Analysis on cooperative yielding maneuver of circulating vehicles to entering vehicles at Roundabouts

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According to the priority rule at roundabouts (RAB), circulating vehicles have priority over the entering vehicles. However, the cooperative yielding maneuver (CYM) that some of them decelerate to create a gap for the entering vehicles also happens. The CYM may affect the efficiency and safety of roundabouts. Therefore, this study aims to analyze the CYM of circulating vehicles at roundabouts considering driving characteristics. The observed data of Towacho roundabout is used to analyze the CYM using indicators such as the post-encroachment time (PET). Then, the CYM is defined according to the deceleration maneuver of circulating vehicles. Empirical analysis related to the CYM are also discussed. From the results, it was found the circulating vehicles started decelerating when the entering vehicles entered the RAB. With a higher speed of entering vehicle as well as a longer distance to conflict point, the circulating vehicle tends to choose the CYM.

Key Words: *roundabout, circulating vehicle, entering vehicle, cooperative yielding maneuver*

1. INTRODUCTION

Roundabouts have advantages on improving operational performance (Brilon, et al.[1)]). They reduce the number of conflict points so that vehicles only need merging maneuvers to enter the RABs. The circulating vehicles is given the priority (Highway Capacity Manual[2)], HCM 2010). In Japanese manual, the entering vehicles are also supposed to give way to the circulating vehicles which have priority.

However, the CYM that circulating vehicles create a gap for entering vehicles often happened. Although this maneuver is inconsistent with the existing traffic rule, it can be regularly observed in the field. Furthermore, current capacity and operational models for roundabouts may not be accurate as they do not account for the CYM. It is unclear as to whether the CYM has a positive or negative impact on capacity.

Thus, the objective of this study is to investigate the CYM characteristics of circulating vehicles as well as the influencing factors that affect vehicle maneuvers such as vehicle speed, distance to the conflict point, and expected PET.

2. LITERARURE REVIEW

A review of current gap-acceptance, and game theory methods is presented. Limitations in existing methods with respect to modeling driver maneuvers at the roundabout are discussed.

(1) Gap-acceptance models

Gap acceptance frameworks assume vehicles waiting on the entry approach will only enter a gap in the circulating stream of traffic that provides a safe entering opportunity. Typically, these gap opportunities are within the four to five second range

at roundabouts (Kimber, et al.[3]).

The Highway Capacity Manual (HCM) 2010 method for roundabout analysis is gap acceptance-based and is an empirical regression fit to capacity observations in the United States. The HCM 2010 method uses critical gap and follow-up time as adjustment parameters while assuming that follow-up time will always be less than critical gap time. The HCM 2010 does indicate, however, that simplified gap-acceptance models may not produce reliable results when there are effective changes in priority.

However, these frameworks are grounded on theories originally developed for stop-controlled intersections (Tanner, et al.[4]) and their applicability to roundabouts is questionable. The major limitation of gap acceptance theory for roundabouts is its failure to account for specific vehicle maneuver which is the CYM. It is caused by circulating vehicles which decelerate to create a gap. Therefore, gap-acceptance based methods have significant limitations for roundabouts.

(2) Game theory models

Many researchers proposed to present the CYM based on game theory model. A cooperative maneuver planner at lane closures was studied by Li et al.[5] in by following a cooperative-scheduling and trajectory planning approach. The authors represent all potential crossing orders through a spanning tree, trajectories are then calculated for each of them, and the best one is chosen. Lenz et al.[6] proposed a cooperative combinatorial motion planning based on Monte Carlo Tree Search. Summarizing, the approach uses a traffic model to predict the outcome of different feasible driving maneuvers and triggers the best one. Furthermore, Awal et al.[7] tackled the design of a cooperative lane-change algorithm that minimizes fuel-consumption, pollutant-emission, and the impact of the lane-change maneuver on the traffic flow. However, these models entirely disregard the existing priority rule in the interest of efficiency enhancement.

3. DATA COLLECTION AND PROCESSING PROCEDURES

(1) Study site and data observation

In order to investigate the CYM, video data was collected at Towacho RAB in Iida City, Japan. **Table 1** presents the observation time, and the circulating vehicle and entering vehicle demands during observation periods. Both peak and off-peak hours were observed. In this observed site, there are large vehicle volumes at west and north approaches so that there are a lot of interactions between the entering vehicles from the north approach and circulating vehicles from the west approach were observed.

