A Haptic Communication Method for A Preceding Vehicle Following System

Shohei Ueda 1) Takahiro Wada 2)

1) Ritsumeikan University, Graduate School of Information Science and Engineering, 1-1-1 Noji-higashi, Kusatsu, Shiga, 525-8577, Japan
2) Ritsumeikan University, College of Information Science and Engineering, 1-1-1 Noji-higashi, Kusatsu, Shiga, 525-8577, Japan

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ABSTRACT: A new preceding vehicle (PV) following system with a haptic communication method, Haptic Adaptive Cruise Control (HACC), is proposed. HACC addresses the intention mismatch between a driver and a conventional adaptive cruise control system in a complex environment. HACC uses the torque around the steering wheel as the interface. The driver can easily find the current PV displaying the direction of the PV with the system’s torque around the steering wheel. In addition, the driver can change the PV to another one by adding torque to resist the presented torque of the system. Driving simulator experiments showed that the HACC method reduced the collision risk when the system erroneously changed the PV suddenly, and the haptic information effectively increased the driver’s understanding of the system’s intention. Furthermore, the driver’s intention could be easily communicated to the system.

KEY WORDS: safety, adaptive cruise control system, human machine interface, driving support, human interface, recognition / shared control, haptic interface [C1]

1. Introduction

Adaptive Cruise Control (ACC) systems successfully reduce a driver’s workload by assisting the driver’s pedal operation when following a PV. It has been pointed out, however, that sometimes it is difficult for the driver to notice a change in the PV in complicated traffic situations(1), although this situation rarely occurs. Nevertheless, the driver’s automation surprise could occur and consequently distrust the system(2, 3). It also may lead to a risky situation if the driver misunderstands which vehicle is the PV. Furthermore, it could be difficult for the driver to communicate his or her change of intention to the ACC regarding which vehicle the driver wishes to follow, or in which lane of the road the driver wishes to drive. In fact, when the driver starts to change lanes, a conventional ACC starts to accelerate after the vehicle completes the lane change. This happens because the system recognizes a PV based on the lane in which the host vehicle (HV) is driving. This could lead to driver frustration.

The purpose of the present paper is to establish a new preceding vehicle following system using haptic communication to cope with the problem of inconsistency between the intentions of the driver and the driver assistance system. It is expected that haptic communication will enable the human operator to interact and communicate continuously with the assistance system(4, 5).

In the present study, HACC is proposed. HACC is a PV following system that attempts to cope with the intention mismatch by using haptic communication. The proposed HACC uses a steering wheel for the haptic interface. A motor is attached to the steering shaft to exert torque around the steering wheel. The proposed system essentially works as an ACC. However, haptic information is provided by the system to indicate the lateral position of the PV. The driver can then easily notice when the system’s PV is different from the driver’s intention through the haptic information. This function makes the system’s intention regarding the PV tangible and increases the driver’s situation awareness. In addition, the driver’s intention, such as changing lanes, can be easily communicated to the system by the driver’s steering operation. The effectiveness of the proposed system is demonstrated by comparing it with the conventional ACC in driving simulator experiments.

We presented the basic idea of the proposed method and some preliminary results(6). The present paper, which is an extended version of it, adds a detailed explanation of the proposed method and the results. The driving behavior analysis, especially for the false detection scenario, is included in detail to see how the proposed method works for reducing collision risk in the case of a system’s error.

2. Haptic Adaptive Cruise Control

As stated above, the proposed HACC basically works as an ACC. The velocity of the HV is controlled to follow the PV. If a PV does not exist, the velocity of the HV is controlled to remain constant, which is commonly known as Cruise Control (CC). The HACC interface includes the steering wheel with a servo motor. The HACC allows the human driver and the system to communicate each other via haptic information by the torque around the steering wheel. The direction of the PV is displayed by the torque from the system to the human driver. The driver’s intention can be communicated to the system by the resisting
steering operation against the system’s steering operation when the driver wants to change the PV.

2.1. Velocity Control for Following Preceeding Vehicle

A PV following function is constructed based on the ACC\(^7\). The system controls the time gap\(^8\), \(t_g\), between the HV and the PV by velocity control of the HV. The \(t_g\) was set at 2 seconds according to the general settings of the ACC.

