Effectiveness and Driver Acceptance of a Semi-Autonomous Forward Obstacle Collision Avoidance System

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Abstract (100-150 words)

This paper proposes a semi-autonomous collision avoidance system for the prevention of collisions between vehicles and pedestrians and objects on a road. The system is designed to be compatible with the human-centered automation principle, i.e., the decision to perform a maneuver to avoid a collision is made by the driver. However, the system is partly autonomous in that it turns the steering wheel independently when the driver only applies the brake, indicating his or her intent to avoid the obstacle. With a medium-fidelity driving simulator, we conducted an experiment to investigate the effectiveness of this system for improving safety in emergency situations, as well as its acceptance by drivers. The results indicate that the system effectively improves safety in emergency situations, and the semi-autonomous characteristic of the system was found to be acceptable to drivers. (135 words)

Keywords: advanced driver assistance systems, adaptive automation, collision avoidance

1. INTRODUCTION

Pedestrian fatalities account for approximately 35% of motor vehicle-related fatalities in Japan (National Police Agency of the Government of Japan, 2012), 10% in the US (NHTSA, 2008), and 10%-20% in Europe (International Transportation Forum, 2012). Retting et al. (2003) developed engineering measures to reduce vehicle-pedestrian collisions, such as speed control and separation of pedestrians from vehicles. However, it is also necessary to develop an assistance function for vehicles in order to avoid collisions with pedestrians.

Parasuraman et al. (2000) provided a model of automation for information acquisition, information analysis, action selection, and action implementation. Automated information acquisition and/or information analysis can play a fundamental role in reducing the possibility of vehicle-pedestrian collisions. In fact, NHTSA (2008) reported that pedestrians are most likely to be killed in collisions between 3 am and 6 am, suggesting that drivers fail to recognize pedestrians walking on or crossing the road under dark conditions. Typical examples of devices to reduce collisions include night vision enhancement systems (e.g., Hiraoka et al., 2007; Tsimhoni et al., 2007). Collision warning systems would also be useful. However, in some situations, systems that support driver information acquisition and analysis may fail to prevent a vehicle-pedestrian collision. For example, NHTSA (2008) found that 12% of fatal vehicle-pedestrian collisions are caused by pedestrians unexpectedly running into the road.

Conventional commercialized driver assistance systems are generally not able to avoid collisions autonomously in emergencies. The design decision not to implement such functionality is due to a wide variety of concerns about automatic collision avoidance systems (e.g., Dingus et

al., 1998). These concerns are related to issues of decision authority (Inagaki, 2003), trust (Lee and Moray, 1992; Parasuraman and Riley, 1997), risk compensation (Wilde, 1994), and behavioral adaptation (OECD, 1990). Among them, the authority issue is strongly related to the responsibility for safety. Human-centered automation principles (Billings, 1997; Woods, 1989) claim that the human operator must have final authority over automation.

Theories on adaptive automation (Inagaki, 2003; Parasuraman et al., 1992; Rouse, 1988; Scerbo, 1996), however, claim that automation should be given the authority for decision and action in certain situations (e.g., Flemisch et al., 2008; Inagaki, 2000; Kaber and Endsley, 2003; Miller & Parasuraman, 2007; Moray et al., 2000; Prinzel et al., 2003; Wilson and Russel, 2007); automatic emergency brake systems for collision avoidance have been developed (Coelingh et al., 2010; Isermann et al., 2010; Kaempchen et al., 2009; Wada et al., 2010), and some existing commercialized automatic brake systems work in the low-speed range (e.g., Distner et al., 2009). Society seems to have accepted these systems and recognized their value.

It is thus becoming important to design and evaluate collision avoidance functions that control the lateral position of the vehicle by maneuvering the steering wheel. Tanaka et al. (2010) conducted a driving simulator experiment and found cases in which either a steering or a braking maneuver was missing when both were necessary. This paper proposes a semi-autonomous forward obstacle collision avoidance system in which the system performs a steering maneuver as well as a brake-assisting maneuver upon detection of the driver applying the brakes.

The problem with such a system is that it is not clear whether the system is allowed to perform a steering maneuver autonomously and whether the driver would accept the system's action. This paper attempts to answer the following two questions: (1) How much does a semi-autonomous forward obstacle collision avoidance system reduce the frequency of collisions and

the time to collision (TTC)? and (2) Is the system acceptable to drivers? The second question was further divided into the following two questions: (2-i) Do drivers believe that the system is helpful for avoiding collisions? and (2-ii) Do drivers think that the intervention of the autonomous system is appropriate in emergencies? An experiment with a medium-fidelity driving simulator was done to investigate these research questions.

2. METHODS

2.1 Participants

Twenty drivers (8 females and 12 males) between the ages of 20 and 39 years (mean, 27.0; s.d., 5.9) participated in the experiment. Their driving experience ranged from 6 months to 19 years. Each participant had a valid driver's license and drove more than three days per week.

2.2 Apparatus

A driving simulator (Honda DA-1105) was used in this study (Figure 1). A motion cue was not given to the participants in order to avoid simulator sickness. The vehicle dynamics is precisely calculated in the simulation computer. Three image generating computers, connected to the simulation computer via a local-area network, receive the necessary information and generate the driving view. The view is shown to the driver by one projector for the front view, and other three liquid crystal displays for the rear-view mirror, the right side-view mirror, and the left side-view mirror. The field of view of the front screen was approximately 120 degrees. The cockpit is

a real mockup of a Honda vehicle without no passenger seats, having the motor-controlled steering wheel. The host vehicle can be controlled either by using the control device or from an external computer. When the external computer controls the vehicle, the rotation angle of the steering wheel can be changed according to the input value given to the vehicle, but the strokes of the accelerator and brake pedals cannot. A sound system was available so that drivers could hear engine sounds, road noises, and auditory alerts.

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Insert Figure 1 about here

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A 400-m-long, two-lane, straight rural course was used in this experiment, as shown in Figure 2. The width of each lane was 5 m. There was no shoulder, but the area adjacent to the road was similarly drivable. There were no buildings along the road.

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Insert Figure 2 about here

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2.3 Task

Participants were instructed to drive safely in the left-hand lane of the two-lane experimental course from one end to the other. A trial drive lasted for approximately 1 minute. The vehicle was equipped with a speed governor that limited its maximum speed to 50 km/h.

