Toward Trustworthy Haptic Assistance System for Emergency Avoidance of Collision With a Pedestrian

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This paper proposes a haptic assistance system that provides momentary steering wheel torque to help the driver choose the steering direction for avoiding collision with a pedestrian. The results of an experiment with a driving simulator showed that reaction time was reduced significantly when using haptic assistance and that the system was effective in enhancing appropriate selection of a steering direction in many cases. However, there were cases in which the drivers’ choice was opposite to the system’s proposal. In order for the system to be acceptable to drivers, the drivers’ natural choice of direction should be taken into account.

Keywords: Shared control, advanced driver assistance systems, safety, pedestrian

Introduction

Wide discussions on automated or self-driving vehicles are taking place today (Gasser & Westhoff, 2012; NHTSA, 2013; SAE International, 2014). However, it has often been pointed out that full automation (self-driving) is not likely to happen, as drivers (i.e., human operators) are needed even in highly automated systems (e.g., Billings, 1997; van Paassen, 2010; Woods, 1989). In fact, there are many concerns regarding highly autonomous vehicles, for example, too much reduction or imbalance of mental workload (Itoh, 2008), lack of situation awareness (Merat & Janssen, 2008), overtrust or overreliance (Inagaki & Itoh, 2013; Itoh, 2012), and reduction of skills (Mulder & Abbink, 2011).

It is thus becoming a common understanding that haptic shared control is a promising approach for car driving (Abbink, Mulder, & Boer, 2012; Flemisch, Kelsch, Löper, Schieben, & Schindler, 2008; Griffiths & Gillespie, 2005). Many works on haptic shared control have focused on driver assistance in relatively peaceful traffic conditions, such as lane following (Griffiths & Gillespie, 2005), curve negotiation (Forsyth & MacLean, 2006; Mulder, Abbink, & Boer, 2008), voluntary lane changes (Nishimura, Wada, & Sugiyama, 2013; Tsoi, Mulder, & Abbink, 2010), and parking (Hirokawa, Uesugi, Furugori, Kitagawa, & Suzuki, 2014). Additionally, the idea of haptic shared control has been expanded and applied to emergency evasive maneuvers (Della Penna, van Paassen, Mulder, Abbink, & Mulder, 2010; Itoh, Horikome, & Inagaki, 2013), road departure prevention (Katzourakis et al., 2011), and blind-spot collision prevention, which is so-called protection (Itoh & Inagaki, 2014).

Such emergency systems with haptic assistance could be independent of the haptic shared control systems that work under peaceful situations. That is, human drivers can normally perform driving maneuvers themselves, but a haptic assistance system is activated when a collision is imminent. In this case, there is concern whether the driver can work successfully with such an assistance system or not. Della Penna et al. (2010) proposed negative steering wheel stiffness to enhance the driver’s performance of some evasive maneuver. It is important to note that the approach of Della Penna et al. did not give the driver any “active” guide for the evasive maneuver.
We believe that this approach is compatible with the design principle of human-centered automation (Billings, 1997; Woods, 1989), which claims that the human must be the final authority. Itoh et al. (2013) proposed an assistance system for emergency pedestrian avoidance, where the system assists the steering maneuver only when the driver performs a triggering maneuver, such as turning the steering wheel or hitting the brake. However, such a “human-centered” approach has a limitation in that the assistance system can do nothing if the driver does nothing.

In a real emergency situation, there are cases where a human cannot perform evasive maneuvers due to being surprised. In these cases, this kind of “human-centered” assistance system cannot be helpful at all. One way to solve this problem is to “automate” the critical decision (Itoh, Horikome, & Inagaki, 2011). Strictly speaking, however, such an approach violates the human-centered automation principle. Another approach is to provide the human driver a small amount of haptic guidance in order to suggest how to avoid a hazard. This paper proposes a human-centered haptic guidance for emergency pedestrian avoidance. The relationship between related previous works and this paper is summarized in Table 1.

An experiment with a high fidelity driving simulator was conducted to evaluate the system’s effectiveness.

