12th International Symposium on Advanced Vehicle Control
September 22-26, 2014

AVEC '14

20149298

A Preceding Vehicle Following System Based on Haptic Communication

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A new preceding vehicle (PV) following system, Haptic Adaptive Cruise Control (HACC), is proposed. Intention mismatch between a driver and the system might occur with a conventional adaptive cruise control system in a complex environment. HACC attempts to cope with the intention mismatch between the driver and the system by haptic communication using the steering wheel. The haptic information is provided to indicate the lateral position of the vehicle followed by the system. In addition, the driver's intention can be easily communicated to the system by his or her steering operation. As a result, the driver can find the system's PV easily and can change the PV for another. Experiments in a driving simulator showed that HACC's haptic information is effective in increasing the driver's understanding of the system's intention. In addition, the driver's intention could be easily communicated to the system.

Topics / Active safety and driver assistance systems

1. INTRODUCTION

Adaptive cruise control (ACC) systems successfully reduce a driver's workload by assisting the driver's pedal operation when following a preceding vehicle (PV). The ACC follows a preceding vehicle while the system detects it. It has been pointed out, however, that it is difficult for the driver to notice a change in the PV during complicated traffic situations [1], although this may only occur rarely. It might lead to the driver's automation surprise and/or driver's distrust in the system[2][3]. It also may lead to a risky situation when a driver misunderstands which vehicle is the PV. On the other hand, it is difficult for a driver to communicate the ACC his or her change of intention to the ACC which vehicle the driver wishes to follow, or which lane the driver wishes to drive. In fact, when the driver starts to change lanes, a conventional ACC starts to accelerate after the vehicle finishes the lane change by detecting the lane markers. This is because the system recognizes the PV based on the lane where the host vehicle drives. 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 the haptic communication will enable the human operator to interact and communicate continuously with the assist system through a haptic interface (see [4], [5] for an overview).

In the present study, a Haptic ACC (HACC) is proposed. It is a preceding vehicle 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. In addition, the haptic information is provided by the system to indicate the lateral position of the PV. Thus, the driver can 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 lane changing, 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. The experiments showed ease of detecting the system's intention, and of communicating of the driver's intention to change lanes to the system.

2. HAPTIC ADAPTIVE CRUISE CONTROL

In this section, a proposed haptic adaptive cruise control (HACC) system is described. The proposed HACC essentially works as an ACC. In addition, it has a torque display function to display the direction of the PV. Furthermore, the driver's intention can be

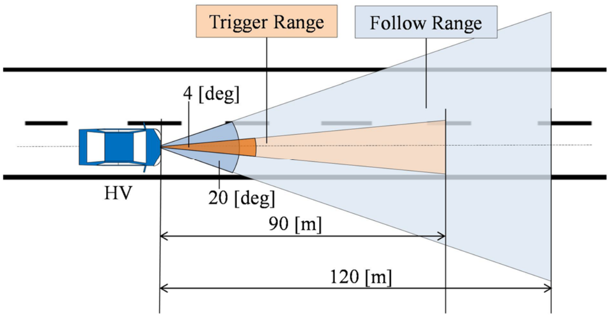


Fig. 1 HACC's two sensor areas

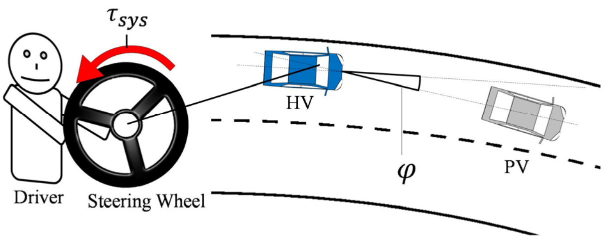


Fig. 2 Presentation of PV's direction

communicated to the HACC system using the steering wheel when the driver wants to change the system's intention.

2.1 Velocity control for following preceding vehicle

A PV following function is constructed based on the ACC described in [6]. The system controls the time gap (TG) [7] between the host vehicle (HV) and the PV, by using velocity control of the HV by acceleration and deceleration. The TG was set at 2 s according to the general settings of the ACC.

