Cooperative Adaptive Cruise Control Human Factors Study: Experiment 1—Workload, Distraction, Arousal, and Trust

PUBLICATION NO. FHWA-HRT-16-056 DECEMBER 2016

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
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FOREWORD

This report presents human factors experimental results from an examination of the effects of cooperative adaptive cruise control (CACC) on driver performance in a variety of situations. The experiment was conducted in a driving simulator using a scenario in which the subject driver was embedded in a platoon of CACC-equipped vehicles. CACC is envisioned as an automated vehicle application that complements the capabilities of the vehicle operator without degrading the vehicle operator's alertness and attention.

The CACC system was effective in helping drivers avoid collisions when the vehicle at the head of the platoon decelerated with maximum force. No differences in driver alertness or arousal levels were found when comparing CACC with manual gap control. Drivers reported significantly less workload with CACC.

This report informs the discussion among transportation professionals about how automated vehicle applications will be embraced by everyday drivers. The experiment results should be useful to researchers and transportation professionals interested in the effects of automation on driver behavior.

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Research and Development

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA-HRT-16-056	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Cooperative Adaptive Cruise Control Human Factors Study: Experiment 1—Workload, Distraction, Arousal, and Trust		5. Report Date December 2016 6. Performing Organization Code:
7. Author(s) Vaughan W. Inman, Steven Jackson, and Brian H. Philips		8. Performing Organization Report No.
9. Performing Organization Name and Address Leidos, Inc. 6300 Georgetown Pike McLean, VA 22101-2296		10. Work Unit No. 11. Contract or Grant No. DTFH61-13-D-00024
12. Sponsoring Agency Name and Address Office of Safety Research and Development Federal Highway Administration 6300 Georgetown Pike McLean, VA 22101-2296		13. Type of Report and Period Covered Final Report, 10/1/2013–12/1/2015 14. Sponsoring Agency Code HRTM-30

15. Supplementary Notes
The Contraction Officer's Representative was David Yang, and the Government's Task Manager was Brian Philips.

16. Abstract

This study set out to examine the following diverse questions regarding cooperative adaptive cruise control (CACC) use:

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

These questions were addressed in an experiment conducted in the Federal Highway Administration Highway Driving Simulator. A total of 49 licensed drivers were tested, with 12 or 13 participants in each of 4 groups. All of the groups drove in the third position in a five-vehicle platoon in which all of the other vehicles were equipped with simulated CACC. The groups differed as to whether the participant vehicle was equipped with CACC and the type of event at the end of the drive that disturbed the longitudinal spacing of the platoon.

As assessed by the National Aeronautics and Space Administration Task Load Index, the CACC system did reduce perceived driver workload relative to driving without cruise control. CACC users appeared slightly more likely to engage in diversionary activities (e.g., listening to the car radio) than control group drivers. CACC yielded a substantial and statistically reliable reduction in the probability of a crash. No evidence was obtained to suggest that use of CACC leads to lower levels of driver arousal than manual gap control. Participants showed a great deal of trust in the CACC system. In a situation where all of the control participants used the brake to maintain a comfortable gap, only 2 of 36 CACC users overrode the system with the brake or accelerator.

17. Key Words Cooperative adaptive cruise control, CACC, human factors, driving simulation, attention, distraction	18. Distribution Statement No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161. http://www.ntis.gov

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	42	N/A

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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 ABBREVIATIONS

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

CHAPTER 1. INTRODUCTION

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 and speed and location of other CACC vehicles, including vehicles that the driver cannot see.[1]

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 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. Smaller gaps should subsequently increase the roadway capacity without increasing the amount of roadway.

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 the human factors research of which this study is a part is to investigate the effects of CACC on driver workload, situational awareness, and distraction. The goal is not to address all human factors issues associated with CACC platooning but rather to serve as an initial experiment that may suggest additional lines research that may be required to model the influence of human drivers on overall CACC performance.

Current cruise control systems, both conventional and ACC, are marketed as convenience systems that reduce driver workload and stress by relieving the driver of the need to continuously regulate vehicle speed and following distance.[2,3] 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).[4] When these newer capabilities are combined with DSRC to comprise a CACC system, several driver adaptations are possible.

By reducing the drivers' workload or stress, their physiological arousal levels may be reduced. The desired effect of stress reduction would be to optimize the drivers' performances and feelings of well being. However, the Yerkes-Dodson law suggests that for tasks of moderate difficulty, low and high levels of arousal will lead to lower levels of performance than some moderate levels of arousal.[5] In accordance with this law, a less favorable CACC outcome might be to reduce driver arousal below the optimum level and may result in poorer driver performance. Driver performance remains important in semi-autonomous systems such as CACC. 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. One method of evaluating the effects of CACC on drivers would be to monitor changes in physiologic arousal level and to observe the relationship between those changes and driver performance. Of concern would be a finding that CACC reduces driver workload thereby resulting in low levels of physiological arousal that in turn result in reductions is measures of driver performance. Performance in this experiment was assessed in terms of drivers' ability to avoid a collision.

It is not a given that the workload relief provided by a CACC system would result in a lower level of physiological arousal or that workload relief would have the same effect on all drivers. The task difficulty homeostasis model would predict that if the CACC system caused an undesirable lowering arousal, drivers might engage in behaviors that would increase arousal back to a desirable level.(6) In his task difficulty homeostasis model, Fuller suggests that drivers will manage speed to regulate task difficulty.(6) However, the system controls speed in a CACC platoon, which forces drivers to find another way to regulate task difficulty. Several researchers have observed that the alternative of choice is to engage in secondary (non-driving) tasks.(7–9)

Jamson et al. conducted a driving simulator study in which participants drove in manual and fully automated mode on a simulated motorway (the equivalent of a six-lane freeway in the United States).(7) Conditions with light and heavy traffic were simulated (600 and 1,800 vehicles/lane/h, respectively). The fully automated mode consisted of ACC plus lane control, and participants were free to engage and disengage it. The findings showed that, on average, drivers were willing to drive at lower speeds with fewer lane changes in the fully automated mode.(7) With light traffic, drivers in fully automated mode engaged in more secondary tasks and had less gaze time to the forward roadway than drivers in manual mode or drivers in fully automated mode and heavy traffic. Consistent with Fuller's task difficulty hypothesis, drivers in fully automated mode and light traffic had lower heart rates and more eye-closure time than drivers in the other conditions.(6)

Llaneras et al. reported on a test-track experiment with a vehicle equipped with both ACC and lane keeping.(8) When both ACC and lane keeping were active, drivers engaged in many more secondary tasks than when driving with ACC alone. Glances away from the forward roadway with the combined lane keeping and ACC systems were also reported to be more frequent and slightly longer than with ACC alone.

