5.40, critical gap cannot be directly utilized in conflict area model. Instead of critical gap, "rear gap" and "front gap" need to be set in conflict area model. "Rear gap" is defined as the minimum time lag before a vehicle in major road entering into conflict area, which can be used for major road to cross or enter into the major flow. "Front gap" is defined as the minimum time lag after a vehicle in major road leaving the conflict area, which can be used for a vehicle in minor road to cross or enter into the major flow. According to these definitions, the relationship of critical gap and "rear gap" and "front gap" can be shown by **Fig. 2**. "Front gap" is calculated by front distance and speed of subject in major road. Front distance D_F is defined as the minimum distance between the subject in major road which has crossed conflict area and the downstream edge of conflict area in major road which can be used for the subject in minor road to cross or merge into the major flow.

At roundabout, circulating vehicles and pedestrians are given priority. Thus, the front distances regarding circulating vehicles and pedestrians are assumed to be 2.5m and 1.5m in this study, respectively. According to the inputting vehicle speed and pedestrian speed, the values of front gap which are related to circulating vehicles and pedestrians are calculated to be 0.5sec and 1.35sec, respectively. The lengths of vehicle and conflict area are assumed to 4.5m and 3.5m, respectively. Critical gaps regarding circulating vehicles is observed in several places in Japan and selected to be 4.5sec in this study. Thus, based on the relationship of critical gaps and the parameters in the function of "conflict area" in **Fig. 2**, rear gap regarding circulating vehicle is calculated to be 2.7sec. For the conflict of entry vehicles and pedestrians, in this research, it is assumed that when far-side pedestrian recognized rate (FPRR) is in the range [0,1), for the unrecognized far-side pedestrians, all entry vehicles stop at the moment when the pedestrians are about to leave the middle line of the crosswalk as the same as the situation that physical splitter island is installed. When FPRR is equal to 1, the assumption is that that all entry vehicles stop at the moment when pedestrians are about to cross the edge of crosswalk regardless pedestrian approaching sides under the condition without physical splitter island. These assumptions are also applied on the case of exiting vehicle and near-side pedestrians. In order to realize these assumptions, the "rear gap" for near-side and far-side pedestrians under the condition without physical splitter island is necessary to be given the value of 1.7sec and 6.00sec. If the value of "rear gap" is smaller than these input values, entry vehicles will cross the crosswalk even pedestrians already enters the crosswalk. The setting of parameters in the function of "conflict area" regarding entry vehicles is shown in **Table 1(a)**. For exit vehicles, the values for near-side pedestrians and far-side pedestrians are mutually exchanged.

ii) Car-following behavior

Follow-up time and minimum headway are realized by the function of driving behavior model in VISSIM 5.40. Two car-following models, i.e., "Wiedemann 74" and "Wiedemann 99" are applied in driving behavior function. "Wiedemann 74" model is selected since this model is more appropriate to apply on urban road. Three parameters in "Wiedemann 74" model are calibrated, i.e., "average standstill distance" which is defined as the average desired distance between stopped cars, "additive part of desired safety distance" and "multiplic. part of desired safety distance" which are the parameters to affect the computation of the safety distance. The values of follow-up time crossing pedestrian flow and merging into circulating flow are assumed to be identical which is equal to 3.2sec, and minimum headway of circulating vehicles is assumed to be 2.2sec, which are selected based on empirical data. The follow-up time and minimum headway are adjusted on entry road and circulating roadway, re-

Table 1 Input value of parameters in simulation

(a) The function of "conflict area"

	circulating vehicles	Pedestrians			
		With physical island		Without physical island	
		Near-side	Far-side	Near-side	Far-side
Front gap (sec)	0.450	1.35			
Rear gap (sec)	2.70	1.70			6.00

(b) "Wiedemann 74" car-following model

	Average standstill distance (m)	Desired safety distance (m)	Multiple part
Entry road (t_f=3.2 sec)	2.00	2.00	3.00
Circulating roadway (τ=2.2 sec)	1.50	2.00	3.00

