# The Situation Awareness and Usability Research of Different HUD HMI Design in Driving While Using Adaptive Cruise Control

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**Abstract.** Head-Up display (HUD) is increasingly applied to automobiles. However, HUD might have also shortcomings causing new driving problems. This paper investigates the effects of different Human Machine Interfaces (HMI) of HUD under ACC function on situation awareness (SA) and system usability for cut-in driving scenarios. The laboratory-based controlled experiment conducted used a driving simulator with a total of 8 participants. Each participant performed three different tasks, using three different HMIs including two HUD HMI and one baseline HMI (dashboard HMI). The results indicate that HUD display can influence the participants' SA and system usability, and that different HUD design can have different effects. The HUD design with dynamic directivity of augmented reality brings about better SA and system usability. The research suggest that it is possible to improve the SA and system usability through improved HUD-HMI design.

**Keywords:** Situation awareness · Usability · HUD-HMI design · ACC · Driving simulator

## 1 Introduction

### 1.1 Adaptive Cruise Control

During the last years an increasing number of Advanced Driver Assistance Systems (ADAS) has been developed to improve the driving safety and comfort. ACC is one of the most important semi-automated functions which is a longitudinal support system that can adjust the speed and maintain a time-based separation from the vehicle in front. In order to achieve the speed and headway, the ACC system has authority over the throttle and brakes.

ACC systems can have positive and negative effects on driving safety. ACC provides a potential safety benefit in helping drivers maintain a constant speed and

C. Stephanidis et al. (Eds.): HCII 2020, LNCS 12429, pp. 236–248, 2020.
https://doi.org/10.1007/978-3-030-59987-4_17

headway [1]. Therefore, the driver has more resources available to attend to other tasks, such as looking at route signs and traffic signals. Also, when ACC is provided, drivers pay more attention to lateral control than when ACC is not provided [2]. However, drivers may glance “off-road” more frequently and longer when using ACC [3], which decreases safety. As drivers rely on the ACC system, they do not monitor the surrounding as carefully and might thus lose some of their situation awareness [4]. Overall, human drivers and vehicles need to drive together when using ACC, which requires an exchange of information between the person and the car. Therefore, for the designer, it is necessary to consider the general mental model of the driver when using ACC, so as to design the better HMIs of ACC function.

### 1.2 Head-up Display (HUD, Including Windshield HUD (W-HUD) and Augmented Reality HUD (AR-HUD))

HUD technology in aviation has been known about since the 1940s. It keeps the pilot’s attention focused outside of the cockpit and supports aircraft control by information visualization within the pilot’s main sight line on a transparent combiner [5]. In the automobile industry, General Motors employed color W-HUD first time in 1988 [6]. Today, there is a growing interest in HUD form vehicle manufacturers following considerable advances and maturity in the technology [7]. W-HUD uses the windshield of a car as display device directly. The position of the W-HUD picture is floating above the bonnet, in front of the street. This picture can cover critical traffic environments outside of the windshield. In recent years, with the development of AR technology, more and more car manufacturers have begun to work on the development of AR-HUD. AR-HUD picture can be shown not only in drivers’ line of sight, but also matching the real traffic environment and providing a true augmented experience.

It is found that HUD allows improving “eyes on the road” time by reducing the number of glances to the in-vehicle [8, 9]. HUD allows more time to scan the traffic scene [10] and enhances understanding of the vehicle’s surrounding space particular under low visibility conditions [11]. This benefit in terms of increasing situation awareness can impact the probability a driver will success in detecting a time-critical event [12]. However, Stanton and Young find that provision of a head-up display (HUD) reduces reported situation awareness [25]. Perhaps one of the reasons for this finding is that with the instrument cluster display, drivers can have discretion over when they want to sample the information, whereas with the HUD the data is displayed all the time. Therefore, the HUD might have made the driving task more visually complex and reduced overall situation awareness.