If increasing levels of automotive automation lead to a greater willingness to engage in secondary tasks and glances away from the roadway, it can be hypothesized that drivers' awareness of their environment (i.e., situational awareness) would decline.

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 a driver's state of knowledge of his or her vehicle and the environment in which it is operating. Endsley breaks 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 means concerning future system states.(10,11) Intuitively, the situational awareness construct makes sense for examining the how the driver and CACC system will 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 is in a platoon of CACC vehicles and relying on the system to maintain a safe gap to the vehicle ahead. In that situation, will the driver be aware of whether the CACC system is functioning correctly and whether the system is capable of correcting a rapidly closing gap? If the driver fails to notice a closing gap that the system is not capable of correcting, then it could be said that the driver lacked situational awareness.

Although the situational awareness construct makes intuitive sense, it is 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 phenomenon. As described by Endsley, situation awareness relies on long-term memory, automaticity, and various information processing mechanisms (e.g., working memory), as well as the driver's goals and objectives, expectations, experiences, and abilities.(10) Furthermore, the system, interface design, driver stress, driver workload, and system automation will affect situation awareness, driver decision-making, and driver performance.(10) This definition of situation awareness makes its measurement problematic unless all of the underlying components can be controlled, manipulated, or measured.

Chapter 2 describes an experiment conducted in a driving simulator in which the effects of simulated CACC on workload, physiological arousal, distraction, crash avoidance, and trust in the CACC system were assessed. Situational awareness was not assessed in this experiment. Use of a driving simulator imposes limitations on the conclusions that can be reached regarding drivers' responses to the use or non-use of CACC. The two major concerns are (1) differences between a simulated driving environment and a real one and (2) that in a single simulated driving session, regardless of length, long-term driver adaptations (i.e., adaptations that might take place over days, weeks, or years) cannot be assessed. Precautions to partially mitigate the former concern are described in chapter 2. It is unlikely that there is any practical way to assess long-term adaptions in a driving simulator, and that concern will need to be addressed with observation of long-term use in the real world.

CHAPTER 2. METHOD

This chapter provides an overview of the approach to assessing workload, arousal, distraction, and crash avoidance as well as extensive details on the experimental design and procedures.

APPROACH

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, while the fourth group manually controlled their following distance within a platoon in which all 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] This subjective workload measure is typically administered through a series of two paper-and-pencil ratings after a task (e.g., a flight or drive) is completed. For this method, participants rate mental demand, physical demand, temporal demand, effort, and frustration by placing a mark on a rule where one end of the rule is labeled "low" and the other "high." Similarly, respondents rate their performance by marking on a rule where one end is labeled "good" and the other "poor." After providing these ratings on each of these workload factors, respondents are asked to consider all possible pairings of the six factors and indicate which member of the pair was the most important contributor to their workload. Because the present interest was to examine workload during different phases of a single drive, the typical paper-and-pencil method for administering the NASA-TLX would have been unwieldy. It would have required either stopping the drive while the participant completed the forms or relying on participants' recall of each phase after the drive was completed. To get a more immediate workload rating while allowing the participants to continue the drive, the NASA-TLX was verbally administered. Although the verbal administration technique has not been formally validated, participants seemed to accept the method, and, as is discussed in chapter 3, the results appear to be interpretable.

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 assessment 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 assessment was intended to determine the workload imposed by a vehicle halving the following distance between the participant and the vehicle ahead. The third assessment occurred 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. These events are described in detail in the following subsections. The first assessment (i.e., the practice assessment) was not analyzed; however, the second and third 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. The final workload assessment was intended to assess the workload associated with the various events. Although participants continued to drive while workload was assessed, none of the other performance measures reported were collected during workload assessment.

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: (1) before the first merge event, (2) after the start of the first merge event and before the NASA-TLX assessment, (3) 15 min into the drive and before the NASA-TLX administration, (4) just before the final event, and (5) during the final events. Thus, these measures were intended to assess changes in arousal as a result of the initial merge event, after 10 min of uneventful driving, and as a result of the final events.

Distraction

Automation is generally believed 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 feels free to engage in more non-driving tasks that might subsequently result in less attention to the driving task. The shift in attention away from the driving task might be termed "distraction." However, distraction is a psychological construct that may have many different operational definitions and associated theoretical measurement methods.[(13)] In this study, participants were allowed to play the radio, use their cell phones, or otherwise engage in non-driving-related activities. Engagement in non-driving 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 non-driving 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 and the other, the control group, was manually maintaining the 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 the CACC group might experience more crashes than the control group, which, because they were 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 about 0.4 g, and in this scenario, braking was initiated before the brake lights of the lead car came on. Also, when the CACC system began to brake, a loud series of beeps was intended to alert the driver of the need to take longitudinal control. This beep carried a meaning similar to that of a forward collision warning. With the automated assistance of the CACC system, the CACC group might gain the slight reaction time advantage they would need to avoid a crash. This test of crash avoidance would be specific to the warning and brake response programmed into the system, and, thus, the results cannot be expected to generalize to all potential CACC implementations. Nonetheless, they should give a clue as to whether similar CACC systems will be more likely to be a boon or detriment to safety and may provide a starting point for exploration of CACC warning parameters and the effects of automated braking.

Equipment and Materials

The Driving Simulator

The experiment was conducting in the Federal Highway Administration (FHWA) Highway Driving Simulator. The simulator's screen consisted of a 200-degree portion of a cylinder with a radius of 8.9 ft. Directly in front of the driver, the design eye point of the simulator was 9.5 ft from the screen. The stimuli were projected onto the screen by 5 projectors with resolutions of 2,048 horizontal by 1,536 vertical pixels. Participants sat in a compact sedan. The simulator's motion base was not enabled in this experiment. The car's instrument panel, brake, and accelerator pedal all functioned in a manner similar to real-world compact cars. The steering wheel did not function as intended in this experiment because the force feedback mechanism was not functioning. As a result of the steering system malfunction, the vehicle's response to steering inputs was immediate and not modulated by vehicle dynamics so that participants needed to continually correct responses to prior steering inputs. The effect of the steering malfunction was to generate an unintended level of driver workload.

The simulator was equipped with a hidden intercom system that enabled communications between the participant and a researcher who ran the experiment from a control room. The researcher in the control room could also view the face video from the eye-tracking system and thereby monitor the participant's well-being.

