Psychological Analysis of Right-Turn Driving Behavior for Development of Autonomous Vehicles

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***Abstract*—In this paper, the right-turn behavior at a left-hand traffic intersection was analyzed in order to control autonomous vehicles not only for a safe drive but also for a drive that does not cause discomfort to occupants of both the autonomous vehicle and the surrounding vehicles. The trend of the decision to make a right turn was investigated at an intersection where there were a vehicle turning right and a vehicle oncoming straight focusing on discomfort of occupants of both vehicles. The results suggested the importance of considering psychological aspects.**

***Index Terms*—Autonomous vehicle, discomfort, psychological margin between vehicles**

I. Introduction

Research on autonomous vehicle technology began as early as the around the 1950s [1]. It is necessary to maintain a margin, specifically a safe distance between vehicles for safety, both in autonomous and manual driving. The situation where the vehicle leading straight, that is traveling in the same straight lane at the same speed as the subject vehicle, suddenly brakes for some reason is considered here. If the subject vehicle can immediately apply the same force brake without delay, the following distance to avoid a collision is as same as the brake reaction distance. Although this is an extreme argument, it can be the minimum safe distance (call "minimum margin" for comparative measure). In actual situation, a longer distance should be maintained for sudden brake of the leading vehicle and for braking delays of the subject vehicle. If the leading vehicle collides with a large vehicle stopped on the road and stops almost immediately for example, the subject vehicle should maintain the stopping distance according to its speed, which includes the braking distance. This maybe a sufficient following distance for safety (call "sufficient margin" for comparative measure). The intersection there are a vehicle turning right and vehicles oncoming straight at a left-hand traffic is considered similarly. If the right-turning vehicle has the minimum margin for the oncoming vehicle, it will not collide with it. This minimum margin is described as the rear end of the right-turning vehicle and the front end of the oncoming vehicle do not contact at the end of right turn. In actual intersection, the sufficient margin for a vehicle traveling straight not to collide regardless of the behavior of a right-turning vehicle should be maintained. The sufficient margin must also consider that the right-turning vehicle may stop in the oncoming lane due to pedestrian sudden crossing. The control of autonomous vehicles needs to be discussed separately, but it is focused on physical (logical) safety. On the other hand, personal space is applied for autonomous vehicles [2]. So we consider the psychological aspects of the driver. In the previous example, the leading vehicle may not stop instantly, and the driver may be able to operate the steering wheel in addition to braking. In the intersection example, the oncoming vehicle may not only brake but also steer to avoid a collision. A passenger car may not completely block the intersection. Some occupants (drivers and passengers) may feel dissatisfaction about too long margin. It is beneficial to consider not only safety but also the psychological margin to realize autonomous vehicles. The margin that occupants feel appropriate without discomfort is called as "psychological appropriate margin." In this paper, the right-turn behavior at a left-hand traffic intersection was analyzed in order to control autonomous vehicles not only for a safe drive but also for a drive that does not cause discomfort to occupants of both the autonomous vehicle and the surrounding vehicles. The trend of the decision to make a right turn was investigated at an intersection where there were a right-turning vehicle and an oncoming vehicle focusing on discomfort of occupants of both vehicles. The results suggested the importance of considering psychological aspects.

II. Experiment

A. Experiment Overview

We investigate how the psychological appropriate margin between a right-turning vehicle and an oncoming vehicle (right-turn margin distance and time) that does not cause discomfort changes according to the speed of the straight vehicle. The intersection has one lane in each direction that crosses at a right angle, and no traffic signals. The blue car in Fig. 1(a) (① in Fig. 2) is the "right-turn vehicle," the red car (② in Fig. 2) is the "straight vehicle," and the gray cars ahead of it (③ in Fig. 2) are the "leading vehicles." The straight vehicle and leading vehicles travel at a constant speed. There are no vehicles on the intersecting road. The right-turn vehicle waits to turn right at a position beyond the stop line. The distance between the leading vehicles is shorter than the minimum margin mentioned later, so the right-turn vehicle cannot turn through that gap. The right-turn vehicle turns at a constant speed after the last leading vehicle and before the straight vehicle, or after all oncoming vehicles including straight one. The participants operate either the right-turn or straight vehicle, while the simulator controls the other vehicles. The vehicle operated by the participants is called the "subject vehicle," and the participants' view turning right and traveling straight are shown in Fig. 1(b) and (c).