2.2 Algorithm for determination of the followed vehicle

A conventional ACC system determines the PV as the vehicle that is the closest to the HV in the lane where the HV is driving. In contrast, the HACC utilizes two kinds of sensor areas to determine the PV, as shown in Fig. 1. The trigger area determines which vehicle is the PV. A vehicle in the trigger area that is closest to the HV is determined as the PV. The vehicle continues to be the PV while it remains is in the following area. When a new vehicle enters within the trigger area, and is closer to the HV than the current PV, the new vehicle is determined as the new PV. The trigger area spans 4 deg and 90 m, and the following area spans 20 deg and 120 m (Fig. 1). The trigger area is small, so that the determination of the PV is expected to coincide with the driver's intention because the trigger area is just in front of the driver or the HV. In addition, it prevents the system from following the wrong vehicle. On the other hand, the following area is large so that it is expected to work appropriately when following on a curved road or a junction. In addition, the system has the haptic presentation function, whose effect is described later.

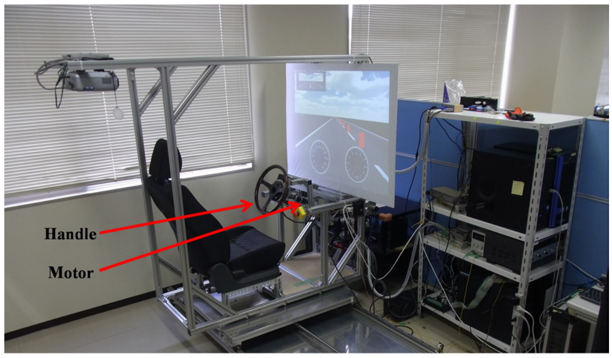


Fig. 3 Driving simulator

2.3 Display of preceding vehicle's direction

Fig. 2 shows a method to display the direction of the PV. Torque τ_{sys} is exerted around the steering wheel axis according to the direction of the PV as eq. (1):

$$\tau_{sys} = K\varphi(t) \tag{1}$$

where $\varphi(t)$ denotes the direction of the PV measured from the heading direction of the HV. A gain K was determined as $K = 0.4$ in the present paper so that the torque would not disturb the driver's operation.

2.4 Communication of driver's intention to HACC system

The driver's intention can be communicated to the system by the steering operation. In [8], the cooperative status between a driver and an assistance system was estimated by the mechanical work on the steering. In the present paper, a driver and the HACC system are judged to be uncooperative with each other when eqs. (2) and (3) are satisfied.

$$|\overline{\tau_{dr}}| > \varepsilon \tag{2}$$

$$\left|\overline{\tau_{dr}} - \overline{\tau_{sys}}\right| > \Delta\tau \tag{3}$$

where $|\overline{\tau_{dr}}|$ denotes the mean torque around the steering wheel exerted by the driver in the past two seconds. The scalar ε is a small positive value that represents a threshold of whether the driver applies force to the steering wheel. The scalar $\Delta\tau$ is a positive number and was determined as $\Delta\tau$ = 2 Nm in this paper by trial and error. The HACC system stops following any vehicle and starts to work as a cruise control (CC) system when eqs. (2) and (3) are satisfied. Then, if another car enters the HACC's trigger area, the HACC starts to follow the car.

This function allows the driver to stop the preceding vehicle following function by resisting the HACC's torque.

Table 1 Attributes of participants

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

3. EXPERIMENTS

3.1 Experimental method

The effectiveness of the proposed HACC was evaluated by experiments comparing it to a conventional ACC in a driving simulator, as shown in Fig. 3. A 250 W brushless DC motor (Maxon Corporation) was attached to the steering shaft to generate torque around the axis. The experimental participants were six males in their 20s and six females their 30s and 40s who gave informed consent. The participants were given a pre-paid card of 500 JPY for purchasing books as a reward. The age, sex and driving experiences of the participants are shown in Table 1.

Each participant experienced a driving trial with the conventional ACC, followed by a driving trial with the proposed HACC. The driving trial is defined as one trip from a starting point to the goal. The test track in the simulator was a straight one-way two-lane road 1 km long and 4 m wide per lane, with some forked roads. At the beginning, the HV is located at the center of the left lane, and the initial velocity was set to 80 km/h. There were four scenarios in the driving trial.