Participants were asked to maintain the speed of the vehicle at 50 km/h and to keep the vehicle centered in the left lane as much as possible.

In each trial drive, an object (a red traffic cone) suddenly appeared once in the driving lane to imitate the sudden appearance of a pedestrian on the road. The lateral position of the cone could be 2.0 m or 3.0 m from the left edge of the 5-m wide host lane. The bottom radius of the cone was 0.3 m and the height was 0.7 m. Participants were instructed to avoid the obstacle in some way and to stop the vehicle safely. The drivers were allowed to choose any one of the following alternatives: (1) enter the adjacent lane (no other vehicles appeared in this experiment); (2) drive off the road (the surface was drivable in the same way as the road); or (3) apply the brake hard. No vehicles or objects appeared other than the traffic cone. Each trial drive terminated when the vehicle came to a complete stop. If a collision occurred, the experimenter informed the participant of the collision immediately after the trial in which the collision occurred. No haptic or visual feedback was given when a collision occurred.

2.4 Collision Avoidance Assistance

In this experiment, the vehicle was equipped with a “steer-by-wire” technology-based collision avoidance system. The steering angle input given by the driver to the vehicle may not be the same as the physical rotation angle of the steering wheel; that is, the system has the capability to override the driver steering input and to perform the steering maneuver freely. Nevertheless, the system was designed so that it could be compatible with the human-centered automation principle in the following ways:

(I) The system performs an action for avoiding a collision with the obstacle only when it detects the driver's intention to avoid the obstacle.

(II) The driver can override the system when he or she determines that the system's intention is inappropriate.

More specifically, the system works as follows:

(1) When the system detects an obstacle ahead and the estimated TTC is less than 2.0 sec, the system produces a single auditory alert consisting of two consecutive sounds at frequencies of 1.0 kHz and 0.8 kHz; the total length of both sounds is approximately 1 second. The volume of the sounds was individually tuned to allow each participant to hear the sounds easily but to avoid disturbing the participant while performing the avoidance maneuver.

(2) Suppose a driver performs an avoidance maneuver. The assistive functionalities of the system depend on the value of the TTC at that moment:

(a) When $1.2 \leq TTC < 2.0$, the system applies the maximum brake pressure irrespective of the type of collision avoidance maneuver initiated by the driver. That is, the maximum system brake is applied even when the driver performs only a steering maneuver without braking. The maximum brake pressure enables the vehicle to stop before reaching the obstacle.

(b) When $TTC < 1.2$, the system identifies an optimal path to avoid the collision by taking into account the TTC and the horizontal offset distance in meters between the vehicle and the obstacle.

i. Suppose the driver applies the brake only without turning the steering wheel. The system computes an optimal steering angle and implements it by controlling the

steering automatically. The physical rotation angle of the steering wheel changes according to the steering input given by the system with some delay. The physical steering angle may not be exactly the same as the input angle to the vehicle, but the driver may see and/or feel the rotation of the steering wheel so that the action of the system is noticeable. The torque given by the system is so mild that the participant is able to override the system if necessary.

ii. When a driver turns the steering wheel, the system behavior depends on the turning direction.

a. If the direction is the same direction determined by the system, the total steering angle input to the vehicle is the sum of the driver input and the system's corrective input for achieving the optimal path to avoid the collision. Again, the physical rotation angle is changed according to the total steering angle input to the vehicle. In this case, the system also gives brake assistance to achieve 0.3G deceleration. If the driver braking yields deceleration greater than 0.3G, the system itself does not apply the brake.

b. If the driver turns the steering wheel in the opposite direction to that intended by the system, the system does not provide any steering input to the vehicle. In this case, the system applies the maximum brake to mitigate collision damage.

(c) If the driver does not perform any avoidance maneuver, the system does nothing except to sound an auditory alert.

No visual indication was given to the participants of the system's directional preference for the steering maneuver. Participants were able to recognize the preferred direction by visual observation or by the tactile feeling of the steering wheel movement.

2.5 Independent Variables

This experiment set two independent variables: Assist Mode and Initial TTC. For the Assist Mode, two modes were distinguished: the driver assistance system for forward obstacle collision avoidance was available (A), or the driver assistance system was not available (NA). For the Initial TTC when the obstacle appeared, three conditions were possible: 1.08 sec (the headway distance was 15 m), 1.51 sec (21 m), and 2.02 sec (28 m). Since the maximum vehicle speed was limited to 50 km/h by the speed governor and the participants were asked to press the gas pedal strongly to maintain the speed at 50 km/h, the actual initial TTC was precisely as it was set. For each combination of Assist Mode and Initial TTC, each participant conducted five trial drives. Thus, each participant responded to 30 drive trials in total.

The reason for setting three levels of Initial TTC was to enable participants to experience as many types of system behavior as possible. If the Initial TTC is 2.02 sec, the ordinal reaction of the participants should be to apply the brake when $1.2 \leq TTC = 2.0$ (case (2)-(a)). If the Initial TTC is 1.51 sec, participants may tend to only apply the brake but not perform the steering maneuver even though the TTC would be less than 1.2 sec when the participants started braking (case (2)-(b)-(i)). If the Initial TTC is 1.08 sec, participants might perform a steering maneuver because it would be impossible to stop the vehicle before hitting the traffic cone (case (2)-(b)-(ii)).

2.6 Dependent Variables

To evaluate the effectiveness of the system, driver reactions and system reactions were recorded and analyzed. Driver reaction timing was evaluated by the Reaction TTC, which is the value of the TTC when the participant began to perform the avoidance maneuver. The system reaction was also recorded. It is possible that the intended direction of the system was quite different from that of the participant; therefore, it was necessary to evaluate to what extent the intended directions of the driver and the system coincided with one another. Thus, the Steering Coincidence Ratio, the ratio of the maximum actual steering angle to the optimal steering angle calculated by the system, was calculated for each trial. Negative values of the Steering Coincidence Ratio represent cases in which the driver steering direction was different from the intended direction of the system. The Reaction TTC and Steering Coincidence Ratio are intermediate indices of safety.

