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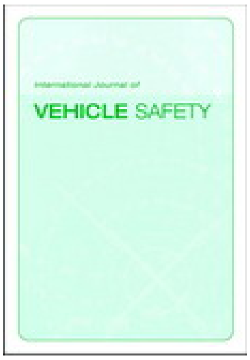

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Analysis of driving behaviour for right-turn manoeuvres at intersections with different types of traffic participants

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Abstract: The influence of different types of traffic participants on driving behaviour during a right turn at an intersection was investigated. A driving simulator was used to investigate the car's velocity and driver's gaze while conducting a right-turn manoeuvre. Five scenarios were presented randomly, with or without the presence of pedestrians and preceding or oncoming cars: driven car only, one preceding car turning right, three preceding cars turning right, one oncoming car travelling straight and one oncoming car turning left. The highest average velocity at which the driven car entered intersections was identified for the scenario with three preceding cars. The average travelling velocity in the intersection was also higher for the scenario with three preceding cars than those for other scenarios. The length of time that a driver gazed at a pedestrian, as a fraction of the total time pedestrians were visible, was the lowest for the scenario with three preceding cars. These results suggest that this scenario, among the five evaluated, might constitute the greatest danger to pedestrians at intersections.

Keywords: driving behaviour; gaze; right-turn manoeuvre; intersection; preceding car; pedestrian protection.

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1 Introduction

Japan recorded 2678 traffic fatalities in 2023, representing an increase of 68 compared to the cases reported in 2022 (National Police Agency, 2024). Pedestrian fatalities constituted the highest percentage (36%, n = 973) of all fatalities (National Police Agency, 2024). With respect to pedestrian deaths that occurred while walking, cases involving pedestrians crossing roads accounted for 68% (n = 610) of total fatalities while walking. Of all fatal traffic accidents in 2021, 34% occurred at intersections (ITARDA(a), 2022a). Furthermore, with respect to automobile behaviour associated with those fatal pedestrian accidents in Japan that were caused by automobiles travelling at low velocities, automobiles turning right accounted for a higher percentage of accidents (Matsui and Oikawa, 2019). However, the reasons why automobiles turning right are associated with a higher fatality rate have not yet been clarified. Of pedestrian deaths at crosswalks caused by drivers violating the law, 56% were struck by cars. According to a report (ITARDA, 2013), 97% of right-turn accidents caused by automobiles occurred because of cognitive delays; that is, the driver failed to notice the pedestrians at all or only noticed them immediately before the accident. Among the various factors causing automobile accidents involving pedestrians, alcohol consumption by drivers and/or pedestrians primarily results in fatal traffic accidents because of poor judgement or unsafe behaviours (GHSA, 2023). Drivers who have consumed alcohol present greater risks of causing traffic accidents (WHO, 2023). Additionally, several accidents result from driver drowsiness caused by long driving times or fatigue, which significantly affect the physiological and cognitive functions of the driver (Perrotte et al. 2024). Existing research has shown that a driver's driving behaviour may be affected by the traffic environment surrounding the road (Ohtani, 2009), road geometry and the presence of other automobiles (Kountouriotis and Merat, 2016), all of which can distract a driver's attention. Yoshitake et al. (2020) focused on the velocity and trajectory of right turns and evaluated the effects of the traffic environment, including traffic lights, signs and roadway width, on driving behaviour.

To improve road safety, several advanced technologies have been developed, including the autonomous emergency braking system with pedestrian detection (pedestrian-AEB). In this system, when a sensor on the automobile detects a pedestrian, the pedestrian-AEB system sounds a warning for the driver. If the driver still fails to take preventive measures, such as braking, the system automatically reduces the vehicle speed to avoid collision. Cicchino et al. (2022) studied real-world data reported by the police and found that pedestrian-AEB systems effectively reduced the risks of pedestrian-related collisions. However, a previous study that investigated the influence of pedestrian-AEB systems in intersection scenarios using a virtual simulator revealed that they could not appropriately detect pedestrians in cases of occlusions, such as stopped vehicles (Abdel-Aty et al., 2022).