Table 1. Comparison between related works on “human-centered” assistance for pedestrian-vehicle collision avoidance.

<table>
<thead>
<tr>
<th>Decision to perform a maneuver:</th>
<th>Della Penna et al. (2010):</th>
<th>Itoh et al. (2011):</th>
<th>This work:</th>
</tr>
</thead>
<tbody>
<tr>
<td>The system provides negative steering wheel stiffness to enhance driver performance of the steering maneuver; however, there is no direction guidance.</td>
<td>Manual only.</td>
<td>The system proposes the direction to avoid a collision.</td>
<td></td>
</tr>
<tr>
<td>Assistance of the maneuver:</td>
<td>None.</td>
<td>The system provides assists in order to avoid a collision.</td>
<td>None, but it is assumed that the assistance system as discussed in this paper is applied.</td>
</tr>
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</table>

**Steering Direction Assistance (SDA) System**

Let us suppose that a host vehicle is driving on a road, and a pedestrian suddenly appears crossing the road. We assume that there are no other vehicles in the next lane or on the road’s shoulder. The initial appearance point of the pedestrian is either on the left or right edge of the lane. The sensors in the SDA system can measure the longitudinal distance between the host vehicle and the pedestrian, while assessing the pedestrian’s horizontal position in the road. The SDA system can also identify if the pedestrian is moving. We assume that the SDA system just ignores any pedestrian outside of the driving lane. This assumption is to design a system that reduces unnecessary guidance as far as possible.

The system's assistive functionality depends on the value of Time-To-Collision (TTC), which is the longitudinal distance between the host vehicle and the pedestrian divided by the vehicle’s speed. Let $T_{\text{max}}, T_{\text{min}}, T_{\text{min}}$ be the maximum TTC for issuing an auditory alarm, the minimum avoidable TTC only by braking, and the minimum avoidable TTC by steering, respectively. (We
assume that \( T_{S_{\text{min}}} < T_{B_{\text{min}}} < T_{A} \). The control logic of the system is as follows:

(a) When \( T_{B_{\text{min}}} < \text{TTC} \leq T_{A} \), the SDA system issues an auditory alert once to inform the driver of the pedestrian’s appearance.

(b) When the value of \( \text{TTC} \) becomes \( T_{B_{\text{min}}} \), the system adds torque of 3.0 Nm for 0.05 s to the steering wheel in the system’s proposed direction to avoid the pedestrian. We continue by discussing how the proposed direction is determined. The values of the torque and the length of time to add the torque were determined by a preliminary experiment.

(c) When the value of \( \text{TTC} \) becomes \( (T_{B_{\text{min}}} - T_{S_{\text{min}}})/2 \), again, the system adds the same torque as in (b), to the steering wheel.

(d) If the value of \( \text{TTC} \) is less than \( T_{S_{\text{min}}} \), the system does nothing.

In the driving simulator used for the experiment, adding the above torque results in rotating the steering wheel up to 20 degrees if the driver does not hold the steering wheel. However, this system assumes that the driver has been driving manually and that the driver is holding the steering wheel. By conducting preliminary experiments, we have confirmed that the torque is weak enough for a human driver to overrule the system if the driver wants to continue going straight.

The direction that the system adds the torque to the steering wheel is determined by the position and the speed of the pedestrian:

Figure 1. The SDA system’s choice of direction to avoid a collision

(i) Suppose the pedestrian stops immediately after the appearance. If the pedestrian is on the right edge, the host vehicle should move to the left (Fig. 1a) in order to reduce collision risk. The SDA system proposes steering to the left in this case. If, on the other hand, the pedestrian is on the left, the vehicle should move to the right (Fig. 1b).