In some studies, researcher also give some design suggestion of automotive HUD. According to Wang et al. [32], the information elements of HUD-HMI are mainly presented in two forms: text and graphic symbols. It is also found that prompt and warning information should be in the state of low brightness or no brightness in general, and the driver’s attention should be aroused by increasing brightness, flashing or making prompt sound when necessary [33]. For some large automotive industries (e.g. BMW, Audi, Benz and Volvo), we find that all of the HUD constant information is displayed in white. We also find that the HUD information elements basically contain speed, navigation and warning by comparing the HUDs of different cars. One of the main differences is that if the vehicle is equipped with driving assistance system, the design elements of driver assistance features will be supplemented in HUD, such as Lane Departure Warning (LDW). And another main difference is that HUD design of different cars may have different color combinations, for example, BMW uses white, green and orange, while Benz uses white, blue and red.

### 1.3 Situation Awareness

When driving, situation awareness can be defined as the driver's mental model of the current state of the vehicle and mission environment [13]. This indicates that the driver's situational awareness of the ACC system and the road environment is very important for driving performance during the use of ACC. A formal definition of SA is "The perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" [14]. The SA model encompasses three levels of SA. Level 1 includes the perception of elements in the current situation (e.g. reading the set speed and time gap), level 2 is the comprehension of the current situation (e.g. knowing whether the vehicle is following a leading vehicle), and level 3 is the projection of future status (e.g. anticipating status changes of vehicle, and avoiding conflict) [13]. Driving can be thought of as a dynamic control system in which system input variables change over task time. In theory, the construct of SA in dynamic systems fits very well to this domain [15]. Though advanced automation technologies have been expected to improve system and operator safety, efficiency and comfort, such technologies may also generate negative effects on driver behavior [16]. Then some researchers put forward the view that increasing the driver's situation awareness is a key to successful automation [17].

There are four classes of approaches to evaluate situation awareness—process measures, direct measures, behavioral and performance measures [18]. Process measures include eye tracking, information acquisition, and analysis of communications [19]. Direct measures of SA attempt to directly assess a person's SA through subjective measures and objective measures. Subjective measures ask the users to rate their SA on a scale. Objective measures collect data from users on their perceptions of the situation and compare them to what is actually happening to score the accuracy of their SA [19]. Behavior measures infer the operators' level of SA based on their behavior. Performance measures infer SA based on how well an operator performs a given task as compared to a predetermined standard, or how good the outcomes of a scenario are (e.g., number of successful missions) [18].

In this experiment, performance measure and objective measure are adopted. We measure the driving performance by the driver's lateral control of the vehicle. And we measure objective SA by Situation Awareness Global Assessment Technique (SAGAT). The SAGAT assesses level 1 (perception), level 2 (comprehension) and level 3 (projection) SA by asking the driver questions related to the relevant features of the car and external environment necessary for safe driving [20]. In the experiment of this paper, because the program pause will affect the execution of task, participants complete the SAGAT immediately after each task. Endsley's study has shown that SA data are readily obtainable through SAGAT for a considerable period after a stop in the simulation (up to 5–6 min) [20]. In this experiment, the execution time of each task is about 1 min, so SAGAT can be used after each task without affecting the SA inquiry effect as much as possible.

### 1.4 Usability Test

For the development and design of ADAS, system usability should be improved while ensuring safety. The definition of usability that can be found in the ISO DIS 9241-11 [21] is "The effectiveness, efficiency and satisfaction with which specified users can achieve specific goals in particular environments." [22]. The system with high usability can perform functions effectively, by which users can complete tasks efficiently and have a high degree of satisfaction with the interaction process. In the usability study, the System Usability Scale (SUS) is a classic scale [23] and consists of 10 topics including a positive statement of odd items and a negative statement of even items, requiring participants to score 5 points for each topic after using the system or product. Several empirical studies have shown that SUS works well [17, 24]. There are also large sample studies indicate that the reliability coefficient of SUS is 0.91 [17]. Our usability test will use the SUS framework.

Endsley [25] argues that interface design should ideally provide an overview of the situation and support projection of future events, as well as providing cues of current mode awareness. Thus, in our case, it is important to know the exact influences of the HUD design on SA when using ACC.

## 2 Research Question

In this study, we evaluate the HUD design under the ACC function, and mainly propose the following two hypotheses:

1. HUD designs can increase drivers' situation awareness and system usability when using ACC.
2. Compared to static HUD design, HUD design with dynamic guidance can increase situation awareness and system usability better.

