Designing of brake timing of autonomous emergency braking system to avoid collision to pedestrians

Keisuke SUZUKI*, Hiroaki YAMAGUCHI* and Takaharu OGURI**

* Kagawa University
2217-20 Hayashi-cho, Takamatsu-city, Kagawa 761-0396, Japan
E-mail: ksuzuki@eng.kagawa-u.ac.jp

** DENSO CORPORATION
1-1 Syowa-cho, Kariya-city, Aichi 448-8661, Japan

Abstract
This study analyzes the brake operation behavior of drivers when a pedestrian runs out onto a road with good visibility. For this purpose, 15 subjects were observed in a driving simulator. As the evaluation criteria, we adopted the TTC to avoid the collision to pedestrian in the front/back direction at the start of braking and the spare distance between the pedestrian and the vehicle in the sideways direction at the start of braking. To determine the reliability of these test results, we also analyzed the initiation timing of a driver's braking operation in a real road environment using drive recorders and compared these results with those test results. Then, based on the results of this driving simulator test, we proposed the lowest 1% of the cumulative frequency of the driver's operation timings as the time of starting the brake operation in autonomous emergency braking. Finally, this proposed brake control timing’s adequacy was validated in an experiment. The system’s brake control did not interfere with the drivers’ brake operation, confirming that driver overconfidence in the system was controlled.

Key Words: Driving support, Autonomous emergency braking system (AEB), Driving simulator, Braking behavior, Overconfidence

1. Introduction
1.1 Evaluation of autonomous emergency braking by the New Car Assessment Program

Preventative safety support systems that reduce driver burden and prevent road traffic accidents are being actively researched and developed. To evaluate the effectiveness of these support systems, several countries have adopted the New Car Assessment Program (hereafter referred to as NCAP). Evaluation roadmaps of the NCAPs implemented in Europe and Japan (Euro-NCAP and J-NCAP, respectively) can be seen in Figure 1 (MLIT, 2016, JNCAP, 2016, Euro NCAP, 2016).

Autonomous emergency braking (hereafter referred to as AEB), one of the preventative safety support systems, has been tested for the prevention of crashing into the car ahead since 2014 and for pedestrian collision prevention since 2016. Figure 2 shows the temporal changes in the number of fatal accidents per 100,000 people in Japan, separated by type (MLIT, 2017). The number of fatal accidents involving pedestrians has slightly decreased in recent years. Pedestrian protection in AEB systems is expected to further reduce these fatalities.
1.2 Driver overconfidence in AEB

Overconfidence is the false belief in “this system is fully reliable,” without realizing that the system is not consistently reliable.

Lee et al. (Lee and Moray, 1992) showed that reliability or trust can be expressed in four dimensions.

1. Basic: Agrees with social order and the laws governing the natural world
2. Ability: Consistently stable and desirable behavior; ability can be expected
3. Method: The method, algorithms, and rules that realize behavior can be understood
4. Purpose: The aim and underlying motivation can be understood

An overconfident user will erroneously judge that all four conditions are satisfied, when three or fewer are actually satisfied.
In a frequently operating system with many “opportunities to observe (Inagaki, 2005),” the driver can easily “construct a mental model” of the system (Itoh, 2003). Therefore, even if the system operation is not correctly understood, the multiple opportunities for observation enable easy amendment of the mental model; however, if there are few opportunities to observe the system operation, constructing a mental model becomes more difficult. An AEB system is normally non-operational, responding only in an emergency situation with a high risk of impact. Thus, an AEB system provides little opportunity for system observation. Therefore, in the design of the timing for initiating AEB control, apart from increasing the ability of the system to avoid collisions, it is important to optimize the timing of the initiation of the system control with respect to the human–machine interface, such as the suppression of system overconfidence, by optimizing the extent of interference between the system control and the driver behavior.