As the outcome indices of safety, the number of collisions and the minimum TTC in each trial were analyzed. In this paper, the TTC is defined as d/v_o, where d denotes the distance between the vehicle and the obstacle, and v_o is the vehicle velocity to the obstacle (see Figure 3). The TTC was recorded from the appearance of the traffic cone to the passing of the cone every 1/60 sec. The minimum TTC was defined as the minimum value of the recorded TTCs in the trial. In Figure 3, the radius of the circle around the vehicle and the radius around the obstacle are 2.3 m and 0.4 m, respectively. If the distance between the vehicle and the obstacle became zero, a collision was considered to have occurred and the minimum TTC was set at zero.

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Insert Figure 3 about here

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Subjective ratings on a 7-point scale were collected to investigate the participants' acceptance of the system. Participants were asked the following questions after each trial if the participant recognized the system maneuver in that trial:

(1) To what extent do you think your collision avoidance capability is improved with the aid of the system? (1: not at all, 4: not sure, 7: very much)

(2) To what extent do you think the system's maneuvers were appropriate? (1: not at all, 4: not sure, 7: very much)

2.7 Procedure

Each participant completed the experiment in approximately 2 hours on a single day. First, informed consent was obtained from all participants. After receiving written instructions on the driving task, participants were completed practice drives to familiarize themselves with the simulator. No obstacles appeared during the practice drives, but the speed governor was active.

Half of the participants completed 15 trials under condition NA first, followed by 15 trials under condition A. The other half of the participants completed 15 trials under condition A first, followed by 15 trials under condition NA. Each participant was randomly assigned to one of two experimental groups. The Initial TTCs were presented in random order. Each participant completed training trials before conducting the experimental trials under condition A so that they

could see how the obstacle collision avoidance system behaved. In the training trials, the obstacle was placed in the driving lane from the beginning of the trial, and the participant was asked to react in one of the following five ways: (i) perform no avoidance maneuver; (ii) apply early and mild deceleration; (iii) apply late and rapid deceleration after coming very close to the obstacle; (iv) turn the steering wheel to the right after coming very close to the obstacle; or (v) turn the steering wheel to the left after coming very close to the obstacle. Each participant completed two training trials each for cases (i) through (v): the first time under condition NA and the second under condition A. The system provided no assistance in case (i), braking assistance only in case (ii), automatic control of the steering wheel with mild braking in case (iii), and assistance with steering control and mild braking in cases (iv) and (v). In the training trials, participants did not experience trials in which they steered in the "wrong" direction so that only braking forces were applied by the system.

3. RESULTS

Table 1 shows the driver reactions to the appearance of the obstacle. A chi-square test revealed a significant difference between conditions A and NA ($\chi^2(3)=15.1$, $p<0.01$). This result suggests two tendencies. First, participants tended to steer to the right irrespective of the Assist Mode (steer to right=178+143=321, steer to left = 44+33=77), even though steering to the right and steering to the left were equally selectable because the road shoulder was also drivable. A possible reason for the tendency to choose right is the position of the driving seat. As illustrated in Figure 3, the obstacle was on the left side from the driver if it appeared 2.0 m from the left edge of the lane; thus the driver would choose left. When the obstacle appeared 3.0 m from the

left edge, the obstacle was just in front of the driver; thus the choice could be fifty-fifty. As a whole, the drivers tended to choose right when they did steering maneuver.

Second, the frequency of applying the brake only was higher when the system was available (122 cases) than when it was not available (78 cases). This result might reflect the participants' adaptation to the system in the sense that the participants became reluctant to perform the steering maneuver and let the system to do it.

Based on these observations, it is important to determine whether the participants actively attempted to avoid collisions by themselves. Figure 4 depicts the mean and the standard deviation of the Reaction TTCs for each condition. "Order" refers to the order number of trial experiences under each condition (from the 1^{st} to the 5^{th}). A three-way ANOVA on the Reaction TTC having repeated measures with the Assist Mode (A and NA), the Initial TTC (1.08 sec, 1.51 sec, and 2.02 sec), and the Order (1 through 5) showed that the main effect of the Assist Mode ($F(1, 13)=8.12$, $p=0.01$), the main effect of the Initial TTC ($F(2, 26)=1445.0$, $p<0.01$), the main effect of the Order ($F(4, 52)=2.78$, $p=0.036$), and the three-way interaction ($F(8, 104)=2.10$, $p=0.04$) were statistically significant. However, no evidence of a learning effect was observed. In particular, Tukey's HSD test on the main effect of Order showed no significant difference for any pair of responses. This suggests that the behavioral adaptation of participants was not substantial from a macroscopic point of view.

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Insert Table 1 about here

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Insert Figure 4 about here

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Next, the effectiveness of the system was investigated with respect to safety. Table 2 shows the frequency of the system reaction for each type of driver reaction. In 79 of 300 cases, the system performed a steering maneuver autonomously upon detecting braking applied by the driver. Table 3 shows the number of collisions out of a total of 100 cases (5 cases/participant * 20 participants) for each condition. The number of collisions under condition A was almost half that under condition NA. A chi-square test on the number of collisions was performed to compare conditions A and NA; the result showed that there was a nearly significant difference between these two conditions ($\chi^2(1)=2.76$, $p=0.097$). A chi-square test on the number of collisions was also conducted to compare the three Initial TTCs and revealed that the effect of the Initial TTC was significant ($\chi^2(2)=53.4$, $p<0.01$). The differences between each pair of levels of the Initial TTC were tested by chi-square tests with Ryan's multiple comparisons procedure. The results showed that a significant difference existed between 1.08 sec and 2.02 sec of the Initial TTCs ($\chi^2(1)=31.3$, $p<0.01$), and 1.08 sec and 1.51 sec of the Initial TTCs ($\chi^2(1)=25.5$, $p<0.01$). That is, the number of collisions was higher when the Initial TTC was 1.08 sec than when the Initial TTC was 1.51 sec or 2.02 sec.

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Insert Table 2 about here

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Insert Table 3 about here

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We also considered the individual differences in the number of collisions. Figure 5 shows the number of collisions for each participant. Participants who do not appear in Figure 5 (#6, #7, #10, #11, #18, and #19) did not collide with the cone at all.