In the right-turn experiment, the participants operating the right-turn vehicle decide whether to turn right when the rear end of the last leading vehicle crosses the center line of the intersecting road. In the straight experiment, the oncoming right-turn vehicle begins to turn at this timing. The gap ⓐ in Fig. 2 at this time represents the right-turn margin. After the right-turn margin time from the right-turn start time (right-turn decision time), the front end of the oncoming vehicle just reaches the intersection. The path from the right-turn start to the intersection exit, i.e., the rear end of the right-turning vehicle leaves the intersection, is called the right-turn path (ⓑ in Fig. 2). The right-turn path divided by the speed of the right-turning vehicle is the right-turn time. The minimum right-turn margin time required for the right-turning vehicle to exit the intersection without contact with the oncoming vehicle is equal to the right-turn time. The sufficient right-turn margin for the oncoming vehicle to stop safely before the intersection is the sum of the right-turn time and the stopping time of it, because it may brake emergently after the right-turning vehicle stops just before completing the turn due to pedestrian sudden crossing.

B. Experiment System

A large monitor (SHARP PN-L702B, 69.5 inches (width 1538.9 mm, height 865.6 mm)) was used in the experiment, and displayed driver's view. The participants sat so that their field of view was 90 degrees. The subject vehicle was assumed to be a Toyota Aqua (length 3.995 m, width 1.695 m, height 1.445 m), and the other vehicles were assumed to be Honda Legend (length 5.03 m, width 1.89 m, height 1.48 m). The vehicles' motion was limited to constant speed and constant rate deceleration (braking) for simplification, although an actual vehicle gradually speeds up. The oncoming vehicles were already in constant speed at the start of the experiment. The lane width was 3.25 m. The speed of the right-turning vehicle and the right-turn time were set assuming the right-turn path of 9.5 m and the right-turn time of 3 seconds (i.e., the right-turn speed was 11.4 km/h constant speed). The braking deceleration of the straight vehicle was 0.3G [3], which is the threshold at which it begins to feel uncomfortable.

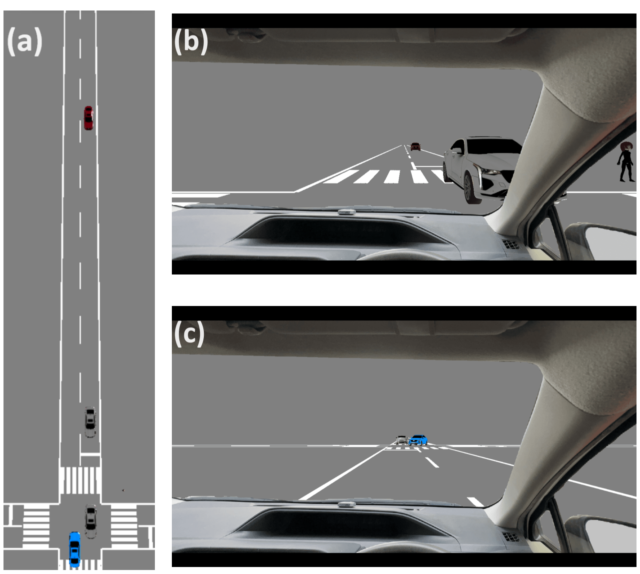


Fig. 1: Scenes of experiment: (a) bird's-eye view of the intersection, (b) driver's view turning right, (c) driver's view traveling straight