1.3 Existing research regarding driver behavior in response to pedestrians running out onto the road

In their analysis of collision avoidance behavior, Utsumi et al. (Utsumi and Ishigaki, 2009) report that when a driver avoids collisions, state variables such as velocity or pedestrian speed depend on driver behavior rather than that of their cars. Moreover, other researchers have modeled driver collision avoidance behavior of pedestrians running out from behind parked cars (Iwaki et al., 2013, Iwaki et al.,2015, Imanaga et al., 2015, Iwaki et al., 2016). Hiramatsu et al. (Hiramatsu and Sunda, 2012) and Saito et al. (Saito et al., 2016) also quantified the latent risks that lead to collision between vehicles and pedestrians when there is a high collision risk. In these studies, the authors analyzed driver avoidance behavior in response to pedestrians running out onto the road. However, there has been little research regarding how to set the timing of AEB braking control to suppress overconfidence based on the result of a detailed analysis of collision avoidance behavior of drivers with respect to pedestrians.

1.4 Purpose of research

In this research, as an example, we use an AEB system to prevent collision with pedestrians and propose braking control timing that can suppress both a reduction in trust in the system as well as overconfidence in the system.

We summarize our research objectives below:
1) Analysis of driver braking operation behavior with respect to a pedestrian running out onto the road
2) Analysis of the impact of a driver’s driving style on his/her braking operation behavior
3) Proposal of braking control timing that suppresses overconfidence by regulating the control interference between the driver and the system

2. Experimental method

2.1 Experiment device

In the experiment, we used a driving simulator (hereafter, DS) manufactured at Kagawa University. To draw the driver’s view, we set up three 100-inch screens to provide a vision range wider than 130 degrees in the forward direction. We also set up a two-sheet LCD monitor for the driver to have a view of the rear. Since there were no motion devices installed on this fixed-type DS, we anticipated that it might be difficult for the driver to sense the level of speed reduction after starting to brake. Therefore, when the deceleration was more than 5.5 [m/s²], we generated a skid-sound to simulate the noise that occurs when there is friction between the road and the tires. In addition, in Section “3.4 Braking operation timing reliability” below, we compared drivers’ braking timing when using the DS versus that of drivers in a real road environment and considered the accuracy of the analysis of braking control behavior when using a DS.

2.2 Experimental conditions

In this experiment, we matched the initial positions of pedestrians with each condition. Moreover, we set several estimated positions of impact between the vehicle and the pedestrian for the case when a driver does not apply the brake. As a reference in this experiment, we set the speed of vehicles driven by the subjects at 40 km/h, based on an accident database (JSAE, 2008) that analyzes collision accidents between cars and pedestrians in Japan. Moreover, based on the
average walking speed determined from survey results of 707 walkers’ speeds on a city road (Matsumoto et al., 2009), we set the speed of a pedestrian crossing the road to 5 km/h. As indicated in Section “3.2 Braking operation timing for different pedestrian crossing speeds and vehicle velocities,” the analysis results also show the results at different crossing velocity of pedestrians and the velocity of vehicles.

We conducted the experiment with reference to five conditions, three of which relate to the predicted collision position between the pedestrian and the vehicle as occurring on the left side, center, or the right side of the vehicle and the other two regarding the near-miss with no collision and the pass-by condition. We matched the initial positions of the pedestrians and, to change the estimated positions of impact, we changed the timing of the pedestrians running onto the road for different conditions. We set the time at which the pedestrian ran out onto the road so that the impact timing between the vehicle and the pedestrian on the left side of the vehicle would be in the estimated impact position, i.e., the time to collision (TTC) = 3.00 s. Figure 3 and Table 1 show the collision impact position and the timing of the pedestrian running onto the road, respectively. Furthermore, we modeled Japanese roads in which vehicles travel on the left side of the road and walkers run out from the left side.

![Diagram showing the relationship between pedestrian and vehicle speeds](image)

Figure 3 Estimated position of impact of the vehicle and pedestrian, given the five standard conditions in the experiment

<table>
<thead>
<tr>
<th>Event conditions</th>
<th>Estimated position of impact</th>
<th>Timing of pedestrian running out in terms of TTC (=D[m]/V[m/s])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Approaching</td>
<td>0.90 m to the left from the left edge of the vehicle</td>
<td>TTC=2.35 s</td>
</tr>
<tr>
<td>Left edge</td>
<td>Left side of vehicle</td>
<td>TTC=3.00 s</td>
</tr>
<tr>
<td>Centre</td>
<td>Centre of vehicle</td>
<td>TTC=3.65 s</td>
</tr>
<tr>
<td>Right edge</td>
<td>Right side of vehicle</td>
<td>TTC=4.30 s</td>
</tr>
<tr>
<td>Passing</td>
<td>0.90 m to the right from the right edge of the vehicle</td>
<td>TTC=4.95 s</td>
</tr>
</tbody>
</table>