Table 1 entry volume from each approach

Observation time	N	NW	W	S	E	Total volume (per hour)
13:00-14:00	344	112	492	344	296	1588
14:00-15:00	722	163	939	667	701	3192
15:00-16:00	411	148	545	432	350	1886
16:00-17:00	675	162	1019	800	632	3288

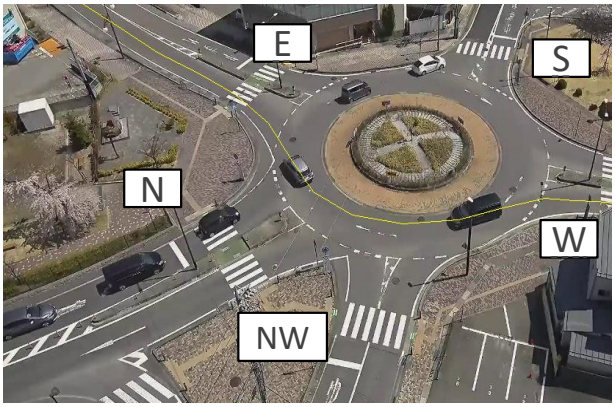


Fig.1 Vehicle trajectory collection

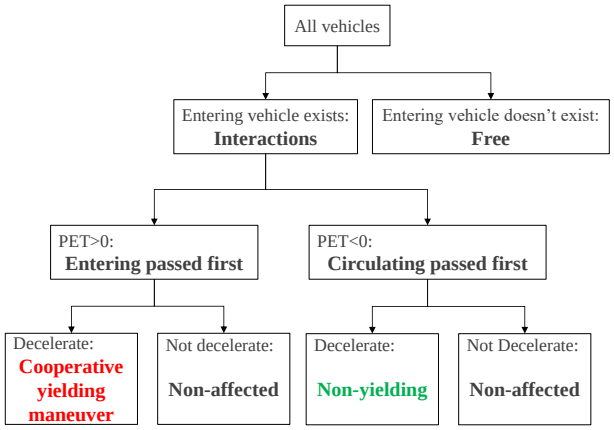


Fig.3 Definition of CYM

Vehicle trajectories, which include the positions and the timings, were extracted from video data. The positions of each vehicle were extracted every 0.3s. The point where the right-rear wheel is touching the ground is the reference observation point for all vehicles. All video observations were conducted from high buildings surrounding the intersections; thus, for all videotapes, the observation angle is large. This allows us to track the right rear wheel of all turning vehicles without issues such as occlusion or high coordinate transformation error. **Fig.1** shows one example of vehicle trajectory data (yellow line).

(2) Coordinates conversion and Kalman smoothing

The corresponding video coordinates were converted to global coordinates by Python-OpenCV. In order to validate the accuracy, the differences between the true crosswalk length and width and converted results were calculated using the **Eq.(1)**. All the differences are smaller than 5%. The transformed trajectories were smoothed by the Kalman smoothing method.

$$\delta = \frac{|l_{trans} - l_{true}|}{l_{true}} \times 100\% \quad (1)$$

Where,

δ : differences between the true length and converted results (%),

l_{trans} : the length calculated based on the converted coordinates (m), and

l_{true} : the true length obtained from the global coordinates (m).

4. METHODOLOGY

(1) Definitions

In this study, the vehicle interaction refers to the circulating vehicle passing the RAB when entering vehicle exists (illustrated in **Fig.3**). Free vehicles are defined as the vehicles not affected by others - not only entering vehicles, but also leading vehicles. That means their maneuvers are only influenced by geometric conditions. Therefore, free vehicles are just for comparison in the following analysis part.

For analyzing the vehicle interactions, researchers have long relied on using surrogate safety measures (SSMs) such as the post encroachment time (PET) measures. The PET is calculated between two interacting vehicle trajectories as shown in **Fig.4**. Conflict point is defined as the point where the trajectories of two users intersect. According to the calculated results (shown in **Fig.5**), there are two groups within vehicle interactions which are the entering passed first with positive PET values and the circulating passed first with negative PET values. In **Fig.5(a)**, only the interactions with PET value larger than -10s and all the interactions in **Fig.5(b)** were included in the following analysis.