(ii) If the pedestrian is moving, the preferable direction for avoiding a collision becomes complicated. In this system, it is assumed that the pedestrian may continue moving or stop some time later, but the pedestrian never goes back. This assumption is
based on the fact that the TTC is in between $T_A$ and $T_{B\text{min}}$ when the pedestrian enters the road (i.e., the pedestrian is very close to the vehicle and a limited length of time, up to 2 s, is available for the participant. (If the initial appearance point is further away, the emergency avoidance steering maneuver may not be needed.) Therefore, it is almost impossible for the pedestrian to go back before the SDA system starts haptic guidance. Thus, the SDA system considers that the host vehicle should avoid entering the masked area in Figs. 1c–d. For the case shown in Fig. 1d, however, the appropriate direction to avoid a collision could be right if there is no room on the left.

If there are other obstacles on the desired path to avoid a collision with the pedestrian, the path will be disregarded. In this case, if there is no room to avoid a collision with the pedestrian or the obstacles, the assistance system will supply only a damage-mitigation brake.

In the real world, it is natural to suppose that the proposed system is combined with a vehicle-pedestrian collision avoidance system, such as the one in Itoh et al. (2013). In that case, the “human-centered” collision avoidance system will be activated when the driver performs a “triggering” maneuver, such as turning the steering wheel to the right. However, the haptic direction guidance system alone will be tested in this paper, because we are interested in whether such a guidance system is really helpful for the driver to determine the steering direction.

**Experiment**

Participants

Twenty male graduate and undergraduate students at the University of Tsukuba between the ages of 20-29 participated in the experiment. Two of them did not complete the experimental tasks due to driving simulator sickness. Thus, the data of eighteen participants will be analyzed. Informed consent was gained from all participants.

The experiment lasted for approximately three hours for each participant. Each participant was compensated JPY 820 ($ ≈ 7 USD) per hour.

Apparatus

In this study, we used a motion-base driving simulator (HONDA DA-1105). However, the motion cue was not given to the participants, because many participants felt ill due to simulator sickness in preliminary experiments when the motion cue was provided. With an external computer, the experimenter could dynamically add torque to the steering wheel at any level. The driver’s front field of view was approximately 120 degrees. The simulated host vehicle had Antilock Brake System (ABS) functionality.

A straight road in a town driving course was used in this experiment, as shown in Fig. 2. The driving lane was approximately 4 m wide with a narrow shoulder, where the visual scale factor was 1.0. The host vehicle was 3.5 m long and 1.6 m wide. A curb separated the road and the sidewalk.

**Figure 2.** A view from the cockpit (as a pedestrian crosses the road from left to right).
Driver’s task

The participants were instructed to drive safely along a straight road from one end to the other end. A speed governor installed in the vehicle limited maximum speed to 60 km/h. That is, the vehicle’s speed never became greater than 60 km/h, even if the driver pressed the gas pedal completely. Note here that the vehicle speed may become lower than 60 km/h when the gas pedal stroke is small. Participants were asked to maintain the speed of the vehicle at 60 km/h with the speed governor and to maintain the lateral position of the vehicle at the center of the left lane as far as they could.

In each drive, a pedestrian appeared once suddenly on one edge of the driving lane. This sudden appearance simulated the driver looking away from the road. The appearance point of the pedestrian varied from trial to trial. There were four appearance points in this experiment (see Fig. 3). Since our focus is on emergency situations, the initial TTC against the pedestrian was less than 2 s, which was the threshold value for issuing auditory alerts. In this experiment, the initial TTC was 1.25 or 1.75 s. When the initial TTC is 1.75 s, the vehicle can stop before the pedestrian, if the driver hits the brake hard immediately after the appearance. On the other hand, braking is not enough to stop before the pedestrian when the initial TTC is 1.25 s (but it is still possible to avoid collision if the driver immediately performs an appropriate steering maneuver.)