Eye-Tracking System

The simulator was equipped with a four-camera dashboard-mounted eye-tracking system that sampled at 120 Hz.(14) 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. Gaze direction accuracy varied by participant. The mean accuracy of gaze position across all participants was 1.4 degrees (radius) with a 0.9-degree standard deviation for the left eye and 1.7 degrees with a 1.3-degree standard deviation for the right eye. In this study, the eye-tracking system was primarily used to determine which vehicle displays the participant was looking at. The following display locations were tracked:

- Multifunction touch screen display that hosted either the CACC user interface or the control group gap ribbon.
- Instrument panel (with speedometer and tachometer).
- Rear view mirror.
- Left side mirror.

- Right side mirror.
- Out the windshield (projection screen).

In addition to tracking the direction of gaze, the eye-tracking system computed eyelid opening and pupil diameter. These measures were also recorded at a 120 Hz.

Multifunction Display

The model of sedan used for the simulator was not originally equipped with cruise control. 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 contained three interactive elements. On the left side of the screen, the selected speed was displayed, and two arrows could be touched to modify the selected speed. Touching the upward-pointing arrow increased the set speed by 1 mi/h, and the downward-pointing arrow could similarly be used to decrease the set speed. In the center of the screen were three bars that when touched would cycle through the three available gap selections (near, medium, and far). On the right side of the screen was a touch screen button that toggled the CACC system on and off. Although set speed and gap adjust buttons altered the displayed settings, those display settings did not affect the simulated performance of the CACC system. Throughout the experiment, the set speed remained 70 mi/h, and the gap target remained 1.1 s. The participants were informed that the gap and speed setting adjustments were non-functional and intended only to assist in explaining the ACC concept. No participants were observed trying to change these settings. The engage button on the right side of the display was fully functional. When CACC was engaged, the set speed arrows, near gap adjust bar, and engage button were green. When the CACC system was not engaged, all three elements were a shade of red or magenta.

For the control group, the multifunction display appeared as shown in figure 1. The control group display 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 and maintain a 1.1-s gap and keep the black bar in the green region of the ribbon.

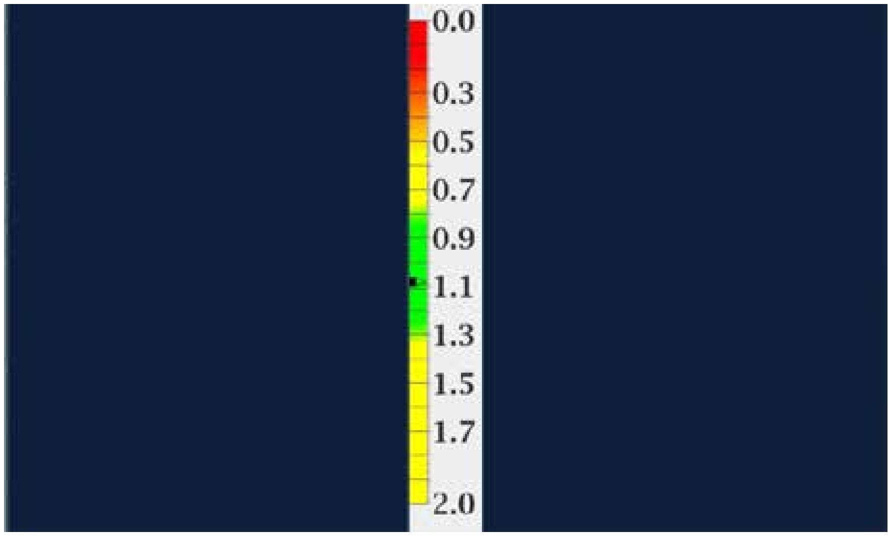


Figure 1. Screen capture. Appearance of control group multifunction display.

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.

Simulation Scenarios

Participants drove in a dedicated lane (i.e., lane adjacent to the median) on a simulated eight-lane interstate highway (four lanes in each direction). This lane was separated from the other lanes by F-type barriers. A typical portion of the roadway is depicted in figure 2. The center dedicated lane was accessed from the left side of the roadway from a ramp with a ramp meter. The ramp meter is depicted in figure 3. 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. Vehicles in CACC mode were set to maintain a 1.1-s gap. There were a few simulated vehicles in the lanes to the right of the dedicated CACC lanes that could be viewed when looking over the barrier.

Figure 2. Screen capture. Typical section of the simulated roadway.

Figure 3. Screen capture. Entrance ramp meter.

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.

- **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 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 by about 22 ms of near silence.

Calibration of CACC Vehicle Size

In previous testing in the simulator and in pilot testing for the present experiment, most individuals showed a reluctance to follow other vehicles with a 1.1-s gap and indicated that they never followed that closely. Because the literature suggests that a 1.1-s gap is greater than most people consider safe, an experiment was conducted in which six drivers from the FHWA research center (Federal employees and contractors) drove an instrumented vehicle in the field while following a Jeep® Grand Cherokee and followed the same simulated vehicle in the driving simulator.[15] 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 with 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 gap at the same distance as with ACC/CACC.

In the field, the participants drove an instrumented Cadillac® SRX that was equipped with ACC. In the simulator, the eye point of the simulator cab was positioned to approximate the eye height of a Jeep® Grand Cherokee. The procedures in the field and in the simulator were the same. Participants first drove for 5–7 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 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, 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 leading 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 4.