Driving Simulators (DSs) have been employed to investigate drivers' operations in dangerous situations involving collisions (Li et al., 2019). A DS possesses the advantage of simulating a traffic environment according to what is desired. Consequently, a DS has been used to measure attentional resources while driving, using simulations specifically prepared for drivers participating in a study (Futagami et al., 2019). Futagami et al. (2019) conducted a DS experiment wherein the gaze data of the driver were obtained using a measurement device attached to their head. They placed stationary objects on the sidewalk at an intersection where a car would make a right turn, the object was temporarily erased by inserting a black screen (150 ms). They expected that inserting a black screen would have an effect of reducing stimulation to the driver's peripheral vision and confirmed that the driver recognised the object only when his/her attention was directed toward it. The scenario did not include other automobiles or pedestrians. Regarding traffic accidents involving right-turning automobiles, ITARDA reported that the presence and travelling directions of preceding or oncoming automobiles can cause drivers to deviate from safe driving practices (ITARDA, 2020). When preceding automobiles turn right, the driver in the following automobile may assume that the preceding ones have already ensured that it is safe to turn right. A survey revealed that the most common factor in right-turning automobile crashes involving pedestrians was drivers' failure to verify the safety of pedestrians at crosswalks owing to oncoming automobiles (ITARDA(b), 2022b).

This study aimed to clarify the effects of various traffic participants on drivers' right-turn manoeuvres. To achieve this objective, we conducted a DS experiment and investigated the car's velocity and the driver's gaze at an intersection. In the study, we focused on a set of different traffic participants, including pedestrians and oncoming or preceding cars.

2 Research methods

We conducted an experiment using a DS that can simulate dangerous situations that are likely to lead to collisions with pedestrians. All the participants in the experiment drove under the same set of conditions. The study focused on the car's travelling velocity and the driver's gaze while performing a right-turn manoeuvre.

2.1 Experimental participants

Thirteen (13) university students (11 men and 2 women; mean age: 22.8 years, Standard Deviation (SD): 0.86 years) who had driving licenses participated in the experiment. Among them, seven held the license since one to three years and six since three to five years. Additionally, participants who wore prescription glasses while driving were also asked to wear them during the driving experiment. Before starting the experiment, they were instructed to adjust the seat position such that they could hold the steering wheel properly and not to intentionally adjust the seat while driving. Participants were instructed to operate the ego car on the DS in the same manner in which they normally drive. Each participant performed each scenario twice. The experimental protocol was approved by the Tokyo Metropolitan University Ethics Committee.

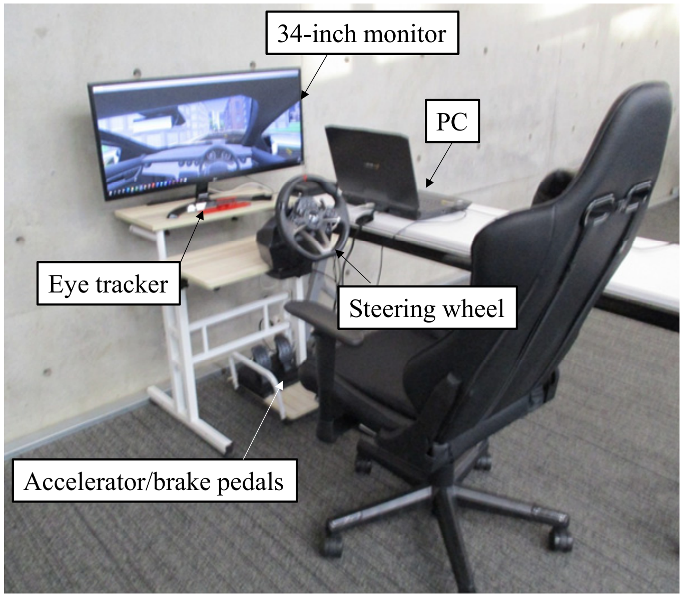
2.2 Driving simulator

The DS used in the experiment consisted of a 34-inch monitor (34UM59; LG Electronics, 2024), a steering wheel, accelerator/brake pedals (HORI Co. Ltd., 2024), an eye tracker (Tobii(a), 2024a), and a personal computer, as shown in Figure 1. The resolution, effective display area, and viewing angles of the monitor were 2560 × 1080 pixels, 799 × 335 mm, and 178° (horizontal)/178° (vertical), respectively. The spatial resolution was 0.34 mrad, where the horizontal eyes-to-monitor distance of the driver was 90 cm. The driving data of the DS, based on Unity (2024), were recorded at a rate of 5 Hz. We recorded the participants' driving characteristics when driving the subject car ('ego car'), their gaze and the movements of other cars and pedestrians.

