Summary Report: Cooperative Adaptive Cruise Control Human Factors Study

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Pedestrian and Bicycle Safety

FOREWORD

This report presents results of human factors research to examine the effects of cooperative adaptive cruise control (CACC) on driver performance in a variety of situations. CACC has been envisioned as an automated vehicle application that complements the capabilities of the vehicle operator without degrading the vehicle operator's alertness and attention.

Four experiments are summarized that were conducted in a driving simulator. Three of these experiments focused on the effects of CACC when drivers in a string of CACC-equipped vehicles had to respond to other drivers merging into the string or to rapid deceleration of the lead vehicle in the string. The remaining experiment focused on the human factors issues that arose when a driver merged into an existing string of CACC vehicles.

This report informs the discussion of how automated vehicle applications will be embraced by everyday drivers and affect their behavior. It should be useful to engineers, researchers, and transportation professionals who are evaluating and implementing connected vehicle technologies that include longitudinal vehicle control.

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Acting Director, Office of Safety
Research and Development

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This summary report provides a high-level overview of four experiments that investigated human factors issues surrounding cooperative adaptive cruise control (CACC). CACC combines three driver assist systems: (1) conventional cruise control, which automatically maintains the speed a driver has set, (2) adaptive cruise control, which uses radar or light detection and ranging sensors to automatically maintain a gap the driver has selected between the driver's vehicle and a slower-moving vehicle ahead, and (3) dedicated short-range communications to transmit and receive data with surrounding vehicles so that the cruise control system can more quickly respond to changes in speed and location of other CACC vehicles, even vehicles that the driver cannot see. This report describes a series of experiments that examined how use of a CACC affected drivers' workload, propensity to distraction, level of physiological arousal, ability to avoid a crash, merging abilities, and trust in the system.
The first experiment compared driving with CACC in a string of four or five vehicles with manual control of the following distance in the same strings. The second experiment explored driver performance when merging into a string of CACC vehicles. The third experiment took a closer look at the source of a substantial crash reduction benefit obtained with CACC in the first experiment. The fourth experiment examined the effect of a driver's preferred following distance on performance and workload when using short and long CACC gap settings.</td></tr>
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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LIST OF ACRONYMS AND ABBREVIATIONS

ACC	adaptive cruise control
CACC	cooperative adaptive cruise control
DSRC	dedicated short-range communications
FHWA	Federal Highway Administration
GEE	generalized estimating equation
GSR	galvanic skin response
NASA-TLX	National Aeronautics and Space Administration Task Load Index
TTC	time to collision

CHAPTER 1. INTRODUCTION

This summary report provides an overview of four human factors experiments conducted in support of the Federal Highway Administration's (FHWA) connected vehicle program. The methods, findings, and conclusions from these experiments are more completely described in the following FHWA reports:

- FHWA-HRT-16-056, *Cooperative Adaptive Cruise Control Human Factors Study: Experiment 1—Workload, Distraction, Arousal, and Trust*.[1]
- FHWA-HRT-16-057, *Cooperative Adaptive Cruise Control Human Factors Study: Experiment 2—Merging Behavior*.[2]
- FHWA-HRT-16-058, *Cooperative Adaptive Cruise Control Human Factors Study: Experiment 3—the Role of Automated Braking and Auditory Alert in Collision Avoidance Response.*[3]
- FHWA-HRT-17-024, *Cooperative Adaptive Cruise Control Human Factors Study: Experiment 4—Preferred Following Distance and Performance in an Emergency Event*.[4]

Cooperative adaptive cruise control (CACC) combines the following three driver assist systems: (1) conventional cruise control, which automatically maintains the speed a driver has set, (2) adaptive cruise control (ACC), which uses radar or light detection and ranging sensors to automatically maintain a gap the driver has selected between the driver's vehicle and a slower-moving vehicle ahead, and (3) dedicated short-range communications (DSRC) to transmit and receive data with surrounding vehicles so that the cruise control system can more quickly respond to changes in speed and location of other CACC vehicles, including vehicles that the driver cannot see.[5]

When using CACC, drivers share vehicle control with an automated system that includes vehicle-to-vehicle and vehicle-to-infrastructure communications. Communications between nearby CACC-equipped vehicles would enable automated coordination and adjustment of longitudinal control through throttle and brake activations. Automated control should enable CACC-equipped vehicles to safely travel with smaller gaps between vehicles than drivers could safely manage on their own. According to Shaldover et al., smaller gaps should subsequently increase the roadway capacity without increasing the amount of roadway.[6]

Although technically feasible from computational and communications perspectives, the ability of users to safely interact with CACC-equipped vehicles in the scenarios envisioned by engineers has yet to be demonstrated. The goal of this CACC human factors study was to investigate the effects of CACC on driver performance, workload, situational awareness, and distraction. The goal was not to address all human factors issues associated with CACC use but rather to suggest additional lines of research that might be required to model the influence of human drivers on overall CACC performance.

Cruise control systems, both conventional and adaptive, have been marketed as convenience systems to reduce driver workload and stress by relieving the driver of the need to continuously regulate vehicle speed and following distance.[7,8] Some newer adaptive systems have been combined with forward collision warning and forward collision avoidance systems. Collision avoidance systems may have full braking authority (i.e., they may have the maximum deceleration possible and may brake to a full stop when necessary).[9] Combining these newer capabilities with DSRC to comprise a CACC system brings about several possible driver adaptations.

By reducing the driver's workload or stress, the driver's physiological arousal level may be reduced. The desired effect of stress reduction would be to optimize the driver's performance and feelings of well-being. However, the Yerkes-Dodson law holds that for tasks of moderate difficulty, low and high levels of arousal lead to lower levels of performance than some moderate levels of arousal.[10] In accordance with this law, a less favorable CACC outcome might be to reduce driver arousal below the optimum level and result in poorer driver performance. Driver performance continues to be important in semi-autonomous systems such as CACC. In particular, CACC systems do not maintain lateral control of the vehicle, and braking is not always the best or safest response to a slower or stopped vehicle ahead. For this reason, several of the experiments conducted for this study assessed drivers' subjective workload and physiological measures of arousal.

Situational awareness is defined as the state of knowledge of an operator of a complex dynamic system. In the context of CACC, situational awareness refers to the driver's state of knowledge of his or her vehicle and the environment in which it is operating. Endsley divided this state of knowledge into three parts: (1) knowledge of all the elements of the system that are related to the driver's goals, (2) what the state of those elements means relative to those goals, and (3) what the current state mean concerning future system states.[11] Intuitively, the situational awareness construct would make sense for examining how the driver and CACC system would perform together. With the CACC system, the driver must be aware of the mode of the system (i.e., manual, conventional cruise control, ACC, or CACC), lane position, the presence and trajectory of other vehicles, obstacles, and orientation relative to intended destination. It is possible to imagine a situation in which the driver was in a platoon of CACC vehicles and relying on the system to maintain a safe gap to the vehicle ahead. In that situation, would the driver be aware of whether the CACC system was functioning correctly and whether the system was capable of correcting a rapidly closing gap? If the driver failed to notice a closing gap that the system was not capable of correcting, then it could be said that the driver lacked situational awareness.

Although the situational awareness construct makes intuitive sense, it was built on a number of other theoretical constructs, each of which is based on paradigms and theories that are intended to organize and explain various behavioral phenomena. As described by Endsley, situational awareness relies on long-term memory; automaticity; various information processing mechanisms (e.g., working memory); and the driver's goals and objectives, expectations, experiences, and abilities.[11] Furthermore, the system, interface design, driver stress, driver workload, and system automation would affect situation awareness, driver decisionmaking, and driver performance.[11] This definition of situation awareness would make its measurement problematic unless all of the underlying components could be controlled, manipulated, or measured. Thus, although some of the results of the four experiments reported here may be thought of in terms of driver situational awareness, no attempt was made to directly assess this hypothetical construct.

Four experiments were conducted as part of the CACC human factors study. All four experiments were conducted in a driving simulator. The first three experiments were conducted in the FHWA Highway Driving Simulator. That simulator is described in chapter 2. The fourth experiment was performed in a less sophisticated fixed-base driving simulator, a National Advanced Driving Simulator MiniSim™.

Chapter 2 describes the first experiment, which compared driving with CACC in a string of four or five vehicles with manual control of the following distance in the same size vehicle strings. Chapter 2 also briefly describes calibration of the simulator visuals to ensure that the simulated following distance perceptually matched real-world perception of following distance.

Chapter 3 describes an experiment that explored driver performance when merging into a string of CACC vehicles.

Chapter 4 describes an experiment that took a closer look at the source of a substantial crash reduction benefit obtained with CACC in the first experiment.

Chapter 5 describes an experiment that examined the effect of a driver’s preferred following distance on performance and workload when using short and long CACC gap settings.

Chapter 6 summarizes key findings and recommendations that resulted from the four human factors experiments.

CHAPTER 2. WORKLOAD, DISTRACTION, AROUSAL, TRUST, AND CRASH AVOIDANCE

This chapter presents an overview of the experiment assessing workload, arousal, distraction, trust, and crash avoidance.

METHOD

Four groups drove the simulated vehicle over the same 39-mi stretch of limited-access roadway. Three of the four groups drove a CACC-equipped vehicle in a platoon with other CACC-equipped vehicles, but the nature of the event that occurred at the end of the drive differed. The fourth group manually controlled its following distance within a platoon in which all of the other vehicles used CACC. For most of the distance traveled, the roadway and the behavior of other vehicles was the same for all groups.

Workload Assessment

Driver workload was assessed by administration of the National Aeronautics and Space Administration Task Load Index (NASA-TLX).[12] Workload was assessed four times. The first assessment was during a practice drive and was intended to familiarize participants with providing verbal responses to the NASA-TLX protocol. The second workload administration was 5 min into the main scenario, just after a vehicle merged into the platoon between the participant's vehicle and the vehicle the participant had been directly behind. This NASA-TLX administration was intended to assess the workload imposed by a vehicle halving the following distance between the participant and the vehicle ahead. The third assessment was 15 min into the drive and was intended to assess the workload associated with driving in a CACC platoon when no changes in the platoon had occurred for 10 min and 11.7 mi of uneventful driving. The final assessment was near the end of the drive and immediately followed the events that varied between groups. The second and third workload assessments enabled comparison of workload between the three CACC groups (which should not have differed from each other at these points) and the control group (which had to manually maintain gap).

Physiological Arousal

Physiological arousal was assessed by measuring eyelid closure, pupil diameter, and skin conductance. These measures were assessed at five 30-s periods during the drive. These measures were intended to assess changes in arousal as a result of an initial merge event, after 10 min of uneventful driving, and as a result of the final events.

Distraction

Automation has generally been intended to reduce driver workload. A positive result of automation would be a more relaxing and rewarding driving experience. A less positive result might be that the driver felt free to engage in more nondriving tasks that might subsequently result in less attention to the driving task. Participants were allowed to play the radio, use their cell phone, or otherwise engage in nondriving-related activities. Engagement in nondriving activities was neither encouraged nor discouraged. Participants were instructed to drive as they normally would with the exception of CACC usage and gap maintenance. The extent to which participants engaged in voluntary nondriving activities and how these correlated with physiological arousal and crash avoidance was observed. Aside from assessing these correlations, no attempt was made to measure the extent, if any, to which these activities might be distracting.

Crash Avoidance

At 34.6 mi from the start, the behavior of other vehicles varied between groups. Two groups experienced a non-CACC-equipped vehicle cutting in front of the platoon and overturning. Of these two groups, one was using CACC with a 1.1-s gap, and the other, the control group, was manually maintaining a 1.1-s gap. This manipulation was intended to test whether CACC-equipped drivers would be more or less likely to avoid a crash when sudden hard braking was required. If the convenience of CACC induced drivers to become complacent, distracted, or unaware or to have a very low level of arousal, then it might be expected that the CACC group would experience more crashes than the control group, which, because it was forced to monitor gap distance manually, might be expected to be more aware, aroused, and attentive. However, the CACC system had partial braking up to 0.4 g, and in this scenario, braking was initiated before the brake lights of the lead car activated. Also, when the CACC system began to brake, there was a loud series of beeps intended to alert the driver of the need to take longitudinal control. This beeping carried a meaning similar to that of a forward collision warning. With the automated assistance of the CACC system, it was theorized that the CACC group might gain the slight reaction time advantage. This test of crash avoidance would be specific to the warning and brake response programmed into the system, and thus, the results could not be expected to generalize to all potential CACC implementations. Nonetheless, they should give a clue whether similar CACC systems would be more likely to be a boon or detriment to safety and might provide a starting point for exploration of CACC warning parameters and the effects of automated braking.

Equipment and Materials

The following subsections describe the equipment and materials used for this experiment.

The Driving Simulator

The experiment was conducted in the FHWA Highway Driving Simulator. The simulator’s screen consisted of a 200-degree portion of a cylinder with a radius of 8.9 ft. The design eye point of the simulator was 9.5 ft from the screen. The stimuli were projected onto the screen by five projectors with resolutions of 2,048 horizontal by 1,536 vertical pixels. Participants sat in a compact sedan. The car’s instrument panel, brake, and accelerator pedal all functioned in a manner similar to real-world compact cars.

Eye-Tracking System

The simulator was equipped with a four-camera dashboard-mounted eye-tracking system that sampled at 120 Hz. The system tracked horizontal gaze direction from approximately the right outside mirror to the left outside mirror and vertical gaze direction from the bottom of the instrument panel to the top of the windscreen. In this study, the eye-tracking system was primarily used to determine at which vehicle displays the participant was looking. In addition to tracking the direction of gaze, the eye-tracking system computed eyelid opening and pupil diameter.

Multifunction Display

The model of sedan used for the simulator was not originally equipped with cruise control controls or displays. For this experiment, a 7-inch diagonal liquid crystal display touch screen was mounted on the center console above the radio. For the CACC conditions, the touch screen was used to toggle the CACC system on and off. Throughout the experiment, the set speed remained 70 mi/h, and the gap target remained 1.1 s. The participants were instructed that the gap and speed setting adjustments were nonfunctional and intended only to assist in explaining the ACC concept. No participants were observed trying to change these settings.

The center console display for the control group was not interactive. A black bar on the colored ribbon displayed the current gap between the control participant's front bumper and the rear bumper of the vehicle ahead. Control participants were asked to try to maintain a 1.1-s gap and keep the black bar in the green region of the ribbon (i.e., between 0.8 and 1.3 s).

Skin Conductance Sensor

Galvanic skin response (GSR) was measured with silver-chloride salt electrodes placed on the palmar-side base of two fingers on the participant's left hand. The electrodes were connected to a small sensor with a Bluetooth® transmitter strapped to the left wrist.