2.2. Algorithm for Determination of the Preceding Vehicle

A conventional ACC system determines the PV as the vehicle closest to the HV in the same lane where the HV is driving. In contrast, the HACC utilizes two sensor areas to determine the PV, as shown in Figure 1. The method to determine the PV is shown by Algorithm 1 (Figure 2). The vehicle that is in the trigger area and is closest to the HV becomes the PV. The vehicle continues to be the PV while it remains in the follow area. When a new vehicle enters the trigger area and is closer to the HV than the current PV, the new vehicle is determined to be the PV. The size of the trigger and follow areas were given by Figure 1. Such small trigger area was determined to coincide with the driver’s intention on the PV and to prevent the system from following the wrong vehicle. In contrast, wider size of the follow area was designed to cover 7.8m in the lateral direction at \(t_g = 2\) s ahead and it achieves to follow the PV during mild curves and a junction.

2.3. Interface

2.3.1 Haptic Interface

The proposed haptic interface shown in Figure 3 allows for communication between the driver and the HACC. The torque around the steering wheel is used for communication between the driver and the HACC. The torque sensor measures the torque exerted on the steering wheel by the driver, whereas the servo motor controls the torque exerted by the HACC.

2.3.2 Visual Interface

The visual interface shown in Figure 4 was used to display the current state of the HACC. Figure 4(a) shows the following PV state, Figure 4(b) shows the CC state, Figure 4(c) shows that the system is turned off.

2.4. Communication of Preceding Vehicle’s Direction

Figure 5 shows the method to display the direction of the PV. Torque \(\tau_{sys}\) is exerted around the steering wheel axis according to the direction of the PV, as shown in equation (1).

\[
\tau_{sys} = K\psi(t),
\]

where \(\psi(t)\) denotes the direction of the PV measured from the heading direction of the HV. \(K\) denotes a gain, which was set to

\begin{algorithm}
\begin{algorithmic}
\Require
\Statex\hspace{1cm} car[i] is other car,
\Statex\hspace{1cm} distance[n] is distance between car[n] and HV,
\Statex\hspace{1cm} distancePV is distance between PV and HV
\Statex\hspace{1cm} PV is nothing at first
\Loop
\ForEach{\text{car}[i] in Trigger area}
\If{distance[i] < distancePV}
\Statex\hspace{1cm} PV is \text{car}[i]
\EndIf\endIf\endFor
\Statex\hspace{1cm} HV follows PV that is in Trigger and Follow area
\If{the driver resists the system}
\Statex\hspace{1cm} PV is lost
\EndIf\endIf\endEndLoop
\end{algorithm}
\end{algorithm}

Fig. 2 Algorithm of determination method of PV.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig3.png}
\caption{Overview of haptic interface.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig4.png}
\caption{Visual interface of the HACC: (a) Adaptive cruise control on, (b) Cruise control on, (c) System off.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{Two sensor areas of the HACC.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig5.png}
\caption{Two sensor areas of the HACC.}
\end{figure}
0.4 in this paper, so the maximum torque is \( \tau_{sys} = 0.8 \) from trigger area. The gain \( K \) was set to avoid disturbing the driver’s operation by the preliminary experiment.

2.5. Communication of Driver’s Intention to HACC System

The driver’s intention can be communicated to the system by the steering operation. The cooperative status between a driver and an assistance system was estimated by the pseudo work on the steering \( (9) \). In the present paper, a driver and the HACC system are judged to be uncooperative with each other when equations (2) and (3) are satisfied.

\[
\begin{align*}
|\tau_{dr}| & > \varepsilon, \\
|\tau_{dr} - \tau_{sys}| & > \Delta \tau,
\end{align*}
\]

where \( \tau_{dr} \) denotes torque by the driver, and each of the \( |\tau_{dr}| \) and \( |\tau_{sys}| \) denote mean torques around the steering wheel exerted by the driver and by the HACC in the past two seconds. When equations (2) and (3) are satisfied, the HACC system stops following any vehicle and starts to work as a CC system. This function allows the driver to deactivate the function for following a PV by resisting the HACC torque. We set \( \varepsilon = 0.2 \) Nm, and \( \Delta \tau = 2 \) Nm in this paper by trial and error.

3. Experiments

3.1. Experimental Method

The effectiveness of the proposed HACC was evaluated by experiments comparing it to a conventional ACC. The driving simulator shown in Figure 6 was used in the experiments. A 250 W brushless DC motor (Maxon Corporation) was attached to the steering shaft to generate torque around the axis. The simulator has a pair of screen and projector to display the traffic environment. The driver can operate the HV by the steering wheel, the accelerator pedal and the brake pedal. The vehicle dynamics was updated at 1000Hz, and the visual information was updated at about 30Hz.