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Insert Figure 5 about here

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Next, the minimum TTC was investigated. Large differences appeared in the standard deviations among the experimental conditions: m=0.07, s.d.=0.06 (Assist Mode=NA, Initial TTC=1.08); m=0.17, s.d.=0.10 (Assist Mode=A, Initial TTC=1.08); m=0.32, s.d.=0.25 (Assist Mode=NA, Initial TTC=1.51); m=0.38, s.d.=0.21 (Assist Mode=A, Initial TTC=1.51); m=0.69, s.d.=0.50 (Assist Mode=NA, Initial TTC=2.02); m=0.82, s.d.=0.51 (Assist Mode=A, Initial TTC=2.02). Straightforward ANOVA could not be conducted because the homogeneity of the variance was not proved (Cochran's $C=0.42$, $p<0.01$). In addition, the shape of the histogram appeared to be one-tailed. A logarithmic transformation therefore was done for each value of the minimum TTC to reduce the differences in the standard deviations among the conditions in the raw data, and to fit the distribution to the normal distribution. Cases in which the minimum TTC was zero were discarded, as logarithmic transformation could not be performed. Figure 6 shows the logarithm of the minimum TTC to the base 10 (error bars represent standard deviations). The

homogeneity of the variance was still rejected, but the shape of the histogram was better than that of the raw data. Two-factor repeated-measures ANOVA with the Assist Mode (A and NA) and the Initial TTC (1.08, 1.51, and 2.02 sec) on the minimum TTC showed that the main effects of the Assist Mode ($F(1, 562)=57.8$, $p<0.01$) and the Initial TTC ($F(1, 562)=214.2$, $p<0.01$) were significant. Tukey's HSD test showed a significant difference for each pair of conditions ($p<0.01$). The interaction was also statistically significant ($F(2, 562)=8.635$, $p<0.01$). In addition, Tukey's HSD test revealed significant differences between condition NA and condition A when the Initial TTC was 1.08 sec ($p<0.01$) and 1.51 sec ($p<0.01$). No significant difference was found between condition NA and condition A when the Initial TTC was 2.02 sec.

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Insert Figure 6 about here

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The above results suggest that driving with a collision avoidance system is safer than driving without the aid of the system. However, collisions still occurred even when the semi-autonomous collision avoidance system was available. To clarify why these collisions occurred, we investigated the timing and the appropriateness of the steering direction of driver avoidance maneuvers. Figure 7 shows the relationship between the Reaction TTC and the Steering Coincidence Ratio in condition S. In only one of the 11 collision cases under condition A, the participant did nothing to avoid the collision; this case is not shown in Figure 7. Seven of the remaining 10 collisions under condition A were actions taken too late to avoid a collision. In these seven cases, the Reaction TTCs were less than 0.5 sec, indicating that the system attempted

to turn the steering wheel and apply the brake upon detecting the driver reaction, but the collision occurred before the system maneuver was fully activated. The remaining three collisions were caused by the driver's inappropriate steering maneuver (i.e., the Steering Coincidence Ratio was negative).

These findings suggest that a collision avoidance system that is activated only when the driver's intention to avoid an obstacle is detected, such as the system tested in this experiment, may not be effective in preventing collisions if the driver's avoidance maneuver is not performed or is delayed for some reason. Thus, it is necessary to develop autonomous collision avoidance systems that can perform collision avoidance maneuvers even when the driver fails to show his or her intention at an appropriate time, although such a system would not be fully compatible with the human-centered automation principle. In addition, driver reactions to the appearance of an obstacle may be delayed if the driver becomes excessively familiar with the assistive functionality of the system (in this experiment, participants received 15 trials under condition A). However, this type of delay does not appear to be relevant, as drivers likely have few opportunities to observe the system behavior in the real world.

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Insert Figure 7 about here

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Figure 8 shows the participants' subjective ratings on the improvement of collision avoidance capability. Kruskal-Wallis test with the Initial TTC (1.08, 1.51, and 2.02 sec) on the subjective rating showed that the main effect of the Initial TTC was statistically significant (H (2,

N= 229) =35.4, $p<0.01$). A post hoc test found statistically significant differences between any two conditions ($p<0.05$). This suggests that the participants felt that the avoidance capability was improved by the system when the Initial TTC was small (e.g., 1.08 sec). This is because it was difficult to avoid a collision without the system functionality. Conversely, participants thought they could avoid a collision without assistance from the system when the Initial TTC was large (e.g., 2.02 sec).

Because the system reacts differently depending on the driver's triggering maneuver, it is important to investigate the subjective feelings behind each type of driver reaction. We investigated the differences in participants' subjective feelings between cases triggered by driver braking and those triggered by driver steering (see Table 4), where "braking" refers to cases in which the driver applied only the brake to avoid a collision, and "steering" refers to cases in which the driver turned the steering wheel. As shown in Table 4, the numbers of cases of each type of driver reaction differed depending on the Initial TTC. This is because subjective ratings were collected only when the participants recognized the system maneuver. Mann-Whitney test was performed for each Initial TTC to compare the difference in the subjective feelings with respect to collision avoidance capability between cases triggered by braking and those triggered by steering. No significant differences were found between the two triggers for any Initial TTC. Furthermore, no significant differences in subjective ratings of collision avoidance capability were found between braking and steering for each initial TTC condition.

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Insert Figure 8 about here

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Insert Table 4 about here

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Figure 8 also shows participants' subjective rating of the appropriateness of the system's driver assistance maneuvers. Kruskal-Wallis test with the Initial TTC (1.08, 1.51, and 2.02 sec) did not show the significant main effect of the Initial TTC. This result suggests that participants found the system maneuver appropriate for each initial condition. This property holds even when the data were categorized by the types of driver action taken to avoid a collision with the obstacle (see Table 5). Again, in Table 5, the numbers of cases of each type of driver reaction differed depending on the Initial TTC. This is because subjective ratings were collected only when the participants recognized the system maneuver. Mann-Whitney test was performed to compare the differences in participants' subjective feelings with respect to the appropriateness of the system behavior. The value of the Initial TTC was not taken into account here because the Kruskal-Wallis test showed no significant main effect of the Initial TTC. No significant difference was found between the two triggers. Thus, it appears that the participants considered it appropriate for the system to perform the steering maneuver autonomously, even when the driver applied only the brake without turning the steering wheel.