Two lateral initial positions of the pedestrian were distinguished (i.e., the left edge of the lane and the right edge). The pedestrian never appeared suddenly at the center of the lane, because the sensor of the vehicle could detect the pedestrian immediately when the pedestrian entered the lane. If the pedestrian appeared on the left (or right) edge, the vehicle may move to the right (or left) to avoid collision. In this experiment, the speed of the pedestrian could be: 0 m/s, 1 m/s, 3 m/s, ‘1 m/s and stop,’ or ‘3 m/s and stop.’ The condition where a pedestrian moved at 1 m/s was for simulating walking. The condition at 3 m/s was to simulate running. In both cases, it was assumed that the pedestrian was not aware of the host vehicle. The conditions ‘1 m/s and stop’ and ‘3 m/s and stop’ mean that the pedestrian stops in the center of the driving lane. The stopping of the pedestrian was simulating that the pedestrian became aware of the approaching vehicle but did not know what to do at all.

In summary, there were twenty conditions regarding pedestrian movement (‘two initial TTCs’ x ‘two lateral positions’ x ‘five speeds’). Participants were instructed to avoid the pedestrian. Drivers were allowed to choose one of the following alternatives: (1) steer to the right (which may result in entering the next lane), (2) steer to the left (which may result in entering the road shoulder), or (3) apply the brake only. Note that there were no other vehicles, bikes, or pedestrians other than the hazardous pedestrian appearing on the road, but the participants were not explicitly told this. Thus, the participants have to take into account the traffic conditions in order to determine how to avoid an imminent collision. However, it is highly possible that the participants imagined that no other objects would appear in the experiment based on repetitive experience of the trials.
Even if a collision happens, no haptic feedback on the collision was given to the participants in order to reduce the participants’ uncomfortable feeling of hitting the pedestrian. Additionally, we did not actively inform the participants of the result (collided or not) in any way, since we were not interested in the effectiveness of SDA on collision avoidance. The participants could recognize collision with the pedestrian by looking at the front display, but it was sometimes difficult to judge whether a collision had occurred or not.

Experimental design and hypothesis

In this experiment, Assist Mode was the only independent variable and used as a within-subject factor. Three levels were distinguished for Assist Mode (i.e., No Assist mode, Alarm mode, and Alarm and Steering Direction Assist [Alarm+SDA] mode). Under the No Assist mode, the drivers had to avoid a collision themselves. The Alarm mode provided only an auditory alert when a pedestrian appeared on the road and the TTC was less than $T_A$. Under the Alarm+SDA mode, the SDA system described in the previous section was available. In this paper, the values of $T_A, T_{run}, T_{run}$ were set at 2.00, 1.25, and 0.90, respectively. This was based on the characteristics of the vehicle model in the driving simulator. In order to investigate whether the haptic guidance was really effective in enhancing the driver’s ability to plan an appropriate collision-avoidance maneuver, the SDA system with alarms was compared with the alarm-only system (i.e., Alarm mode).

The hypothesis is that the SDA system is effective to guide the driver appropriately. In order to test this hypothesis, the following questions were examined:

1. To what extent did the participants recognize the steering guidance, and to what extent was the recognition correct?
2. To what extent was driver reaction time affected?
3. To what extent did the participants obey the steering guidance?
4. Were the driver’s opposite choices inappropriate?

Measures

Participants’ chosen steering directions were recorded and analyzed. If a participant rotated the steering wheel more than 30 degrees, it was regarded as a driver’s avoidance maneuver. Note that the steering ratio is 20:1 in this driving simulator. The SDA system may rotate the steering wheel up to 20 degrees if the driver does nothing for steering maneuver. Driver reaction was classified as one of the following: (i) no steering maneuver, (ii) steering to the right, and (iii) steering to the left. If the driver performed a steering maneuver and his/her steering direction was the same as that by the SDA system, the suggestion was regarded as a success.

The reaction time, which was the elapsed length of time from the pedestrian’s appearance to the time when the steering angle became more than 30 degrees, was also recorded and analyzed. We did not evaluate whether the host vehicle collided with the pedestrian or not. This is because collision avoidance could be enhanced by a haptic assistance system once a driver performs a triggering avoiding maneuver (Itoh et al., 2013).