Based on the outcome of the research question above, we will make suggestions for HUD design under ACC function.

## 3 Experimental Method

### 3.1 Participants

8 participants including students, teachers and other school staff from the Tongji University, China were recruited. One male and seven females. They were aged between 20 and 50 (M = 26.13, SD = 7.27). All participants had valid driving licenses, 5 of them (62%) had a driving license for 1–5 years, and 3 of them (38%) had a driving

license for 6–10 years. 1 people (12%) knew nothing about ACC, 5 people (63%) knew something about ACC but never use it, and 2 people (25%) had ever used ACC.

In this study, we explained everything about ACC and the simulator operations to all participants before experiment. And the traffic conditions in the experimental tasks are relatively simple, so the participants could handle them with common real-life driving experience. In order to minimize the impact of driving experience on the experimental results, the subjects did undergo a complete training session to be fully familiar with the driving simulator before starting the experimental tasks.

## 3.2 Technical Equipment

The experiments with the driving simulator was conducted in a laboratory at the Tongji University, Shanghai, China. There are two driving simulators. One serves as the main test vehicle and the other as the auxiliary test vehicle. Main test vehicle consisted of longitudinally adjustable seat, Logitech G27 force-feedback steering wheel and pedals. During the experiment, three LED screens were designed and used to display the driving scene. Auxiliary test vehicle consisted of Logitech G27 force-feedback steering wheel, pedals and three LED screens. The programs in both driving simulators, are developed based on Unity software. They all have basic driving functions, and the two test vehicles run in the same traffic scene and can see each other. In addition to the basic driving functions, the main test vehicle has the function of ACC (including adjusting the set speed, adjusting the time gap, normal follow-up, etc.) with dashboard display and HUD display. When the auxiliary test vehicle is running, the experimenter can see the value of relative distance and THW which are used for the experimental conditions.

In the experiment setting (Fig. 1), the participants carried out the test task by driving the main test vehicle, and the experimenter completed the cut in working condition with the main test vehicle by driving the auxiliary test vehicle. The Supervisory Control and Data Acquisition system (SCADA) was also used in the experiment to record and save the driving data such as speed and steering wheel angle to the csv file in real time, so that the data can be statistically analyzed after the experiment.

**Fig. 1.** Experimental Equipment (a is the main test vehicle, c is the auxiliary test vehicle, and b is SCADA).

## 3.3 Experimental Design

A dual-task within-subject approach was applied. The experimental dependent variables are drivers' situation awareness and system usability. The experimental independent variables are three different HMI design schemes, dashboard HMI design, dashboard and HUD1 HMI design, dashboard and HUD2 HMI design (referred to as dashboard-HMI, HUD-HMI1 and HUD-HMI2).

1. Dashboard-HMI (Fig. 2): The HMI of ACC is only displayed on the dashboard. Design elements of ACC have been adapted and displayed with reference to vehicles equipped with ACC on the market. These design elements include speed, ACC logo, setting speed, identifier of leading vehicle and time gap.

**Fig. 2.** Dashboard-HMI (baseline HMI that design elements are displayed only on the dashboard).

2. HUD-HMI1 (Fig. 3): Compared to dashboard-HMI, the display mode of HUD (including W-HUD and AR-HUD) is added. And we use the same design elements for the dashboard and the HUD.

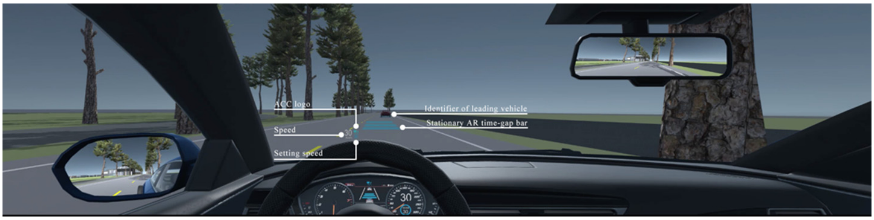

**Fig. 3.** HUD-HMI1 (the AR time-gap bar is relatively stationary with the main test vehicle).

3. HUD-HMI2 (Fig. 4): Compared to HUD-HMI2, the design form of AR time-gap bar is different. The time-gap bars in the two design schemes display the time gap information of the ACC. The difference is that the AR time-gap bar in the HUD-HMI1 is relatively stationary with the main test vehicle, and the AR time-bar in the HUD-HMI2 dynamically points to the leading vehicle.