The Simulation Scenarios

Participants drove in a dedicated lane on a simulated eight-lane interstate highway (four lanes in each direction). Participants drove in the lane adjacent to the median. This lane was separated from the other lanes by F-type barriers. A typical portion of the roadway is depicted in figure 1. The center dedicated lane was accessed from the left side of the roadway from a ramp with a ramp meter. The simulation began with the participant's vehicle in the third position within a platoon of four vehicles. When the ramp meter turned green, the platoon accelerated and merged into the CACC lane and cruised at 70 mi/h.

Figure 1. Screen capture. A typical section of the simulated roadway.

For the first 5.8 mi or 5 min, the platoon proceeded as formed. At 5.8 mi, a CACC vehicle merged into the platoon from the left in front of the participant driver. The merge was from a ramp identical to the initial ramp. Initially, the gap between the participant and the merging vehicle was about 0.5 s or 51 ft. At the 34.8 mi point, one of the following critical events occurred:

- **Event 1:** A vehicle traveled rapidly down a ramp and entered the dedicated lane ahead of the lead vehicle and overturned out of the view of the participant driver. The lead vehicle decelerated at 32 ft/s^2 to avoid the overturned vehicle. In the CACC vehicles, this event was indicated by a 1,000-Hz warning tone of four beeps, with each beep duration lasting about 140 ms and separated from the next by about 22 ms of near silence.

- **Event 2:** A non-CACC vehicle merged into the platoon between the first and second vehicles in the platoon. That vehicle then decelerated at 6 ft/s^2 until it reached 55 mi/h.

- **Event 3:** Loss of communication and tracking required manual resumption of longitudinal control. Vehicles ahead then decelerated at 12.8 ft/s^2 to 55 mi/h. In CACC vehicles, this event was accompanied by the same auditory warning as for event 1.

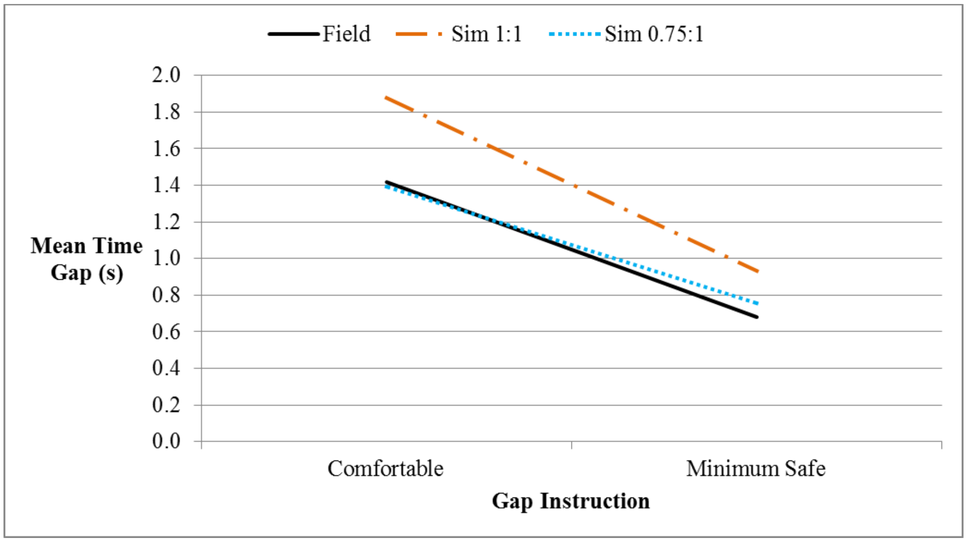
Calibration of CACC Vehicle Size

In previous testing in the simulator and in pilot testing for this experiment, most individuals showed a reluctance to follow other vehicles with a 1.1-s gap and indicated that they never followed that closely. The literature suggested that a 1.1-s gap was greater than most people considered safe.[13] To examine this phenomenon, trials were conducted in which six drivers from the FHWA research center (Federal employees and contractors) drove an instrumented vehicle in the field while following a full-sized sport-utility vehicle and followed the same simulated vehicle in the driving simulator. The field data collection was conducted on limited-access managed lanes with minimal traffic. The simulated roadway was the CACC-managed lane used in this experiment. Each of the drivers was asked to follow both the real and simulated vehicles according to the following instructions:

- Follow at a comfortable distance.
- Follow at the minimum safe distance.
- Drive with ACC/CACC set at the near following distance.
- Manually control the gap at the same distance you had been following with ACC/CACC.

In the field, the participants drove an instrumented luxury sport-utility vehicle that was equipped with ACC. In the simulator, the eye point of the simulator cab was positioned to approximate the eye height as the lead vehicle. The procedures in the field and in the simulator were the same. Participants first drove for 5 to 7 min to accustom themselves to the vehicle/simulator. They then caught up to the lead vehicle, which was traveling with cruise control set to 65 mi/h, and were instructed to follow at a comfortable distance. After following constantly for about 1 min at what the participants said they felt was a comfortable distance, participants were asked to back off a substantial distance (greater than 4 s). Next, the participants were asked to accelerate and follow while maintaining the minimum safe distance (the shortest gap they believed to be safe). This procedure of catching up to follow at comfortable and minimum safe distances was repeated at least twice. After backing off to more than 4 s again, participants were asked to engage the ACC/CACC system that was set to follow with the near setting. The near setting sought a 1.1-s gap. Once they had followed at the near distance for at least 1 min, the system was again disengaged, and the participants backed off to a distance of more than 4 s. The final request was to accelerate to and maintain the same following distance they had driven with the ACC/CACC system engaged. On all trials, steady state following was recorded for approximately 1 min.

With the simulated lead vehicle set to have a visual angle subtended precisely the same as it would be in the real world, participants maintained a following distance about 1.3 times the distance they had maintained in the field. This suggested that the lead vehicle’s size needed to be reduced to induce the same perceived following distance the participants maintained in the field. As a first approximation, the lead vehicle size was reduced to 75 percent of the correct size based on 1:1 visual angle correspondence. Several weeks later, five of the original six participants returned to the simulation laboratory and followed the original procedure but following a reduced size lead vehicle. Participants were not informed about the changes that had been made to the lead vehicle. In the second simulation drive, the participants nearly duplicated the comfortable and minimum safe distances they had driven in the field. The results of this testing are shown in figure 2.



Sim = Simulation.

Figure 2. Graph. Results of field and simulator gap maintenance testing.

As a result of this testing, it was decided to reduce the size of the other vehicles in the CACC string to 75 percent of the size of a 1:1 depiction. This same size reduction was used in all four experiments reported in this summary.

Procedure

A slideshow presentation with embedded videos was shown to explain the CACC concept. Participants assigned to one of the CACC conditions were presented with the warning tone that was triggered when more braking was needed than the CACC system could provide. The CACC-related instructions were as follows:

- Set the gap to near.
- Set the speed to 70 mi/h.
- You will control steering—follow the car in front.
- The system will accelerate and brake up to a limit.
    - You need to monitor the situation at all times—the system can fail.
    - You can take over control by pressing the accelerator or brake.
    - Pressing the brake disengages the CACC system.
    - If you need to take control, press ENGAGE as soon as possible when the situation allows.

Except for these CACC-related instructions, the control group instructions were the same except the control group was instructed as follows:

- Aside from maintaining a 1.1-s gap, you should drive as you normally would.
- Stay alert for unexpected events.

A practice drive, NASA-TLX practice, eye-tracker calibration, and attachment of the GSR sensor preceded the experimental drive.

The experimental session began with the participant seated in the third vehicle of a string of four vehicles. The string was stopped on a ramp in front of a ramp meter showing a red indication. When the ramp meter turned green, the vehicles ahead began to accelerate down the ramp toward the CACC travel lane. Participants in the CACC conditions were asked to engage the CACC system. With CACC engaged, the participant's vehicle followed the two preceding vehicles with a 1.1-s gap. Participants in the control condition were asked to follow the preceding vehicles and try to keep the gap close to the 1.1-s target.

About 5 min into the drive, a CACC vehicle came down a ramp on the left and merged into the gap directly in front of the participant's vehicle, which momentarily cut the gap to half of what it had been. The CACC-equipped vehicles behind the merged vehicle responded by decelerating with engine braking until the gap was again 1.1 s. If necessary, a researcher would remind control participants to return to the 1.1-s following distance. As soon as the platoon stability was reestablished, which generally took about 30 s, the NASA-TLX was administered to assess workload during the merge event (i.e., during the preceding minute or so).

After the conclusion of the NASA-TLX, about 10 min elapsed before another NASA-TLX was administered. This administration was intended to assess workload during uneventful cruising in a CACC platoon (also described as during the last minute or so). The cruise was again uneventful for the next 31 min until the critical event (described previously in the section entitled The Simulation Scenarios). At the conclusion of the critical event, a final NASA-TLX was administered, after which the participant was asked to take the next exit ramp and come to a stop.

After exiting the simulator, participants were asked to complete a final simulator sickness questionnaire, debriefed, and paid for their participation.

Experimental Design

The primary between-group independent variable was whether the participant vehicle was equipped with CACC. The experimental design called for 36 participants to drive with CACC and 12 to drive without cruise control but within a string of simulated CACC vehicles. Participants driving with CACC were assigned to one of three critical events, with 12 participants assigned to each event.

Thus, there were the following four distinct participant groups:

- **Control:** Manually controlled longitudinal speed/gap. Was exposed to critical event 1 (vehicle crashing ahead of platoon/crash avoidance).
- **CACC with crash avoidance:** Drove with CACC engaged. Was exposed to critical event 1 (vehicle crashing ahead of platoon/crash avoidance).
- **CACC with cut-in:** Drove with CACC engaged. Was exposed to critical event 2 (CACC vehicle merging between the first and second platoon vehicles).

- **CACC with communications failure:** Drove with CACC engaged. Was exposed to critical event 3 (loss of communication and tracking).

Participants

The participants were 49 licensed drivers recruited from the Washington, DC, metropolitan area. Table 1 shows the age group and gender counts by treatment group for the participants who provided useable data. The mean age of the younger participants was 30.4 years (ranging from 21 to 38). The mean age of the older participants was 60.4 years (ranging from 49 to 76).

Table 1. Demographic breakdown of participants in experiment 1 by treatment group.

Condition	Young Females	Young Males	Older Females	Older Males	Total
Control	3	3	3	3	12
CACC with crash avoidance	3	4	3	3	13
CACC with cut-in	3	3	3	3	12
CACC with communications failure	2	3	3	4	12
Total	11	13	12	13	49

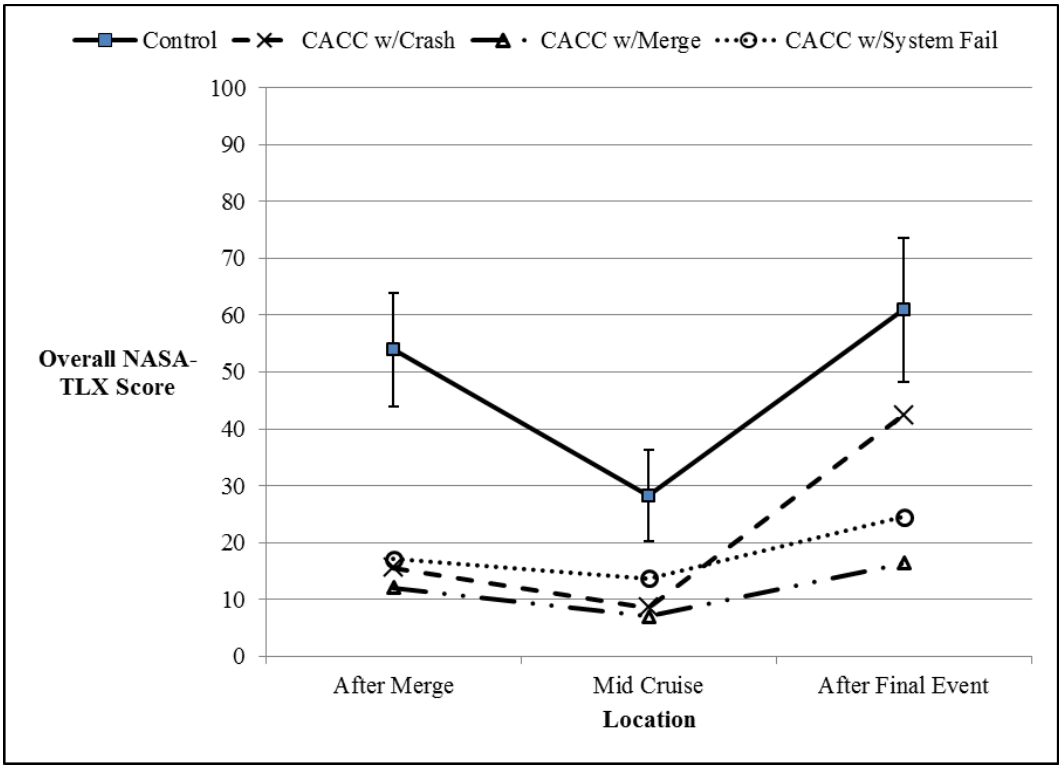
Participants were paid $60 for their participation.

RESULTS

The following subsections describe the results of the experiment for workload, physiological arousal, distraction, gaze location, crash avoidance, minimum time to collision (TTC), reaction time, and trust in the CACC system.

Workload

The mean NASA-TLX scores by condition and period are shown in figure 3. The control group consistently rated workload higher than the CACC groups (F (1, 3) = 14.5, p < 0.001). There was also a significant location-by-condition interaction (F (6, 90) = 27.4, p < 0.001), which was the result of the CACC with crash group rating their workload higher than the other CACC groups after the critical crash event.



Note: Error bars represent estimated 95-percent confidence limits of the means.

Figure 3. Graph. NASA-TLX scores as a function of treatment group and location in the scenario.

Physiological Arousal

The physiological measures of arousal were GSR, eyelid opening, and pupil diameter.