The participants encountered one of the following four scenarios in a driving trial. The participants experienced four trials in the experiments with each system. Each of the four scenarios was assigned to one of four trips, so that each participant experienced all of them once. The order of the scenarios was randomly determined. The details of each scenario are as follows (Fig. 4):

(1) Forked road:

A forked road is a straight road with a branched road to the left side (Fig. 4(a)). The angle between the straight road and the branched road is 30 deg. The participants were asked to drive on the straight road while the PV drove onto the left branch road.

(2) False detection:

When the HV followed a PV in the left lane, a vehicle in the right lane (ROV) passed the HV and PV (Fig. 4(b)). In that situation, the assistance system

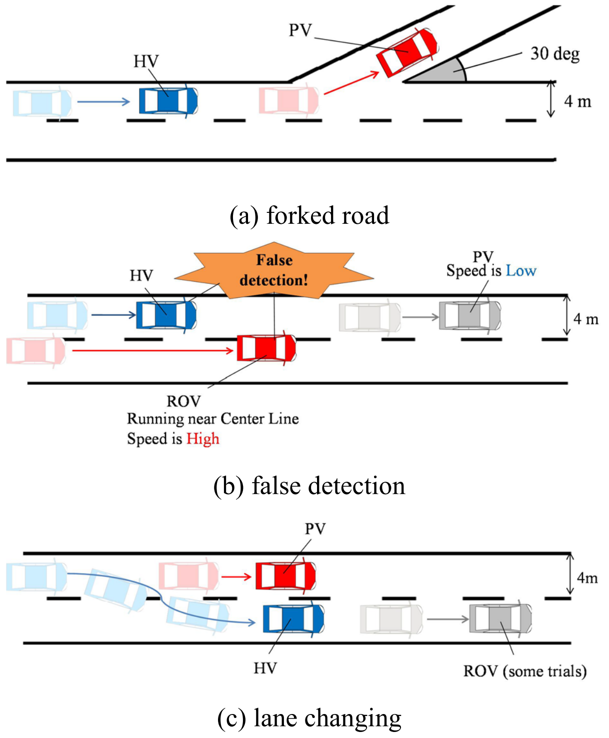


Fig. 4 Overview of three scenarios

recognizes the ROV as the PV by a malfunction of the system. Then, the assist system tries to follow the ROV. The participants needed to notice the fault and to avoid following the wrong vehicle, because this situation creates a risk of colliding with the vehicle in the left lane.

(3) Lane changing (LC)

When the HV followed a PV in the left lane, the participants were asked to change lanes to overtake the PV (Fig. 4(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.

(4) Standard scenario

The participants could follow the PV without problems. 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 (1), 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 false detection scenario (2), the effect of displaying the system's intention by the torque was investigated by time to collision (TTC) with the PV.

In the LC scenario (3), the effect of communicating the driver's intention to change lanes to the HACC system was evaluated by timing of the acceleration of the assistance system. Here, the No System level was added to compare the cases with and without the HACC system. The driving data of the No System level was gathered in a preliminary investigation using the same scenario as the LC scenario. Seven males and females in their 20s participated in this preliminary investigation.

3.3 Results

Fig. 5 shows the SDLP of the HACC and the conventional ACC in the forked road scenario (1). The error bars of Fig. 5 depict the standard deviation (SD). Here, participants 1, 8, 9, 10, and 12 changed to the left 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 entering the branch could not be analyzed. A t-test between the HACC and the conventional ACC showed no significant differences ($p = 0.86$).

Fig. 6 shows the mean minimum TTC (min-TTC) of the HACC and the conventional ACC after the system recognized the ROV as the PV to follow in the false detection scenario (2). The error bars depict the standard deviation. Here, participant 11 changed to the left lane before the system's false detection; this driving data was excluded from the analysis. The t-test between the HACC and conventional ACC showed that the min-TTC of the HACC was significantly larger than that of the conventional ACC ($p = 0.0013$). The mean min-TTC of the HACC was three times as large as that of the conventional ACC.

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 was excluded from the analysis for the reason mentioned above. Fig. 7 shows the average min-TTC for groups A and B. The t-test showed that the min-TTC of group A with the HACC was significantly larger than for the conventional ACC ($p = 0.0065$). The average min-TTC for group B with the HACC was larger than for the conventional ACC, but the t-test showed no significant difference ($p = 0.1164$).