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Insert Table 5 about here

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4. DISCUSSIONS

Generalization of the above findings in this experiment should be done with caution. Further studies are necessary to determine whether drivers accept semi-autonomous steering for collision avoidance in a more realistic driving context. In the present study, drivers could predict the appearance of an obstacle and could interact with the system repeatedly; thus, they were able to establish their own mental models of the system based on their multiple interactions with the system. Moreover, the drivers and the system could steer to the right or the left freely without any fear of collisions with other obstacles or vehicles. Another limitation of this experiment lies in the precision for identification of the obstacle position as well as the prediction of the movement of the obstacle if it is a pedestrian. In the present experiment, it was assumed that the position of the obstacle was identified without any error, and the obstacle did not move from its original position. It is necessary to address the issue of the prediction of the obstacle (a pedestrian), in other words, the future trajectory of the obstacle, because the obstacle could move in reality. In addition, it was assumed that the system could identify where was drivable. When the assumption does not hold, a conflict of intentions can occur between the driver and the system regarding which direction to steer to avoid a collision with the obstacle. Such a conflict can not only cause decrease of driver trust in the system, but also cause a dangerous situation (E.g., the vehicle is directed by the system towards a riverside while avoiding the obstacle. Apparently, the driver will try to overtake the control in that case if he or she recognizes the system's dangerous action, but the overtaking could be too late.). It is also possible that differences exist in the driver reactions to an inanimate obstacle such as a traffic cone and a pedestrian. In the experiment in this paper, the drivers were often able to respond smoothly and quickly to the appearance of the

obstacle. As collision statistics suggest (e.g., ITARDA, 2004), however, drivers in the real world are often too surprised to appropriately respond to the sudden appearance of an obstacle.

Since cases exist in which drivers fail to perform an avoidance maneuver even when a collision avoidance system is available, autonomous collision avoidance is needed to improve safety for those cases. Further investigation is necessary regarding the effectiveness of autonomous collision avoidance systems that initiate the collision avoidance maneuver even when the driver fails to explicitly show his or her intention to avoid a collision, especially when a collision is severely imminent (i.e., system-initiated automation invocation might be necessary).

5. CONCLUSIONS

The present paper investigated the safety effects and driver acceptance of a semi-autonomous forward obstacle collision avoidance system that provides the driver with assistance by controlling the steering wheel automatically. As for the research question regarding the reduction of the frequency of collisions and the TTC, the results demonstrated that the system contributed appreciably to improved safety in emergency situations. The results of analyses on driver behavior and safety also suggested that a semi-autonomous collision avoidance system may not be effective in avoiding a collision if the driver fails to perform an avoidance maneuver or if the avoidance maneuver is delayed for some reason.

As for the second research question, drivers positively evaluated the assistance system with respect to its value in avoiding collisions, especially under extreme emergency situations. For the third research question, drivers also positively evaluated the appropriateness of the system behavior irrespective of the initial value of the TTC at the appearance of the obstacle.

These tendencies were true even when the system initiated an avoidance steering maneuver when the driver applied the brake only.

REFERENCES

Billings, C.E., 1997. Aviation automation - The search for a human-centered approach. Lawrence Erlbaum Associates, Mahwah, NJ.

Coelingh, E., Eidehall, A., Bengtsson, M., 2010. Collision warning with full auto brake and pedestrian detection – a practical example of automatic emergency braking –, in Proc. 2010 13th International IEEE Annual Conference on Intelligent Transportation Systems, Madeira Island, Portugal, 155-160. doi: 10.1109/ITSC.2010.5625077

Dingus, T.A., Jahns, S.K., Horowitz, A.D., Knipling, R., 1998. Human factors design issues for crash avoidance systems, in: Barfield, W., Dingus T.A. (Eds.), Human factors in intelligent transportation systems. Lawrence Erlbaum Associates, Mahwah, NJ, pp. 55-94.

Distner, M., Bengtsson, M., Broberg, T., Jakobsson, L., 2009. City safety - a system addressing rear-end collisions at low speeds, in Proc. 21st International Technical Conference on the Enhanced Safety of Vehicles, No. 09-0371, Stuttgart, Germany. Retrieved from http://www-nrd.nhtsa.dot.gov/pdf/esv/esv21/09-0371.pdf

Flemisch, F., Kelsch, J., Löper, C., Schieben, A., & Schindler, J. 2008. Automation spectrum, inner/outer compatibility and other potentially useful human factors concepts for assistance and automation, In D. de Waard, F. O. Flemisch, B. Lorenz, H. Oberheid, & K. A. Brookhuis (Eds.) , *Human Factors for Assistance and Automation* (pp. 1-16). Maastricht, the Netherlands: Shaker Publishing.

Hiraoka, T., Tanaka, M., Nishihara, O., Kumamoto, H., Saito, H., Hatanaka, K., 2007. Effective assessment of night vision enhancement system based on driving simulator experiments,

in Proc. 14th World Congress on Intelligent Transport Systems, CD-ROM, Beijing, China.

Inagaki, T., 2000. Situation-adaptive autonomy for time critical takeoff decisions. International Journal of Modelling and Simulation 20(2), 175-180.

Inagaki, T., 2003. Adaptive automation: Sharing and trading of control, in: Hollnagel (Ed.), Handbook of cognitive task design. Lawrence Erlbaum Associates Mahwah, NJ, pp. 147-170.

Inagaki, T., Itoh, M., Nagai, Y., 2007. Support by warning or by action: Which is appropriate under mismatches between driver intent and traffic conditions? IEICE Transactions on Fundamentals E90-A(11), 2540-2545.

International Transportation Forum, 2012. Pedestrian Safety, Urban Space and Health, OECD Publishing. Retrieved from doi: 10.1787/9789282103654-en

Isermann, R., Mannale, R., Schimitt, K., 2010. Collision avoidance systems PRORETA: situation analysis and intervention control, in Proc. 6th IFAC Symposium in Advances in Automatic Control, Munich, Germany, 461-470.

ITARDA, 2004. Road Traffic Crash Investigations Report, Tokyo, Japan: ITARDA (in Japanese).

Itoh, M., 2009. Toward preventive ACC systems against crashes due to another vehicle's cut-in, in: Xie, M., Xiong, Y., Xiong, C., Liu, H.,Hu, Z. (Eds.), Lecture Notes in Computer Science: Vol. 5928. Intelligent Robotics and Applications. Springer-Verlag, Berlin Heidelberg, Germany, pp. 226-234. doi: 10.1007/978-3-642-10817-4

Kaber, D.B., Endsley, M.R., 2003. The effects of level of automation and adaptive automation on human performance, situation awareness and workload in a dynamic control task. Theoretical Issues in Ergonomics Science 5(2), 113-153.