The experimental participants were six males in their 20s and six females in their 30s and 40s who gave informed consent. The participants were given a pre-paid card of 500 JPY for purchasing books as compensation. The age, sex, and driving frequency of the participants are shown in Table 1.

| Participant | Age | Sex | Driving frequency |
|-------------|-----|-----|-------------------|
| 1           | 20s | M   | 1/month           |
| 2           | 20s | M   | 0/year            |
| 3           | 20s | M   | 5/year            |
| 4           | 20s | M   | 10/year           |
| 5           | 20s | M   | 1/week            |
| 6           | 20s | M   | 1/year            |
| 7           | 40s | F   | Everyday          |
| 8           | 40s | F   | 3/week            |
| 9           | 40s | F   | 5/week            |
| 10          | 40s | F   | Everyday          |
| 11          | 40s | F   | 6/week            |
| 12          | 30s | F   | Everyday          |

Every participant encountered following four scenarios in each driving trial.

(a) Forked road scenario
(b) False detection scenario
(c) Lane changing scenario
(d) Standard scenario

The three scenarios except for (d) are set as a situation where it is difficult for the driver to recognize which vehicle is the PV. The order of the scenarios was randomly determined. The details of each scenario are shown in Figure 7:
(a) Forked road scenario
A forked road is a straight road with a branched road to the left side (Figure 7(a)). The angle between the straight road and the branched road is 30 degree. The participants were asked to drive on the straight road while the PV drove onto the left branched road.

(b) False detection scenario
When the HV followed the PV in the left lane, a vehicle in the right lane (ROV) passed the HV and the PV (Figure 7(b)). The speed of ROV is faster than PV, and ROV was running near the center line when it passed the HV and the PV. In this situation, the assistance system recognizes the ROV as the PV by the system’s false detection. Then, the assistance system tries to follow the ROV. To avoid anticipation of the participants, they also experienced a situation in which the system detected PV correctly even when the vehicle location of this situation is same as the false detection situation in each driving trial. This situation was named NOT false detection.

(c) Lane changing scenario
When the HV followed the PV in the left lane, the participants were asked to change lanes to overtake the PV (Figure 7(c)). This means that the HV stops following the PV. At that time, during some of the trials, an ROV was driving in the right lane in front of the HV.

(d) Standard scenario
The participants could follow the PV without problems on the left lane of the straight road. This scenario was used to prevent the participants from anticipating the next scenario. Therefore, this scenario was not evaluated.

3.2. Evaluation Method

In the forked road scenario (Figure 7(a)), the driver was added the torque by the HACC system until the PV drove onto left branched road in the case using the HACC system. Therefore, the effect of the torque exerted on the steering axis on the vehicle’s motion was investigated by the standard deviation of the lane position (SDLP) of the HV in the whole of the forked road.

In the false detection scenario (Figure 7(b)), the drivers needed to notice the fault and to avoid following the wrong vehicle, because this situation created the risk of collision with the vehicle in the left lane. Therefore, the effect of displaying the system’s intention by the torque was investigated by the velocity difference from the minimum to the maximum and the time to collision (TTC: $t_{cc}$) with the PV to investigate the risk of collision. In addition, driving data were analyzed in the $t_{cc}$ plane to investigate RP (Risk Perception) index \(^{10}\). Where $t_{cc}$ time gap between the HV and the PV.

In the lane changing scenario (Figure 7(c)), the system released the PV on the left lane after the driver begin the lane changing via haptic communication. Therefore, the effect of communication of the driver’s intention to change lanes to the HACC system was evaluated by the timing of the acceleration of the assistance system. Here, the no system level in which any system did not work was added to compare with conventional ACC and proposed HACC. The driving data of the no system level were collected in a preliminary investigation using the lane changing scenario. Six males and one female in 20s participated in this preliminary investigation. They were different from the participants in Table 1.

3.3. Results

(a) Forked road scenario
Figure 8 shows the SDLP of the HACC and the conventional ACC in the forked road scenario (a). The error bars of Figure 8 represent the standard deviation (SD). Here, participants 1, 8, 9, 10, and 12 changed to the right lane before the PV entered the left branch road. They were excluded from the analysis because the effects of the torque exerted by the HACC when the PV entered the branch could not be analyzed. A t-test between the HACC and the conventional ACC showed no significant differences ($p=0.86$).