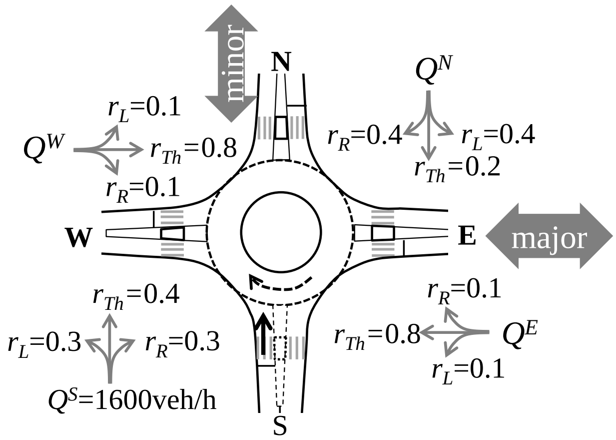


Fig.3 Setting of vehicle traffic flow and turning ratio at each entry

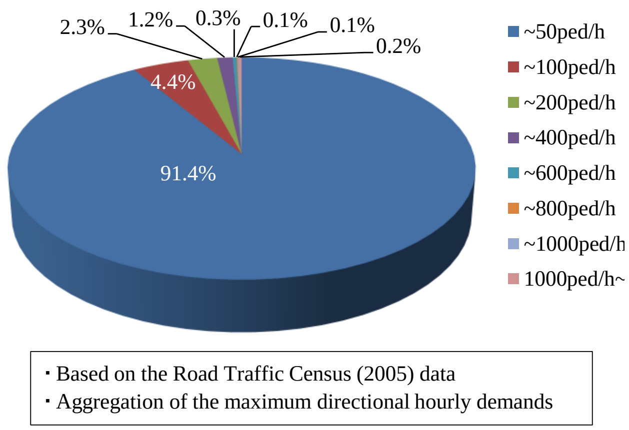


Fig.4 Pedestrian demands at major intersections in Japan (Source: MLIT [9])

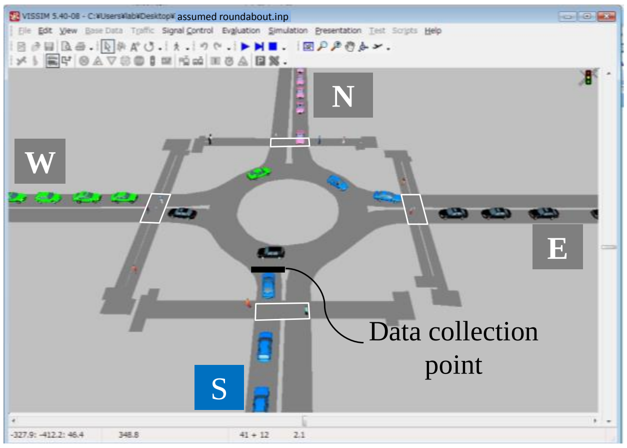


Fig.5 Screenshot of simulation

spectively. The values of three parameters in "Wiedemann 74" are shown in **Table 1(b)**.

(3) Simulation design

a) Vehicle flow

In order to observe entry capacity, saturated condition of entry flow, 1600veh/h is created at Entry S. Based on **Equation (1)**, entry capacity is affected by the headway distribution $h(t)$, which is determined by arrival rate of circulating flow. Since circulating vehicles are composed of entry vehicles from each entry, the arrival rate is affected by entry flows of each entry. The roundabout is assumed to locate under the condition that the ratio of traffic demand between major road and minor road is equal to 8:2. Entries E and W are in the major road and Entries N and S are in the minor road. For each major and minor road, a fixed turning ratio is given. Circulating flow is composed of flow E→W, E→N and N→W. The ratio of major flow to minor flow and the turning ratio of each entry are shown in **Fig. 3**.

b) Pedestrian flow

Pedestrian demand is referred to the observation in Japan which is provided by Ministry of Land, Infrastructure, Transport and Tourism[9]. **Fig. 4** shows this record in this report and it is found that based on the census data, pedestrian demand is lower than 200ped/h/approach at most roads (more than 99%).