GSR

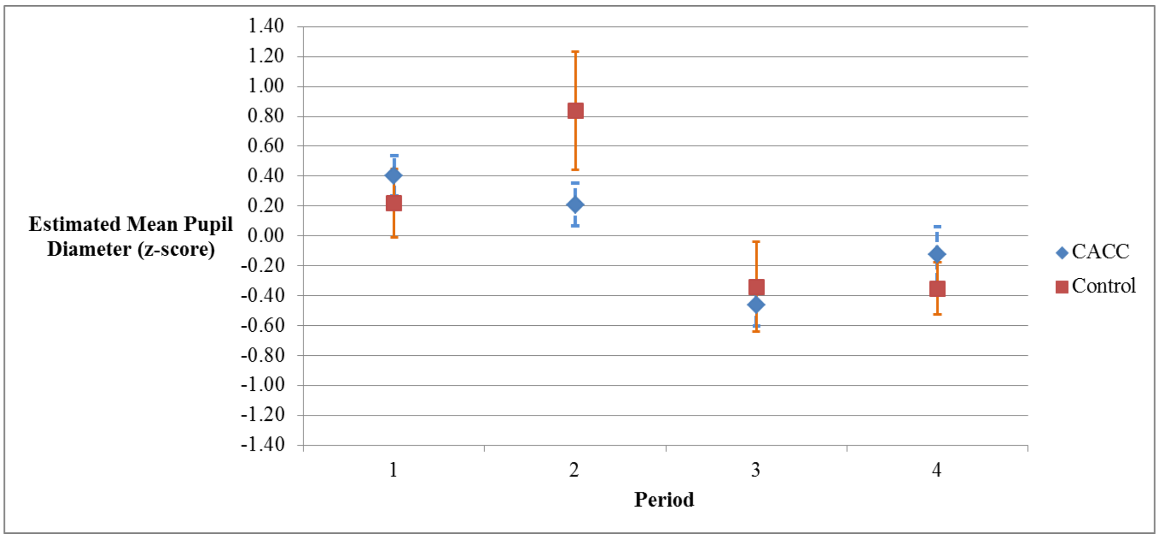
No statistically significant differences in physiological arousal, as measured by standardized GSR, were detected between the control group and the three CACC groups.

Eyelid Opening

The eyelid opening data were quite noisy, and more than half of the data were rejected because the eye-tracking software indicated low confidence in the reported readings. No reliable differences in eyelid opening were identified either between groups or as a function of the time the readings that were taken during the drive.

Pupil Diameter

Pupil diameter measurements for which the eye-tracking software reported less than 75 percent confidence were excluded from analyses. These exclusions resulted in retention of 73.7 percent of the observations. As with GSR and eyelid opening, each participant's pupil diameter observation across the five 15-s periods was converted to a *z*-score. The first period was immediately after the first merge event. The second period was after 15 min of uneventful driving. The third period was just before the critical event, and the fourth period was just after the critical event. The *z*-scores were then submitted to a generalized estimating equation (GEE) model with condition, period, and their interaction as factors. Figure 4 shows the estimated standardized means as a function of condition and period, where the three CACC groups have been collapsed into one CACC condition. The condition-by-period interaction was significant, ($\chi^2(12) = 36.12$, $p < 0.01$), as was the main effect of period, ($\chi^2(4) = 74.04$, $p < 0.01$). The source of the main effect was obvious—pupil diameters for all conditions were greater during the first two periods (after 5 min of driving) than in the last three periods (after 15 or more minutes of driving). The interaction does not result from any easily explainable phenomenon; the control group had atypically large pupil diameters in period 2, perhaps related to the larger amount of time spent glancing at the gap display (see Gaze Location results presented later in this section). The CACC with communications failure group had larger pupil diameters than the other groups in period 4. Because all three CACC groups were exposed to the same stimulus conditions until period 5, there was no obvious explanation for the pattern that resulted in the significant interaction.



Note: Error bars represent estimated 95-percent confidence limits of the means.

Figure 4. Graph. Standardized pupil diameter as a function of condition and period.

Overall, the physiological measures provided no evidence that CACC resulted in a greater reduction in arousal over time than the control condition.

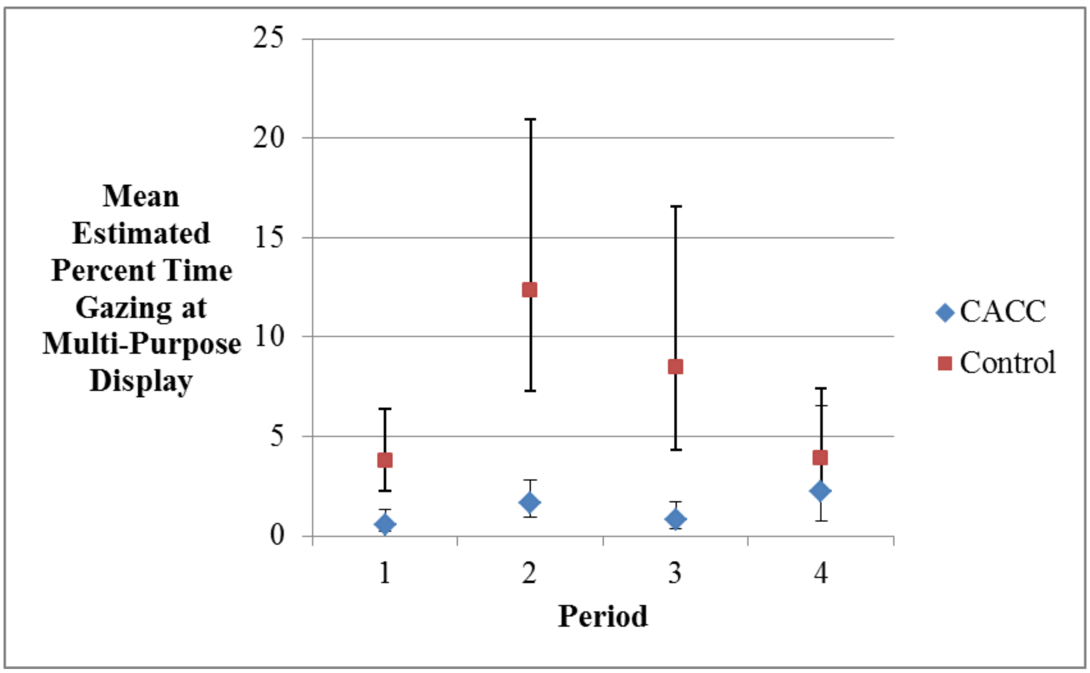
Distraction

The physiological data, which were quite noisy, showed no clear indication of reduced levels of arousal that might lead to inattention errors. However, people can mitigate the tendency toward reduced arousal on long drives by engaging in arousal-stimulating secondary activities. In this experiment, participants were not discouraged from engaging in these activities. While care was also taken to avoid encouraging these activities, participants were told that they could listen to the car radio or do what they normally did while driving. Because all of the CACC participants were treated the same prior to the critical event, the three CACC groups were collapsed into one group, and their probability of engaging in observable diversions before the critical event was compared with the control group. The estimated mean probability of control group members engaging in diversions (0.36) was less than the estimated mean probability of CACC group members engaging in diversions (0.52). This difference was statistically significant ($p < 0.05$).

Gaze Location

The control group spent considerably more time gazing in the direction of the multifunction display than did the CACC groups. Gaze time in the direction of the multifunction display came at the expense of monitoring the road ahead. It should be noted that the road ahead classification included any recorded gaze direction other than at the defined objects (e.g., multi-purpose display or rear-view mirror) and within the 200- by 40-degree area of the projection screen.

Because the only difference in treatment of the CACC groups occurred in observation period 5, the data for the three CACC groups were collapsed into a single CACC group for periods 1 through 4. A GEE model with negative binomial response distribution and log link function was used to analyze the gaze distribution among objects in periods 1 through 4 and CACC group versus control group. This model revealed a significant main effect of period ($\chi^2(3) = 19.5$, $p < 0.01$) and condition ($\chi^2(1) = 24.6$, $p < 0.01$). These effects are shown in figure 5. For the CACC participants, gaze time in the direction of the display in periods 2 and 4 may have resulted from the need of some participants to reengage the CACC system. The large percentage of time that the control group spent gazing in the direction of the multi-purpose display in period 2 was likely the result of the changes in gap caused by the cut-in vehicle in that period.



Note: Error bars represent estimated 95-percent confidence limits of the means.

Figure 5. Graph. GEE estimated mean percentage of time gazing at the multifunction display as a function of condition and period.

Crash Avoidance

None of the participants in the CACC group with cut-in or CACC group with system failure collided with another vehicle. This was not the case for participants in the crash avoidance condition in which the lead vehicle of the platoon decelerated to a stop from 70 mi/h at a rate of 32.2 ft/s^2. As shown in table 2, five control group members crashed into the vehicle ahead, but only one member of the CACC with crash avoidance group crashed. The difference in crash rates was significant by Fisher's Exact Test ($p < 0.02$).

Table 2. Crash counts for the two groups that were exposed to the crash avoidance event.

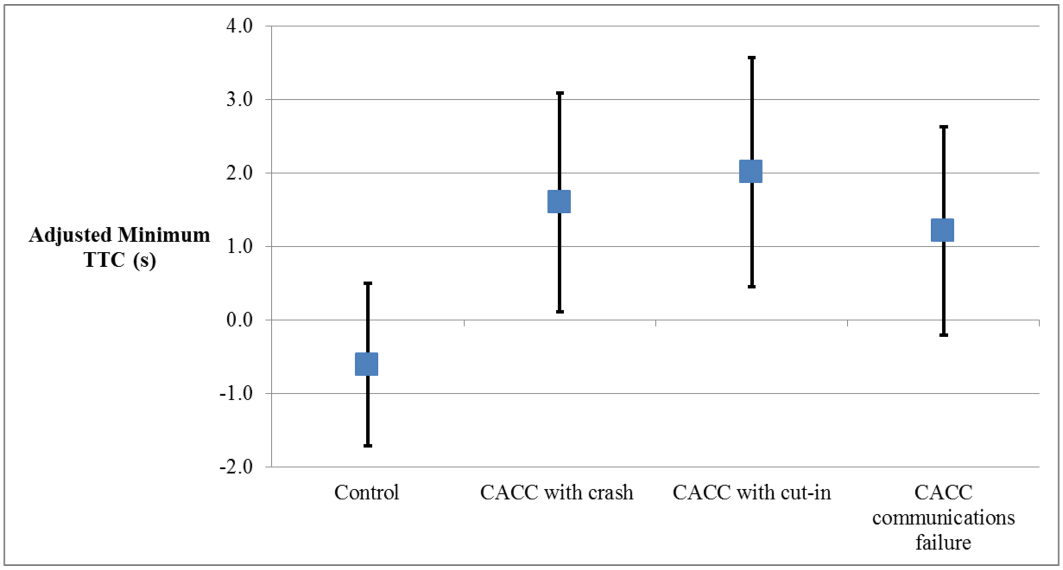
Group	Crashed	Avoided	Total
Control	5	6	11
CACC with crash avoidance	1	12	13

Crashes have often been considered the ultimate measure of highway safety. However, crashes are a rather crude safety measure because they are rare outside driving simulations and are generally reported in terms of number of crashes per million miles driven. TTC has been used as a surrogate for crashes because the frequency of near misses (i.e., very short TTCs) has been thought to be highly correlated with crash frequency but easier to observe.[(14)] To further evaluate the probability of a crash in scenarios like those in the simulation, TTC was analyzed.

Minimum TTC

To enable analysis of TTC even when collisions occurred, Brown's adjusted minimum TTC was used.[(15)] The adjusted minimum TTC takes into account velocity at the time of collision. The adjusted minimum TTC thus reflects the severity of the crash or near-crash event regardless of whether collision avoidance was successful. If a collision does not occur, the minimum TTC is the same as the traditional TTC measure and represents the amount of additional time the driver had to respond. If a collision does occur, then minimum TTC is negative and represents the difference between the time available and the time the driver needed to avoid the collision.[(15)] One CACC with crash avoidance participant showed no reaction to the rapid deceleration of the lead vehicle. When the following vehicle fails to decelerate, the adjusted TTC goes to negative infinity, and minimum TTC becomes meaningless, at least in terms of computing mean TTC. Therefore, this participant was excluded from the adjusted minimum TTC analysis.

The overall test showed that the mean minimum TTCs between groups were significantly different (Wald χ^2 (3) = 9.2, p <0.03). As can be seen in figure 6, the control group TTC was significantly less than that of the three groups that used CACC.



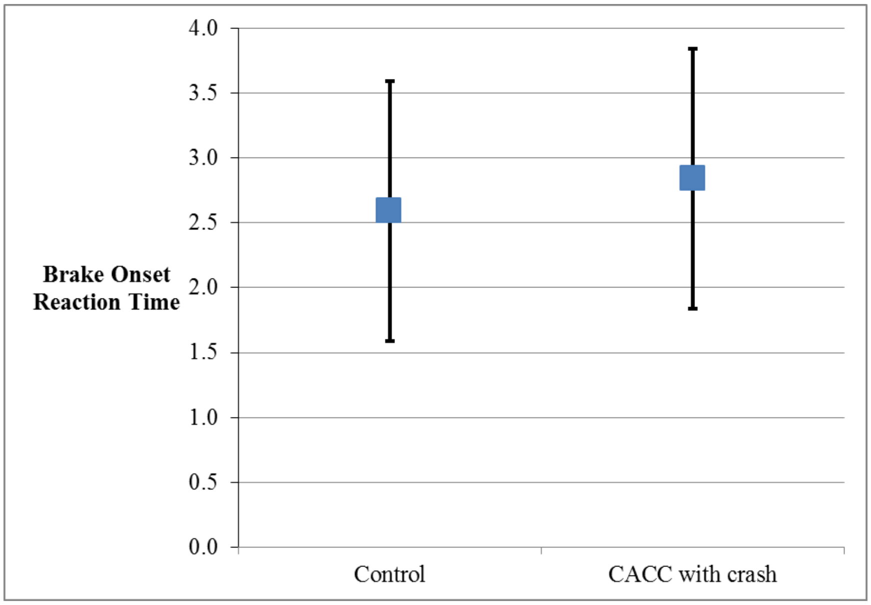
Note: Error bars represent estimated 95-percent confidence limits of the means.

Figure 6. Graph. Estimated adjusted mean TTC.

Reaction Time

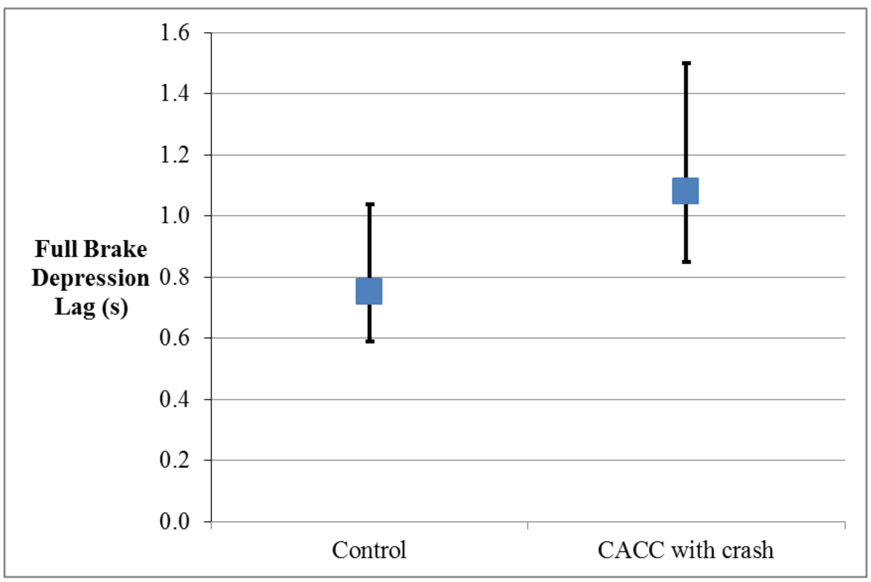
Brake reaction time was defined as the time between when the car immediately ahead of the participant began braking and the time the participant first began to depress the brake pedal. One control and two CACC crash avoidance participants were excluded from this analysis because they swerved out of the travel lane before braking or never braked.