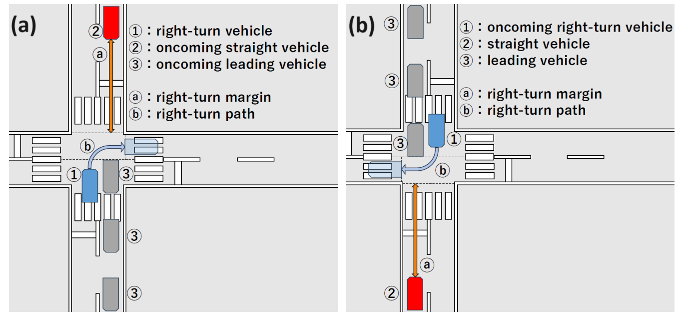


Fig. 2: Term explanation: (a) right-turn experiment, (b) straight experiment

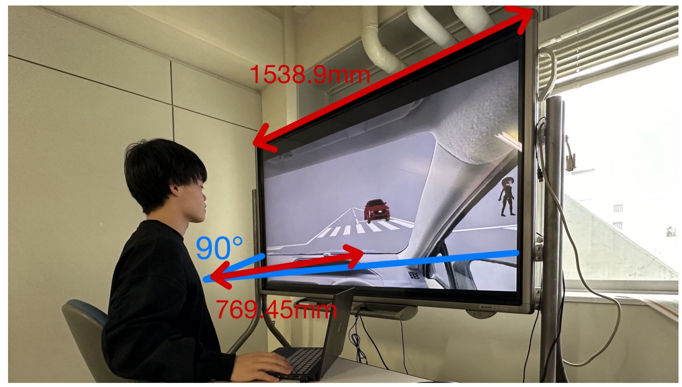
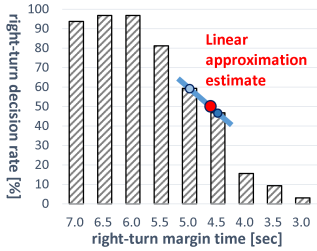


Fig. 3: Appearance of experiment

C. Experiment Procedure

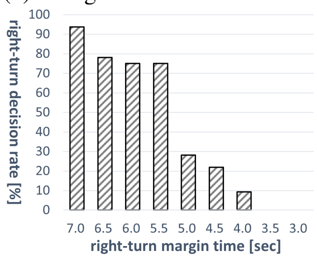
The Appearance of experiment is shown in Fig. 3. The participants first practiced right turn. They needed to decide whether to turn or not while paying attention to both the oncoming vehicle and pedestrians, considering the possibility of pedestrians suddenly crossing (pedestrians would randomly appear in practices). Next, they practiced traveling straight. The straight vehicle did not stop immediately even if it braked. Then they moved on to the right-turn and straight experiments. In the right-turn experiment, they had to decide whether they could complete the right turn without causing discomfort to the oncoming vehicle. They did it after the rear end of the last leading vehicle passed the center line of the intersecting road, and until it entered there. In other words, they made right turn when they judged that a psychological appropriate margin was

(a) Straight vehicle: 60 km/h



time	3.0	3.5	4.0	4.5	5.0
7.0	**	**	**		
6.5	**	**	**	*	
6.0	**	**	**	*	
5.5	**	**	**		
5.0	**	*			
4.5					

(b) Straight vehicle: 50 km/h



time	3.0	3.5	4.0	4.5	5.0	5.5
7.0	**	**	**	**	**	
6.5	**	**	**	*		
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5.5	**	**	**	*		
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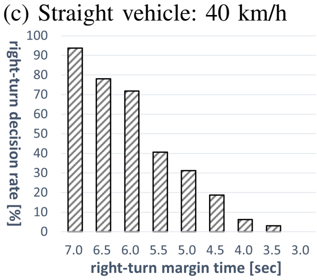
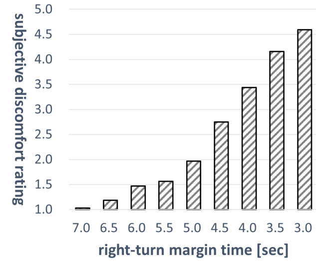
(c) Straight vehicle: 40 km/h



time	3.0	3.5	4.0	4.5	5.0	5.5	6.0
7.0	**	**	**	**	**	*	
6.5	**	**	**	**			
6.0	**	**	**	*			
5.5	*						
5.0							

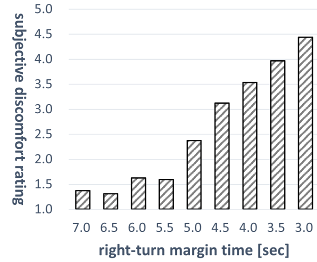
Fig. 4: Right-turn decision rates and significant differences between each pattern in right-turn experiment