Fig. 8 illustrates an example of driving data for a false detection scenario. In this figure, time 0 refers to the moment of false detection by the system. Fig. 8(a) shows the brake pedal depression percentage (BPDP). Fig. 8(b) shows vehicle velocity. Fig. 8(c) shows a torque by a driver with a HACC (HACC Driver), a torque by a conventional ACC (Conventional ACC), and a torque by a system using HACC (HACC System). As seen from Figs. 8(a) and (b), the velocity increased, then the brake pedal was depressed by the driver in the case of the conventional ACC. In contrast, no brake operation by the driver was observed in the case of the HACC. Fig. 8(c) shows that the torque by the HACC was exerted immediately after the false detection. In addition, it was shown that the participant added reverse torque at that time.

Fig. 9 shows the average timing of acceleration by each system for HACC and conventional ACC, as well as by drivers for the No System case in the lane changing scenario (3). The error bars are the standard

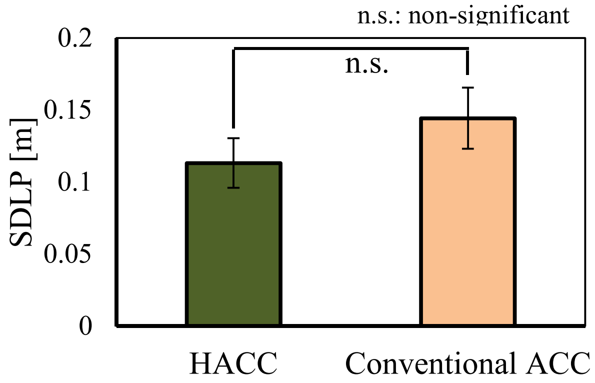


Fig. 5 Effect of the torque to SDLP

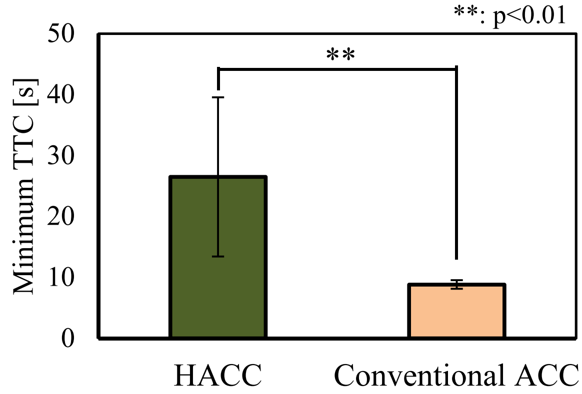
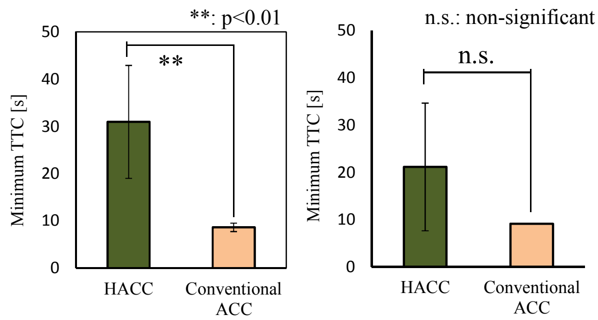


Fig. 6 Minimum TTC from False detection



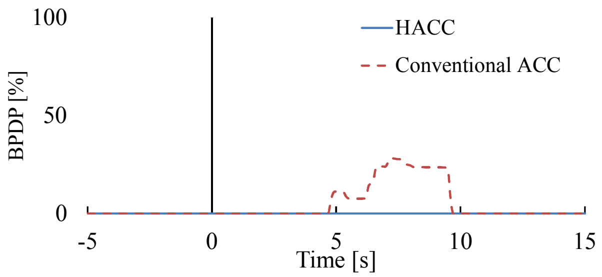
(a) group A (b) group B

Fig. 7 Minimum TTC of two groups

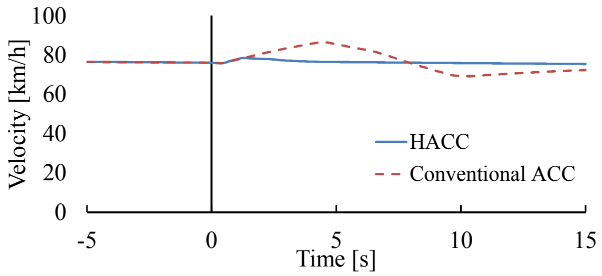
deviations. The vertical axis in Fig. 9 represents the time duration from when the HV crossed the lane marker between two lanes to the time when the driver started to accelerate. A positive value represents a situation when the HV started to accelerate after crossing the lane marking. The acceleration 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