(b) False detection

(c) Lane changing

(d) Standard scenarios

Fig. 7 Overview of four scenarios.
Conventional ACC of Conventional ACC = 2.

Conventional ACC Conventional ACC System of HACC

0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
Velocity [km/h]

0 50 100BPDP [%]

HACC Conventional ACC

-2 -1 0 1 2
Torque [N m]

Driver of HACC
System of HACC
Driver of Conventional ACC

(b) False detection scenario

Figure 9 illustrates an example of the driving data for the false detection scenario. In this figure, time \( t = 0 \) refers to the moment of false detection by the system. Figure 9(a) shows the brake pedal depression percentage (BPDP). Figure 9(b) shows the velocity of HV. As the velocity increased, the brake pedal was depressed by the HV driver in the case of the conventional ACC.

In contrast, no brake operation by the HV driver was observed in the case of the HACC. Figure 9(c) shows the torque around the steering wheel exerted by the driver in the HACC condition, by the HACC system, and by the driver in the ACC condition. As shown in Figure 9(c), the torque by the system of the HACC was exerted immediately after the false detection. In addition, it was shown that the participant added the opposite torque at that time. Figure 9(d) shows which car was followed as the PV by the systems. Here, the vertical axis represents which vehicle was detected as PV, where description of RV and LV denote a vehicle running in the right and left lanes, respectively, and nothing denotes no vehicle was followed. It is shown that the PV of the HACC changes faster than that of the conventional ACC.

Figure 10 shows an examples of the vehicle behavior in the \( t_{c-1} - t_c \) plane in the false detection scenario of a participant. The driving data for 10 s from the false detection data were used for analysis. The situation of Figure 10(a) is NOT a false detection. Figure 10(b) shows an example of the false detection. The RP curve in Figure 10 is represented as the curve of \( 1/ t_{c} + 4 / t_{c} = 2 \).

To put this into a meaningful context, it is known that most people press the brake pedal when \( 1/ t_{c} + 4 / t_{c} > 2^{(10)^{(10)}} \). As shown in Figure 10(a), the trajectory of the conventional ACC in the NOT false detection situation is far from the RP curve. In contrast, the trajectory of the conventional ACC is closer in the false detection situation in (b). The HACC is similar to the conventional ACC in the NOT false detection example. However, in the false detection, the trajectory is not closer to the RP curve. Note that the same tendency was observed in the results of other participants.

Figure 11 shows the mean of velocity difference among participants. The velocity difference is defined as the difference between the maximum and the minimum velocity. This difference can be interpreted as false acceleration by the system. The driving data for 15 second from 5 second before the false detection were used for the analysis. The error bars depict the SD. The \( t \)-test between the HACC and the conventional ACC shows that the velocity difference of the HACC was significantly smaller than that of the conventional ACC (\( p = 0.0098 \)).

Figure 12 shows the means of the minimum TTC \( (t^{\text{min}}_{c} \text{[s]}) \) of the HACC and those of the conventional ACC after the system recognized the ROV as the PV. The error bars depict the SD. Here, participant 11 changed to the left lane before the system false detection; therefore, this driving data was excluded from the analysis. The \( t \)-test between the HACC and the conventional ACC showed that the \( t^{\text{min}}_{c} \) of the HACC was significantly larger than that of the conventional ACC (\( p = 0.0013 \)). The mean \( t^{\text{min}}_{c} \) of the HACC was three times as large as that of the conventional ACC.
Next, the participants were divided into two groups: group A of six young males and group B of five middle-aged females. Note that female 11 is excluded from the group because her data were excluded from the analysis for the reason mentioned above. Figure 13 shows the means of $t_e^{min}$ for groups A and B. The t-test showed that the $t_e^{min}$ of group A with the HACC was significantly larger than the group with the conventional ACC ($p = 0.0065$).

(c) Lane changing scenario

Figure 14 shows the means of the timing of acceleration by each system for the HACC and conventional ACC, as well as by drivers for the no system case in the lane changing scenario (Figure 7(c)). The error bars are the SD. The vertical axis in Figure 14 represents the time duration from when the HV crossed the lane marker between two lanes to the time when the driver started to accelerate. A positive value represents the situation when the HV started to accelerate after crossing the lane marker. The acceleration in the HACC case occurs before the vehicle crosses the line. This tendency is similar to the case of no system driving, while the acceleration of the conventional ACC occurs after crossing the lane marker.