Procedure

The experiment was done in one day for each participant, and total time was approximately three hours. After receiving written instructions on the driving task, the participants were given opportunities for practice, so they could acquire familiarity with the driving simulator. Sometimes a red traffic cone appeared in the driving lane during practice drives. The participants had to perform a maneuver to avoid the traffic cone.

After practice drives, data collection trials were completed for each assist mode. The order of assist mode was counterbalanced. There were six order types of assist modes, and each participant was assigned to one of the six orders randomly. Before conducting trials under the Alarm or Alarm+SDA mode, each participant received written explanations of the corresponding system and experienced additional practice drives with the system so that they could learn how the system worked.

Every participant performed 20 trials (1 trial for each type of pedestrian appearance condition)
for each assist mode. The order of experiencing conditions was randomized in each assist mode in order to cancel learning effects. After completion of one assist mode, each participant was given a short break.

Results and Discussions

Awareness of steering direction assistance

Under the Alarm+SDA condition, there were 360 cases (‘2 initial TTCs’ x ‘2 lateral positions’ x ‘5 speeds’ x ‘18 participants’). Among them, there were 318 cases (88.3%) where the participants recognized the haptic steering direction guidance. However, the participants did not recognize the haptic guidance in 17 cases (4.7%), and they were not sure in 25 cases (6.9%). In the 318 recognized cases, there were 200 cases (62.9% of the recognized cases) where the participants recognized the guided direction correctly. Thus, the correct recognition rate in total was 55.6%.

Effect of steering direction assistance on reaction time

Fig. 4 illustrated the mean reaction time for each assist mode. We conducted an ANOVA on the reaction time, and the result showed a significant main effect of assist mode type (F(2, 1077) = 7.814, p < 0.01). A Tukey’s HSD test on the reaction time revealed significant differences between the No Assist and the Alarm+SDA modes (p < 0.01) and between the Alarm and the Alarm+SDA modes (p < 0.01). That is, the Alarm+SDA mode was different from the other modes. It can be thus claimed that the driver’s reaction time is significantly reduced if the SDA system is available.

Effect of steering direction assistance on driver choice

Next, we analyzed how the driver’s steering direction was affected by the SDA system. Since situational specifics will determine which direction the driver should turn the steering wheel, we identified four types of experimental conditions, as shown in Fig. 5:

Type A: The pedestrian appeared at the left border but stopped immediately. The system proposed steering to the right. Apparently, the drivers would also choose steering to the right.

Type B: The pedestrian appeared at the right border but stopped immediately. The system proposed steering to the left. Apparently, the drivers would also choose steering to the left.
Type C: The pedestrian appeared at the left border and moved to the right. The system proposed steering to the right, because there was not enough room to avoid the pedestrian in the left hand side under the risk of a sudden pedestrian stop. However, the drivers’ choice might vary.

Type D: The pedestrian appeared at the right border and moved to the left. The system proposed steering to the right, because the avoidable area would be decreasing in the left hand side, but there was enough room to avoid the pedestrian in the right hand side. However, the drivers’ choice may again vary.

The numbers of the scenarios for each type were as follows: one for Type A, one for Type B, four for Type C (1 m/s, 3 m/s, 1 m/s and stop, 3 m/s and stop) and four for Type D (1 m/s, 3 m/s, 1 m/s and stop, 3 m/s and stop). Apparently, the system could predict whether the pedestrian would stop in the lane or not.

Fig. 6 showed reaction time for each type of experimental conditions. As a whole, data shown in Fig. 6 were consistent with data shown in Fig. 4. The reaction time for Type D was longer than that in the other types of cases under the No Assist mode condition (i.e., it was essentially difficult for the drivers to determine the steering direction when the pedestrian appeared at the right edge and moved). On the other hand, the reaction time for Type D was not so high under Alarm and Alarm+SDA conditions. That is, the alert system and the SDA system were effective for the drivers to make a decision immediately.