2.3 Driver's gaze tracking

The measurement of drivers' gaze was conducted with an eye tracker (Tobii Eye Tracker 4C) (Tobii(b), 2024b). An installation-type device was used to measure the driver's direction of view on a monitor. Before starting the measurements, a calibration was conducted to adapt the algorithms in the device to the driver's perspective. Because the eye tracker was robust against changes in the head position of the driver, it did not require readjustments during recording once it was calibrated (Tobii(c), 2024c). A Unity script was used to output the drivers' gaze coordinates, as obtained by the eye tracker.

Figure 1 Hardware configurations of the DS (see online version for colours)

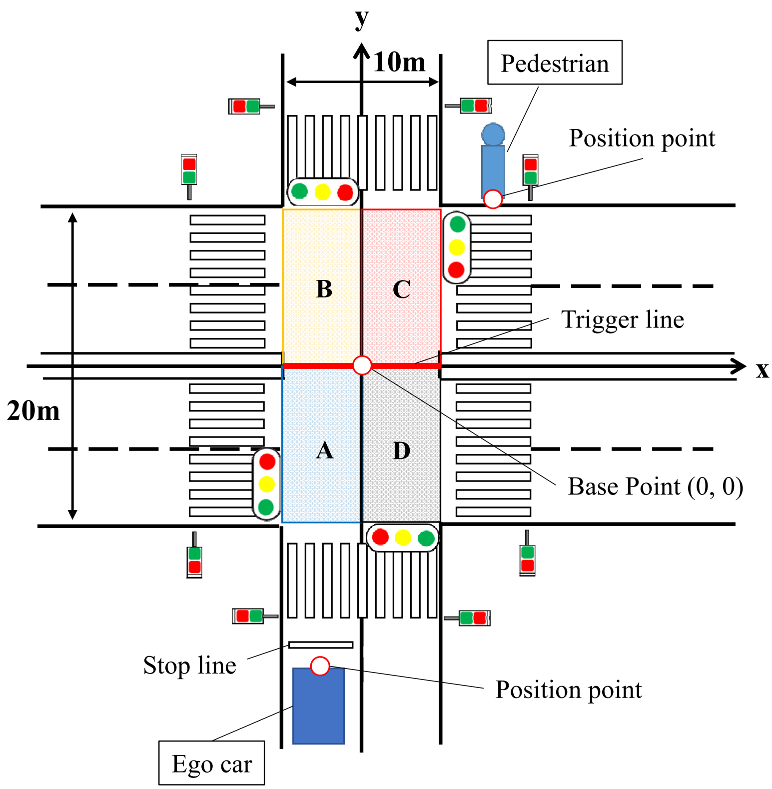


2.4 Traffic environment

In Japan, automobiles drive on the left, which was simulated using the DS. ITARDA (2012) reported that traffic accidents involving right-turning cars occurred most frequently (44%) at intersections with traffic lights in Japan. ITARDA also indicated that on wider roads, it might become tougher for drivers to assess a situation and the presence of pedestrians, implying a heightened possibility that they might neglect to pay sufficient attention to pedestrians. Based on these reports, a signalised intersection was presented in the experimental simulations, as shown in Figure 2. The widths of the roads towards the intersection were 10 m. Those through the intersection were 20 m. When the ego car approached the intersection, the traffic light facing the ego car was set to be red, in order to make the driver come to a stop before entering the intersection. We confirmed beforehand that when the ego car was approaching the stop line and was approximately 20 m from the trigger line, the pedestrian standing in front of the crosswalk was visible to the driver at the horizontal eyes-to-monitor distance of 90 cm.