Kaempchen, N., Schiele, B., Dietmayer, K., 2009. Situation assessment of an autonomous emergency brake for arbitrary vehicle-to-vehicle collision scenarios. IEEE Transactions on Intelligent Transportation Systems 10(4), 678-687.

Lee, J.D., Moray, N., 1992. Trust, control strategies and allocation of function in human machine systems. Ergonomics 35(10), 1243-1270.

Moray, N., Inagaki, T., Itoh, M., 2000. Adaptive automation, trust, and self-confidence in fault management of time-critical tasks. Journal of Experimental Psychology: Applied 6(1), 44-58.

Miller, C., Parasuraman, R., 2007. Designing for flexible interaction between humans and automation: Delegation interfaces for supervisory control. Human Factors 49(1), 57-75.

National Police Agency of the Government of Japan, 2012. Road Traffic Crash Statistics in 2011 (in Japanese). Retrieved from http://www.e-stat.go.jp/SG1/estat/List.do?lid=000001086731

NHTSA, 2008. National Pedestrian Crash Report, DOT HS810 968.

OECD, 1990. Behavioral Adaptations to Changes in the Road Transportation System. OECD, Paris.

Parasuraman, R., Bahri, T., Deaton, J.E., Morrison, J.G., Barnes, M., 1992. Theory and design of adaptive automation in aviation systems (Progress Rep. No. NAWCADWAR-92033-60). Naval Air Development Center Aviation Division, Warminster, PA.

Parasuraman, R., Riley, V., 1997. Humans and automation: Use, misuse, disuse, abuse. Human Factors 39(2), 230-253.

Parasuraman, R., Sheridan, T.B., Wickens, C.D., 2000. A model for types and levels of human interaction with automation. IEEE Transactions on Systems, Man, and Cybernetics 30(3), 286-297.

Prinzel III, L.J., Freeman, F.G., Scerbo, M.W., Mikulka, P.J., Pope, A.T., 2003. Effects of a psychophysiological system form adaptive automation on performance, workload, and the event-related potential P300 component. Human Factors 45(4), 601-613.

Retting, R.A., Ferguson, S.A., McCartt, A.T., 2003. A review of evidence-based traffic engineering measures designed to reduce pedestrian-motor vehicle crashes. American Journal of Public Health 93(9), 1456-1463.

Rouse, W.B., 1988. Adaptive aiding for human/computer control. Human Factors 30(4), 431-443.

Scerbo, M.W., 1996. Theoretical perspectives on adaptive automation, in: Parasuraman, R., Mouloua, M. (Eds.), Automation and Human Performance. Lawrence Erlbaum Associates, Mahwah, NJ, pp. 37-63.

Tanaka, H., Itoh, M., Inagaki, T., 2010. Analysis of driver's error in pedestrian collision avoidance. IEICE Technical Report, SSS2010-13, 5-10, Tsukuba, Japan (in Japanese).

Tsimhoni, O., Flannagan, M.J., Mefford, M.L., Takenobu, N., 2007. A simple and effective display for night vision systems, in Proc. Fourth International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design. Retrieved from http://drivingassessment.uiowa.edu/DA2007/PDF/047_TsimhoniFlannigan.pdf

Wada, T., Doi, S., Tsuru, N., Isaji, K., Kaneko, H., 2010. Characterization of expert drivers' last-second braking and its application to a collision avoidance system. IEEE Transactions on Intelligent Transportation System 11(2), 413-422.

Wilde, G.J.S., 1994. Target Risk, PDE Publications, Toronto, Ontario, Canada.

Wilson, G.F., Russell, C.A., 2007. Performance enhancement in an uninhabited air vehicle task using psychophysiologically determined adaptive aiding. Human Factors 49(6), 1005-1018.

Woods, D. D. (1989). The effects of automation on human's role: Experience from non-aviation industries, In S. Norman & H. Orlady (Eds.), Flight Deck Automation: Promises and realities (NASA CR-10036, 61-85). NASA-Ames Research Center, Moffett Field, CA.

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subjective ratings could be 1 and 7, respectively. The numbers of cases in each initial TTC depends on whether a driver recognized the system assistance.

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Figure 8: Mean subjective ratings on collision avoidance capability and on appropriateness of the system maneuver for each Initial TTC. Error bars represent standard deviations. White bars were on the collision avoidance capability, and blacks were on the appropriateness of the system maneuver.

Table 1

Assist Mode	Driver reaction			
	Brake	Steer to right	Steer to left	None
Not Available	78	178	44	0
Available	122	143	33	2

Table 2

Driver reaction	System reaction			
	Brake assist for avoidance	Brake assist and autonomous steering	Brake assist for damage mitigation	None
Brake	43	79	-	-
Steer to right	33	103	7	-
Steer to left	11	22	0	-
None	-	-	0	2

Table 3

	Initial TTC		
Assist Mode	1.08	1.51	2.02
Not Available	18	2	0
Available	11	0	0

Table 4

	Initial TTC					
	1.08		1.51		2.02	
	Driver action		Driver action		Driver action	
	Brakin	Steerin	Brakin	Steerin	Brakin	Steerin
	g	g	g	g	g	g
Mean	5.4	5.8	5.2	5.1	4.1	4.6
s.d.	1.3	1.0	1.2	1.2	1.5	1.2
Number of cases	34	56	41	56	19	22

Table 5

	Initial TTC					
	1.08		1.51		2.02	
	Driver action		Driver action		Driver action	
	Brakin	Steerin	Brakin	Steerin	Brakin	Steerin
	g	g	g	g	g	g
Mean	5.1	5.5	4.9	5.3	5.1	4.6
s.d.	1.6	1.2	1.6	1.4	1.3	1.2
Number of cases	34	56	41	55	19	22