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2.3 Pedestrian event

We classified the events wherein pedestrians stepped out on the road into two types - main and false events. Compared to the main event, for which there is a risk of collision owing to a pedestrian running out onto the road, we assumed the ratio of the occurrence of a false event, in which the pedestrian stops before running onto the road, to be 1:9 (90%). Furthermore, we termed the events involving a “sudden stopping event (high risk)” in which the pedestrian stops just before going onto the road and an event (low risk) in which the pedestrian stops long before nearing the road as dummy events. We randomly selected these main and false events.

We used 40 drives per experiment participant for each run out onto the road. Of these, we set four drives in 40 drives to be main events in which pedestrians actually run out and set the timing of these movements for each of the pedestrians who ran out.

2.4 Secondary task for the experiment participants

In addition to the braking operation of pressing the brake pedal in response to a pedestrian running onto the road, as a secondary task, we set an arithmetic task for the experiment participants (Uchida-Kraepelin vocalization task) to apply a mental workload. The secondary task suppressed overconfidence with respect to pedestrians running out onto the road and we set the settings to match those in real environment situations. In this experiment, we imposed this arithmetic task on drivers as a secondary task. A driver performs vision search which finds the pedestrian who runs out onto a road as a primary task. For this reason, we set up a mental arithmetic task which does not compete with a vision task. In driving of the car in actual traffic environment, mental distraction, such as thought in everyday life, influences cognitive judgment of a driver. In this research, in order to reproduce driving of the car in such actual environment, we set up the mental distraction using an arithmetic task.

2.5 Experiment participants

The experiment participants comprised 15 male drivers (average age of 23.0 ± 1.41 years) who used cars to attend school, from whom we obtained informed consent. Before starting the experiment, the experimental ethics committee of Kagawa University examined the content of the experiment in detail.

3. Experiment results

3.1 Timing of braking operation

Figure 4 shows the starting position of the braking operation of the experiment participants in false events (high risk), in which we observed the drivers' braking operations, as well as main events, in which pedestrians ran out. The horizontal axis shows a pedestrian's horizontal position at the time an experiment participant initiated braking operation, with the central line in the horizontal direction of the vehicle at 0 m. The vertical axis shows the TTC [s], which indicates the spare time in the forward/backward direction between the pedestrian and the vehicle when the participant applies the brakes. As a judgment criterion of the horizontal distance or TTC, we can see that the experiment participants are applying the brakes of their vehicles up to a certain point.

Figure 5 shows the horizontal positions of the pedestrian at the start of braking operation by the experiment participants. The vertical axis shows the spare distance in the horizontal direction between the pedestrian and the horizontal center of the vehicle. We used the Bonferroni method to determine the differences in the mean values and found a significant difference between the “right end” and “passing” conditions and the three “approaching,” “left end,” and “center” conditions. From these results, we suggest that in cases wherein time before collision is available and not available, the driver uses different judgment criteria with respect to initiating braking operation. For example, if a pedestrian runs out onto the road with no time available before collision, we consider that the driver conducts a braking operation based on the judgment regarding the sideways distance between the vehicle and the pedestrian rather than the TTC, which is the spare time in the forward/back direction between the driver and the pedestrian until collision.

Furthermore, we observed extremely late braking behavior of one driver compared to other drivers in the experimental results in the runs for one of the passing conditions. When we investigated the braking control behavior of these experiment participants, we determined that even in other conditions for which braking timing can be late, braking timing
can differ depending on the driver. In Section “3.3 Driver group categories based on driving characteristics” below, we consider the driving characteristics of drivers and how differences in driving characteristics affect the initiation of the driver braking control.

Figure 4 Horizontal position of the pedestrian and TTC to pedestrian from the time when the experiment participant began to brake

Figure 5 Sideways distance between the pedestrian and the horizontal center of the vehicle when the experiment participant began to brake

* : p < 0.05  ** : p < 0.01
3.2 Braking operation timing for different pedestrian crossing speeds and vehicle velocities

In the above experiments, the results pertain to vehicles and pedestrians moving at fixed speeds. If these speeds change, there is the possibility that the timing of the initiation of drivers’ braking operations will also change. Below, we consider the timing for drivers initiating braking operations at vehicle speeds of 20, 40, and 60 km/h and pedestrians crossing the road at 5 and 8 km/h. In this experiment, we set the timing of a pedestrian starting to walk to be TTC = 3.00 s and the estimated position of impact to be on the left side of the vehicle. Figure 6 shows the experimental conditions.