There was no significant difference in brake reaction time between the control group and the CACC crash avoidance group. The brake reaction times for these two groups are shown in figure 7. This finding suggests that the better crash avoidance and larger minimum TTCs for the CACC group were the result of the CACC system automatically braking at 0.4 g. Alternatively, the larger CACC TTCs could have resulted if the CACC group had responded with more vigorous braking than the control group (i.e., if the CACC group went from zero to full brake pedal depression faster than the control group). This alternative explanation was rejected because the control group tended, but not significantly so, to brake more vigorously (i.e., reached full brake depression sooner) than the CACC group. Figure 8 shows the time taken to move the brake pedal position from off to full braking. The difference between groups was not significant.



Note: Error bars represent estimated 95-percent confidence limits of the means.

Figure 7. Graph. Estimated mean brake onset reaction times for the two groups that had the crash avoidance final event.



Note: Error bars represent estimated 95-percent confidence limits of the means.

Figure 8. Graph. Estimated mean time from beginning of brake pedal depression to full braking.

Trust in the CACC System

About 6.8 min into the drive (the moment that ended period 1 and began period 2), a simulated CACC vehicle merged into the gap between the participant's vehicle and the car ahead, approximately halving the participant's following gap distance. All participants were exposed to this merge event. One measure of trust in the system was whether the participants in the CACC conditions trusted the system to maintain speed/gap control or intervened by braking to increase the gap or by pressing the accelerator to return to a 1.1-s gap. Only 1 of 36 CACC participants braked during the merge event, and 1 participant pressed the accelerator pedal. By comparison, all of the control condition participants used the brake pedal during the merge event.

DISCUSSION

The first experiment addressed the following questions regarding CACC:

- Does CACC reduce driver workload compared with manual gap control?
- Does CACC increase the probability of driver distraction compared with manual gap control?
- Does CACC result in reduced driver arousal compared with manual gap control?
- Does CACC increase the ability to avoid a crash when exposed to an extreme breaking event?
- Will drivers trust the CACC system?

Does CACC Reduce Driver Workload?

As assessed by the NASA-TLX, the CACC system did reduce perceived driver workload in this experiment.

Does CACC Increase the Probability of Driver Distraction?

The CACC group was more likely to listen to the radio or engage in other observable diversionary activities than the control group. It remains to be determined whether this tendency was the result of the CACC system relieving the drivers from the responsibility to continually manage gap or because the control group had the added diversion of monitoring the gap indication of the multi-purpose display. As a result of this finding, an additional experiment was proposed in which the control group was equipped with ACC rather than CACC so that a gap display would not be required.

Does CACC Reduce Driver Arousal?

The attempts to assess the effect of CACC on physiological arousal were largely unsuccessful. The GSR measurements were noisy and inconclusive. The eyelid opening data were also inconclusive, and the eyelid opening quality readings output by the eye-tracking software suggest that researchers should not rely on these readings. The pupil diameter readings were fairly reliable, assuming the eye-tracking software quality ratings are to be believed. The finding that pupil diameter decreased in the second half of the drive suggests all groups were somewhat less aroused during the second half of the drive. There was no indication that arousal differed between groups, but this could be the result of the aforementioned tendency of participants to engage in diversionary activities to keep their arousal at comfortable levels.

Does CACC Reduce Crash Risk?

The results of the crash avoidance event to which the control group and CACC with crash avoidance group were exposed suggest that CACC provided a substantial safety benefit. Half the control group crashed into the car ahead with substantial force, as indicated by negative TTC scores. By contrast, only one CACC participant crashed, and that participant's response was questionable because he never attempted to brake and proceeded to drive through three of the vehicles ahead.

Because the control group's brake reaction time and time to reach maximum braking were not significantly different from the CACC group in the crash avoidance scenario, the most likely explanation of the crash avoidance benefit from the CACC system was the 0.4-g braking that the system engaged in soon after the car ahead began braking. This moderate braking enabled the CACC-equipped drivers to brake slightly later and with slightly less force than control drivers while being much less likely to have a collision.

Will Drivers Trust CACC?

The CACC-equipped drivers showed considerable trust in the system. Only 1 of 36 CACC drivers braked when a CACC vehicle merged into the platoon, and only 1 of 36 CACC drivers used the accelerator to close the gap at the end of the merge event when the system slightly overshot the 1.1-s target while slowing to reestablish the set gap. Furthermore, none of the CACC drivers in the CACC with cut-in group braked during the period 5 cut-in event. Although CACC-equipped drivers showed considerable trust in the system, there was no evidence of over trust in the system; all but one CACC driver responded appropriately to the crash avoidance critical event.

CHAPTER 3. MERGING BEHAVIOR

The viability of CACC as a successful and widely used technology is dependent on many factors. One of these factors is the ability of drivers to enter and exit strings of closely spaced CACC vehicles. It has been hypothesized that in the early stages of CACC market penetration, there will be a dedicated CACC lane.(6) The lanes would function much like high-occupancy vehicle or managed lanes. Drivers would only be allowed to travel in the dedicated lane if certain requirements were met. In this case, the drivers would have to be using CACC-equipped vehicles. These lanes would presumably have some sort of physical separation from the regular flow of traffic. This would prevent the disruption of the CACC flow due to non-CACC-equipped vehicles attempting to enter the traffic stream.

This chapter describes an experiment that explored the ability of drivers to enter and exit CACC strings in a dedicated lane. The goal of this research was to address human factors issues. Specifically, the goals of this experiment were to (1) investigate drivers' abilities to successfully enter a dedicated CACC lane and join an already established vehicle string and (2) assess the workload associated with this maneuver.

CACC can be implemented in many ways. This experiment was based on several critical assumptions concerning vehicle technology and roadway infrastructure. These assumptions did not imply that the CACC system would ultimately be implemented in exactly this manner. Rather, they served as points of reference for addressing human factors issues.

There are several ways in which a driver could enter a CACC string in a location other than the front or rear (i.e., as the first car or the last vehicle in a string). One way would involve requesting permission to move into the platoon. In this case, the driver would request permission, permission would be granted, a larger gap would be provided between two of the vehicles in the existing string, and the driver would merge into the string. This method would require more complexity in the CACC operating system and driver interface than other methods. A second way in which a driver could enter a CACC platoon would be one in which vehicles did not request entry into a string, and an extra gap for those vehicles would not be created. Instead, the driver would have to merge into the platoon, and the other vehicles in the platoon would adjust speed to restore the desired gap and to accommodate the new platoon member. This method would result in a variety of human factors issues, especially when vehicles were traveling with short gap distances.

A third way to accomplish a merge into a CACC string would be to enable CACC longitudinal control of the merging vehicle during the merge itself. At 65 mi/h, a 1-s gap would leave approximately 95 ft between vehicles. Previous studies have shown that drivers felt both comfortable and safe traveling with gaps shorter than 1 s. For example, in an on-road study testing drivers' choices in following distances, drivers regularly used gap settings shorter than 1 s. In fact, overall, when following another vehicle, drivers elected to set the gap at 0.7 s or 0.6 s 80 percent of the time.(16) However, with a 0.6-s gap, there would be only 57 ft between vehicles. If the average vehicle length was assumed to be 20 ft, this would leave less than 18.5 ft of buffer in the front or rear for a merging vehicle. As a result, drivers might not feel comfortable or have the skill to merge into a string without longitudinal assistance. Similarly, drivers might not feel comfortable allowing the system to assume longitudinal control during such a merge. For this reason, driver acceptance of longitudinal acceleration by the CACC system to merge was explored.

This experiment explored the following three different types of merges:

- Merge with non-CACC vehicle into CACC strings with varying vehicle gaps.
- Merge with CACC vehicle into a continuous stream of CACC-equipped vehicles without speed assistance.
- Merge CACC vehicle into a CACC string with longitudinal speed assistance.

METHOD

Three participant groups drove the same stretch of simulated limited-access roadway used in experiment 1. All groups were asked to exit and enter the roadway four times. The first group completed this task with no cruise control. The second group used CACC while traveling in the main roadway stream but was required to adjust the vehicle speed when entering and exiting the CACC stream. The third group was provided with CACC that controlled speed both while in the travel lane and while merging and exiting the CACC string.

Workload Assessment

The NASA-TLX was administered four times during the drive. The first assessment was during a practice drive to accustom participants to providing verbal responses to the workload protocol. The second workload administration was 5.8 mi into the drive, immediately after the first complete exit and reentrance into the CACC string. This administration assessed subjective workload imposed by the merge. The third assessment was 20 mi into the drive and assessed subjective workload associated with driving in a stable, unchanging state (i.e., a baseline index). At this point, drivers were between merging events and were likely to feel comfortable with the driving task. The fourth administration was immediately after the final merging event, approximately 23 mi into the drive. This final workload assessment was intended to assess the change in subjective workload that might have occurred following successive string exits and merges.

Physiological Arousal

Physiological arousal was assessed by measuring eyelid closure, pupil diameter, and skin conductance. These measures were assessed at eight different 15-s periods during the drive. Four of these periods were immediately before exiting the roadway (i.e., cruise periods), and four were in the last portion of the merge events.

Merging Behavior

At exits 4, 8, 12, and 16, participants were asked to leave the CACC platoon by using a left ramp and then reenter the traffic stream using a left onramp. The exits were approximately 1.45 mi apart. The CACC platoon movement was continuous and did not stop, which forced participants to enter mid-string. The two groups with CACC were required to join the CACC string in which each vehicle maintained a 1.1-s gap. The group with CACC merge assist was not required to adjust speed in any way. The CACC system maintained longitudinal control during the entire drive unless the participant pressed the brake. The group without CACC merge assist was required to manage and adjust its own vehicle speed while merging into a 1.1-s gap. The third group drove without CACC and maintained longitudinal control at all times. This group was provided with a variety of gap sizes to merge into, which, it was hoped, would help determine whether participants generally preferred shorter or longer gap distances or showed no preference (i.e., drivers would accept any gap).

Equipment and Materials

The following subsections describe the equipment and materials used for this experiment.

The Driving Simulator

As with experiment 1, this experiment was conducted in the FHWA Highway Driving Simulator. For this experiment, the simulator's motion base was enabled. Typical motion for roll, pitch, and yaw fell within ± 4 degrees.

Eye-Tracking System

The same eye tracking system was used as in experiment 1. Because merges were from the left, the right-side blind spot area was included as an area of interest rather than being included as part of the road-ahead as in experiment 1.

GSR

As in experiment 1, GSR was measured with silver-chloride salt electrodes placed on the palmar-side base of two fingers on the participant's left hand. The electrodes were connected to a small sensor with a Bluetooth® transmitter strapped to the left wrist.

The Simulation Scenarios

The roadway was the same one used in experiment 1 with a few minor variations. The entrance to the center dedicated lane was accessed from the left side of the roadway from a ramp. The simulation began with the participant's vehicle as the third in the CACC platoon queue. Once the participant was ready to begin, the two vehicles in front of the participant accelerated and merged into the CACC lane and cruised at 70 mi/h. The two groups that drove with CACC engaged the system, and the participant's vehicle maintained a 1.1-s gap between it and the vehicle in front of it. The control group participants could follow at any distance they chose.

There were 18 exit ramp/entrance ramp pairs, each placed approximately 1.45 mi apart. Participants were asked to use exits 4, 8, 12, and 16. Exit ramps to the left of the main travel path that were not used by the participants were blocked by traffic barrels. This was intended to serve as a reminder to participants of which exit ramps to use.

As in experiment 1, the CACC vehicles were scaled to be 75 percent of the actual size of the model of vehicle represented so that participants could more accurately perceive following distance.

Procedure

Participants in all three experimental conditions were told the following:

> I am going to ask you to exit and reenter the freeway every fourth exit. I will give you verbal reminders to exit the freeway. There will be orange construction barrels blocking the other exit ramps. There will be other traffic on the freeway. The traffic is continuous and will not stop.

Participants were given the following additional condition-specific instructions.

The CACC with merge assist instructions were as follows:

- Set the gap to near.
- Set the speed to 70 mi/h.
- You will control steering—follow the car in front.
- The system will accelerate and brake.
    - You do not need to use your brake on the exit/entrance ramps.
    - You can take over control by pressing the accelerator or brake.
    - Pressing the brake disengages the CACC system.
    - If you need to take control, press ENGAGE as soon as possible.

The CACC without merge assist instructions were as follows:

- Set the gap to near.
- Set the speed to 70 mi/h.
- You will control steering—follow the car in front.
- The system will accelerate and brake in the CACC lane.
    - The system will turn off once you leave the CACC lane (i.e., take the exit ramp).
    - The CACC system will NOT control your speed while merging.
    - After you reenter traffic, you will need to engage the CACC system again.
    - You can take over control by pressing the accelerator or brake.
    - Pressing the brake disengages the CACC system.
    - If you need to take control, press ENGAGE as soon as possible.

The control condition instructions were as follows:

- The speed limit is 70 mi/h.
- Drive as you normally would.

The experimental scenario began with the participant seated in the third vehicle of a platoon of four vehicles. Once the participant was ready to begin, the two vehicles in front of the participant accelerated and merged into the CACC lane and cruised at 70 mi/h. The two groups that drove with CACC engaged the system, and the participant's vehicle maintained a 1.1-s gap between it and the vehicle in front of it. Participants in the control condition were asked to drive as they normally would, with no specific instructions given about following distance.

Participants were verbally reminded to exit the travel lane and then reenter traffic at the appropriate ramps. As soon as the participants successfully merged into traffic in the dedicated lanes after the first (exit number 4) and fourth (exit number 16) ramps, the NASA-TLX was administered to assess workload during the merge event (during the preceding minute or so). The NASA-TLX was also administered as soon as exit number 14 was passed. (Participants did not use this exit.) This administration was intended to assess workload during uneventful cruising in a CACC platoon (also described as during the last minute or so).

Experimental Design

The primary between-group independent variable was the level of cruise control automation used throughout the scenario.