Accordingly, at any entry, the maximum pedestrian demand of one entry is set to be 200ped/h in order to include the case of high pedestrian demand and with the interval of 50ped/h when pedestrian demand is lower than 200ped/h. Moreover, pedestrian demand at Entries N, W and E is set to satisfy the condition $Q_{ped}^{N} = Q_{ped}^{W} = Q_{ped}^{E}$.

c) Far-side pedestrian directional ratio r_{far}

Far-side pedestrian directional ratio r_{far} is defined as the proportion of far-side pedestrians in total pedestrian demand regarding one entry. At Entry S, three ratios are examined, 0, 0.5 and 1. The value of r_{far} at other entries is assumed to be identical and the value of 0.5 is given.

d) Far-side pedestrian recognition rate FPRR

Under the condition without physical splitter island, FPRR at Entry S is examined by three levels 0, 0.5 and 1. Under the condition with physical splitter island, since all entry vehicles are assumed to stop at the moment when far-side pedestrians are about to leave the edge of physical splitter island, FPRR is not examined.

e) With/without physical splitter island

At Entry S, physical splitter island is assumed to be installed and uninstalled through adjusting the gap parameter of pedestrians in the function of "conflict area" whereas at other entries, physical splitter island are assumed to be installed.

Thus, in total 6,300 combinations were computed. For every combination of input conditions, the VISSIM model was run for 10 times with a unique random number seed. And each of them was run for 1h15min simulation time with 15min warm-up time. The data in first 15min of warm-up time was not included in results. Performance statistics were measured at 15min intervals. The measured entry flow (veh/h) was averaged based on 10 simulation runs. **Fig. 5** shows a screenshot of the VISSIM model during a simulation run.

4. RESULTS AND DISCUSSIONS

(1) Maximum entry flow without pedestrians

Fig. 6 shows the entry capacity from simulation under the condition without pedestrians at any entry.

The simulation output is compared to the estimated result by German formula to examine the accuracy of simulation output. The German formula is shown in **Equation (5)**.

$$c_{cir} = \frac{3600}{t_f}(1 - \tau\frac{q_{cir}}{3600})\exp\left[-\frac{q_{cir}}{3600}(t_c - \frac{t_f}{2} - \tau)\right] \qquad (5)$$

c_{cir} is entry capacity considering only circulating flow, q_{cir} is circulating flow, t_f is follow-up time which is equal to 3.2sec, τ is minimum headway of circulating vehicles and equal to 2.2sec and t_c is critical gap which is equal to 4.5sec.

It is found that simulation output matched well with estimated result when circulating flow is in low level and the simulation output is lower than the estimated result when circulating flow is increased. Generally, it can be concluded that the simulation output is reasonable according to the t-value at 95% confidence comparing to the estimated result.

(2) Pedestrian demand at subject entry

Fig. 7 shows the result of estimated entry capacity under the conditions (1) with physical splitter island; (2) no pedestrians across other entries; (3) r_{far}=0.5 and (4) FPRR=1. It is found that at the same level of circulating flow, entry capacity is reduced when pedestrian demand increases.

(3) Far-side pedestrian directional ratio r_{far}

Fig. 8 plots the estimated entry capacity considering pedestrian approaching side (r_{far}=0 and r_{far}=1) under the conditions (1) without physical splitter island; (2) no pedestrians across other entries and (3) FPRR=1. The result under the pedestrian demand 200ped/h was selected as the examples.

It is found that under the condition without physical splitter island, entry capacity is reduced most significantly when all pedestrians are from far-side. A better performance on entry capacity is obtained when all pedestrians are from near-side. This is because the waiting time for pedestrians from far-side is longer than that for pedestrians from near-side under the assumption that all entry vehicles stopped at the moment when pedestrians are about to cross at the curb of crosswalk and wait until pedestrians complete crossing the conflict area. It implies that entry capacity will be reduced more at the entrance when more pedestrians are from far-side, especially under the condition without physical splitter island.