The experiment participants comprised 25 male drivers, which is 10 more than in the earlier experiment (average age of 22.5 ± 0.94 years). In all cases, we obtained agreement via informed consent for their participation in the experiment.

Figure 6 Test conditions for different pedestrian crossing and vehicle speeds

Figure 7 shows the time at which the 25 experiment participants initiated braking operations. We see that the braking timing with regard to pedestrians running out onto the road tends to be fixed even when the running speeds of the cars differ. Moreover, even when a pedestrian's speed changes, we observed no significant differences and a fairly fixed state. We used the Bonferroni method to determine the difference in the mean values of the timing when braking was initiated in different experimental conditions. The results reveal no significant differences in the means for different conditions.

Figure 7 Timing of the initiation of braking operation by the 25 experiment participants for different pedestrian crossing or vehicle speeds
3.3 Driver group categories based on driving characteristics

As the driving characteristics of drivers change, the timing of their braking control may also change. Using a driving style questionnaire (DSQ) comprising 18 questions, as proposed by Ishibashi et al. (Ishibashi, 2008), we categorized driver’s driving characteristics based on eight evaluation items, as shown in Table 2.

<table>
<thead>
<tr>
<th>DSQ</th>
<th>Eight items for evaluation in DSQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>Existence of confidence in the driving skills</td>
</tr>
<tr>
<td>S</td>
<td>Negativity regarding driving</td>
</tr>
<tr>
<td>Q</td>
<td>Tendency to drive in a rushed manner</td>
</tr>
<tr>
<td></td>
<td>Scrupulous driving tendency</td>
</tr>
<tr>
<td></td>
<td>Driving style whereby there is advanced preparation with respect to traffic flow</td>
</tr>
<tr>
<td></td>
<td>A car that is a status symbol</td>
</tr>
<tr>
<td></td>
<td>Tendency to drive unstably</td>
</tr>
<tr>
<td></td>
<td>Tendency to drive cautiously</td>
</tr>
</tbody>
</table>

We conducted a cluster analysis of the eight DSQ evaluation items using the experiment participants as variables. In our cluster analysis, we used Equation (1) below to obtain the Euclidean space distance between the experiment participants with respect to variables specific to the participants.

\[ d_{ij}^2 = \sum_{k=1}^{p} (X_{ik} - X_{jk})^2 \]  

\( d \): Distance between participants  
\( i, j \): Participant number \((i, j = 1, 2, \ldots, 8)\)  
\( p \): Variable number \((p = 1, 2, \ldots, 8)\)  
\( X \): Values of variables

We formed groups by combining experiment participants based on their proximity to the Euclidean space distance. We used the Ward method (Jin, 2005) with a high level of categorization sensitivity as our cluster analysis method. Figure 8 shows our cluster analysis results based on the eight DSQ evaluation items for each driver as variables. Based on a tree diagram obtained from the cluster analysis, we established a boundary line and categorized 15 experiment participants into three driver groups.
Figure 8 Categorization of the driving styles of experiment participants based on cluster analyses of DSQ results

Figure 9 shows the DSQ results for each of the driver groups. In group A, the items “existence of confidence in the drivers’ skills” and “a car that is a status symbol” are significant, but a “cautious driving” is less. In group B, although we found no notable characteristics for each item, the “negative on driving” is strong compared to that of other groups. In group C, items such as “advanced preparation for driving,” “unstable driving,” and “cautious driving” have high values.

Figure 9 Characteristics of the driving style for each of the driver groups categorized in the DSQ

Figure 10 shows the times from when pedestrians started to walk until the experiment participants initiate braking control for each driver group. Owing to the small amount of data for each group, we do not show the standard deviation on the graph. The braking timing with respect to pedestrians running out onto the road is quickest in group C and slowest in group A.

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Figure 10 Reaction time for each of the categorized DSQ driver groups between the time of pedestrian starting to walk and the start of braking operation

Figure 11 shows the distance between the pedestrian and the vehicle when it is stopped for each of the driver groups. The spare distance between the pedestrian at the time when the vehicle stops was longest in group C and the shortest in group A.