To measure the relationship between the ego car and the pedestrian, the origin of coordinates was put at the base point (x-axis = 0, y-axis = 0) in the intersection, as shown in Figure 2. The horizontal line passing through the base point was set as the triggering line. A pedestrian waiting for the traffic light to turn green was presented at an intersection on the left side from the driver's perspective. The crossing direction of the pedestrians was based on a report that the rate of cases for pedestrians approaching from the left (53%) was higher than that for those approaching from the right (47%), in collisions with automobiles turning right during the daytime (ITARDA, 2012). The pedestrian was set to start walking when the moving ego car touched the trigger line. In addition, we set the position points at the centre front of the ego car and the footsteps of the pedestrian. To clarify the relation between the gaze time at the pedestrian and the ego-car location when the driver was looking at the pedestrian, the intersection was divided into four areas. The first area where the ego car travelled in the intersection was designated as Area A, and the other three areas were defined as Areas B, C and D in a clockwise sequence from Area A, as shown in Figure 2.

Figure 2 The intersection in the experiment (see online version for colours)



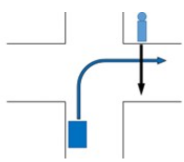
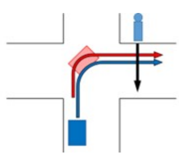
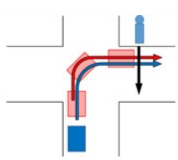
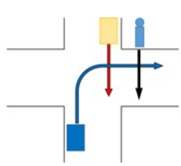
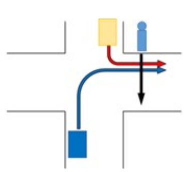
2.5 Scenario

With respect to traffic accidents involving right-turning automobiles, ITARDA reported that the presence and travelling direction of preceding or oncoming automobiles could cause drivers to deviate from safe driving practices (ITARDA, 2020). In the experiment, the driving route consisted of six intersections. At five of the six intersections, different scenarios were presented randomly, with or without the presence of pedestrians and other cars (preceding/oncoming cars), as shown in Table 1. The following scenarios were implemented: the Ego Car only (EC-only), one Preceding Car (PC-one), three preceding cars (PC-three), one oncoming car travelling straight (OC-straight), and one oncoming car turning left (OC-turning). At one of the six intersections, there were no pedestrians and no other cars.

Figure 3 depicts the models of the ego car and pedestrian used in the simulations. The car was a sedan-type passenger car with a white body. The preceding and oncoming cars were of the same type and colour as the ego car. Based on Road Traffic Laws of Japan, the maximum velocity for all cars was set to 60 km/h, which is the maximum speed allowed for cars on public roads in Japan. For all pedestrians, we set an adult male with walking velocity of 1.4 m/s (Mori and Tsukaguchi, 1977).

Figure 3 Models used in the DS: Left: car; right: pedestrian (see online version for colours)

Table 1 Experimental scenarios (see online version for colours)

Ego car, Preceding car, Oncoming car, Pedestrian	*Scenario description*
	(1) Ego-car only (EC-only) There are no preceding or oncoming cars. There is a pedestrian at the intersection on the left side as seen by the driver. When the ego car reaches the trigger line in the intersection during turning right, a pedestrian starts walking on the crosswalk, from left to right as seen by the driver.
	(2) One preceding car turning right (PC-one) There is one preceding car, which stops at the red light before entering the intersection. After the traffic light changes to green, the preceding car turns right at the intersection and the ego car follows it. Just after the preceding car has passed the crosswalk, the pedestrian starts walking on the crosswalk.
	(3) Three preceding cars turning right (PC-three) There are three preceding cars, all of which stop at red light before entering the intersection. After the traffic light changes to green, the preceding cars turn right at the intersection and the ego car follows them. Just after the last preceding car has passed the crosswalk, the pedestrian starts walking on the crosswalk.
	(4) One oncoming car travelling straight (OC-straight) There is one oncoming car, which stops at the red light. After the traffic light changes to green, the oncoming car moves straight through the intersection. When the ego car reaches the trigger line in the intersection during turning its right turn, the pedestrian starts walking on the crosswalk.
	(5) One oncoming car turning left (OC-turning) There is one oncoming car, which stops at the red light. After the traffic light changes to green, the oncoming car makes a left turn. Just as the oncoming car passes through the crosswalk, the pedestrian starts walking on the crosswalk.