We will now discuss how the drivers chose the avoiding direction for each scenario type. Fig. 7 depicted the distributions of the driver steering maneuvers for Type A. Apparently, steering to the
right was reasonable for the Type A scenario. In fact, the SDA system proposed steering to the right, and the drivers chose right as well. The choice was done smoothly when assistance was available. In fact, Fig. 6 suggested that both the Alarm and the Alarm+SDA modes were effective in reducing reaction time. A one-way ANOVA on the reaction time showed a significant main effect of the Assist Mode (F(2,51) = 7.791, p < 0.01). A Tukey’s HSD test revealed significant differences between the No Assist and the Alarm modes (p < 0.05), and between the No Assist and the Alarm+SDA modes (p < 0.01). There was no difference between the Alarm and the SDA modes. In this type, auditory alerts were enough to shorten driver response time.

\[ F(2,51) = 7.791, \quad p < 0.01 \]

A Tukey’s HSD test revealed significant differences between the No Assist and the Alarm modes (p < 0.05), and between the No Assist and the Alarm+SDA modes (p < 0.01).

The result of the Type B was basically similar to that of the Type A (Fig. 8). Most of the drivers’ steering directions were identical to the proposal given by the SDA system. There was no statistically significant difference between the No Assist, Alarm, and Alarm+SDA modes. However, it is worth pointing out that there were cases of no steering in each assist mode. A possible reason for the no steering cases is that the road shoulder was too narrow for the drivers to steer to the left. Drivers, thus, might hesitate to steer to the left. Nevertheless, the SDA system was effective in reducing the reaction time.

A one-way ANOVA for the reaction time showed a significant main effect of Assist Mode (F(2,45) = 5.09, p < 0.05). A Tukey’s HSD test revealed a significant difference between the Alarm and the Alarm+SDA modes (p = 0.01). Note that the Alarm system did not reduce the reaction time for Type B. One possible reason for this Alarm system ineffectiveness is that choosing the direction was more difficult for Type B than for Type A. In fact, all participants chose “right” for Type A, but some of them chose “no steering” for Type B. The difficulty for Type B may come from the fact that Type B is rare in the real world. Drivers may have no clearly understood rule for avoiding a collision in Type B situations.

\[ F(2,45) = 5.09, \quad p < 0.05 \]

A Tukey’s HSD test revealed a significant difference between the Alarm and the Alarm+SDA modes (p = 0.01).

Note that the Alarm system did not reduce the reaction time for Type B.
For Type C, the SDA system proposed steering to the left to the drivers. There were several cases, under the No Assist mode and the Alarm mode, where the drivers steered in the opposite direction (to the left) (Fig. 9). A chi-square test showed that there was a marginally significant difference among the three modes ($\chi^2 = 8.918$, $p = 0.063$). A post hoc test showed that the distribution in the Alarm+SDA mode was marginally different from the No Assist mode ($p = 0.087$) and from the Alarm mode ($p = 0.054$). Results suggest that the SDA system is effective in reducing the possibility of driver’s inappropriate steering for Type C.

![Figure 9. Steering direction choices for each assist mode (Type C). The SDA proposed to steer to the right because there is no enough room to avoid a collision if it is steered to the left. The sum in each condition 72 (18 Participants x 4 trial).](image)

Why were there cases that chose left under No Assist and Alarm modes? We will consider a possible interpretation. Fig. 10 shows how the pedestrian looks from the driver’s point of view (in this figure, the pedestrian’s moving speed is 3 m/s). The horizontal axis in Fig. 10 is the horizontal position in the driving lane (zero means the left edge, and four means the right edge). The vertical axis represents the relative longitudinal position. The vertical axis origin is at the front end of the host vehicle. The circle in the vehicle represents the driver’s head. The pedestrian appears at the left edge of the lane and moves along with the arrow. The dots show the mean timing of driver reaction for the steering maneuver.

![Figure 10. The positions of the pedestrian at the reaction timing (Type C, 3m/s).](image)

Figs. 9 and 10 suggest that the longer reaction is delayed, the more drivers tended to choose to move left, because the pedestrian approached just the front of the driver and there seems enough room on the left hand side. Note that the SDA system provided steering torque suggesting to the
right, because the system adds torque immediately after the pedestrian comes into the lane. At that moment, turning to the right would be better, because there was no room to avoid the collision in the left hand side. Thus, we could claim that the driver’s choice is determined mainly by the relative position of the pedestrian at decision time. This is consistent with the findings in Itoh, Pacaux-Lemoine, Robache, and Morvan (2015).