(a) Straight vehicle: 60 km/h



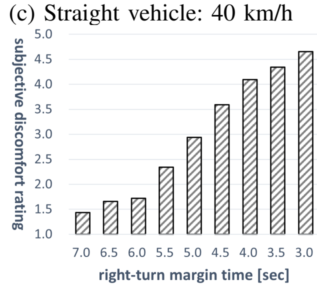
time	3.0	3.5	4.0	4.5	5.0	5.5
7.0	**	**	**	**	*	
6.5	**	**	**	**		
6.0	**	**	**	*		
5.5	**	**	**	*		
5.0	**	**	*			
4.5	**	**				
4.0	*					
3.5						

(b) Straight vehicle: 50 km/h



time	3.0	3.5	4.0	4.5	5.0	5.5
7.0	**	**	**	**		
6.5	**	**	**	**	*	
6.0	**	**	**	*		
5.5	**	**	**	*		
5.0	**	**				
4.5	*					
4.0	*					
3.5						

(c) Straight vehicle: 40 km/h



time	3.0	3.5	4.0	4.5	5.0	5.5
7.0	**	**	**	**	**	
6.5	**	**	**	**	*	
6.0	**	**	**	**	*	
5.5	**	**	**			
5.0	**	**	*			
4.5	*					
4.0						

Fig. 5: Subjective discomfort ratings and significant differences between each pattern in straight experiment

secured. Or they waited for the oncoming vehicle to pass. In the straight experiment, the oncoming right-turn vehicle turned automatically after the same timing. They braked if they felt discomfort due to the oncoming right-turn vehicle, to indicate a psychological appropriate margin was not secured. Then they rated their discomfort on a Likert scale from 1 to 5. One set of experiments consisted of 27 trials with different patterns, combining 9 right-turn margin times (3.0–7.0 seconds, 0.5 second steps) and 3 straight vehicle speeds (40, 50, and 60 km/h). There were no repetitions in these patterns, and each participant had each trial once per set in random order. They had a total of four sets of experiments as two right-turns and two straights, alternating. The participants were 16 undergraduate and graduate students who had an ordinary driver's license.

III. Experiment Results

In the right-turn experiment, each right-turn decision rate was calculated as the number of right-turns divided by the total number of trials for each pattern. In the straight experiment, each average subjective discomfort rating was calculated. They were analyzed by using the Steel-Dwass's multiple comparison test. Fig. 4 shows the right-turn decision rates when the oncoming vehicle was traveling at 60, 50, and 40 km/h. The significant differences between patterns are shown in the table to the right of each graph. There was a significant difference between the 3.0–4.5 second patterns and the 5.0–7.0 second patterns for the oncoming vehicle of 60 km/h, so the right-turn decision boundary was estimated to be 4.75 seconds. It was estimated to be 5.25 seconds for 50 km/h similarly. In the case of 40 km/h, it was assumed that there was a difference in the overlapping area between the 3.0–5.5 second patterns and the 5.5–7.0 second patterns, and it was estimated to be 5.5 seconds. On the other hand, the pattern closest to a 50% right-turn decision rate and the pattern adjacent to it across 50% were focused, then each right-turn decision boundary was directly estimated by linear approximation as 4.63, 5.23, and 5.65 seconds for 60, 50, and 40 km/h respectively (e.g. red point in left graph of Fig 4(a)). The straight experiment results are shown in Fig. 5. The right-turn margin times for subjective judgment boundaries were estimated to be 4.5, 4.5, and 4.75 seconds for 60, 50, and 40 km/h respectively based on the results of significance tests. Additionally, they were directly approximated linearly as 3.96, 4.04, and 4.57 seconds respectively for the judgment boundary of a subjective discomfort rating of 3.5.