Within the above two groups, not all circulating vehicles are influenced by the entering vehicles. **Fig.6** shows the two examples of the "Entering passed first" group, another two examples of "Circulating passed first" group, as well as one free-vehicle for contrast. For each group, compared to the free-vehicle, there is one circulating vehicle's maneuver similar to the free-vehicle even though it passed after the entering vehicle. But it was not influenced since the distance between them is still far away. However, another circulating vehicle in "Entering passed first" decelerates significantly to create a gap for the entering vehicle which is defined as the cooperative yielding maneuver as shown in **Fig.3**. Similar situations also occur in another group, and those affected, resulting in a decrease in speed, are defined as 'Non-yielding'. Within the context of this study, when a circulating vehicle encounters a entering vehicle and remains uncertain about the entering vehicle's intent to abruptly enter the RAB, it

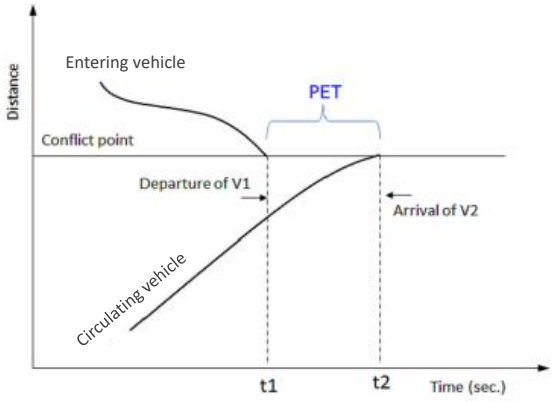
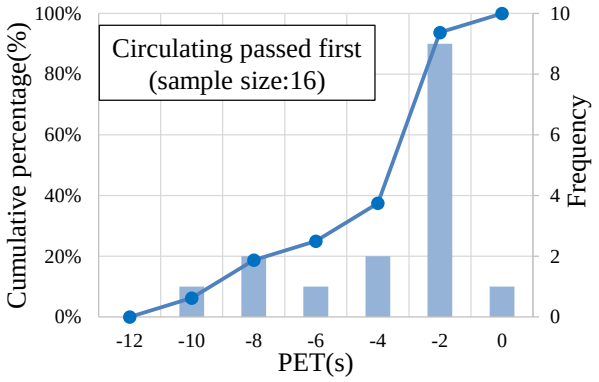
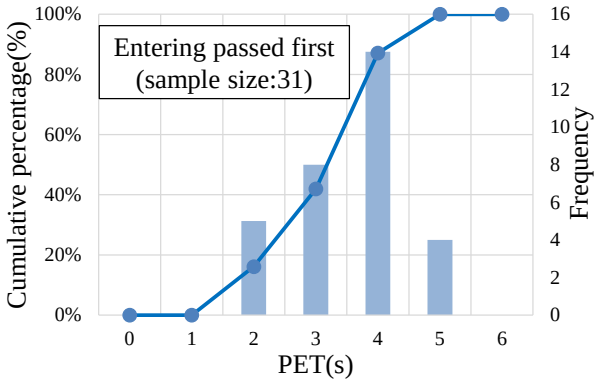


Fig.4 Definition of PET



(a) Circulating vehicle passed the CP first



(b) Entering vehicle passed the CP first

Fig.5 Observed PET values

exhibits deceleration maneuver. Furthermore, in cases where the entering vehicle also decelerates to yield, certain circulating vehicles may opt for prioritized passage. In the scenarios described above, even when the vehicles' maneuvers comply with the established priority rule, deceleration phenomena still manifest.

(2) Expected PET

To investigate the vehicle maneuver at each time step, the indicator expected PET was chosen for analysis. The calculation method is showing in the following **Eq.(2).**

$$Expected\ PET = \frac{d_{c-cp}}{V_c} - \frac{d_{e-cp}}{V_e} \quad (2)$$

Where,

d_{c-cp}: the distances between circulating vehicle and conflict point (m),

V_c: speed of circulating vehicle (m/s),

d_{e-cp}: the distances between entering vehicle and conflict point (m), and

V_e: speed of entering vehicle (m/s).

5. EMPIRICAL ANALYSIS

(1) Characteristics of circulating vehicles

Fig.7 shows the cumulative distribution of circulating vehicles' speed. Based on the results depicted in the figure, it can be observed that vehicles of the CYM category exhibit the slowest velocities. This phenomenon can be attributed to the fact that these vehicles engage in deceleration when encountering entering vehicles, thus creating a gap for the latter to pass. In contrast, the non-yielding vehicles also undergo deceleration due to the interference caused by entering vehicles. However, they continue to adhere to the priority rule and do not yield. Consequently, the velocity of non-yielding vehicles remains closer to that of free-flowing vehicles.