**Fig. 4.** HUD-HMI2 (the AR time-bar dynamically points to the leading vehicle).

### 3.4 Experimental Tasks

The cut-in event is a typical scenario of ACC [26, 27] and it's fairly common in day-to-day driving. In this experiment, each participant performs three tasks corresponding to three different HMI design schemes, all of which are in the cut in scenario involving the ACC function enabled. When the auxiliary test vehicle is cutting in, the speed of both vehicles is 30 km/h and the distance is about 20 meters (THW $\approx$ 2.4 m/s). In order to avoid a learning effect, these three HMI designs are presented to each participant in random.

### 3.5 Experimental Process

The experimental procedure was as follows:

1. First, demographic information was collected from the participants, including name, age, time of possession of driver's license, frequency of driving, and understanding of ACC.
2. The researcher introduced the purpose of the experiment and the general experimental procedure to the participants.
3. After the introduction, the participants were allowed to sit in the driver seat of the simulator for 10 to 15 min in order to familiarize themselves with the basic driving controls and the operation of the ACC (turning on/off, adjusting the set speed, adjusting the time gap). The researcher then introduced the HMI display of the ACC on the instrument panel. To avoid possible learning effects, the traffic scene during the practice session is different from the traffic scene of formal test session.
4. Each participant was asked to keep the simulated vehicle straight in the lane under ACC while braking if any unexpected events should emerge. Each participant completed the experimental tasks after they familiarized themselves with ACC function.
5. Between each task, the participant was asked to rate the situation awareness, system usability via commonly recommended SAGAT and SUS.
6. The process of performing the task on the screen was computer captured and the whole user-simulator interaction process videotaped to facilitate the search and verification after the experiment.

# 4 Results and Preliminary Findings

To investigate the effects of different HMI designs on situation awareness and system usability, we collected user feedback scores of SAGAT and SUS for three different HMI conditions. We also recorded the lateral control data—steering angle of steering wheel through SCADA. Only descriptive statistics were reported, given that there was not enough data to justify confirmatory analyses. The following is the statistical analysis results.

## 4.1 Situation Awareness

**SAGAT.** Average SAGAT scores was broken down by design schemes (Fig. 5). As Fig. 5 shows, the SA scores of HUD (HUD-HMI1 and HUD-HMI2) are both higher than dashboard-HMI, indicating that the subject is aware of fewer of the environment and car under HUD conditions, which is consistent with the Hypothesis 1. Compared to HUD-HMI1, the SA score of HUD-HMI2 is higher, indicating that dynamic HUD design can increase situation awareness, which is also consistent with the Hypothesis 2. Moreover, the SAGAT is designed to evaluate SA from the three dimensions: level 1 (perception), level 2 (comprehension) and level 3 (projection). The driver's scores in different dimensions are shown in Fig. 6. In contrast to best perception (Level 1 SA), participants have worst projection (Level 3 SA) under Dashboard-HMI condition. Participants have the same understanding (Level 2 SA) in the three different design schemes. Generally speaking, HUD-HMI2 reports higher overall situation awareness.

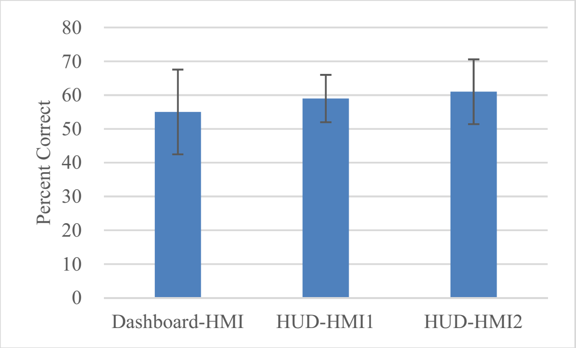

**Fig. 5.** Average overall SAGAT percent correct score. Error bars represent 95% confidence intervals.

**Driving Performance.** During the execution of the experimental task, ACC longitudinally controls the vehicle, liberating the driver's feet, and the driver only needs to operate the steering wheel to laterally control the vehicle. Therefore, we analyze driving performance by the driver's lateral control of the vehicle. In this experiment, we calculate the overall standard deviation (SD) of steering wheel angle from the time