Fig. 11 illustrates driver steering maneuver distributions for Type D. According to a chi-square test, there was no statistically significant difference between the three modes. Interestingly, steering to the left represented the majority of decisions in these cases, even though the SDA system proposed steering to the right. That is, the drivers tended to select the direction opposite to the one that the system preferred. A possible reason for this disagreement is that the pedestrian was initially on the right from the driver’s point of view (see Fig. 5). In particular, under the Alarm and the Alarm+SDA modes, driver reaction time was so reduced (as shown in Fig. 6) that drivers tended to choose left because the pedestrian was still on the right when drivers determined the avoidance direction. Table 2 supports this interpretation. In Type D and 3 m/s cases, the pedestrian might be on the left from the driver’s point of view at decision time under the No Assist mode due to the pedestrian’s fast speed. Thus, the frequency of choosing “steer to the right” is higher under the No Assist mode than under the other modes.

![Figure 11](image.png)

*Figure 11.* The steering direction choices for each assist mode (Type D). The SDA proposed to steer to the right, because the possibility of collision becomes higher if steering to the left. The sum in each condition is 72 (18 participants x 4 trials).

On the other hand, the drivers never chose right under the Alarm+SDA mode, because the driver’s reaction was influenced early by the haptic steering guidance. In fact, the mean reaction time was 0.57 sec. under the Alarm+SDA mode (Fig. 7). Here, reaction time includes the time to rotate the steering wheel 30 degrees, which means that the decision to steer to the right was done at an earlier time. It can be said that the pedestrian tended to be on the right, and thus, the driver determined to steer to the left under the Alarm+SDA mode.

Table 2. The distributions of driver steering directions for each assist mode (Type D, 3m/s and no stop). The SDA proposed steering to the right. The sum of each column is 18 (18 participants x 1 trial).

<table>
<thead>
<tr>
<th></th>
<th>No Assist</th>
<th>Alarm</th>
<th>Alarm+SDA</th>
</tr>
</thead>
<tbody>
<tr>
<td>No steering</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>To the left</td>
<td>9</td>
<td>11</td>
<td>17</td>
</tr>
<tr>
<td>To the right</td>
<td>9</td>
<td>6</td>
<td>0</td>
</tr>
</tbody>
</table>

The above discussion again supports the conclusion that the driver’s choice is determined mainly by the relative position of the pedestrian at the decision time. In particular, for Type D, visual cues were dominant compared to the haptic steering guidance.
Is the opposite choice bad?

The above results show that participants chose the opposite of the system’s proposed direction in some cases. Here a question arises: Were the opposite choices bad? The answer would be negative. Fig. 12 shows the reaction time under Alarm+SDA condition, and the two categories, “same” and “opposite,” were distinguished. The category “same” refers to the cases where the driver had chosen the same direction as the system’s proposal, and “opposite” where the driver had chosen the opposite direction. A t-test showed no statistical difference between the two categories. That is, the time length to determine the direction is not dependent on whether the driver’s obedience to the system’s proposal. As previous analyses revealed, the choice would be based on the lateral relative position of the pedestrian.

![Diagram showing reaction time depending on driver choice.](image)

*Figure 12.* Reaction time depending on driver choice. The ‘same’ (or ‘opposite’) refers to the cases where the driver chose the same (or opposite) direction as the system’s proposal, respectively.

Fig. 13 depicted an example of times series of the vehicle’s lateral position at a scenario Type D (3m/s and stop). Under Alarm+SDA condition, the driver (participant #1) chose left, because the reaction was early. On the other hand, the driver chose right under No Assist and Alarm conditions, because the reaction was late. The opposite choice itself is not bad but simply due to an earlier reaction time.