Based on these results, we provide a summary of braking operation behavior based on driver characteristics with respect to pedestrians running out onto the road for each group of drivers below. We use the results of cluster analysis of the DSQ to explain the differences in driver braking operation behaviors when avoiding a collision with a pedestrian.

Group A: Has confidence in their driving skills. There is no deceleration until there is heightened collision risk and braking operation is initiated with the idea that all would be fine as long as they can stop the vehicle close to the pedestrian.

Group B: Initiates braking operation after checking that the pedestrian is being approached with a smooth deceleration that enables the driver to stop at a position with spare distance between the vehicle and the pedestrian.

Group C: Constantly aware of the risk of collision with pedestrians. Initiates braking operation after checking that the pedestrian is approaching the road with a sudden and strong deceleration to stop in a position with spare distance.
distance between the vehicle and the pedestrian.

3.4 Braking operation timing reliability

To determine the reliability of the DS test results, we analyzed the initiation timing of a driver's braking operation in a real road environment that we investigated using drive recorders and compared these results with those previously described. We analyzed the braking operation in a real road environment using data from 75 cases for which there was heightened risk of collision with a pedestrian with TTC = 4.50 s or less. These data include the data from Japan as well as driver behavior data from Europe, North America, and Asian countries.

In Figure 12, we compare the braking operation timing results of the experiment using a DS described in the previous chapter with those from the braking operation of drivers in a real road environment. As mentioned above, the survey for traveling in this real road environment had a TTC of 4.50 s or less. For the comparison with real world data, the DS experiment data came from 180 runs, excluding data for which pedestrians started their movement at TTC = 4.95 s (Passing, Table 1).

Our significance test (t-test) results for a driver’s braking operation timing in a real road environment and the initiation of a driver’s braking operation in a DS test showed no significant difference between their mean values. As such, the timing of the initiation of braking by the experiment participants in the DS experiments mainly recreates the braking timing of drivers in real road environments, thus verifying the validity of our analysis results for the initiation of braking control in the DS experiments.

4. Braking control timing for suppressing overconfidence

4.1 Proposal of braking control timing to suppress control interference between the system and the driver

Based on the survey results of the initiation of a driver’s braking operation above, we considered ways to suppress both the “overconfidence” and “reduction in trust” to establish a threshold for initiating AEB system braking control.

To suppress overconfidence, the system’s braking control timing must be set to be later than the timing of the driver's braking. However, if the system’s braking control is too late, there will only be few system “observation opportunities” and the driver would worry about whether the system is actually working; hence, the trust on the system would be reduced. To improve the driver's trust on the system, there is a need to set the braking control timing to be earlier than the limit of physical braking avoidance for the slowest braking control timing.

Considering this, we propose a threshold for the initiation of braking control based on the lower 1% limit of the cumulative distribution and on the spare horizontal distance from the pedestrian and the TTC in the forward/backward direction in the braking operation initiation determined for the aforementioned experiment participants.
For each of the estimated positions of pedestrian impact, Figure 13 shows the evaluated results at three stages of the experiment participants’ initiation of braking control. Under the “approaching” condition in which a pedestrian starts walking at TTC = 2.35 s, we found that more than 50% of the driver’s operation was later than the timing that the driver wished to initiate control. In the “left end” condition, when a pedestrian starts walking at TTC = 3.00 s, the timing is close to that at which the driver wants to initiate control. Moreover, if the pedestrian begins to walk earlier than the “central” condition for starting to walk at TTC = 3.65 s, the driver can initiate braking behavior with time to spare.

From these results, as the estimated position of impact in the driver analysis, we used the experimental conditions for which the “left side” was typically evaluated as being close to the time at which the braking operation was initiated. With this left-sided condition, the histograms in Figures 14 and 15 show the survey results related to the horizontal distance of the pedestrian and the TTC in the forward/backward direction, respectively, at the initiation of the experiment participants’ braking operations. We assumed that these histograms have normal distributions and calculated the values that were at the lower 1% limit of the cumulative distribution. Table 3 lists the lower 1% limits and the median values of the horizontal distance from the pedestrian and the TTC in the forward/backward direction at the initiation of braking operations.