2.6 Data analysis

Data analysis was conducted based on four parameters: $Velocity_{entering}$, $Velocity_{average}$, $Time_{visible}$ and $Time_{pedestrian}$. $Velocity_{entering}$ indicates the average velocity of the ego car at the time when it entered Area A of the intersection. We compared $Velocity_{entering}$ in different scenarios using a multiple comparison test for all case combinations. $Velocity_{average}$ indicates the average travelling velocity of the ego car moving in the intersection. We also compared $Velocity_{average}$ in different scenarios using a multiple comparison test for all case combinations. The multiple comparison tests for $Velocity_{entering}$ and $Velocity_{average}$ were performed using paired *t*-test with Bonferroni correction. $Time_{visible}$ is the average total time that a pedestrian could be seen by a driver in the intersection. $Time_{pedestrian}$ is the average total gazing time during which a driver actually looked at the pedestrian in the intersection. Based on $Time_{visible}$ and $Time_{pedestrian}$, we evaluated the percentage of time that drivers were gazing at pedestrians while driving ego cars turning right at intersections. Additionally, we evaluated the average gaze time of the drivers directed at the pedestrian based on the location of the ego car in Areas A, B, C or D of the intersection.

For $Velocity_{average}$, $Time_{visible}$, and $Time_{pedestrian}$, we used the data obtained once the ego car had entered and was travelling in the intersection (Areas A to D). Once the ego car halted at the intersection, the data for the analysis were obtained from the time the ego car travelled in the intersection until it stopped. This ensured that the gazing duration of the driver while they waited for the pedestrian to finish crossing was excluded from the analysis.

3 Results

The average velocities of the ego car when entering the intersection are displayed in Figure 4, for the various scenarios. The highest value of $Velocity_{entering}$ was measured for PC-three (where the three preceding cars turned right) at 16.82 km/h, followed (in descending order) by PC-one (one preceding car turning right) at 15.49 km/h, EC-only (no other cars) at 15.36 km/h, OC-straight (one oncoming car going straight) at 13.69 km/h and OC-turning (one oncoming car turning left) at 13.45 km/h. In the multiple comparison test for all case combinations, we confirmed statistically significant differences in the EC-only/OC-turning, PC-one/OC-turning, PC-three/OC-straight and PC-three/OC-turning parings.

The average velocity of the ego car passing through the intersection is illustrated in Figure 5. $Velocity_{average}$ was the highest (12.51 km/h) for PC-three, followed by PC-one (12.47 km/h), EC-only (11.87 km/h), OC-turning (11.05 km/h) and OC-straight (10.43 km/h). We conducted a multiple comparison test in the same way as for $Velocity_{entering}$. The average velocities of PC-one and OC-straight were significantly different.

Figure 4 Average velocity of the ego car when entering the intersection (see online version for colours)

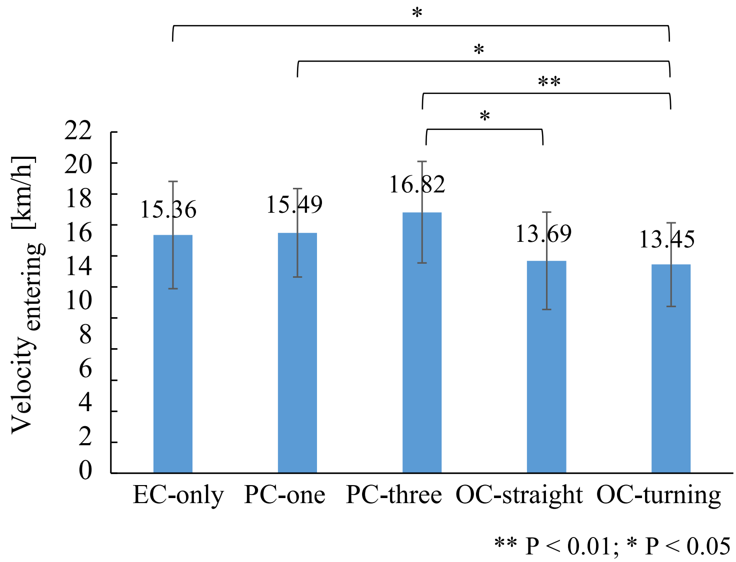
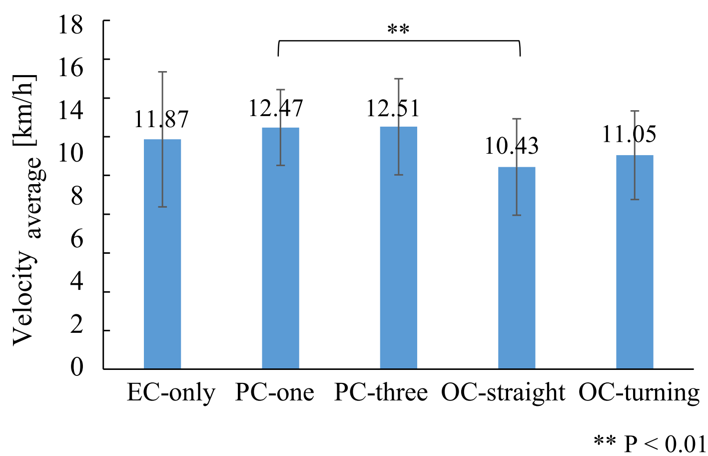