(4) Far-side pedestrian recognition rate FPRR

In the analysis of pedestrian approaching side, all entry vehicles are assumed to react to far-side pedestrians at the moment when pedestrians are about to cross the far-side curb of crosswalk. However, in

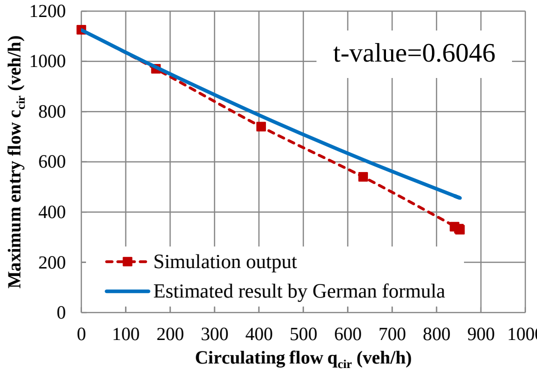


Fig.6 Estimated maximum entry flow without pedestrians

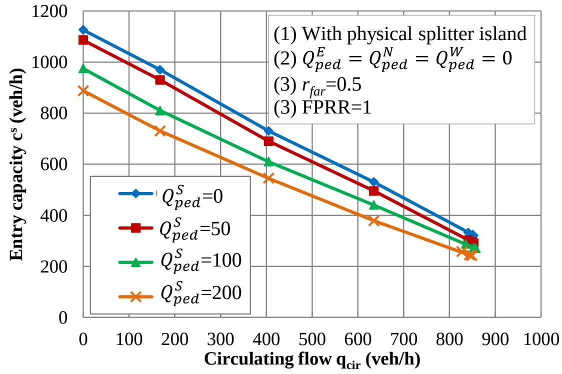


Fig.7 Estimated entry capacity changing with pedestrian demand at subject entry (Entry S)

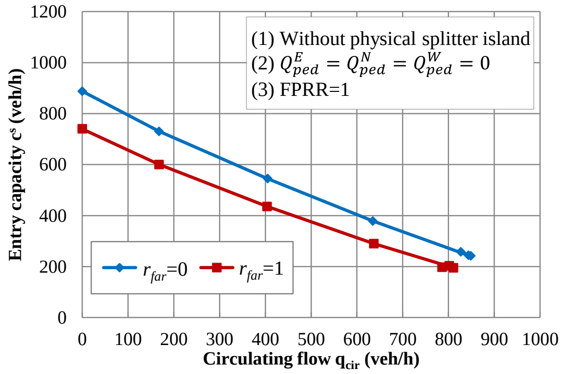


Fig.8 Estimated entry capacity varies as r_{far} under the condition without physical splitter island

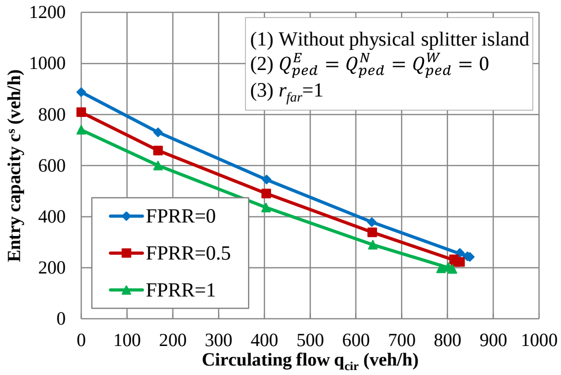


Fig.9 Estimated entry capacity varies as FPRR under the condition without physical splitter island

the real world, not all drivers exactly behave in the same way to recognize pedestrians under the same condition. Therefore, FPRR is utilized to represent this uncertainty.

Fig. 9 represents the estimated entry capacity regarding FPRR under the conditions (1) without physical splitter island; (2) no pedestrians across other entries and (3) r_{far}=1 at Entry S. The result under the pedestrian demand of 200ped/h was selected as the example. It is found that under a certain level of pedestrian demand, entry capacity is reduced with the increase of FPRR. Entry capacity performs the lowest and highest value under the rate of 1 and 0, respectively.

FPRR in the range of (0, 1) reflects the real world situation, which implies that when only assuming FPRR equals to be 1, impact of pedestrian will be overestimated further underestimating entry capacity. It can be suggested that a realistic FPRR should be considered with pedestrian approaching side in entry capacity estimation so that the real world situation can be appropriately reflected.