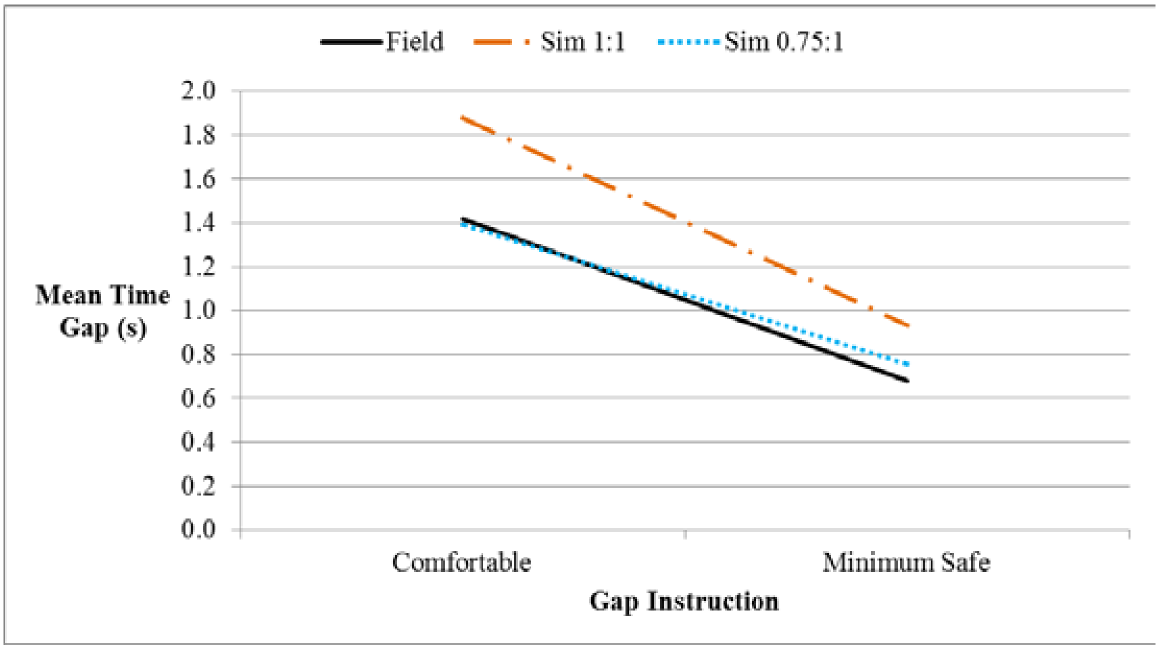


Figure 4. Graph. Results of field and simulator gap maintenance testing.

As a result of this testing, it was decided to reduce the size of the other vehicles in the CACC platoon to 75 percent of the size of a 1:1 depiction. Figure 2 shows a leading vehicle with the original (1:1) scaling. Figure 5 shows a leading vehicle scaled to 75 percent of the original size. Although extensive testing was not done to determine the source of the following distance misperception, the Ponzo illusion appears to be a likely candidate explanation.(16) The Ponzo illusion is illustrated in figure 6, where all three vehicle pictures are the same size, but the upper vehicle appears to be larger than the lower vehicles.

Figure 5. Screen capture. Reduced-size (75 percent) lead vehicle depicted with 1.1-s gap.

Figure 6. Screen capture. The Ponzo illusion. (The vehicles in the picture are all the same size.)

Procedure

Upon arrival at the research center, participants were asked to review and sign an informed consent statement. This was followed by a health screening to ensure that the participants were not at increased risk of simulator sickness as a result of illness or lack of sleep. Participants were asked to show a valid driver's license. A Snellen chart was used to verify visual acuity equal to or better than 20:40, with correction if necessary. 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 is triggered when more braking was needed than the CACC system could provide. The CACC related instructions were as follows:

1. Set the gap to “near.”
2. Set the speed to 70 mi/h.
3. Control steering—follow the car in front.
4. Allow the system to accelerate and brake up to a limit.
   - Monitor the situation at all times—the system can fail.
   - Take over control by pressing the accelerator or brake.
   - Press the brake to disengage the CACC system.
   - Press the “ENGAGE” as soon as possible when the situation allows to reengage CACC.

Except for the previous numbered instructions, the control group instructions were the same. The instructions unique to the control group were as follows:

1. Aside from maintaining 1.1-s gap, drive normally.
2. Stay alert for unexpected events.

The slideshow presentation concluded with an explanation of the NASA-TLX, which was verbally administered while they were driving.

Following the slideshow presentation, participants were fitted with the GSR sensor and seated in the simulator cab where the controls and displays were reviewed, and the instructions were repeated. While seated in the cab, participants were asked to complete the simulator sickness questionnaire (SSQ) to provide a symptom baseline. Finally, the eye-tracking system was calibrated to the participants; the procedure generally took 5 to 10 min.

With the preliminaries completed, participants were asked to perform a brief (less than 10 min) practice drive. On the practice drive, participants were asked to merge onto the dedicated CACC lane, which was free of traffic, and to accelerate to 70 mi/h. They were asked to gently brake and then accelerate, which was followed by a request to brake hard and then accelerate. To enable adaptation to the lateral control, participants were asked to gently change from the travel lane into the breakdown lane and then change back into the travel lane. This was followed by a request to quickly change into and out of the breakdown lane.

Participants in a CACC condition were then asked to engage the CACC system. With no vehicles ahead, the CACC system accelerated to 75 mi/h until it closed on a platoon of CACC vehicles traveling at 55 mi/h. The platoon traveled at 55 mi/h for 2 min and then accelerated to 70 mi/h.

Participants in the control condition were asked to accelerate to 70 mi/h and maintain that speed until they closed on a platoon of CACC vehicles. They were then asked to follow with a 1.1-s gap and refer to the ribbon gap display as necessary. The platoon behaved in the same manner as for the CACC conditions.

After traveling in the platoon at 70 mi/h for 2 min, the NASA-TLX was administered to all participants. This administration was intended to further familiarize participants with the workload assessment tool, which is not typically verbally administered. With the conclusion of the workload assessment, participants were asked to take the next available off-ramp and come to a complete stop.

After completion of the practice drive, participants were asked to exit the vehicle and complete the SSQ.

The experimental session began with the participants seated in the third vehicle of a platoon of four vehicles. The platoon 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. At this time, participants in the CACC condition were asked to release the brake and press the "ENGAGE" button on the multifunction display. With CACC engaged, the participant's vehicle followed the two preceding vehicles in the platoon 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 ("during the preceding minute or so").

From the conclusion of the NASA-TLX, about 10 min elapsed before another NASA-TLX was administered again. 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 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 SSQ, 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 platoon 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).

There was one within-subjects variable, referred to as a "period," with five levels that was intended to distinguish the effects of CACC on driver behavior. The five levels are defined as follows:

- **Period 1:** 15-s period before the initial merge event.

- **Period 2:** 15 s beginning from the time that the initial merging vehicle entered the travel lane.

- **Period 3:** 15 s beginning approximately 16 min into the drive after about 10 min of uneventful cruising.

- **Period 4:** 15 s beginning 30.5 min into the drive after 25 min of uneventful driving and just before the beginning of the critical event.

- **Period 5:** Began with the onset of the critical event and ended when the participant vehicle came to a stop, when the participant swerved out of the platoon, or when 15 s had elapsed, whichever came first.

Participants

Participants were 51 licensed drivers recruited from the Washington, DC, metropolitan area. The goal was to recruit an equal number of males and females over and under the age of 46, which is the median age of participants in the FHWA recruitment database. Participants were required to be at least 18 years of age and were screened for susceptibility to motion and simulator sickness. One participant withdrew before completion because of simulator sickness symptoms. Another participant's data were lost as a result of simulator operator error. 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 years). The mean age of the older participants was 60.4 years (ranging from 49 to 76 years).

Table 1. Demographic breakdown of participants 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.