There were the following three distinct participant groups:

- **Control:** Manually controlled longitudinal speed/gap in the dedicated travel lane. The driver manually controlled longitudinal speed/gap throughout merge.

- **CACC without merge assist:** In the dedicated travel lane, longitudinal speed and gap were controlled by CACC. During the merge, longitudinal speed and gap were manually controlled by the driver.

- **CACC with merge assist**: While in the dedicated travel lane and during the merge, the longitudinal speed and gap were controlled by CACC.

In addition to workload, there was one additional within-subjects variable, labeled period, with eight levels that were intended to distinguish the effects of CACC on driver behavior. The eight periods are described in table 3.

Table 3. Driving period descriptions.

Period	Description
1	15-s period ending 45 s prior to exit for first merge event.
2	15-s period beginning 45 s prior to completing the first merge.
3	15-s period ending 45 s prior to exit for second merge event.
4	15-s period beginning 45 s prior to completing the second merge.
5	15-s period ending 45 s prior to exit for third merge event.
6	15-s period beginning 45 s prior to completing the third merge.
7	15-s period ending 45 s prior to exit for fourth merge event.
8	15-s period beginning 55 s prior to completing the fourth merge.

Participants

Usable data were obtained from 48 participants. Participants were required to be at least 18 years of age and were screened for susceptibility to motion and simulator sickness. Table 4 shows the age group and gender counts by treatment group. The mean age of the younger participants was 33.4 years (range 19.4 to 44.5 years). The mean age of the older participants was 56.6 years (range 46.5 to 77.9 years).

Table 4. Demographic breakdown of participants in experiment 2 by treatment group.

Condition	Younger Females	Younger Males	Older Females	Older Males	Total
Control	4	4	5	4	17
CACC without merge assist	4	4	4	4	16
CACC with merge assist	4	4	3	4	15
Total	12	12	12	12	48

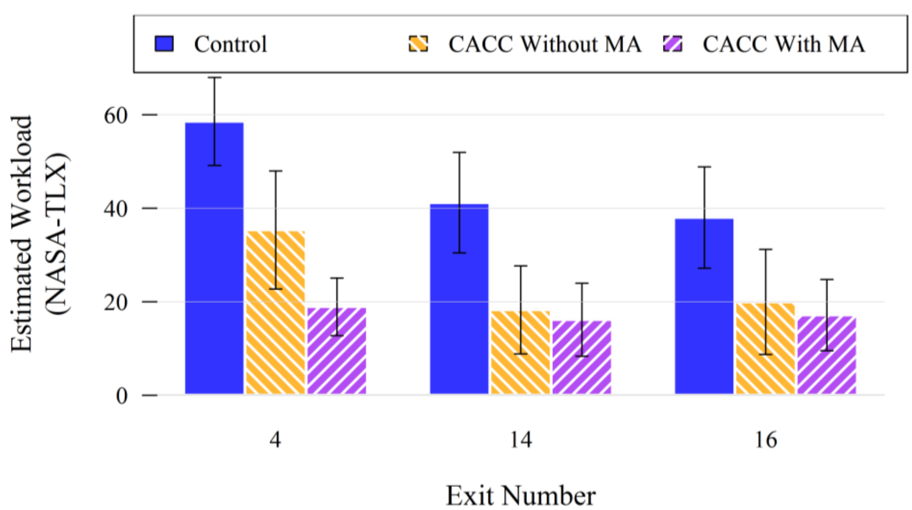
Participants were paid $80 for between 1.5 and 2 h of participation.

RESULTS

The following subsections describe the results of the experiment for workload, physiological arousal, distraction, merge behavior, steering entropy, visual behavior, and trust in the CACC system.

Workload

The NASA-TLX was administered verbally at three points during the experiment: shortly after the first merge (exit 4), roughly halfway between the third and fourth merges (exit 14), and shortly after the fourth merge (exit 16). Mean workload estimates obtained using GEEs are shown in figure 9. The location by condition interaction was significant ($p < 0.02$). The control condition had a significantly greater mean NASA-TLX score than the CACC with merge assist group and CACC without merge assist group (all $p < 0.05$). The interaction resulted because at exit 4, the CACC without merge assist group had significantly greater workload scores than the CACC with merge assist group, whereas this difference did not surface at exits 14 and 16.



Note: Error bars represent estimated 95-percent confidence limits of the means.
MA = Merge assist.

Figure 9. Graph. Estimated mean workload (NASA-TLX) by treatment group and location.

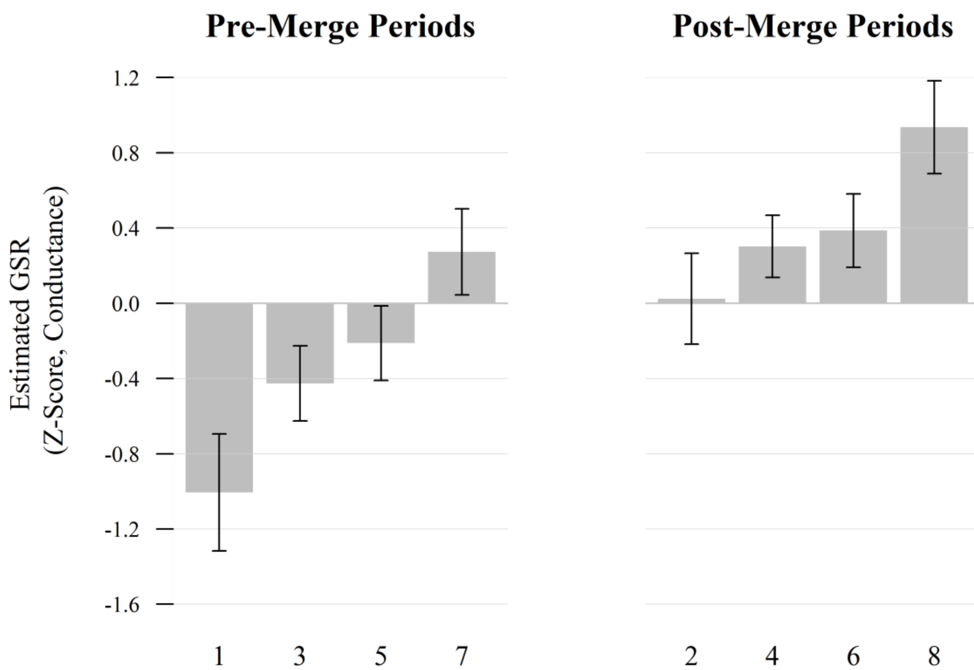
Physiological Arousal

As with experiment 1, the physiological measures of arousal were GSR, eyelid opening, and pupil diameter.

GSR

GSR is generally considered to be sensitive to sympathetic nervous system arousal, and it is more sensitive to spikes in arousal than to gradual changes in arousal for longer periods of time. If merging were indeed stressful, higher levels of GSR should be seen for the merging periods (2, 4, 6, and 8) compared with the cruising periods (1, 3, 5, and 7). Furthermore, the drivers in the control condition should also exhibit greater levels of GSR compared with those who used the CACC system as a result of the arousal-reducing effect of the automation.

Mean-standardized GSR scores were analyzed using GEEs. Resulting mean estimates with 95-percent confidence intervals for each condition and period are shown in figure 10.



Note: Error bars represent estimated 95-percent confidence limits of the means.

Figure 10. Graph. Estimated mean GSR conductance *z*-score by period.

As shown in figure 10, overall, GSR was significantly greater during post-merge periods than pre-merge periods. In other words, participants were more aroused during the post-merge periods than during the pre-merge periods.

However, participant condition did not significantly affect mean GSR values ($\chi^2(2) = 1.49$, $p > 0.05$). That is, the use of CACC did not significantly reduce arousal as assessed by GSR nor did time period interact with condition.

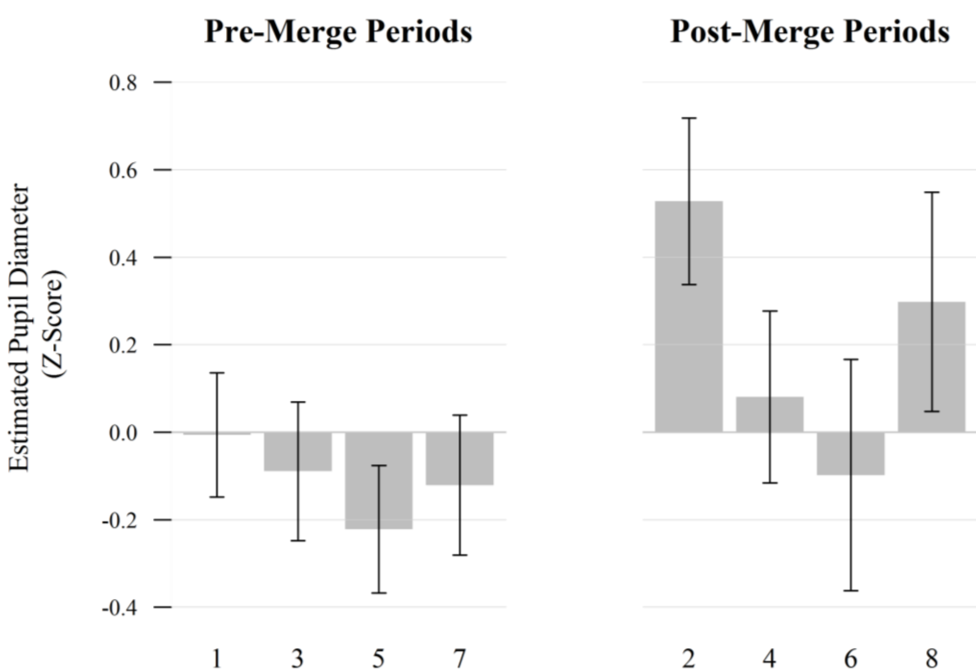
Eyelid Opening

As people become more relaxed or tired, eyelids tend to droop. If CACC reduced alertness, one might expect eyelid opening to be smaller over time. As with GSR, the raw eyelid-opening measures were converted to *z*-scores. Eyelid-opening observations that the eye-tracking software classified with a quality rating less than 75 percent were excluded. This quality rating resulted in the exclusion of 39 percent of the eyelid-opening readings.

Neither experimental condition nor time period significantly influenced eyelid opening. The interaction between time period and condition was also insignificant.

Pupil Diameter

Pupil diameter measurements for which the eye-tracking system reported less than 75 percent quality were excluded from the analysis. As with GSR and eyelid opening, each participant's pupil diameter observations across the eight 15-s periods were converted to *z*-scores. Mean estimates with 95-percent confidence intervals for each condition and period are shown in figure 11.



Note: Error bars represent estimated 95-percent confidence limits of the means.

Figure 11. Graph. Estimated mean pupil diameter (*z*-score, conductance) by period.

Time period in the drive significantly affected pupil diameter ($\chi^2(7) = 44.12$, $p < 0.001$). Mean pupil diameter was significantly greater in period 2 than all other periods except 8 ($p < 0.05$). This suggests that during the first merge of the experimental drive, participants were more alert. In addition, the mean pupil diameter was significantly greater during period 8 than all periods except 2 and 4 ($p < 0.05$).

The experimental condition did not significantly affect pupil diameter, and the interaction between time period and experimental condition was not significant.

Distraction

The NASA-TLX assessment indicated that the CACC system with merge assist reduced workload compared with the control condition. However, no differences were found in physiological arousal levels between the experimental groups. However, people can mitigate the tendency toward reduced arousal on long drives by engaging in arousal-stimulating secondary activities. In this experiment, participants were not discouraged from engaging in these activities. While care was also taken to avoid encouraging these activities, participants were told that they could listen to the car radio or do what they normally did while driving.

To explore potential engagement in other arousal-increasing tasks, nondriving activities were recorded during two segments in the drive. The first segment was the 30 s prior to the beginning of the first exit maneuver (exit 4). The following nondriving-related activities were engaged in by at least one participant:

- Listening to radio.
- Talking/singing.
- Listening to radio and talking.
- Moving hand away from steering wheel.
- Moving hand away from steering wheel and listening to radio.
- Talking and moving hands.
- Talking, moving hands, and listening to radio.
- Listening to radio, pushing buttons on radio, and moving hands away from steering wheel.
- Listening to radio and pushing buttons on radio.

Because most of the observed behaviors were rare, the sum of nondriving activities was analyzed as a function of condition and observation period. Neither experimental condition nor observation period, or their interaction, had a significant effect on the probability of engaging in nondriving activities.

Merge Behavior

Drivers’ actions during each merge were closely monitored to detect differences in driver behavior both over time and as a result of experimental condition. These behaviors included merge success and position, gap selection, and the distance used to complete the merge. The following analyses are not based on the eight previously defined driving segments but rather on the merges themselves. The beginning of each merge was defined consistently across all participants as the moment when the driver passed a specified point on the onramp (shortly after passing through the signalized intersection); merge endings were defined as the moment when half of the driver’s vehicle was laterally inside the CACC platoon in the main lane of traffic.

Merge Success

As in the real world, a successful merge was defined as one in which the driver avoided colliding with other vehicles. As shown in table 5, several participants experienced a collision in their first merge attempt. The collision rate declined with subsequent merges.

Table 5. Frequency of collisions by treatment group and merge number.

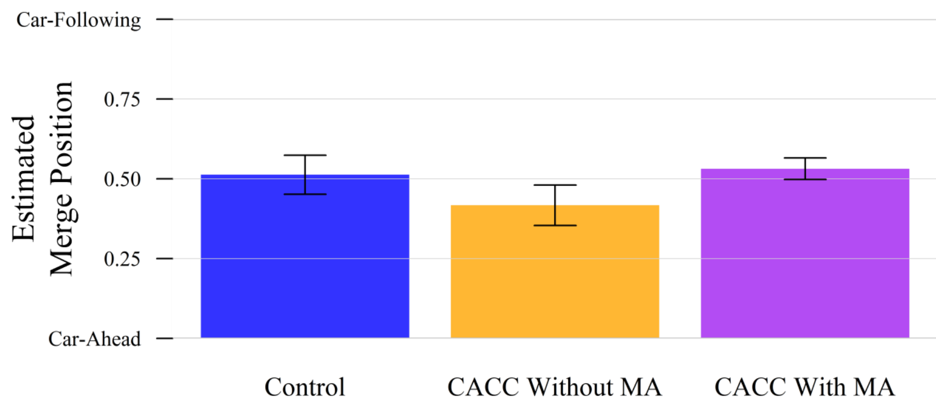
Condition	Merge 1	Merge 2	Merge 3	Merge 4
Control	9	2	2	1
CACC without merge assist	5	1	1	3
CACC with merge assist	0	0	0	0

If the drivers in the CACC with merge assist condition did not override the system or lose control of the vehicle, then it was not possible to collide with another vehicle during the merge. As a result, none of the drivers in the CACC with merge assist group collided with another vehicle, and this group was excluded from further analysis. There was no significant difference in collision rates between the control group and CACC without merge assist group. Participants were more likely to experience a crash during the first merge than in the three subsequent merges (Bonferroni correction for multiple comparisons, $p < 0.05$).