(5) Physical splitter island

The results of estimated entry capacity considering with/without physical splitter island and under the conditions (1) no pedestrians across other entries; (2) r_{far}=1 at Entry S and (3) FPRR=1 are shown in **Fig. 10**. The result under the pedestrian demand of 200ped/h was selected as the example.

From the simulation output, it is found that under certain pedestrian demand, entry capacity performs higher value under the condition with physical splitter island since more vehicles can pass and waiting time is shortened under this condition. In addition, the difference of entry capacity at a certain level of circulating flow between with and without physical splitter island becomes larger when pedestrian demand increases due to increase in total waiting time.

However, in real world, the function of physical splitter island will be not as significant as simulation showing when pedestrian demand is at the high level. Pedestrians will cross as platoon due to high demand so that drivers have to choose to take stopping behavior, no matter physical splitter island existing or not. On the other hand, when pedestrian demand is at low level, although entry capacity varies slightly under the condition with physical splitter island based on simulation output, physical splitter island plays an important role from the safety consideration in real world. Under this condition, most of drivers will pass the crosswalk without giving priority to pedestrians due to low pedestrian demand. Moreover, pedestrians have to mind both of the entry and exit vehicle flows at same time during crossing when

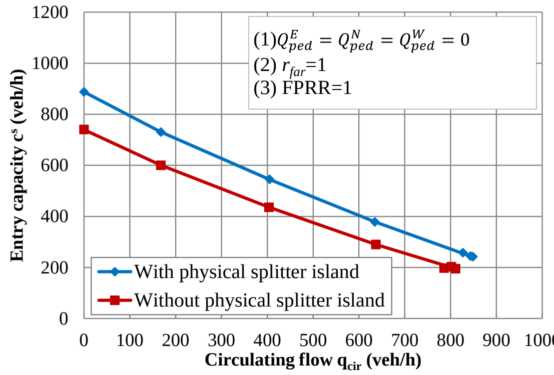


Fig.10 Estimated entry capacity varies as condition with/without physical splitter island

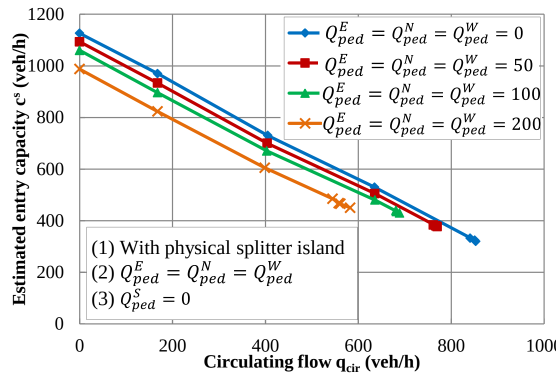


Fig.11 Estimated entry capacity changing with pedestrians across downstream exits

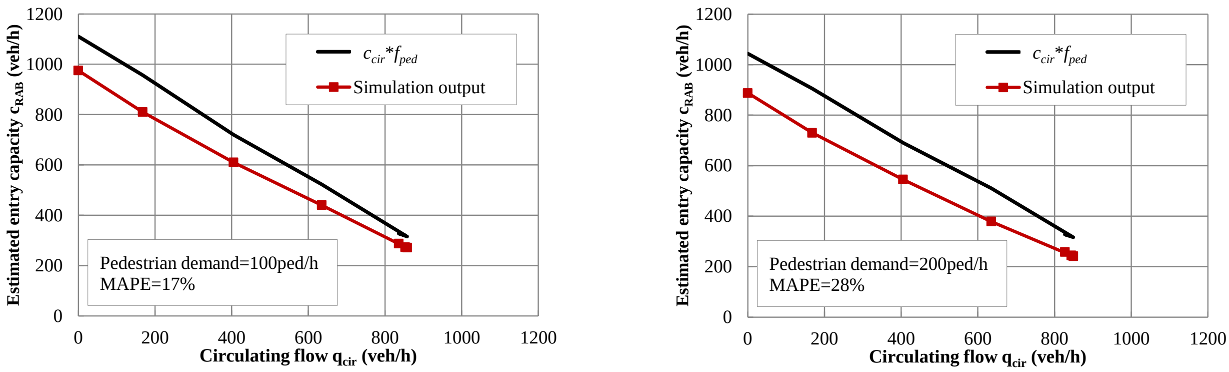
physical splitter island is uninstalled. These cause pedestrians having to wait and increasing the risk during crossing. Therefore, physical splitter island is strongly recommended to be installed at the entrance of roundabouts from the considerations of mobility and safety.