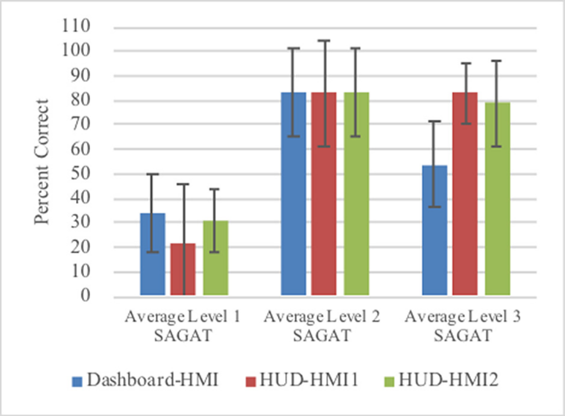

**Fig. 6.** SAGAT score of three levels of situation awareness. Error bars represent 95% confidence intervals.

the auxiliary vehicle starts to cut in to that the main test vehicle follows the leading vehicle steadily, which is used to characterize the driver's lateral control. The greater the value of the SD, the more unstable drivers' lateral control of the vehicle. As Fig. 7 shows, the standard deviation of steering wheel angle of dashboard-HMI is the highest, then HUD-HMI2, and HUD-HMI1 is the lowest. We found that HUD conditions report more stable lateral control than dashboard condition. And HUD-HMI1 condition reports the best driving performance.

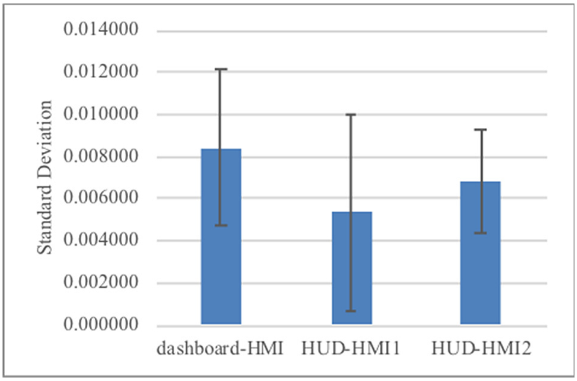

**Fig. 7.** Standard deviation of steering wheel angle. Error bars represent 95% confidence intervals.

## 4.2 Usability

As shown in Fig. 8, the HUD-HMI2 score is higher than both dashboard-HMI and HUD-HMI1, and the scores of dashboard-HMI and HUD-HMI1 are the same.

This result is consistent with the Hypothesis 2. For level of usability, both dashboard-HMI and HUD-HMI1 are level D. However, HUD-HMI2 is level C, indicating that different HMI design of HUD may result in different results, improving or reducing usability. Taken together, usability of ACC system is better under HUD-HMI2 in this study.