Figure 1

Figure 2

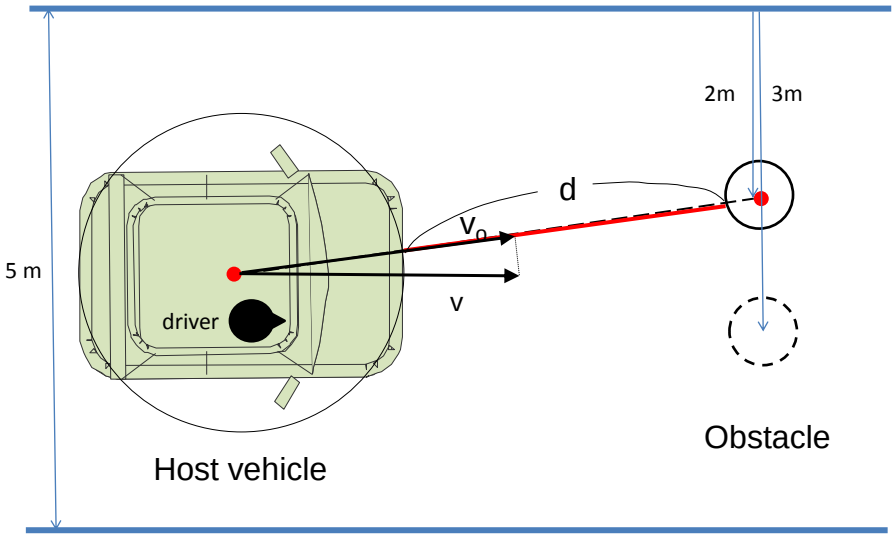
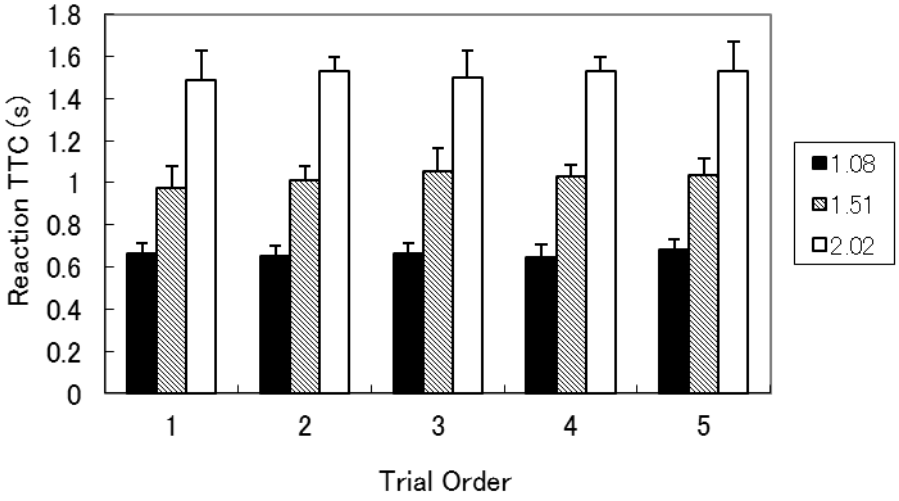
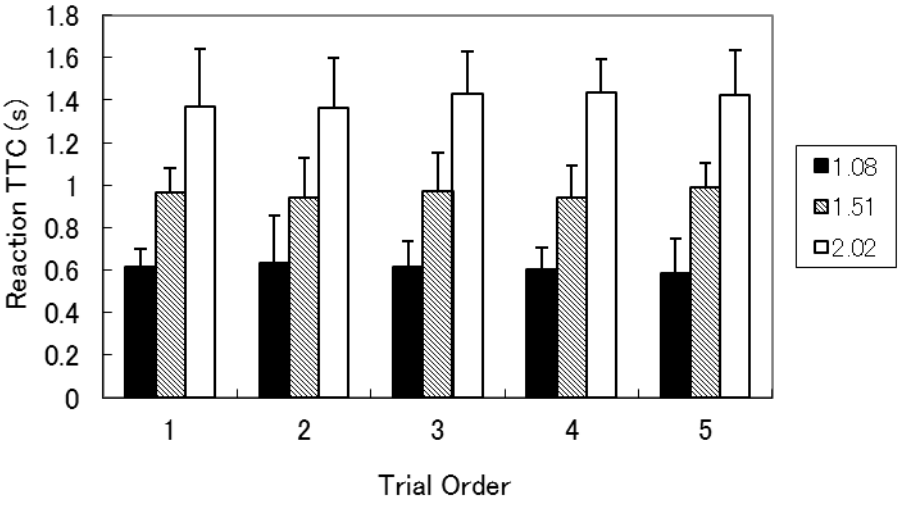


Figure 3



(a) Condition NA



(b) Condition A

Fig. 4

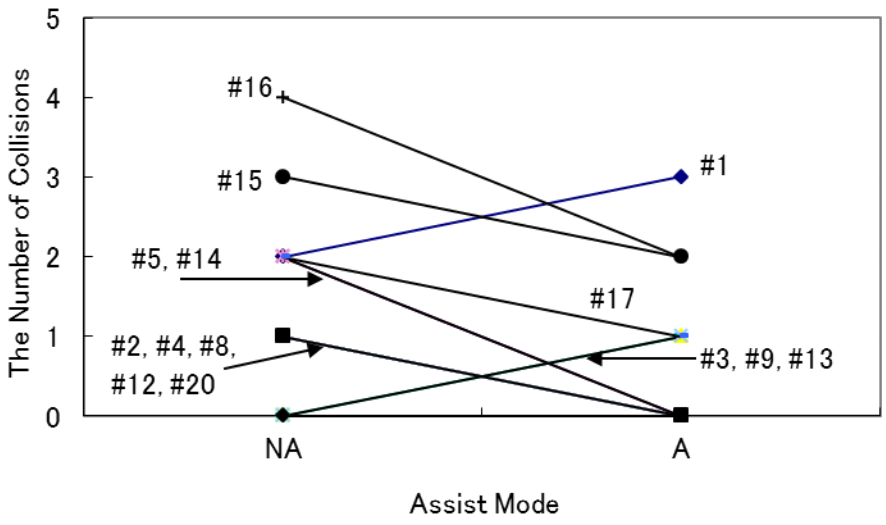

5
4
3
2
1
0
The Number of Collisions
#16
#15
#5, #14
#2, #4, #8,
#12, #20
#1
#17
#3, #9, #13
NA
A
Assist Mode