4. Discussion

In the result of Figure 7(a), the forked road scenario, a significant difference in the SDLP was not found between the HACC and the conventional ACC, as shown in Figure 8. This suggests that the effect of the torque exerted on the steering axis by the HACC on lateral vehicle motion is small.

In Figure 7(b), the false detection scenario, the HV continues to approach the PV if the system keeps erroneously following the ROV. In a conventional ACC, the drivers needed to depress the brake pedal to cancel following the vehicle. Therefore, $t_c$ to the PV tended to be small in the conventional ACC because it took time to notice the vehicle approaching the PV, and the false detection of the system was displayed from only visual information. According to the analysis of driving behaviors in the $t_c^{1} - t_g$ plane, with conventional ACC, the driving data are closer to the RP curve and the trajectory is drawn far from RP curve with the proposed method. This tendency was demonstrated for all participants. The minimum

![RP Curve](image1)

Fig. 10 $t_c^{1} - t_g$ plane.

![RP Curve](image2)

Fig. 11 Comparison of the velocity difference.

![RP Curve](image3)

Fig. 12 Minimum TTC ($t_e^{min}$ [s]) from false detection.

![RP Curve](image4)

Fig. 13 Minimum TTC ($t_c^{min}$ [s]) of two groups.

![RP Curve](image5)

Fig. 14 Acceleration timing.
TTC \( t_{\text{cm}} \) in such a situation was significantly larger with the proposed method than that with the conventional method. In addition, the difference of the vehicle velocity was significantly smaller with the proposed method. From these results, it is shown that, with the HACC, drivers can notice the change of the PV in the system by haptic information, the torque from the steering wheel, and the drivers were able to change the PV by operating the steering wheel. Thus, it can be concluded that a method of displaying the PV’s direction successfully reduced the risk of collision.

Differences caused by the attributes of the participants were considered. Group A showed a significant difference for the minimum TTC \( t_{\text{cm}} \) and group B did not, due to the large SD. However, the means of \( t_{\text{cm}} \) are larger than those for the conventional ACC in both groups. This result suggests that the HACC’s functions are effective for both groups. No clear explanations can be given for the larger SD of \( t_{\text{cm}} \) in group B. In addition, the \( t_{\text{cm}} \) of the conventional ACC are similar in both groups. This means that there is no difference of the avoiding timing of risky situation. On the other hand, the \( t_{\text{cm}} \) of the HACC of group B is smaller than group A. The participants of group B also have high driving frequency. It implies that driving frequency could affect the reaction to the system’s torque, though it could be the effect of gender or age.

Let us consider the ease of communicating the driver’s intention to change lanes from the results in the lane changing scenario in Figure 7(c) (see Figure 14). The drivers started to accelerate before the HV crossed the lane marker in the no system case. The conventional ACC’s timing of acceleration was significantly later than that for the no system driving. In contrast, acceleration timing with the HACC was almost the same as that for the no system driving. This demonstrated the ease of communicating the driver’s intention with the HACC.

5. Conclusion

In order to cope with the inconsistency between the intentions of the driver and the driver assistance system in the traditional car following assist system, a new PV following system with a haptic communication method called HACC, was proposed in this paper. Its haptic interface allows to communicate intentions between the driver and the system using haptic information from the steering wheel. The driving simulator experiments demonstrated that haptic communication decreases the collision risk when false detection of the PV occurs by increased driver’s situation awareness on the PV. Furthermore, the communication to the system of the driver’s intention to change lanes allowed earlier initiation of acceleration at the beginning of the lane change than in the conventional ACC system, and allowed acceleration to begin almost as early as for no system driving. These results strongly suggest that the proposed HACC system achieves effective communication of the intentions between the driver and the system each other, leading to earlier action of the driver and the system in the confusing scenario as well as reducing collision risk in false situation of the PV by the system.

In a future study, a design method of the control parameters in the HACC system should be investigated. In addition, the effects of the proposed HACC will be investigated in various traffic situations such as the curved road. The HACC may behave not comfortable for the driver because it may add the torque among the driver drives the curved road. Therefore, it is needed the correct selection of the parameter such as the curvature or adjusting gains according with the traffic situation.

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