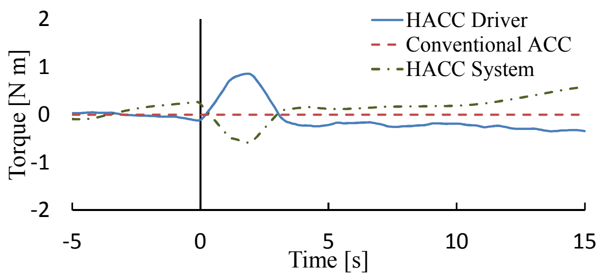
In the result of the forked road scenario (1), a significant difference in the SDLP was not found between the HACC and the conventional ACC, as shown in Fig. 5. This suggests that the effect of the



(a) Brake pedal depression percentage



(b) Vehicle velocity



(c) Steering torque

Fig. 8 An example of driving data in false detection

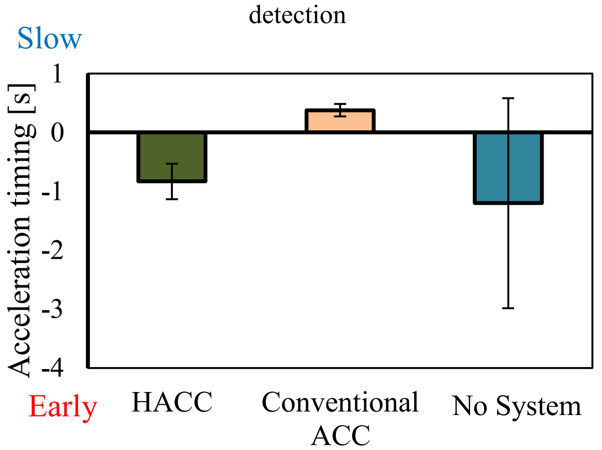


Fig. 9 Acceleration timing

torque exerted on the steering axis by the HACC on the vehicle motion is small in terms of lateral motion.

In the false detection scenario (1), 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, the TTC to the PV tended to be small in the conventional ACC, because it takes time to notice the vehicle approaching the PV and the false detection of the system only from visual information. On the other hand, with the HACC, drivers can notice the change of the PV in the system by haptic information as torque from steering wheel. In addition, drivers were able to change the PV by operating the steering wheel. The experimental results demonstrated that the drivers correctly noticed false detection or a change of PV from the torque. This result means that the method of indicating 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 min-TTC, and group B did not, due to a large SD. However, the averages of min-TTC are larger than for the conventional ACC in both groups. This result suggests that the HACC's functions are effective for both groups.

Let us consider the ease of communicating the driver's intention to change lanes from the results in the lane changing scenario (3) (see Fig. 9). 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 for No System driving. In contrast, acceleration timing with the HACC was almost the same as for No System driving. This demonstrated the ease of communicating the driver's intention with HACC.

5. CONCLUSION

A new preceding vehicle following system HACC was proposed in the present paper. The HACC attempts to cope with the intention mismatch between drivers and the system by haptic communication using the steering wheel. The HACC function of displaying the direction of the PV by haptics increased the driver's situation awareness regarding the PV. In addition, the driver's torque input to the steering wheel allowed the driver to communicate the driver's intention to the system. The simulator experiments demonstrated that the torque from the HACC did not alter the vehicle's motion. In addition, the PV's direction display by haptic information could reduce the risk of collision when the system erroneously changed the PV suddenly, by increasing the driver's situation awareness regarding which vehicle was being followed. 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 the conventional system, and allowed acceleration to begin almost as early as for No System driving.

In a future study, the effects of the proposed HACC will be investigated in various traffic situations.

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Published in: the 12th International Symposium on Advanced Vehicle Control, AVEC '14
(Proceedings, No.ThC1-1, 20149298)
Date of Conference: Sep.2014
Publisher: Society of Automotive Engineers of Japan
Publication Year: 2014