Figure 13 Subjective evaluations by the experiment participants on the timing of their braking control

Figure 14 Forward/backward direction TTC when the experiment participants initiated braking operation
To verify the accuracy of the proposed AEB system’s braking control timing, we conducted an evaluation experiment by adding the initiation timing of two different braking controls for an AEB system. The condition thresholds for initiating the system's braking control are (1) the TTC in the forward/rear direction and the horizontal position of the pedestrian, which is the physical avoidance limit for braking as calculated based on the road friction coefficient $\mu = 0.7$, (2) the TTC and horizontal position of the pedestrian in the forward/rear direction at a lower limit of 1% in terms of driver operation(s), and (3) the TTC in the forward/rear direction and the pedestrian’s horizontal position, which represents the median value of the driver operation(s). We labeled these systems as System #1, System #2, and System #3, respectively, and Table 4 shows the timing of the initiation of braking control and deceleration in each AEB system. Figure 16 shows the range of system operation.

<table>
<thead>
<tr>
<th>System</th>
<th>TTC in the forward/backward direction [s]</th>
<th>Sideways distance from the pedestrians [m]</th>
<th>Deceleration [m/s$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>System #1</td>
<td>Physical limits</td>
<td>-2.00</td>
<td>7.00</td>
</tr>
<tr>
<td>System #2</td>
<td>Lower 1% limit</td>
<td>-3.35</td>
<td>4.00</td>
</tr>
<tr>
<td>System #3</td>
<td>Median value</td>
<td>-4.10</td>
<td>4.00</td>
</tr>
</tbody>
</table>

Figure 15 Horizontal distance from the pedestrian when the experiment participant initiated braking operation

Table 3 Lower 1% limits and median values of driver control

<table>
<thead>
<tr>
<th></th>
<th>Lower 1% limit value</th>
<th>Median value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front/backward TTC [s]</td>
<td>1.40</td>
<td>2.38</td>
</tr>
<tr>
<td>Sideways distance from the pedestrian [m]</td>
<td>-3.34</td>
<td>-4.09</td>
</tr>
</tbody>
</table>
In this experiment, we analyzed the timing in which the braking control by a system does not interfere with the braking operation by a driver. It is because we think that system dependence occurs when braking control of a system is earlier than braking operation of a driver (when operation interferes). Based on this experimental result, we proposed the start timing of the braking control of a system which does not induce excessive system dependence. In the preliminary experiment, we investigated the relation between brake timing and operation interference. When the start timing of braking control of a system was set as the lowest 5% of the cumulative frequency of braking timing of drivers, there was a case where braking control of a system interfered in braking operation of a driver. When operation interference occurs (i.e., when the braking control timing by a system is earlier than braking operation of a driver), a driver may be dependent on the braking control by a system and lose attention on braking control. Moreover, in the case of the lowest 2% of the cumulative frequency, the same tendency was observed. Therefore, in this experiment, we set up the braking control timing of the system based on the timing of the lowest 1% of the cumulative frequency. As a result, as shown in following Fig. 17 (System #2), the timing of braking operation of a driver is earlier than the braking control by a system. In this experiment, we set up the braking control timing of the system on the lowest 1% of the cumulative frequency for the above reason.

There are 15 participants in this experiment. In 15 drivers, we considered 12 drivers who are classified into group B to be typical drivers, and we proposed the braking control timing of the system based on these 12 drivers. In addition, we observed two drivers with late braking operation timing classified into group A. Regarding the braking behavior of drivers who are classified into group A, the braking control of the system proposed in this experiment may interfere in braking operation of a driver. However, it is extremely difficult to set up the braking operation timing with sufficient statistical accuracy based on the data of only two drivers. It is required to increase the number of participants of an experiment and to analyze in detail the braking behavior of the driver classified into this group A.