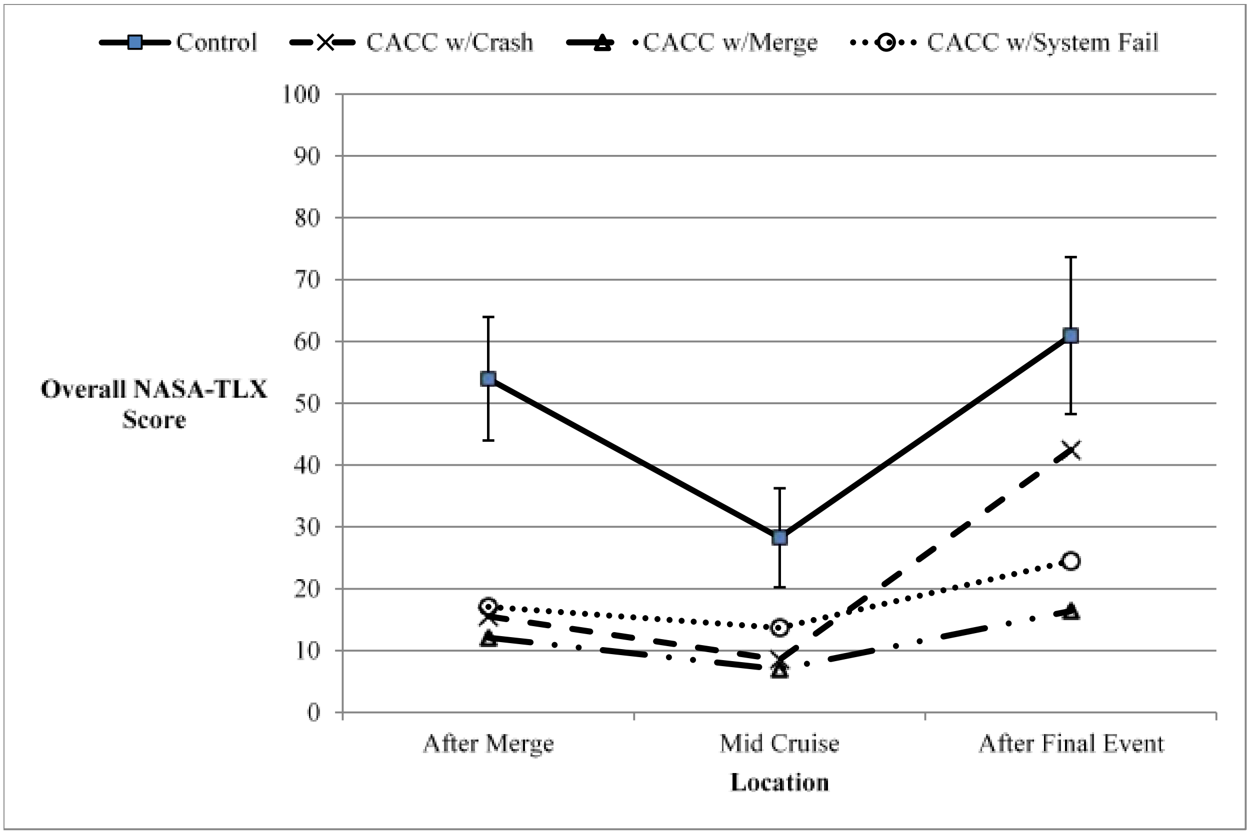
CHAPTER 3. RESULTS

The findings with respect to CACC and workload, physiological arousal, distraction, and crash avoidance are presented separately in this chapter.

WORKLOAD

The NASA-TLX was administered verbally at three points during the test: after an initial merge event, 15 min into the drive, and immediately after the critical event. For the control and CACC with crash conditions, this was after the participant had come to a stop or collided with the preceding vehicle. For the CACC with merge event, this was after the vehicle returned to a speed of 70 mi/h and following distance of 1.1 s. For the CACC with communications failure condition, this was after the CACC system was reengaged and the following distance was again 1.1 s.

The mean NASA-TLX scores by condition and period are shown in figure 7. The test for significant effects in NASA-TLX ratings was a multivariate analysis of variance with location as a repeated measure with three levels and treatment condition as a between-groups factor with four levels. As expected, 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. The 95-percent confidence limits for the means of the control group are shown in figure 7. The confidence limits of the means for the other groups were of similar magnitude but are omitted from the figure to avoid unnecessary clutter.



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

Figure 7. 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. Because each participant drove for approximately 34 min and the data were sampled at up to 120 Hz, subsequent analyses focused on periods identified in the method section.

GSR

GSR is generally considered to be sensitive to sympathetic nervous system arousal. It is more sensitive to spikes in arousal than to gradual changes in arousal over longer periods of time. Because it is more sensitive to transient spikes than long-term shifts in arousal, if the CACC results in lower levels of arousal, then these would be expected to be most pronounced in comparisons of CACC with the control condition at periods 2 and 3 and differences between the CACC with crash avoidance condition and the control condition for periods 4 and 5.

Because absolute levels of skin conductance can and did vary greatly between individuals, the GSR scores for each participant were converted to standardized *z*-scores by subtracting the participant's mean skin conductance from each conductance reading and dividing the difference by the standard deviation of skin conductance.

The resulting *z*-scores were analyzed using three generalized estimating equation (GEE) models with normal response distributions and identity link functions. The first model analyzed the five 15-s periods as a repeated measure and the four treatment groups as a between-groups measure and yielded no significant main effect or interaction.

A second model combined the three CACC conditions and compared this combined grouping with the control across the first four periods. (The fifth period was omitted because the CACC treatment groups were exposed to different events in that period.) The second model also yielded no significant main effect or interaction.

The third model compared the CACC with crash avoidance group with the control group in the fifth period only, where both of these groups were exposed to the crash event. Again, there was no significant difference in standardized GSR between these groups.

The null hypothesis of no difference in physiological arousal as measured by standardized GSR between the control and CACC groups could not be rejected.

Eyelid Opening

If CACC reduces alertness, then one might expect eyelid opening to become smaller as the eyelids begin to droop with lower arousal levels. This might lead to a smaller eyelid opening for the CACC groups as a function of period, particularly in periods 3 and 4 compared to the other periods, which had potentially stimulating events (i.e., starting the drive, the first merge event, and the critical events).