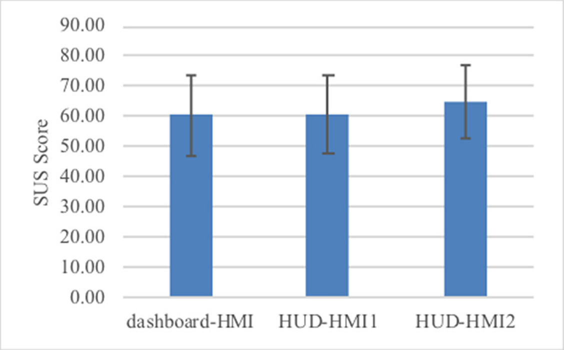

**Fig. 8.** SUS score of three HMIs. Error bars represent 95% confidence intervals.

## 5 Discussion

The result indicates that the participants demonstrated lower overall SA with the dashboard-HMI than HUD-HMI1 and HUD-HMI2. Previous studies [25] found that since the HUD data were displayed all the time, the HUD may have caused the driving task more visually complex and reduced overall situation awareness. Our experimental results show another conclusion. Similar to what Rutley [28] found, the HUD speedometer could increase the awareness of speed. From the analysis of the three different levels of SA, participants had lower perception of relevant elements in the driving environment with HUD, but at the same time they had higher projection. It is possible that HUD may capture too much attention from the drivers, a phenomenon known as cognitive capture [29]. This may lead to that the drivers may focus more on the elements of the HUD, than on the elements in the real world. However, since HUD highlights more driving information related to ACC status [30], drivers begin to process the information contained in the ACC status earlier and more often allowing them to be better prepared for upcoming traffic scenarios. This may lead to a higher level of SA. In our study, we also found that the SA of HUD-HMI2 was higher than HUD-HMI1. This suggests that dynamically changing elements that followed the real traffic scenario could further increase the drivers' SA.

Accidents are caused by drivers who fail to perceive important elements in the driving environment, and do not understand how these elements interact with each other, and/or are unable predict what will happen in the near future [31]. In other words, a lack of situation awareness leads to unsafe driving. In the same way, low SA leads to unstable lateral control when using ACC. In our study, participants have more stable lateral control with HUD than only dashboard, which is consistent with the self-reported SA result. However, the driving performance and SAGAT score are inconsistent under HUD-HMI1 and HUD-HMI2 conditions. One reason for this could be that the small sample size of the data may cause inaccurate statistical results. Moreover, slight numerical changes may not represent the difference in actual driving performance.

In the usability study, dashboard-HMI and HUD-HMI1 were found to have the same usability score. But the HUD-HMI2 had the highest usability score. This indicates that, based on the display mode of the instruments, the addition of HUD would not necessarily improve system usability, but the design elements presented on the HUD would determine system usability. Finally, we found that the HUD design with dynamic directivity could increase usability.

## 6 Conclusion

For the ACC functions that are increasingly used in automobiles, we have designed three HMI display solutions. In order to come up with better design improvements, we conducted an experiment in a driving simulator to assess the SA level and usability of different HMI design in cut-in scenarios of ACC. Our results show that HUD display affects the situation awareness of the participants and system usability. Our study also shows that different HUD design have different effects on situation awareness of drivers and system usability. Based on the research results, HUD design suggestions are proposed.

In this experiment, we used two HUD designs that were compared to a baseline dashboard design. Compared to the dashboard-HMI, the HUD design which is static relative to the main vehicle (HUD-HMI1) increases drivers' SA and reports the same system usability, the HUD design with dynamic guidance effect (HUD-HMI2) increases both SA and system usability.

In summary, the design of the HUD has an important impact on driving, and an important contribution of this study is to propose that the HUD design with dynamic directivity of augmented reality should be recommended as a way of increasing drivers' SA and usability.

## 7 Limitations

The most obvious limitation was the number of participants. A larger population subjects may give more clearer results. In addition, this experiment requires the cooperation of the experimenter. Although the experimenter has rich experience, manual control may cause the instability of the experimental task.

Moreover, this experiment evaluates the HUD design only in the cut in scenario of the ACC function and without the traffic lights and complex traffic conditions under non-motorized vehicles.

## 8 Future Work

The study of HUD design is of great significance to the driving safety. Further research topic continues to focus on HUD design research. In future research, larger cohorts of participants with multiple ages and multiple driving experiences will be used for statistical analysis. Furthermore, we will develop the driving simulator to achieve more traffic scenarios and allow subjects to complete tasks independently without the cooperation of experimenter. In addition to situation awareness and usability, more psychological factors such as workload, trust and so on are studied to evaluate the HUD design from the perspective of cognition and design.

**Acknowledgement.** This work is partially supported by Shenzhen Collaborative Innovation and Technology Program - International Science and Technology Cooperation Project; National Social Science Fund(19FYSB040); Tongji University's Excellence Experimental Teaching Project; Shanghai Automotive Industry Development Fund (1717); Graduate Education Research Project, Tongji University(2020JC35).

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