Figure 5

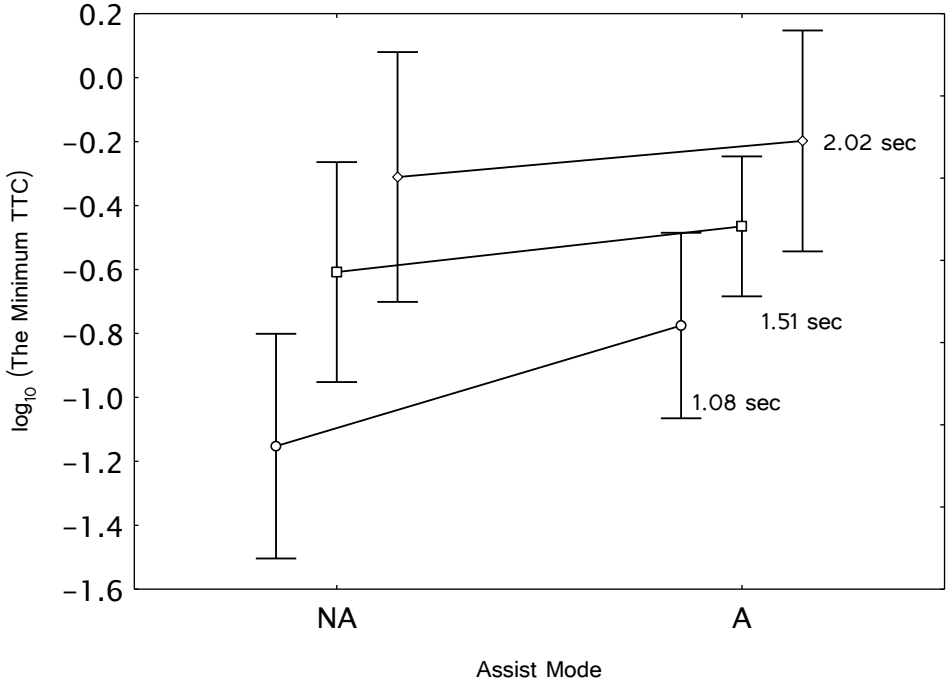

0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
−1.2
−1.4
−1.6
log10 (The Minimum TTC)
2.02 sec
1.51 sec
1.08 sec
NA
A
Assist Mode

Figure 6

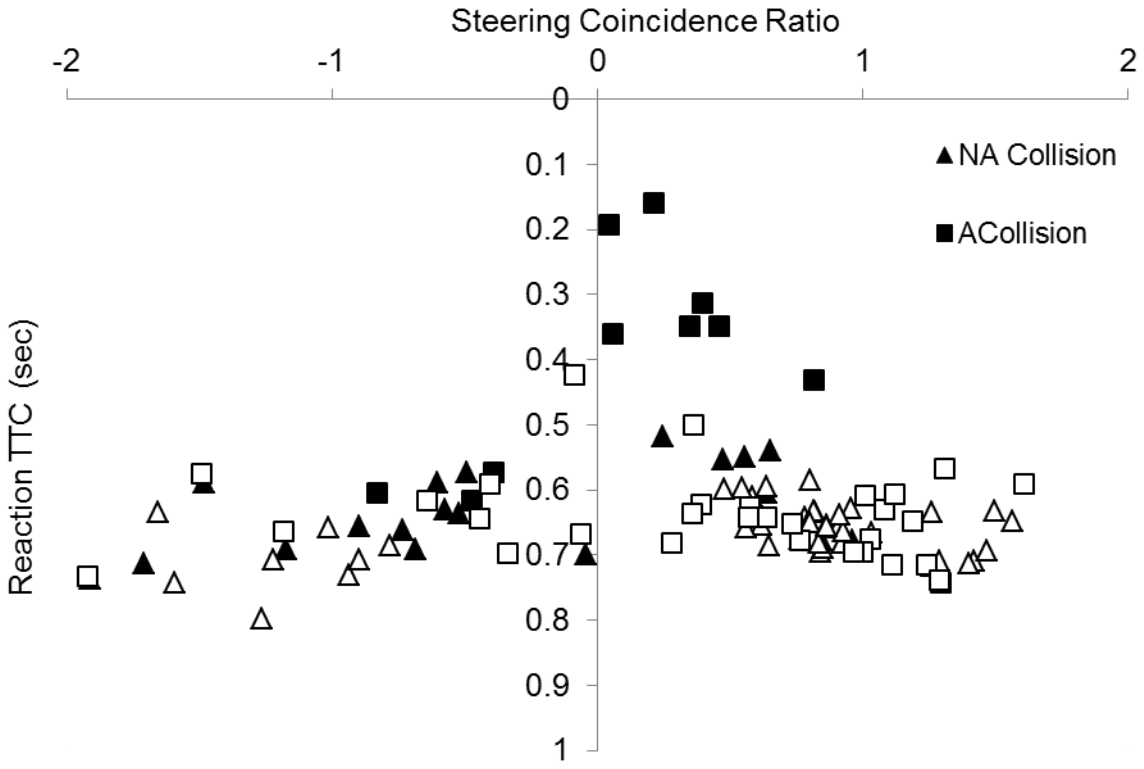

Steering Coincidence Ratio
-2
-1
0
1
2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Reaction TTC (sec)
NA Collision
ACollision

Figure 7

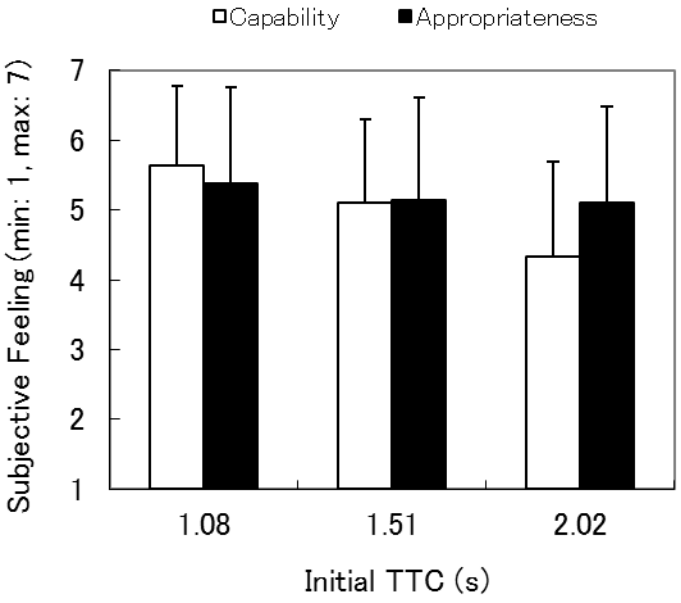

Capability
Appropriateness
Subjective Feeling (min: 1, max: 7)
7
6
5
4
3
2
1
1.08
1.51
2.02
Initial TTC (s)

Figure 8