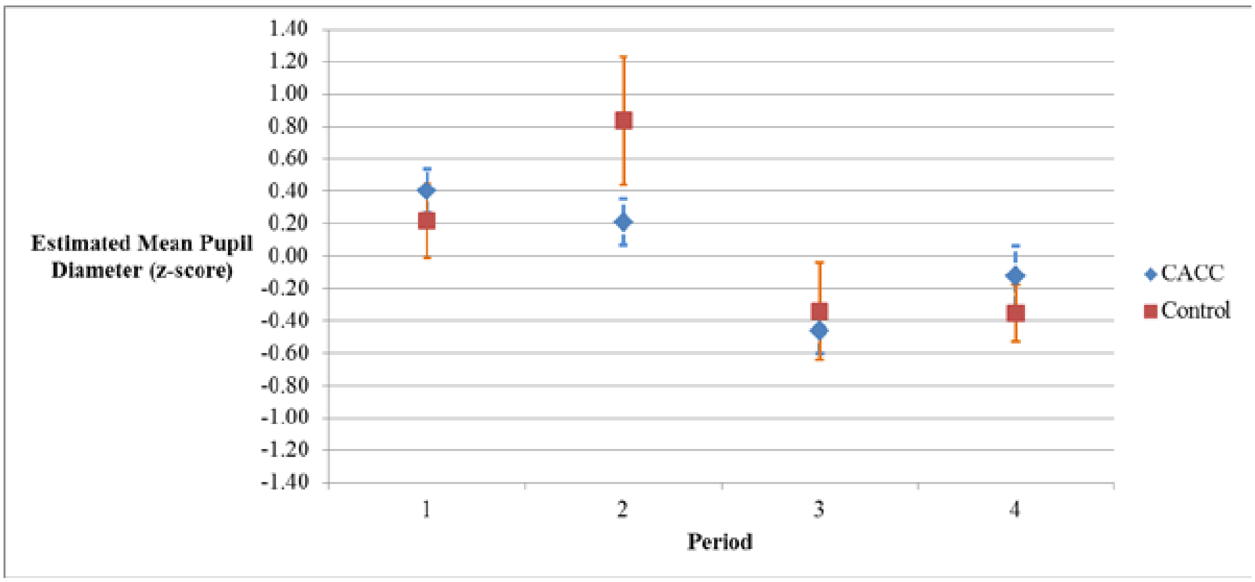
As with GSR, the raw eyelid-opening measures were converted to *z*-scores. Eyelid-opening observations that the eye-tracking software classified with a quality rating less than 75 percent were excluded. This resulted in the exclusion of 69 percent of the eyelid-opening readings.

Two GEE models with a normal response distributions and identity link functions were fit to estimate eyelid opening as a function of condition, period, and their interaction. The first model included all groups and periods. There was a significant condition-by-period interaction, $\chi^2(12) = 24.60$, $p = 0.02$. This interaction appeared to be the result of the control group having significantly smaller eyelid openings in period 4. Because of the large variability in eyelid opening, the large amount of excluded data, and the large number of mean comparisons, this finding should not be given much credence.

The second model compared the control group eyelid opening to the CACC with crash avoidance group in period 5, which included the crash avoidance event. The difference between these groups was not significant.

Pupil Diameter

Pupil diameter measurements for which the eye-tracking 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 *z*-scores were then submitted to a GEE model with condition, period, and their interaction as factors. Figure 8 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 is 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 min or more of driving). The interaction does not appear to result from any easily explainable phenomenon; the control group had atypically large pupil diameters in period 2, and 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 is 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 8. Graph. Standardized pupil diameter as a function of condition and period.

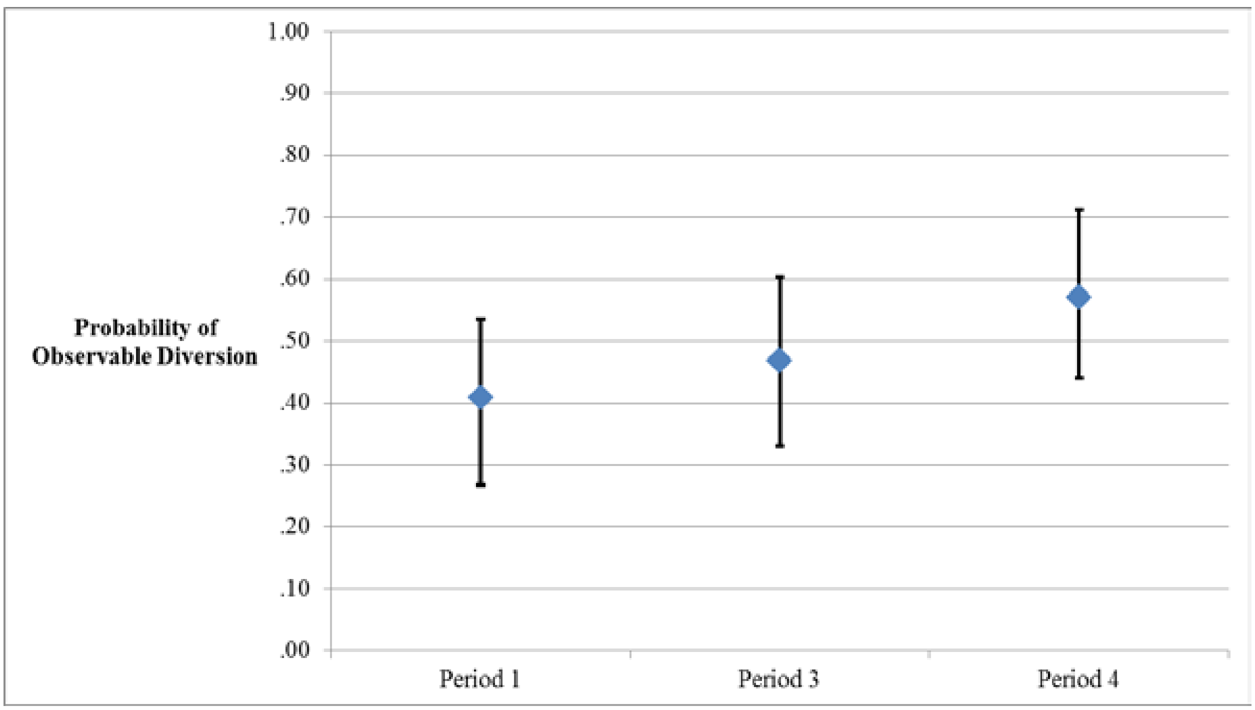
Overall, the physiological measures provided no evidence that CACC resulted in a greater reduction in arousal over time than the control condition.