To investigate when vehicles in the CYM category commence their deceleration and explore the reasons behind their yielding maneuver, we defined deceleration as a continuous decrease in speed occurring three or more times. Furthermore, to eliminate deceleration induced by geometric conditions and other factors upon entering the roundabout (RAB), this study analyzes data from the point at which vehicles cross the yielding line to the exiting line. **Fig. 8** illustrates the distance of entering vehicles from the conflict point when circulating vehicles begin to decelerate. From the figure, it can

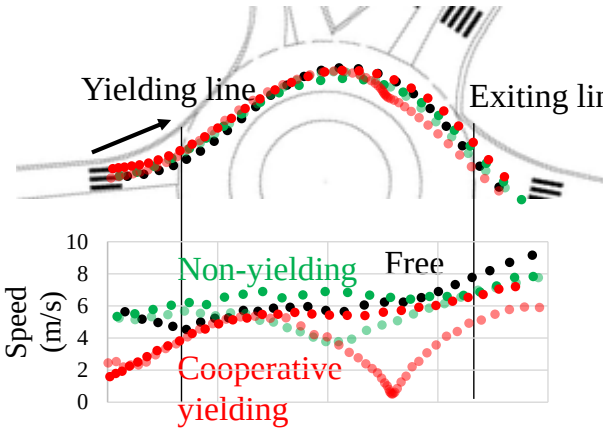


Fig.6 Comparison of CYM and free-vehicles

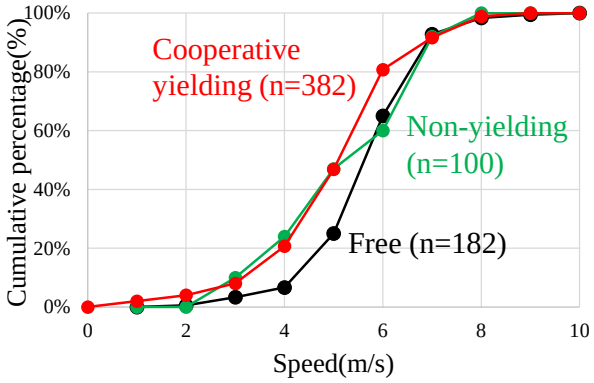


Fig.7 Cumulative distribution of circulating vehicles' speed

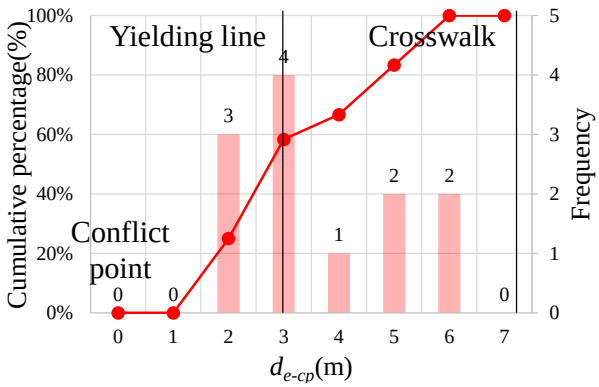


Fig.8 Cumulative distribution of distances between entering vehicles and conflict point

be observed that circulating vehicles initiate their deceleration when entering vehicles are in proximity to the yielding line. Consequently, the choice of CYM by the circulating vehicle is contingent on the entering vehicle's position because, when the entering vehicle crosses the yielding line and enters the RAB, the circulating vehicle has no alternative but to decelerate in order to avoid a collision.

(2) Comparison between cooperative yielding maneuver and non-affected vehicles within the entering passed first

All samples of cooperative yielding maneuver and non-affected vehicles within the "entering passed first" group are plotted in the $d_{c\text{-}cp}$-V_c as shown in **Fig.9**. The figure represents the corresponding circumstances when circulating vehicles initiate deceleration. However, the non-affected vehicles did not exhibit a distinct initiation of deceleration. To facilitate a comparative analysis with the CYM vehicles, and in alignment with the aforementioned findings, we also captured the V_c and $d_{c\text{-}cp}$ as entering vehicles entered the roundabout. The horizontal axis depicts the distance between the circulating vehicle and the conflict point, while the vertical axis represents the speed of the circulating vehicle at that moment. Given the earlier analysis, which indicated that the distance to the conflict point ($d_{e\text{-}cp}$) is nearly constant when circulating vehicles commence deceleration, an examination of V_c and $d_{c\text{-}cp}$ at this moment provides insights into the factors influencing the choice of CYM by circulating vehicles. It is observed that, when the distance to the conflict point is relatively short, vehicles tend to opt for CYM. Conversely, when vehicles are farther from the conflict point, the influence is minimal.