Merge Position

Merge position described the location within the gap between two vehicles in the CACC string into which participants merged. It was defined as the ratio of (1) the distance between the front bumper of the participant's vehicle and the rear bumper of the vehicle ahead and (2) the distance between the front bumper of the vehicle following the participant and the rear bumper of the vehicle ahead, minus the length of the participant vehicle. Thus, values closer to zero reflected merges closer to the vehicle ahead, a value of 0.5 reflected a perfectly centered participant vehicle, and values approaching 1.0 represented a position close to the trailing vehicle. The algorithm used to control vehicle speed for those drivers in the CACC with merge assist was designed to place participant vehicles equally distant between two vehicles, allowing a simple merge with only lateral adjustment in position.

Figure 12 shows the mean merge gap ratios by condition. On average, participants in the control condition tended to merge in a similar location in the gap to those people driving in the CACC with merge assist group. In contrast, the CACC without merge assist group entered the gap significantly closer to the vehicle in front of the participant vehicle ($p < 0.05$).



Note: Error bars represent estimated 95-percent confidence limits of the means.
MA = Merge assist.

Figure 12. Graph. Estimated mean merge position by treatment group.

Gap Selection

All drivers in the CACC conditions were presented with a continuous string of 1.1-s gaps. Drivers in the control condition were presented with a sequence of nine gaps of varying size that continuously repeated. The size and order of these control condition gaps is shown in table 6. The string into which all drivers merged was moving at a nearly constant 70 mi/h. At that speed, each 0.1-s increment in gap size is equivalent to 10.27 ft.

Table 6. Order of control condition recurring sequence of gaps.

Sequence Number	Gap (s)
1	0.7
2	1.1
3	1.5
4	0.9
5	1.4
6	1.2
7	0.8
8	1
9	1.3

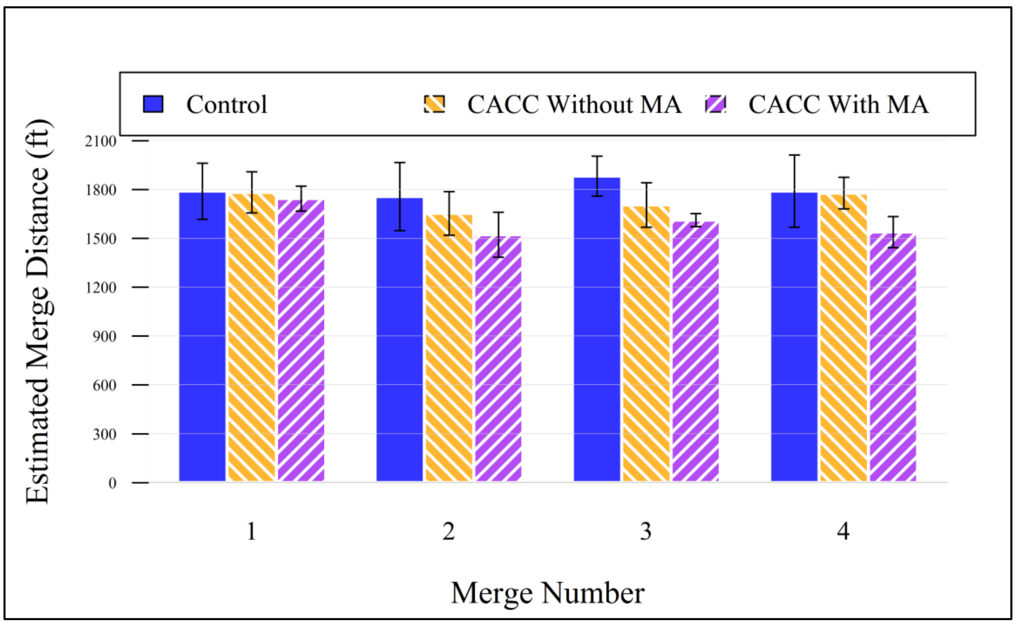
The frequency of selection of each gap by control group participants is shown in table 7. As can be seen in table 7, there was a slight tendency for participants to select gaps larger than 1 s (63 percent of the selected gaps were larger than 1 s). However, because the gap sequence was not random, and because the sequence was always triggered by the participant reaching the top of the onramp, this finding could be an artifact (i.e., in each case, the participant chose the gap that was nearest when the participant reached the merge area). As will be seen in the analysis of distance used, there was very little variation in the distance the control group traveled before completing the merges.

Table 7. Gap selection frequency.

Gap (s)	Occurrences	Cumulative Occurrences	Cumulative Percent
0.7	4	4	6
0.8	8	12	18
0.9	5	17	25
1	8	25	37
1.1	6	31	46
1.2	15	46	68
1.3	5	51	75
1.4	8	59	87
1.5	9	68	100

Distance Used

The distance required to execute a merge might reflect the ease and/or comfort with which drivers made each merge. A short distance could suggest that the driver easily found an acceptable gap, whereas a longer distance could suggest greater difficulty. Mean distances from the top of the onramp to the completion of the merge, computed by GEEs, are shown in figure 13 as a function of merge number and treatment group.



Note: Error bars represent estimated 95-percent confidence limits of the means.
MA = Merge assist.

Figure 13. Graph. Estimated mean distance used to merge by merge number and experimental condition.

Condition significantly affected the distance used to complete a merge ($p = 0.004$). On average, both the control group and without merge assist group used more distance to merge than the CACC with merge assist group. This suggests merge assist might increase onramp throughput.

There was a significant interaction between experimental condition and merge number (p = 0.008). This interaction was the result of significant differences between conditions at both the third and fourth merges. In the case of the third merge, the control group used significantly more distance to complete the merge than both the CACC with merge assist group and CACC without merge assist group. At the fourth merge, the control group and the CACC without merge assist group performed similarly, both using significantly more distance to complete the merge than the CACC with merge assist drivers.

Steering Entropy

Steering entropy is a metric that captures corrective response and has been frequently used to assess driver inattentiveness. Steering entropy was calculated for each subject within each 15-s cruising period (i.e., the periods when drivers were not expected to actively adjust steering to merge). Neither cruising period nor treatment condition yielded significant effects.

Visual Behavior

One way in which visual attention could be inferred was by examining where drivers were looking. Drivers in the CACC with merge assist group did not need to control speed to successfully merge into the main travel lane. As a result, these drivers might not have felt the need to visually track traffic as closely as the control group and CACC without merge assist groups. This possibility was explored. The proportion of glance time in the direction of the merge area (see figure 14) did not vary significantly among treatment groups.

Figure 14. Screenshot. Illustrated dynamic merge area region of interest.

Trust in the CACC System

Both the CACC with and without merge assist groups were required to accept some level of trust in the system. Participants in the CACC with merge assist group were not required to accelerate or brake at any point to successfully complete the merges. Only one participant in this group ever used manual speed controls to override the system. It is not clear, however, whether this participant did not trust the system or simply did not understand how CACC functioned. Throughout much of the drive, that participant manually controlled speed by pressing the accelerator. That participant spun out during the second merge and did not reengage the system during the fourth merge.

Among participants in the CACC without merge assist group, trust was examined only during the cruising periods because these drivers were required to manually control speed when merging. Of the 16 participants in the without merge assist group, 2 engaged the accelerator pedal during a cruise period (1 in period 1 and the other in period 7). However, in both cases, the pedal was used minimally and was possibly the result of resting the foot on the pedal. Thus, it appears that trust in the CACC system was high.

DISCUSSION

CACC with or without merge assist resulted in about a 50-percent reduction in drivers' perceived workload. The reduction in workload did not result in a measureable decrease in driver alertness, as assessed by GSR, eyelid opening, or pupil diameter. The merging activity did transiently increase driver arousal when compared with arousal in a period immediately before exiting the string. Thus, the physiological measures used in this study were sensitive to gross changes in demands on driver attention. The lack of an interaction between condition and measurement periods suggests that even with merge assist, attentional demands on drivers were greater during a merge than during uneventful car following.

The lack of a difference in the number of nondriving activities that drivers in the three treatment conditions engaged in suggests that CACC did not relieve drivers of so much workload that they felt compelled to engage in additional activities to manage their level of arousal.

Merge assist, as defined in this study, has not been widely discussed as a driving task to be automated. The elimination of crashes in the absence of indications of changes in visual scanning behavior suggests that this is an area that should be given higher priority for further development. Furthermore, the present finding that those with merge assist required significantly less distance to complete their merges suggests that traffic operations could benefit from merge assist automation.

The rarity of cases in which participants disengaged the CACC system suggests a reasonable level of trust in the system.

CHAPTER 4. THE ROLE OF AUTOMATED BRAKING AND AUDITORY ALERT IN COLLISION AVOIDANCE RESPONSE

As described in chapter 2, CACC experiment 1 included two conditions in which a crash occurred ahead of the vehicle string in which the participant was driving. The participant could not see the crash and therefore could not anticipate that the vehicles ahead would brake hard with a maximum of 1 g sustained deceleration. This crash avoidance event was experienced by the group referred to as the CACC with crash avoidance group. The other group that experienced this event did not have any type of cruise control and was provided with a multifunction display to assist in maintaining a 1.1-s gap. This other group was referred to as the control group.

Five of the 11 participants in the control group collided with the vehicle ahead. Only 1 of 12 participants in the CACC with crash avoidance group collided with the vehicle ahead. The difference in collision experience between the groups was large and statistically reliable. This finding indicates that CACC systems configured as in experiment 1 could be effective in reducing crashes precipitated by the rapid deceleration of vehicles not within the driver's field of view.

Any one of several factors may have contributed to the difference between the crash probabilities of the CACC-equipped group and the control group. The CACC with crash avoidance vehicles (and all other platoon vehicles other than the lead vehicle) began a 0.4-g deceleration 0.1 s after the platoon lead vehicle initiated a 1-g deceleration. Simultaneously with the onset of the 0.4-g deceleration, the CACC-equipped vehicles sounded an audio alarm. The control group had neither auto-braking nor an auditory alarm. The first cue for control group drivers that they needed to start braking was the looming of the vehicle ahead as it began to decelerate at 0.4 g. The brake lamps on the vehicle ahead were delayed by 1.9 s because these lights were not activated until the simulated driver ahead began to manually brake, which initiated a 1-g rate of deceleration. In addition, the control group was observed to spend more time gazing at the center-stack display, so distraction could not be ruled out as a cause of the higher probability of a crash among control group drivers.

This experiment was conducted to determine the source of the CACC crash probability reduction. This was accomplished by the following:

- Differentiating between the effects of the CACC auditory alarm and auto-braking by including three CACC groups: one with alarm only (CACC-A), one with auto-braking only (CACC-B), and one with alarm and auto-braking (CACC-AB).
- Providing the control group with ACC so that the center-stack display distraction was removed.
- Triggering the lead vehicle brake lamps with the onset of 0.4-g deceleration.

The independent variable factorial design for this experiment is depicted in table 8.

Table 8. Factorial design of experiment 3.

Auditory Alarm	0.4-g Automatic Braking: No	0.4-g Automatic Braking: Yes
No	ACC	CACC-B
Yes	CACC-A	CACC-AB

METHOD

In this experiment, the focus was entirely on the final crash avoidance event, which was described in chapter 2. Dependent measures were the following:

- Collision (yes/no) at the final crash event.
- Reaction time to the final event (onset of brake pedal depression following onset of vehicle-ahead deceleration).
- Onset of full brake depression following onset of vehicle ahead-deceleration.
- Minimum adjusted TTC.

If collision was avoided by steering out of lane rather than braking, then reaction time was defined as steering wheel torque greater than 1.125 lbf following onset of deceleration by the vehicle ahead.

Equipment and Materials

The same FHWA driving simulator was used for this experiment as was used for the experiments described in chapters 2 and 3. However, the visual projection system was updated for this experiment. Three projectors were used to provide a 200-degree (horizontal) by 40-degree (vertical) field of view. Each projector provided a nominal resolution of 4,096 by 2,400 pixels. The updated projection system provided a substantial increase in resolution, brightness, and contrast but a slightly narrower horizontal field of view (200 degrees rather than 240 degrees).

The Driving Simulator Scenario

The simulator scenario was nearly the same as that described in chapter 1 for the two groups that experienced the crash avoidance event. The only change was that the crash avoidance event occurred after 20 min of driving rather than 38 min.

Participants

The study had 112 participants, 28 in each of four groups: control (ACC), CACC with auditory alarm and 0.4-g braking (CACC-AB), CACC with auditory alarm but no braking (CACC-A), and CACC with 0.4-g braking but no alarm (CACC-B). Individuals who participated in the CACC experiment 1 were excluded from participation in experiment 3. To roughly balance the groups on participant age, half the recruits in each experimental group were under the age of 47. Each condition and age grouping consisted of equal numbers of males and females.

RESULTS

The following subsections describe the results of the experiment for crashes, reaction time, and adjusted TTC.

Crashes

Table 9 shows the number of crashes and crashes avoided by each group. Also shown in the table are maximum likelihood estimates of crash probability and the 95-percent confidence limit for those estimates. The probability of a crash was lower with the full CACC system (CACC-AB) compared with the other groups, which did not differ from each other in crash probability. The effect of condition was significant ($\chi^2(3) = 10.6$, $p = 0.01$). Post hoc testing showed that only the CACC-AB group significantly differed from the ACC group ($p = 0.003$).