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 do things to 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. Care was taken to avoid encouraging these activities, although participants were told that they could listen to the car radio or do what they normally do while driving. Table 2 shows the non-driving activities participants engaged in at locations that roughly correspond to periods 1, 3, and 4 in the other analyses. Because all of the CACC participants were treated the same in periods 1, 3, and 4, the three CACC groups were collapsed into one group, and their probability of engaging in observable diversions was compared to the control group. A GEE model with group (control versus CACC), period, and the interaction of group and period yielded a significant effect of period, $\chi^2(2) = 6.9$, $p = 0.04$. Although 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 not statistically significant, $\chi^2(1) = 2.75$, $p = 0.10$. However, because the original null hypothesis was unidirectional (i.e., CACC participants would not engage in more diversions than the control group), a one-sided statistical test is appropriate. A one-sided *t*-test found a significant difference between the groups ($p < 0.05$). Figure 9 shows the estimated mean probability and confidence limits for the means for engaging in a diversion as a function of period.

Table 2. Number of participants engaging in observable non-driving-related activities as the experiment progressed.

Non-Driving Related Activity	Period 1	Period 3	Period 4
No detectable diversion	29	26	21
Listening to radio	19	20	21
Talking/singing/texting	1	3	6
Listening to video on smartphone	0	0	1



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

Figure 9. Graph. Estimated mean proportion of drivers engaged in non-driving-related diversions increased with time into drive.

GAZE LOCATION

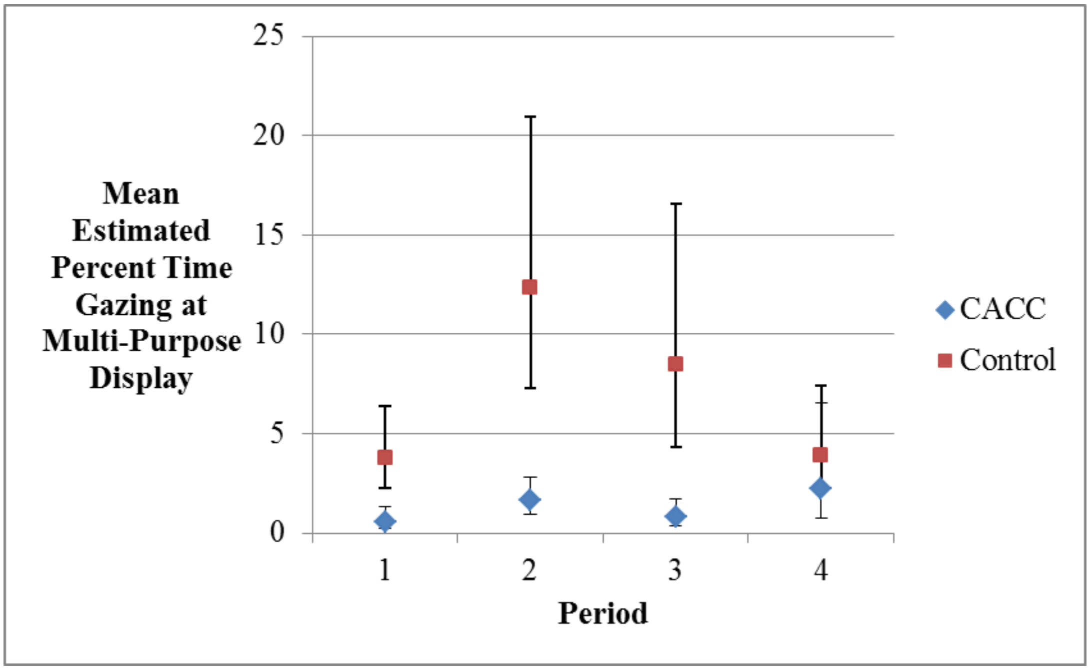
As indicated in chapter 2, an eye-tracking system automatically recorded the estimated location of gazes to objects coded in its model. Table 3 shows the percentage of time spent gazing at each of the world model objects as a function of treatment group and roadway section. As can be seen, the control group spent considerably more time gazing at the multifunction display than did the

CACC groups. Gaze time at the multifunction display appears to come at the expense of monitoring at the road ahead. It should be noted that the "Out of Vehicle" classification included more than just glances to the road ahead. It included any recorded gaze direction other than to the defined objects (e.g., multipurpose display or rear-view mirror) and within the 200- by 40-degree area of the projection screen. Nonetheless, the vast majority of the out-of-vehicle glances were to the road ahead. The "Undetermined" classification in table 3 does not include eye blinks or times when gaze could not be detected for whatever reason (e.g., head down, eyes closed, or hand in front of face), but only cases where the gaze was qualified as good and was not in the direction of any of the defined objects.

Table 3. Percent of gaze time to defined objects as a function of condition and period.

Condition	**Period**	**Multipurpose Display**	**Instruments**	**Rearview Mirror**	**Left Mirror**	**Right Mirror**	**Undetermined**	**Out of Vehicle**
Control	1	3.48	7.08	0.47	0.15	0.06	0.00	88.75
Control	2	11.33	13.45	0.30	0.32	0.06	0.00	74.53
Control	3	7.76	9.02	1.51	0.44	0.05	0.00	81.22
Control	4	3.57	6.49	0.08	0.00	0.00	0.05	89.81
Control	5	3.16	6.42	0.00	0.12	0.00	0.00	90.30
Control	**Mean**	**5.86**	**8.49**	**0.47**	**0.21**	**0.04**	**0.01**	**84.92**
CACC crash avoidance	1	0.94	3.10	0.03	0.09	0.00	0.00	95.84
CACC crash avoidance	2	1.34	15.55	0.05	0.02	0.00	0.00	83.04
CACC crash avoidance	3	0.79	5.95	0.04	0.35	0.00	0.00	92.87
CACC crash avoidance	4	0.97	5.19	0.00	0.00	0.00	0.00	93.85
CACC crash avoidance	5	3.41	1.21	0.00	0.00	0.00	0.42	94.97
CACC crash avoidance	**Mean**	**1.49**	**6.20**	**0.02**	**0.09**	**0.00**	**0.08**	**92.11**
CACC cut-in	1	1.44	6.76	0.08	0.13	0.00	0.14	91.44
CACC cut-in	2	1.03	17.44	0.43	0.00	0.01	0.03	81.07
CACC cut-in	3	0.91	1.87	1.04	0.06	0.00	0.00	96.11
CACC cut-in	4	0.85	2.10	0.33	0.00	0.00	0.07	96.64
CACC cut-in	5	1.21	3.63	0.31	0.22	0.00	0.00	94.63
CACC cut-in	**Mean**	**1.09**	**6.36**	**0.44**	**0.08**	**0.00**	**0.05**	**91.98**
CACC failure	1	0.07	3.10	0.03	0.01	0.00	0.00	96.79
CACC failure	2	2.76	11.76	0.82	0.03	0.00	0.00	84.62
CACC failure	3	0.61	3.27	0.67	0.00	0.00	0.00	95.46
CACC failure	4	5.30	7.05	0.77	0.01	0.00	0.00	86.86
CACC failure	5	3.50	2.32	0.15	0.13	0.00	0.00	93.90
CACC failure	**Mean**	**2.45**	**5.50**	**0.49**	**0.04**	**0.00**	**0.00**	**91.52**
Grand mean		**2.70**	**6.63**	**0.35**	**0.10**	**0.01**	**0.04**	**90.17**

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 versus control groups. 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 can be observed in figure 10. For the CACC participants, gaze time to the display in periods 2 and 4 may have resulted from the need of some participants to re-engage the CACC system. The large percent of time that the control group spent gazing at the multipurpose display in period 2 is 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 10. Graph. GEE estimated mean percent of time gazing at the multifunction display as a function of condition and period.