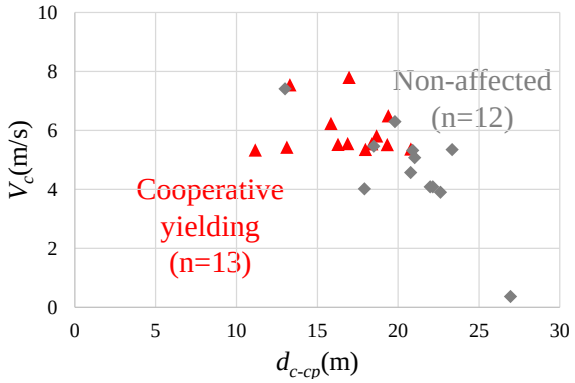


Fig.9 Comparison between cooperative yielding maneuver and non-affected vehicles

(3) Comparison between cooperative yielding maneuver and non-yielding maneuver

Fig.10 illustrates a comparison between the velocities and distances of entering vehicles encountered by circulating vehicles when they initiate deceleration and choose between cooperative yielding and non-yielding. The figure highlights that when the encountered entering vehicle is at a greater distance from the conflict point (greater than 5.3 meters) and exhibits higher velocity, circulating vehicles opt for deceleration and yielding maneuver. But within the non-yielding vehicles, they may decelerate due to unfamiliar to the RAB rather than the entering vehicles. **Fig.11** shows the expected PET values when circulating vehicle start to decelerate. Notably, CYM exhibits consistently lower expected PET values, with the entire distribution falling within the range of 0 to 3 seconds.

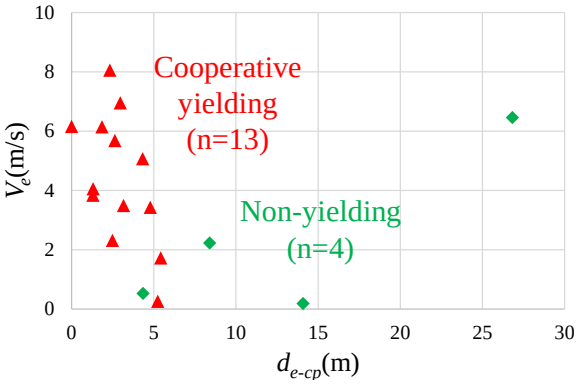


Fig.10 Comparison of CYM and non-yielding maneuver

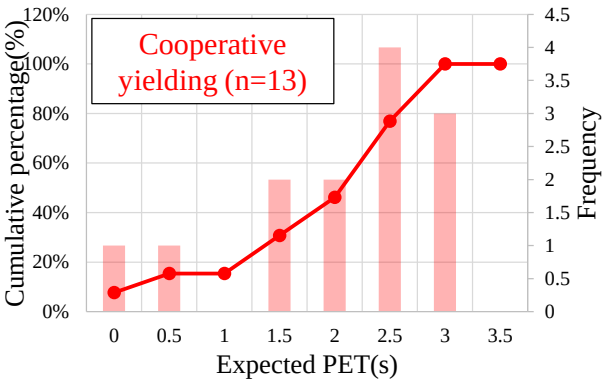


Fig.11 Expected PET values of CYM

6. CONCLUSIONS AND FUTURE WORKS

This research defined and investigated the vehicle cooperative yielding maneuver characteristics. When passing through the RAB, non-yielding vehicles exhibit speeds similar to those of free vehicles and, in comparison to vehicles opting for CYM, they travel at higher speeds. It was found that the circulating vehicles start decelerating when the entering vehicles passed the yielding line within the "entering passed first" group. Besides, the distances from the circulating vehicles to conflict point, and their speed significantly affect the CYM.

However, the number samples of CYM cases are limited in the analysis this time. In future work, more vehicles with non-yielding maneuver, and more sites with different geometric conditions are needed to be selected for developing model. Moreover, more characteristics of circulating vehicles and entering vehicles will be considered.

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