(6) Pedestrians across other entries

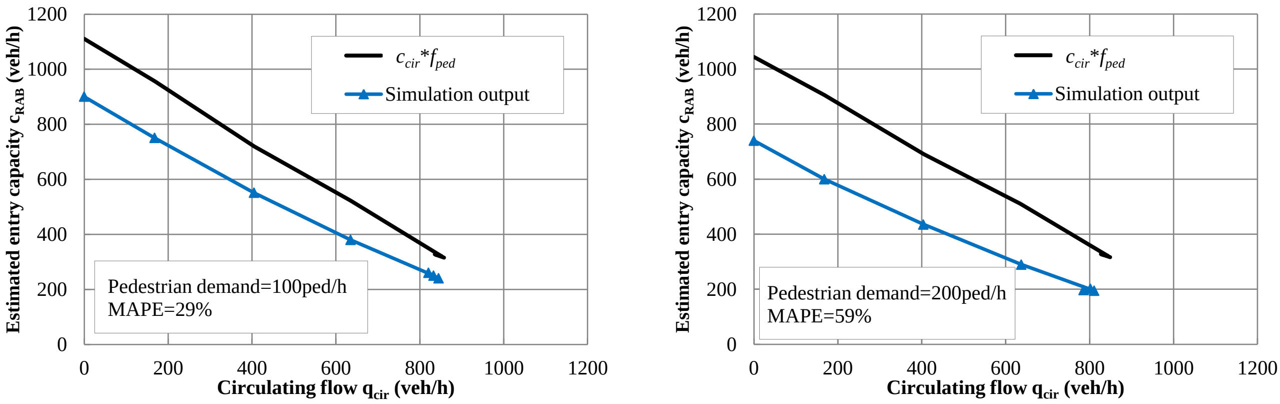
Fig. 11 represents the estimated entry capacity regarding pedestrians across other entries under the conditions (1) with physical splitter island; (2) identical pedestrians demand at other entries and (3) no pedestrians across Entry S. It is found that entry capacity is reduced with the increase of pedestrian demand. This is because the probability of queue in circulating roadway is increased when the pedestrians across downstream exits increase. Thus, entry capacity at upstream entry is reduced more with this higher probability of queue.

(7) Comparison of estimation by f_{ped} model and simulation output

Entry capacity considering pedestrian impact by f_{ped} model was estimated based on **Equation (4)**. In order to focus on identifying the effect of f_{ped}, the difference between c_e estimated by HCM 2010 and the capacity without pedestrians calculated by simulation should be avoided. Thus, the simulation result



(a) With physical splitter island



(b) Without physical splitter island

Fig.12 Comparison of results from f_{ped} model and simulation output

without pedestrians is here input as value c_e of **Equation (4)**. f_{ped} is calculated by **Equations (2)** and **(3)** dependent on the demand of circulating vehicles and pedestrians. Although f_{ped} model was not developed for the situation without physical splitter island, it is necessary to show the difference between the result from f_{ped} method and simulation result to determine whether splitter island can be considered as an influencing factor. The results of simulation under the conditions r_{far}=1, FPRR=1, no pedestrians across downstream exits and pedestrian demands of 100ped/h and 200ped/h at Entry S were selected as examples.

Estimation results by utilizing f_{ped} model and simulation output are shown in **Fig. 12**. It is found that firstly, at each level of circulating flow and pedestrian flow, the estimation result from f_{ped} model is higher than that in simulation output in all situations. Secondly, comparing to simulation output, under certain levels of pedestrian and circulating flows, estimation result from f_{ped} model does not vary dependent on situations. This is because the examined influencing factors, e.g. physical splitter island were not considered in f_{ped} model.