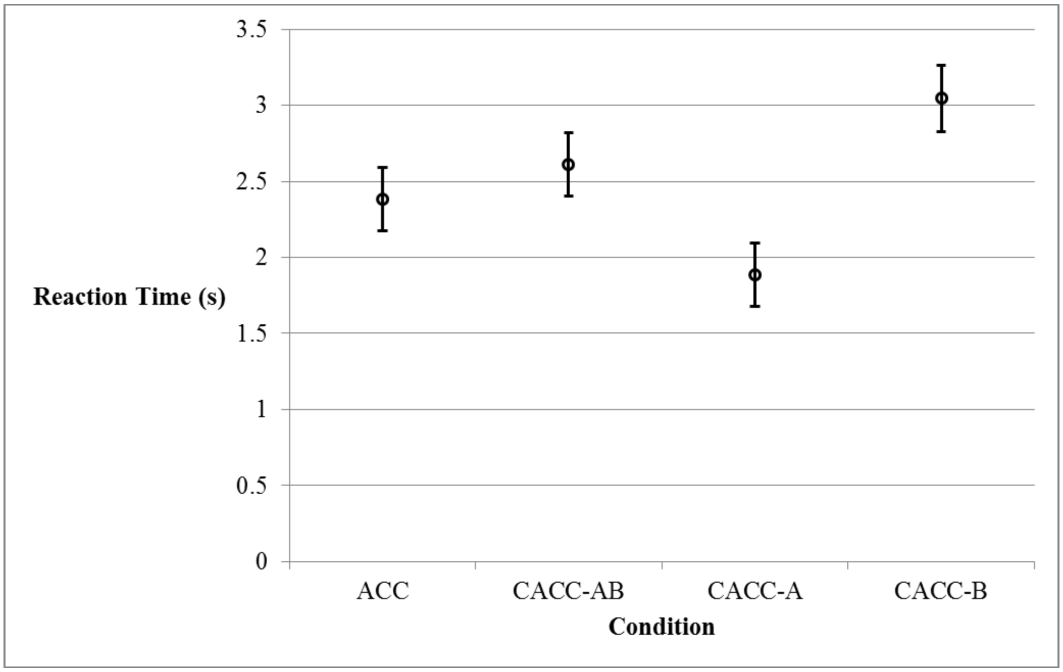
Table 9. Crash results by experimental group.

Condition	Avoided Crash	Crashed	Crash Probability	Lower 95-Percent Confidence Limit	Upper 95-Percent Confidence Limit
ACC	13	15	0.54	0.35	0.71
CACC-AB	24	4	0.14	0.05	0.32
CACC-A	13	15	0.54	0.35	0.71
CACC-B	14	14	0.50	0.32	0.68
Total	64	48	0.43	nc	nc

nc = not computed.

Reaction Time

The reaction times to the onset of the crash event are shown in figure 15. Three participants in the CACC-B group never reacted and therefore were not included in the reaction time analysis. The condition effect was significant ($p < 0.0001$). Post hoc testing showed that the ACC group's mean reaction time did not differ significantly from the CACC-AB group mean but that all the other group mean comparisons yielded significant differences.

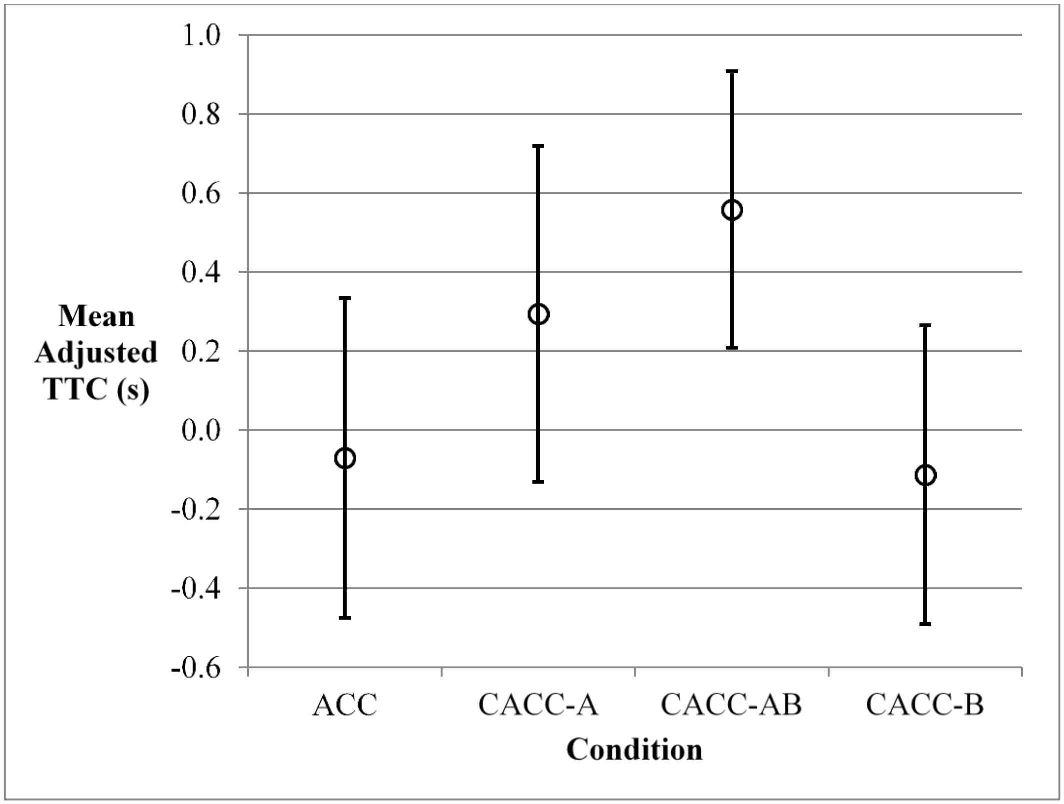


Note: Error bars represent estimated 95-percent confidence limits of the means.

Figure 15. Graph. Reaction time from onset of braking by platoon-lead vehicle.

Adjusted TTC

The TTC findings are displayed in figure 16. The findings are based on a sample size of 92 participants. The remaining 20 participants had uninterpretable adjusted TTC estimates. Three of those 20 had no reaction and never applied the brakes. The remaining 17 participants had uninterpretable adjusted TTC values because they were decelerating at a rate less than that of the lead vehicle (also decelerating) at the time of impact, thereby generating adjusted minimum TTC values of negative infinity. None of the participants with full CACC capabilities (i.e., CACC-AB) had to be excluded from this analysis, and only one participant in the CACC-B group had to be excluded. The participants who failed to brake at all or were decelerating less at the time of collision than the preceding vehicle were evenly distributed between the ACC and CACC-A groups.



Note: Error bars represent estimated 95-percent confidence limits of the means.

Figure 16. Graph. TTC results.

The effect of condition was significant ($p = 0.04$). As can be seen in figure 16, the CACC-AB group had a substantial positive adjusted TTC (i.e., on average, members of this group have almost 0.6 s extra time to respond to the collision event). The ACC and CACC-B groups had significantly lower mean adjusted TTC values than the CACC-AB group. The CACC-A group mean was not significantly different from any of the other three group means.

DISCUSSION

Experiment 3 reinforces the main conclusion of experiment 1; a full CACC system (i.e., as configured for the CACC-AB group) has the potential to provide a substantial safety benefit. The control condition in experiment 3 did not have an in-vehicle display or the requirement to frequently monitor the speedometer—two potential explanations for the high crash rate of the experiment 1 control condition. Nonetheless, the crash rate for the ACC condition in experiment 3 was nearly identical to that in experiment 1. This suggests that it was CACC automatic braking and alarm that provided the apparent safety benefit in both experiments. Removing either the alarm or the automatic braking from the CACC system diminished or eliminated the safety benefit of the full system.

It is not clear from these results why the absence of an auditory alarm (ACC and CACC-B) condition resulted in an increased crash risk. The CACC-B group had the longest reaction times and had the three incidences of no response. The ACC group also had no alarm, yet it reacted as quickly as the group with full CACC. Perhaps this is an example of over trust in the system. The

CACC-B braking force was twice that of the ACC braking (0.4 g versus 0.2 g), so it is conceivable that the CACC-B group felt the system responding and trusted the automated response until it was too late to recover. The mild braking in the ACC condition may have been easier to perceive as inadequate compared with the more aggressive braking in the CACC-B condition.

The CACC-A group, which received an auditory alarm but had no automated braking, responded more quickly than any group but still had a high crash rate. The extra time provided by the 0.4-g automated braking to the CACC-AB group appears to have been the key to enabling that group to respond more slowly while retaining an average of a 0.6-s cushion in extra time available.

The alarm mitigated the apparent over trust of the system, and the automated braking feature provided drivers with the extra time they needed to respond. Whether the combination of alarm and automated braking would be effective with other CACC implementations, such as with shorter gaps between vehicles or more aggressive automated deceleration, remains to be explored.

CHAPTER 5. PREFERRED FOLLOWING DISTANCE AND PERFORMANCE IN AN EMERGENCY EVENT

This experiment examined driver performance as a function of set speed, assigned gap-setting, and preferred following distance.

At 65 mi/h, a 1-s gap would leave approximately 95 ft between vehicles. Previous studies have shown that drivers felt both comfortable and safe traveling with gaps shorter than 1 s. For example, in an on-road study testing drivers' choices in following distances, drivers regularly used gap settings shorter than 1 s; when following another vehicle, drivers elected to set the gap at 0.7 s or 0.6 s 80 percent of the time.(16) However, with a 0.6-s gap, there is approximately 57 ft between vehicles. If an average vehicle length was assumed to be about 17 ft, this would leave less than 20 ft of buffer in the front and rear for a merging vehicle. As a result, at these shorter distances, drivers might not feel comfortable merging or having a vehicle merge in front of them. Furthermore, gap-based discomfort might vary from person to person.

It is possible that individual differences in preferred following time gap might be related to perceived driver workload or driver capabilities to react in events that require the driver to override the CACC system and resume manual control.

This experiment was conducted in two parts. The goal of the first part was to estimate the median preferred following distance of drivers in the participant pool. This estimate was then used in the second part to assign new participants to groups based on their preference for far (i.e., longer than the median preferred following distance) or near (i.e., shorter than the median preferred following distance) car following distance.

The second part was a near replication of CACC with the crash event condition described in chapter 2. The differences between the CACC with crash event scenario described in that chapter were the following:

- Two gap setting groups, 1.1 s (far) and 0.6 s (near).
- No warning tone at the beginning of the crash event.
- Use of a different (fixed base) simulator.
- Illumination of the brake lamps of the vehicle ahead with the onset of the 0.4-g deceleration.

The goals of the second part were the following:

- Assess workload under two different CACC set gaps.
- Observe drivers' reactions to a vehicle merging in front of them.
- Measure drivers' reactions to an emergency event that required driver intervention to avoid collision.

- Assess whether drivers' preferred following distances affected the three previous goals.

PART 1 EXPERIMENT

The following subsections describe the method, equipment, scenario, participants, and procedure for the part 1 experiment.

Method

This section describes the equipment, simulation scenario, participants, and procedures for part 1 of the experiment.

Equipment

A National Advanced Driving Simulator (NADS) ¼ cab MiniSim™ was used. Three 42-inch 720-pixel plasma screens displayed the forward roadway, side, and rearview mirrors. An additional 12-inch widescreen displayed dashboard information. The simulator was fix based and used a subwoofer beneath the driver's seat to generate road feel. As in the preceding experiments (see chapter 2), the simulated vehicles were scaled to 75 percent of the original scale. Several pilot subjects were used to verify that the down-scaling of the lead vehicles was appropriate for this simulator.

The Simulation Scenario

As in the previous experiments, participants drove in a dedicated center lane on a simulated eight-lane interstate highway. Entrance to the dedicated lane was accessed from a left-side ramp. The dedicated lane was separated from other lanes with a jersey barrier. The environment was similar to suburban-rural interstate driving with a mix of trees and buildings along the roadway.

The simulation began with the participant vehicle as the only vehicle on the roadway. During this time period, participants practiced steering and braking to accustom themselves to the feel of the simulated vehicle. After a few minutes, participants came upon another vehicle. That vehicle acted as a lead vehicle and drove at 55, 65, 70, and 55 mi/h for 3 min each.

Participants

Participants were 14 licensed drivers recruited from the Washington, DC, metropolitan area. Participants were required to be at least 18 years of age and were screened for susceptibility to motion and simulator sickness. Half of the participants were male. Age ranged from 22 years to 72 years with a mean age of 46.7 years (median 50.5 years).

Procedure

All participants completed two drives. The goal of the first drive was to assess the participants' comfortable driving distance. Specifically, participants were asked to "...drive at what you consider a comfortable distance. In other words, follow that vehicle at a distance that you would normally follow another car in the real world." Participants were reminded that the lead vehicle would change speed several times and that speed would need to be adjusted to maintain an appropriate following distance. The lead vehicle drove at 55, 65, 70, and 55 mi/h for 3 min each. The first drive lasted between 14 and 17 min.

On completion of the first drive, participants completed a simulator sickness questionnaire.

The goal of the second drive was to assess drivers' perceived minimum safe following distance. This drive was identical to the first except for the instructions. Participants were told the following:

> …instead of following at a comfortable distance, I want you to drive more closely. I'd like you to follow that vehicle at the minimum distance that you might ever follow another car on the roadway. For example, imagine that you are on a busy road and are trying to change lanes. Or even if you were simply in a hurry to get somewhere.

Participants were given an opportunity to ask questions to ensure that the task was fully understood.

PART 2 EXPERIMENT

Each participant in part 2 performed three drives. The first drive was used to determine whether the participant preferred a near or far gap. Driver participants were given the same minimum safe gap choice instructions that were used in part 1. Based on this first drive, participants were assigned to one of two groups. They were assigned to the near preferred gap group if they drove with a minimally safe gap less than 0.9 s in their first drive. Participants who drove with minimally safe gaps greater than 0.9 s in their first drive were assigned to the far preference group.

The second drive was same as the first, but with the comfortable gap instruction to "...drive at what you consider a comfortable distance. In other words, follow that vehicle at a distance that you would normally follow another car in the real world." The second drive was considered practice, and the data from that drive were not used in determining gap preference.

For their third drive, half of those who preferred a near gap in the first drive were assigned to drive with a near (0.6-s) gap, and half to drive with a far (1.1 s) gap. Likewise, half of the participants who preferred a far gap in the first drive were assigned to drive with a near gap and half to drive with a far gap.

Method

This section describes the equipment, participants, and procedure used in part 2.

Equipment

The same MiniSim™ simulator was used for part 2 as was used for part 1.

The Simulation Scenarios

The same simulated eight-lane interstate highway was used in both parts 1 and 2. Participants in part 2 drove the same drives as the participants in part 1. In addition to these two drives, participants completed a third drive. The third scenario used the same roadway as the first two drives.

Participants

Participants were 99 licensed drivers from the Washington, DC, metropolitan area. Of these, 57 were classified as preferring a near gap and 36 as preferring a far gap. Each gap preference group had approximately the same number of males and females and approximately equal numbers of participants over and under 45 years of age. Approximately half of the participants in each preference, gender, and age classification were assigned to the near gap setting and half to the far gap setting.

Procedure

Throughout the first two drives, the procedures were the same as for part 1. After the second drive, participants were briefed on the NASA-TLX and the CACC concept. Participants then moved back to the simulator where they were shown how to use the multifunction display to engage CACC, adjust the set speed, and set the gap distance. The multifunction display was the same as that used in CACC experiments 1, 2, and 3 described in chapters 2, 3, and 4 of this report, respectively. Participants then completed the third drive with the far or near gap setting that they had been assigned.