Figure 5 Average velocity of the ego car in the intersection (see online version for colours)



The values of $Time_{visible}$, $Time_{pedestrian}$, and the ratio of $Time_{pedestrian}$ to $Time_{visible}$ are listed in Table 2. $Time_{visible}$ was the longest for OC-turning (2.49 s), followed in descending order by PC-three (1.98 s), EC-only (1.88 s), PC-one (1.63 s) and OC-straight (1.52 s). $Time_{pedestrian}$ was the longest for OC-turning (1.80 s), followed in descending order by EC-only (1.42 s), PC-three (1.35 s), PC-one (1.30 s) and OC-straight (1.04 s). PC-three had the lowest ratio of drivers' gazing time directed at the pedestrian (68.48%).

Table 2 $Time_{visible}$, $Time_{pedestrian}$, and the ratio of drivers' gazing time at the pedestrians

	EC-only		*PC-one*		*PC-three*		*OC-straight*		*OC-turning*	
	AVG	*SD*	*AVG*	*SD*	*AVG*	*SD*	*AVG*	*SD*	*AVG*	*SD*
(a) $Time_{visible}$ [s]	1.88	1.84	1.63	1.48	1.98	1.18	1.52	1.72	2.49	1.64
(b) $Time_{pedestrian}$ [s]	1.42	1.32	1.30	1.29	1.35	0.86	1.04	1.31	1.80	1.38
(b) / (a) * 100 [%]	75.82		79.72		68.48		68.53		72.22	

Note: AVG: average, SD: standard deviation.

Table 3 summarises the average gazing times directed at pedestrians in each area of the intersection. The final row of the table includes the sums of the average gazing times in Areas A to D ($Time_{pedestrian}$ in Table 2). In Area A, the gazing percentage for EC-only (11.4%) was lower than for any of the other scenarios (PC-one, 26.6%; PC-three, 22.7%; OC-straight, 20.0%; OC-turning, 29.5%). In Area B, the lowest gazing percentage was measured for PC-three (2.8%), whereas OC-turning had the highest percentage (19.7 %), followed by OC-straight (18.5%), PC-one (10.7%) and EC-only (10.3%). In Area C, the gazing percentage for EC-only (76.2%) was higher than that in the other scenarios (PC-one, 58.6%; PC-three, 71.0%; OC-straight, 57.8%; OC-turning, 50.9%). In Area D, the percentages ranged from 0.0 for OC-turning to 4.1% for PC-one.