![Diagram showing vehicle trajectory.](image)

*Figure 13.* An example of vehicle trajectory at a Type D condition (Participant #1, 3m/s and stop).
Conclusions

This paper proposed a driver assistance system that suggests to the driver a steering direction in a haptic manner in order to avoid an imminent collision with a pedestrian. The haptic guide was designed to be strong enough to be noticed by the driver yet weak enough for the driver to overrule the haptic suggestion. That is, the assistance system is consistent with the human-centered automation principle (Billings, 1997; Woods, 1989).

We hypothesized that the SDA system would be effective to guide the driver to the better direction to more easily avoid a collision and to reduce driver reaction time. As for reaction time, the SDA system, in fact, reduced the reaction time significantly. However, the haptic steering guidance might be regarded as just tactile information for the drivers. It is well-known that tactile information is transmitted to the brain more rapidly than other modalities (Harrar & Harris, 2005; Ho & Spence, 2008; Mowbray & Gebhard, 1961). In fact, even though the system was effective in enhancing the driver making an appropriate choice when the pedestrian moved from the road shoulder to the other side, many drivers disagreed with the system’s proposal when the pedestrian moved from the center of the road to the road shoulder. The drivers’ choices were mainly based on visual cues (i.e., lateral relative position of the pedestrian but not based on the haptic guidance). According to interviews after the experiment, several drivers were, in fact, frustrated by experiencing contradictory guidance. Katzourakis et al. (2011) found a similar misconception for an emergency maneuver by a driver assistance system with shared control for road departure prevention.

Thus, haptic steering direction guidance in emergency situations should be designed with care. It is important to establish a way of sharing intention between a driver and an assistance system. In order to make such an assistance system acceptable to drivers, system designers should take into account the fact that drivers tend to choose left or right if a pedestrian is on the right or left when drivers determine their steering direction. It is important to note that the driver’s eyes are not at the center of the vehicle (or lane). A design solution would be dependent on what extent the assistance system is confident of its situational understanding. The system should identify a pedestrian’s current position so precisely that the system can detect the recognition gap between the system and the driver. Naturally random pedestrian movement in the real world might also be problematic. However, this problem is relatively less important, because the pedestrian’s possible movement could be predictable in the highly dangerous situation considered in this paper. The pedestrian’s movement is quite restricted, due to the very limited length of time.

Also, establishment of mutual trust between the driver and the system in peaceful situations could result in acceptance of the system’s emergency maneuver. For avoidance of a collision with a pedestrian, it might be effective to provide haptic guidance to the driver in order to reduce the collision risk when a pedestrian, who is a little bit far away (e.g., 2 to 3 s ahead of the vehicle), is coming close to the lane. If a driver experiences such guidance repeatedly, he or she could possibly accept an emergency system maneuver. Further study is necessary to investigate the effectiveness of such an assist system. The random nature of pedestrian movement also raises an issue to be addressed. Predicting natural pedestrian behavior is more difficult than the situational predictions considered in this paper.

Another solution that may be acceptable to drivers is just to provide a tactile vibration on the steering wheel in order for the driver to reduce the reaction time, because the haptic guidance in this study was as successful as a tactile alert.

There are several limitations with this study. First, the form of the pedestrian’s appearance was tricky. The pedestrian “suddenly” appeared at one edge of the driving lane, but this is not realistic. Second, there were no other road users, such as vehicles, bicycles, or other pedestrians. The choice of the steering direction may depend on how many other road users are there. Another limitation is that the participants repeatedly experienced such emergency situations in quite a short time period. Actual driver reaction to the sudden appearance of a pedestrian might be different from what was observed in this study. We are currently investigating the effectiveness of our proposed system in a more realistic driving context. Based on these works, we will integrate steering direction assistance and collision avoidance maneuvering assistance into one assistance system for vehicle-pedestrian collision avoidance. We hope the upcoming integrated system will be effective for avoiding vehicle-pedestrian collisions and acceptable to drivers and society.
References


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