The third drive was modeled after the drive in experiment 3. The drive began with the participant stopped on an onramp in the third position of a four-car string. When the ramp meter turned green, the string proceeded down the ramp and accelerated to 70 mi/h while maintaining the appropriate gap (0.6 or 1.1 s). Approximately 5 min into the drive, another CACC vehicle merged in front of the participant halfway (30.6 ft or 56 ft) between the participant's vehicle and the vehicle the participant had been following. The CACC system then adjusted the speeds of the affected vehicles to restore the assigned gap. If a participant braked in this situation, the CACC system disengaged and then needed to be reengaged.

Approximately 20 min into the drive, a vehicle sped down an onramp, merged in front of the platoon, and crashed. The crash was not in the participant's line of sight. The crash avoidance event began when the lead vehicle in the string decelerated at 32 ft/s^2 in response to the crash. One-tenth of a second after the lead vehicle began braking, all of the CACC vehicles behind it simultaneously began to decelerate at 0.4 g (12.8 ft/s^2) and activated their brake lights. The simulator's engine noise was configured to exaggerate the change due to the 0.4-g deceleration.

RESULTS

The following subsections describe the results of part 1 of the experiment.

Part 1 Experiment

The goal of part 1 was to estimate the median for perceived minimum safe following distance. This information was used to determine whether participants in part 2 would be labeled as far or near followers.

To provide participants with sufficient time to adjust following gap for each speed change (55, 65, 70, and 55 mi/h), the first 30 s of vehicle following at each speed were excluded from analysis.

Table 10 presents drivers' following time gap distributions by speed averaged across 13 participants during the near following distance drive.

Table 10. Part 1 participant following time gaps by speed during near following drive.

Speed of the Vehicle Ahead (mi/h)	Following Time Gap (s)					
	Minimum	25th Percentile	Median	75th Percentile	Maximum	Mean
55	0.55	0.65	0.92	1.02	1.43	0.89
65	0.41	0.60	0.86	1.10	1.51	0.88
70	0.38	0.64	0.90	1.28	1.70	0.94
55	0.52	0.69	1.03	1.23	1.88	1.04
Mean	**0.38**	**0.64**	**0.91**	**1.15**	**1.88**	**0.94**

The mean median following distance time gap 0.91 s was used to assign participants in part 2 to far- and near-follower groups.

Part 2 Experiment

Participants in part 2 completed the same two drives as participants in part 1. The data from the first comfortable following task were not used to determine following distance preference. To provide participants with sufficient time to adjust following gap for each speed change, the first 30 s of vehicle following at each speed were excluded from analysis.

Data from the second drive were used to assign drivers to far and near following groups, with drivers with a mean following distance less than 0.9 s assigned to the near group. Table 11 presents the gap distribution as a function of speed under the near following distance instruction.

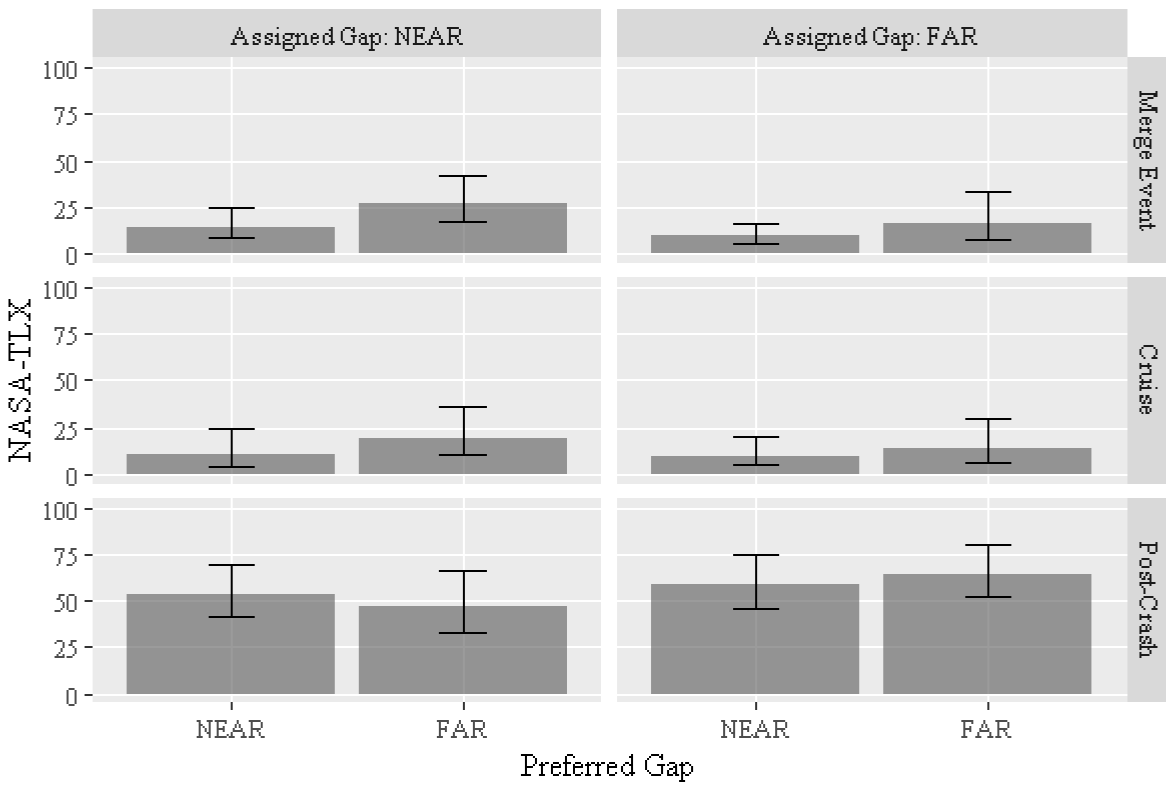
Table 11. Part 2 participant following time gaps by speed during near following drive.

Speed of Vehicle Ahead (mi/h)	Following Time Gap (s)					
	Minimum	25th Percentile	Median	75th Percentile	Maximum	Mean
55	0.30	0.64	0.79	1.12	3.96	0.99
65	0.27	0.59	0.80	1.18	5.25	1.06
70	0.28	0.58	0.82	1.20	6.93	1.08
55	0.35	0.61	0.90	1.27	14.61	1.29
Mean	**0.30**	**0.60**	**0.83**	**1.19**	**7.69**	**1.10**

Workload

The NASA-TLX was administered verbally at three points during the third drive—shortly after the first merge, during a cruise period, and after the final crash event. The effects of preferred following distance and CACC set gap on workload were tested using a GEE with NASA-TLX measurement location as a repeated measure.

Figure 17 shows that as a result of workload being rated substantially higher following the crash avoidance event, perceived workload varied significantly with measurement location ($\chi^2(2) = 129.81$, $p < 0.001$). In addition, there was a significant three-way interaction ($\chi^2(6) = 27.36$, $p < 0.001$) that apparently resulted, because in their post-crash ratings, drivers assigned to the near gap reversed the otherwise consistent trend for drivers who preferred a near gap to rate workload lower than those who preferred a far gap.



Note: Error bars represent estimated 95-percent confidence limits of the means.

Figure 17. Graph. NASA-TLX rating as a function of measurement location, preferred gap, and gap setting.

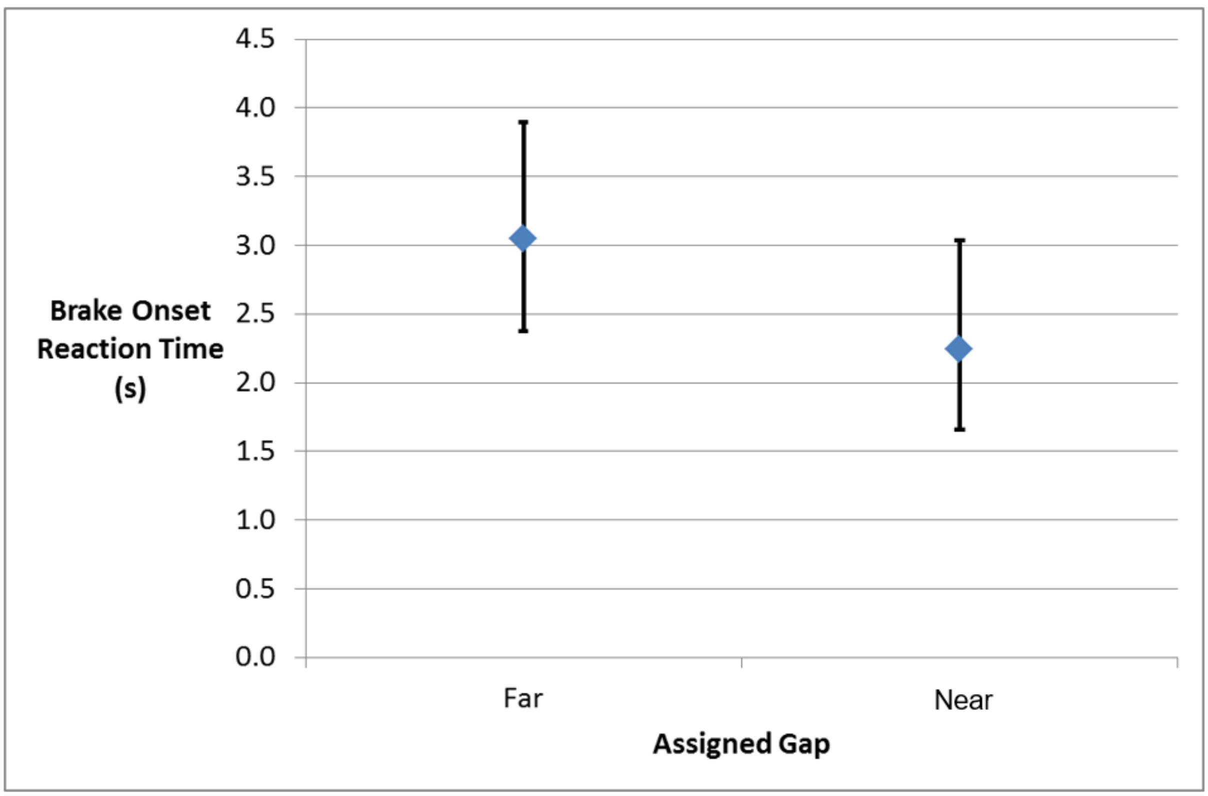
Response to Vehicle Merging

The CACC system was programmed such that it was not necessary to override by manually braking during the merge event that occurred 5 min into the drive. However, the high speed and short distance between the participant and merging vehicles, especially in the near following case, provided a measure of driver trust or comfort. Only 3 of 99 participants depressed the brake pedal during or after the vehicle merge.

Another indication of trust, or caution, was whether participants hovered their foot above the brake during the merge event. Participants in the near following distance condition were significantly more likely to hover over the brake pedal than those at the far distance ($\chi^2(1) = 5.27$, $p = 0.022$). Neither preferred following distance nor its interaction with other variables was statistically significant. The data suggest that following distance preference did not affect trust or caution during the cut-in merge.

Crash Event Reaction Time

Participant reaction time was calculated as the time between when the lead vehicle in the string began decelerating and when the participant initiated brake pedal depression. The results shown in figure 18 are based on data from 73 participants. Data files for six participants were corrupt and could not be read. A simulator failure caused loss of data for one participant. Three participants did not brake at all in response to the crash, and 11 participants were not included in the analysis because they were deemed outliers in that they did not initiate braking within 7.1 s, which represented more than 1.5 times the interquartile range (a standard definition of an outlier).[17] Participants who drove with the near gap-setting depressed the brake pedal significantly sooner than the participants who drove with the far gap-setting ($\chi^2(1) = 4.28$, $p < 0.04$). No difference in reaction time based on preferred following distance was found, nor was the interaction between preferred and assigned following distance significant.



Note: Error bars represent estimated 95-percent confidence limits of the means.

Figure 18. Graph. Brake onset reaction time as a function of preferred and assigned gap.

Crashes

Participants with the near gap setting had a crash probability of 0.82, whereas those with the far gap setting had a crash probability of 0.61. The difference in probabilities was statistically significant ($\chi^2(1) = 4.32$, $p = 0.038$). No other significant effects were found.

Discussion

As in experiment 1, reported in chapter 2, workload was rated higher after the crash event than before, where workload was rated fairly low. Interestingly, preferred and assigned following distance did not affect perceived workload during uneventful driving. Although failures to reject the null hypothesis (i.e., no difference in workload between near and far preference groups) must be viewed with caution, it appears from these results that using a cruise control gap setting less than the preferred following distance does not appreciably affect workload.

Reaction times to the crash event were shorter with the 0.6-s (near) gap than with the 1.1-s (far) gap. This finding should be expected because drivers have more time to react with the longer gap setting. The finding is consistent with cruise control being a convenience feature (i.e., that drivers delay braking to avoid relinquishing that convenience). Also, because there was no warning tone when the 1-g lead car deceleration began, drivers with the longer gap had no immediate reason to perceive a need to quickly intervene.

The reaction time difference between the CACC-B group (which also did not receive an audible alarm) in chapter 4 and the far gap group in this experiment were nearly identical at just over 3 s. This suggests that for car following experiments the higher fidelity moving-base simulator and the lower fidelity fixed-base simulator yield similar results. Based on the results presented in chapters 2 and 4, it is likely that an auditory alarm in this experiment would have reduced the crash rate when the following distance was 0.6 s; however, the extent of that reduction cannot be estimated with the data at hand.

CHAPTER 6. CONCLUSIONS

The results of experiment 1 (see chapter 2) and experiment 3 (see chapter 4) suggest that CACC could provide a substantial safety benefit as long as a salient alarm is triggered when the driver needs to intervene. Such an alarm is advisable even if CACC is implemented with full braking authority because the driver might want to steer rather than brake in some crash imminent circumstances.

Experiment 2 results (see chapter 3) strongly suggest that CACC should be accompanied with merge or steering assist to allow drivers to comfortably and safely merge into the smaller gaps between vehicles. Although most drivers in experiment 3 eventually learned how to adjust their speed to merge into smaller gaps, the learning curve included more collisions than would be desirable.

Experiment 4 results (see chapter 5) suggest that drivers' preferences for following distance (gap) do not affect driver performance relative to an automated gap. Drivers adjust their performance appropriately for the actual gap, and designers do not need to be concerned about individual gap preferences, at least as it relates to driving performance.

Experiments 1, 3, and 4 assessed driver workload with and without CACC. In all three experiments, CACC was perceived to reduce driver workload.

The research summarized in this report suggests that CACC can reduce driver workload while enhancing safety. However, CACC is only one of many vehicle automation technologies in development or early deployment. The role of the driver will be in flux for years to come as putative safety and convenience automation technologies proliferate. Human factors research will need to focus on the ever-changing role of the driver and the resulting effects on the performance of these driver-vehicle systems.

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