4.2 Suppression of the interference between the driver and system controls

Figure 17 shows the survey results regarding the effectiveness of the AEB system for avoiding a collision with pedestrians who have run out onto the road. In System #1, wherein we set the threshold to the physical avoidance limit, all of the experiment's participants avoided collisions by performing braking operations themselves, and the AEB system did not initiate. In System #2, wherein we set the threshold for initiating AEB system braking control to be the lowest 1% limit of the driver’s braking operation timing, the system activated but all the drivers initiated braking control faster.
than the system. This shows that the system helped the drivers' braking operations. Therefore, from these two systems, we can conclude that the system does not interfere with the driver's operation. On the other hand, in System #3, wherein we set the threshold for initiating the AEB system's braking operation to be the median of the driver initiation of braking control, the system started to work first in 50% of the cases and the drivers conducted their braking operations afterwards. Moreover, we confirmed the braking control at this timing to have greater system trust than that at the physical avoidance limit. We can state that the timing of the initiation of the proposed System #2's braking control suppresses overconfidence with respect to AEB as the system's braking operation is not being interfered with by the driver's braking operation behavior. Furthermore, we can conclude that the system can suppress the reduction in trust owing to the late initiation of the system's braking control.

5. Conclusion

5.1 Analysis of driver braking control behavior with respect to pedestrians running out

In this study, we used a driving simulator to investigate the braking operation of drivers with respect to a pedestrian crossing. In a survey by Suzuki et al. (Suzuki et al., 2003) of driver braking control with respect to stopped vehicles, the authors reported that as the velocity of a vehicle increases, the braking timing of the driver becomes faster.

In this experiment, we observed a tendency for the initiation of braking operation based on either the available distance in the horizontal direction between the pedestrian and the vehicle or the available time until collision in the forward/backward direction with respect to the driver and the pedestrian crossing the road. In addition, we conducted an experiment with different pedestrian crossing speeds and vehicle speeds. The results show the timing of the initiation of drivers’ braking operation to be fixed even for different vehicle speeds and pedestrian crossing speeds.

In a DS study, we set up the mental distraction using a mental arithmetic task. In this experiment, we used Uchida-Kraepelin vocalization task as a secondary task. After the experiment, we got the comment about this secondary task. Subjects answered that they did not become sensitive too much to a pedestrian's running-out event. In this study, we think that we could reproduce the mental distraction in actual operation environment.

We conducted this experiment using the driving simulator. Comparison with the braking behavior of the driver in actual traffic environment is indispensable. The braking operation timing in the actual traffic environment that authors analyzed using a drive recorder, and the braking operation timing in a driving simulator are shown in Section 3.4. The braking start timing in actual traffic environment and the braking start timing in the driving simulator show the similar tendency. Therefore, it is possible to say that the result obtained using this driving simulator is almost same with that in the actual traffic environment.
5.2 Analysis of driver's braking behavior for different driving styles with respect to a pedestrian crossing a road

We found that the differences in the timing of the initiation of braking operation depend on driver behavior. Based on the cluster analysis results from a DSQ, we categorized drivers' driving styles into three groups. We conclude that we can use DSQ cluster analyses to explain driver characteristic braking operation behavior to avoid collisions with pedestrians.

For instance, the drivers with the tendency to worry or prepare in advance have also a tendency to be constantly aware of the dangers to pedestrians. As such, when they see a pedestrian approaching, they initiate braking operation by strongly decelerating so that they can leave a large distance between themselves and the pedestrian to avoid a collision.

5.3 Proposed braking control timing to suppress the reduction of both overconfidence and trust

To suppress driver “overconfidence” in the system, we consider that there is a need to set the braking control timing of the AEB system to be later than that of the driver's braking operation. Moreover, to suppress the system's “reduction in trust,” we suggest that the braking control timing of the AEB system be set to be earlier than the timing of the physical avoidance limit. Based on the results obtained using a driving simulator, we propose the use of the lowest 1% limit value of the cumulative frequency of the timing of the initiation of a driver’s braking operation as the timing threshold.

We used a driving simulator to validate the applicability of this braking control timing. In our verification experiment, we confirmed that the control interference between the drivers and the systems is suppressed, it can be possible to control the creation of overconfidence. Moreover, the timing of this braking control confirmed the possibility of suppressing the reduction in trust of the system more than initiating braking control at the physical avoidance limit.

In this experiment, we analyzed the braking behavior of the drivers to a pedestrian's running out in a straight single road. According to the accident statistics database of ITARDA (ITARDA, 2016), the death accident number at single straight road is 45.5% of the whole accidents. The fatal accident number at intersections is 50.1% of the whole. Others are 4.4%. In this experiment, we analyze the braking behavior of the driver straight single roads as the first step of an experiment. In the next experiment, we are planning analysis of the braking behavior of the driver at intersections.

References

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