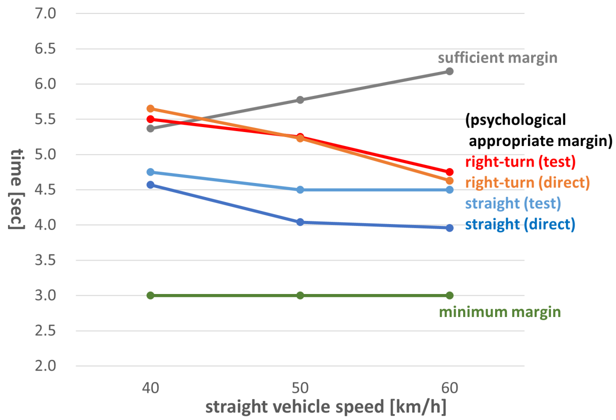


Fig. 6: Right-turn margin time estimates and straight vehicle speed

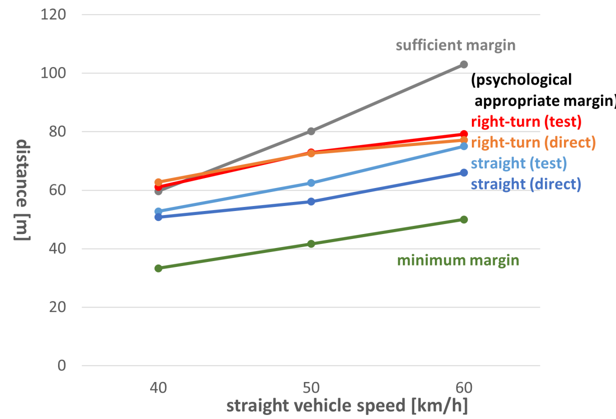


Fig. 7: Right-turn margin distance estimates and straight vehicle speed

Fig. 6 shows the estimated values of the psychological appropriate margin times for straight vehicle speeds. The "test" and "direct" in the parentheses Fig. 6 mean estimation by the Steel-Dwass's multiple comparison test and direct estimation by linear approximation, respectively. Since the right-turn time was constant, the minimum margin time was also constant and independent of the straight vehicle speed. The higher the straight vehicle speed, the longer the emergency braking time, so the sufficient margin time should be longer. It was initially expected that the psychological appropriate margin time would also be longer as the oncoming vehicle speed. However, the experimental results differed from this expectation, and showed that the margin time decreased as it increased. Therefore, the estimated margin distance, which is the multiplication of the margin time by the straight vehicle speed, is shown in Fig. 7. This graph would be as expected, as the higher the straight vehicle speed, the longer the psychological appropriate margin distance. They might have underestimated the time to danger and judged safety from a distance that was easy to see. They might also expect to avoid hazards other than braking after judging that the distance was secured according to the speed. Further study will be needed. It is important not to compromise safety in the realization of autonomous vehicles. It is also beneficial to reduce discomfort of occupants. Furthermore, the psychological appropriate margin was longer than the physical and logical sufficient margin in the right-turn experiment at 40 km/h. The sufficient right-turn margin was calculated under the assumption that the straight vehicle would apply emergency braking after the right-turning vehicle suddenly stopped just before completing the turn. However the actual straight vehicle may reduce its speed just after noticing the right-turning vehicle. The participants only experienced normal braking during practice and did not have the option of weak braking and emergency braking (maximum performance of a passenger car: 0.7–0.9G [4]). So the psychological appropriate margin might have been longer than the sufficient margin. This suggests that the psychological appropriate margin may be longer than the physical and logical margin at low speeds. It will be necessary to consider both safety and psychological aspects of discomfort of occupants in the realization of autonomous vehicles.

IV. Conclusion

In order to control autonomous vehicles not only for a safe drive, but also for a drive that does not cause discomfort to the occupants of both the autonomous vehicle and surrounding vehicles, a VR simulation system was used to analyze the behavior of right turn at a left-hand traffic intersection. The experimental results showed the opposite of the expected trend: the higher the straight vehicle speed, the shorter the psychological appropriate margin time. Additionally, it was longer than the necessary and sufficient safety margin calculated physically and logically, when the straight vehicle speed was low. The importance of considering psychological aspects in addition to safety was highlighted for the implementation of control in autonomous vehicles that is not only safe but also does not cause discomfort to the occupants of the vehicle and surrounding vehicles. In the future, we would like to compare these results with actual traffic conditions to realize comfortable autonomous vehicles.

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