Furthermore, in order to evaluate the relative margin of estimation errors, one statistic is applied: *Mean Absolute Percentage Error* (*MAPE*). *MAPE* returns the absolute percentage difference in both values. The equation is provided below.

$$MAPE = \left(\frac{1}{N} \sum_{i-1} \frac{|x_i - \hat{x}_i|}{x_i} \right) \cdot 100\% \tag{5}$$

where x_i is simulation output, and $\hat{x}_i$ is estimation result from f_{ped} model.

As shown in **Fig.12**, *MAPE* of all samples reveal the estimation error higher than 17% and the value of *MAPE* is increased when pedestrian demand increases. In addition, the estimation error shows higher value under the condition without physical splitter island. It is indicative that without considering various influencing factors and the characteristics of situations in Japan, f_{ped} model may show drawbacks to appropriately estimate roundabout entry capacity under pedestrian impact in Japanese situations.

5. CONCLUSIONS AND FUTURE WORKS

The impacts of several influencing factors on entry capacity from the view point of Japanese situation were examined based on simulation VISSIM 5.40. It was found that considering pedestrian impact, entry capacity was reduced more significantly when more pedestrians are from far-side under the condition without physical splitter island and the assumption that all entry vehicles stopped at the moment when pedestrians are about to cross the curb. Moreover, FPRR was added to make the situation more realistic and entry capacity was found to be decreased as increase in FPRR. After assuming the condition with physical splitter island, entry capacity under the condition of pedestrians from far-side was relatively increased due to the shorter waiting time. Finally, a comparative analysis of simulation output and estimation result from f_{ped} model indicated that estimation result from f_{ped} model will give an overestimated performance on entry capacity due to not considering these influencing factors.

This analysis demonstrated the function of physical splitter islands playing an important role of improving the entry capacity. Therefore, also from the view point of operational performance, the physical splitter island is recommended to be installed at entries/exits, e.g., under the condition of high pedestrian demand and high FPRR. Besides this, from the consideration of safety, physical splitter islands are necessary to be installed at roundabouts with low pedestrian demand, since the crosswalk is divided into two parts and pedestrians can cross entry and exit flow separately. The results of comparison of simulation output and estimation result from f_{ped} model suggested that pedestrian approaching side, FPRR and physical splitter island should also be considered in entry capacity estimation in future.

In this study, due to the limited number of samples regarding pedestrians, the parameters which are utilized to reflect pedestrian behavior in the function of “conflict area” could not be calibrated. Toward this, data collection on the sites with relatively higher pedestrian demand should be conducted in future.

REFERENCES

1) Brilon, W., Stuwe, B., and Drews., O., Sicherheit und Leistungsfähigkeit von Kreisverkehrsplätzen (Safety and Capacity of Roundabouts). Research report. Ruhr-University Bochum, Germany, 1993.
2) Traffic Flow Theory, FHWA, 2010
3) Highway Capacity Manual, Transportation Research Board, 2010
4) FGSV (Forschungsgesellschaft für Straßen- und Verkehrswesen) Merkblatt für die Anglage von Kreisverkehren (Guideline for the design of roundabouts), 2006
5) AUSTROADS: Guide to Traffic Engineering Practice, Part 6-Roundabouts. Sydney, Australia, 1993
6) Tollazzi T., Lerher T. and Sraml M., Simulation of the Pedestrians’ Influence to the Capacity of Motorised Vehicles in a Roundabout, American Journal of Applied Sciences 5(1): 34-41, 2007
7) Duran, C. & Cheu, R.L., Effect of crosswalk location and pedestrian volume on entry capacity of roundabouts. *Proceedings of the 90th Transportation Research Board Annual Meeting*, Washington, D.C., 2011
8) VISSIM Version 5.40 User Manual, 2012
9) 国土交通省道路局，ラウンドアバウトの計画・設計に必要な知見に関する検討，第2回ラウンドアバウト検討委員会配布資料，2014.

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