Table 3 The average gazing time ($Time_{pedestrian}$) at the pedestrian for Areas A, B, C and D in the intersection

	EC-only		*PC-one*		*PC-three*		*OC-straight*		*OC-turning*	
Inter-section	*$Time_{pedestrian}$*		*$Time_{pedestrian}$*		*$Time_{pedestrian}$*		*$Time_{pedestrian}$*		*$Time_{pedestrian}$*	
	[s]	*[%]*	*[s]*	*[%]*	*[s]*	*[%]*	*[s]*	*[%]*	*[s]*	*[%]*
Area A	0.16	11.4	0.35	26.6	0.31	22.7	0.21	20.0	0.53	29.5
Area B	0.15	10.3	0.14	10.7	0.04	2.8	0.19	18.5	0.35	19.7
Area C	1.08	76.2	0.76	58.6	0.96	71.0	0.60	57.8	0.92	50.9
Area D	0.03	2.2	0.05	4.1	0.05	3.4	0.04	3.7	0.00	0.0
Total	1.42	100.0	1.30	100.0	1.35	100.0	1.04	100.0	1.80	100.0

4 Discussion

The value of $Velocity_{entering}$ of the scenarios in which an oncoming car appeared at the intersection (OC-straight and OC-turning) was lower than that in the other scenarios. In OC-straight and OC-turning, it was difficult for the drivers to recognise the behaviour of the oncoming car before entering the intersection because it was some distance from the ego car. Consequently, it could be considered that the $Velocity_{entering}$ would be slower because the driver's gaze was directed to the oncoming car. Conversely, the $Velocity_{entering}$ of the scenarios in which a preceding car was present at the intersection (PC-one and PC-three) was greater than that of the other scenarios. In these cases (especially PC-three), the position at which the ego car was waiting for the traffic light to change (from green to red) was some distance away from the stop line because of the influence of the preceding cars. In addition, the preceding cars turned right and the drivers followed them in these cases. Consequently, the ego car had a relatively high velocity at the time when it entered the intersection.

As listed in Table 2, the gazing percentage was the lowest (68.48%) of the five scenarios in PC-three, wherein the pedestrian on the sidewalk was set to start walking after the three preceding cars had passed the crosswalk. Drivers might have attempted to follow the three preceding cars as they were turning right. To do this, the driver had to focus their attention on the preceding cars rather than on the pedestrian, which might have decreased their gazing time at the pedestrian. To gain a comprehensive perspective on their surrounding environment, including the presence and motion of a pedestrian, it would have been necessary for the drivers to pay more attention to the pedestrian. Consequently, PC-three could be considered the most dangerous of the five scenarios considered in this experiment.

The gazing percentage in Area A was higher for the OC-turning scenario than for any other scenario (see Table 3). In that scenario, one oncoming car turns left (from its perspective) into the intersection; that is, the travelling direction of the oncoming car is the same as that of the ego car. Once the driver of the ego-car had confirmed the oncoming car's behaviour before entering the intersection, it could be assumed that the pedestrian standing at the crosswalk was already in their line of sight, which might have led to an increased focus on the pedestrian during OC-turning.

There were several limitations in this study. The participants were young drivers (average age: 22.8 years). Driving behaviours might differ between young and elderly drivers. Owing to age-related decline in physical ability, elderly drivers may be less attentive to pedestrians. Conversely, years of driving experience might enhance attentional awareness while driving. Therefore, it will be necessary to clarify age-related differences in future studies. Moreover, the manner in which the pedestrians appeared in the scenarios was limited to one adult male walking in one direction from the same location. However, there are many potential situations and combinations, including gender, age, number of pedestrians and clothing, creating substantially more complicated scenarios in actual traffic environments. It is necessary to conduct experiments under different scenarios that are based on actual traffic conditions.

5 Conclusion

The features of driving behaviour while turning right at an intersection under different conditions were obtained, using a DS that could measure the drivers' gaze. We focused on the effects of traffic participants, such as pedestrians or other cars, creating five traffic scenarios: EC-only (no other cars); PC-one (a preceding car turning right); PC-three (three preceding cars turning right); OC-straight (an oncoming car going straight, passing through the intersection) and OC-turning (an oncoming car turning left). We found that PC-three was associated with higher values of $\text{Velocity}_{\text{entering}}$ and $\text{Velocity}_{\text{average}}$ than the other four scenarios, whereas the ratio of drivers' gazing time at the pedestrian was the lowest for the PC-three scenario. These results suggest that the presence and behaviour of other cars may have influenced drivers' behaviour while turning the ego car to the right at the intersection. Among the five scenarios, PC-three, in particular, could be considered the most dangerous of the five scenarios.

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