CRASH AVOIDANCE

None of the participants in the CACC with cut-in or CACC with system failure groups collided with another vehicle. This was not the case for participants in the crash avoidance condition in which the lead vehicle of the platoon braked to a stop from 70 mi/h at a rate of 32.2 ft/s^2. As shown in table 4, five control group members crashed into the vehicle ahead, but only one of the CACC with crash avoidance members crashed. The difference in crash rates was significant by Fisher's Exact Test ($p < 0.02$).

Table 4. 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 are often considered the ultimate measure of highway safety. However, crashes are a rather crude safety measure because they are rare outside of driving simulations and are generally reported in terms of number of crashes per 1 million mi driven. Time-to-collision (TTC) is used as a surrogate for crashes because the frequency of near misses (i.e., very short TTCs) is thought be highly correlated with crash frequency but easier to observe.[(18)] To further evaluate the probability of a crash in scenarios like those in the simulation, TTC was analyzed.

MINIMUM TTC

The classic definition of *TTC* is range (R) divided by range rate ($\mathring{R}$), where range rate is the difference in between the leading vehicle velocity and the following vehicle velocity. With this classical measure, minimum TTC suffers from a ceiling effect when R is zero (i.e., the following vehicle collides with the lead). To enable analysis of TTC even when collisions occur, Brown's adjusted minimum TTC was used.[18] 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 or not collision avoidance is successful. Brown describes the adjusted minimum TTC as follows:

> The amount of "spare time" the driver has based on the avoidance response chosen by the driver. Positive values indicate the amount of extra time the driver had based on the deceleration profile. Negative values indicate how much earlier the driver would have needed to begin the response in order to have avoided the collision.[18](pp. 42)

The formula for the adjusted minimum TTC, which is only necessary if a collision occurs, is shown in figure 11, where V_F and V_L are the velocities of the following and lead vehicles, respectively, and a_F and a_L are the average accelerations of the following and lead vehicles, respectively, from the time the following vehicle begins to brake.

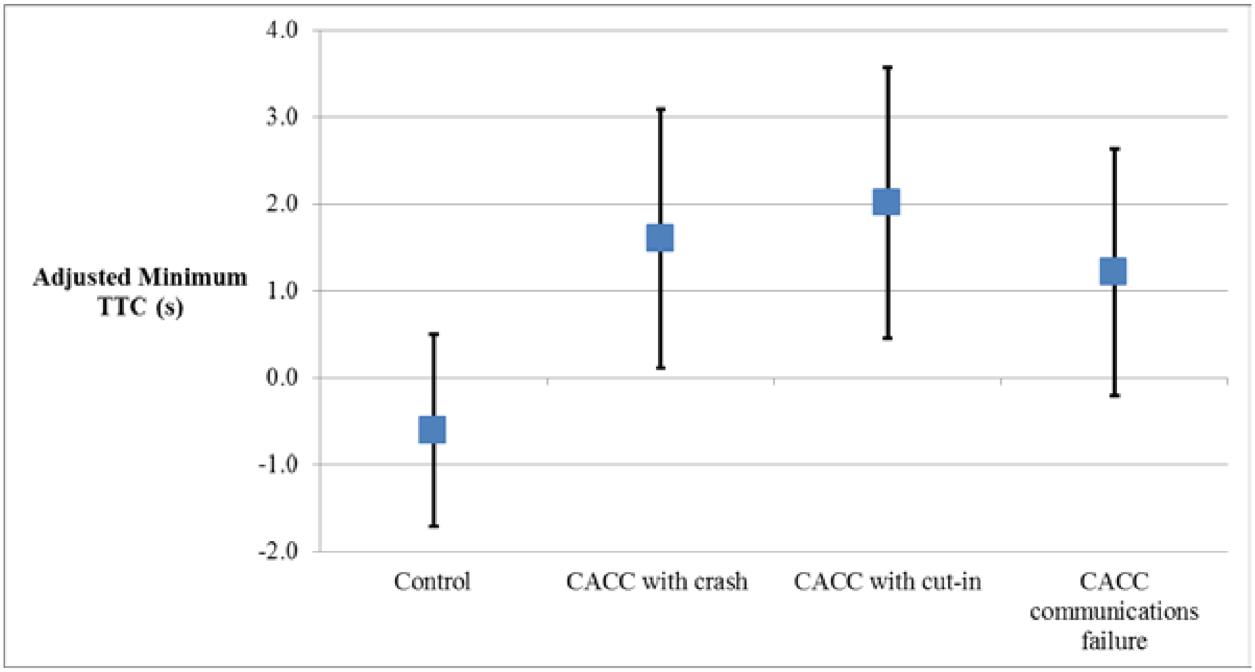
$$Adj.Min.TTC = \frac{V_F - V_L}{a_F - a_L}$$

Figure 11. Equation. Adjusted minimum TTC.

It should be noted that one control participant was missing gap data because of an experimenter error during data collection. For that participant, minimum TTC was calculated by assuming that the initial gap was 1.1 s. Review of the video of this participant confirmed that the participant did not crash and the 1.1-s initial gap assumption was reasonable.

One CACC with crash avoidance participant showed no reaction to the rapid deceleration of the lead vehicle. When the following vehicle failed to decelerate, the adjusted TTC went to negative infinity, and minimum TTC became meaningless, at least in terms of computing mean TTC.[18] Therefore, this participant was excluded from the adjusted minimum TTC analysis.

Because the minimum TTC data did not appear to be normally distributed, a generalized linear model (GLM) with a gamma response distribution and log link function was used for significance testing. Also, because the gamma distribution cannot include negative values, each participant's minimum TTC was transformed by adding 8.0 s, which shifted the range to 1.4 through 29.4. 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 12, which reflects the original scale (i.e., -8.0), the control group TTC was significantly less than that of the three groups that used CACC.



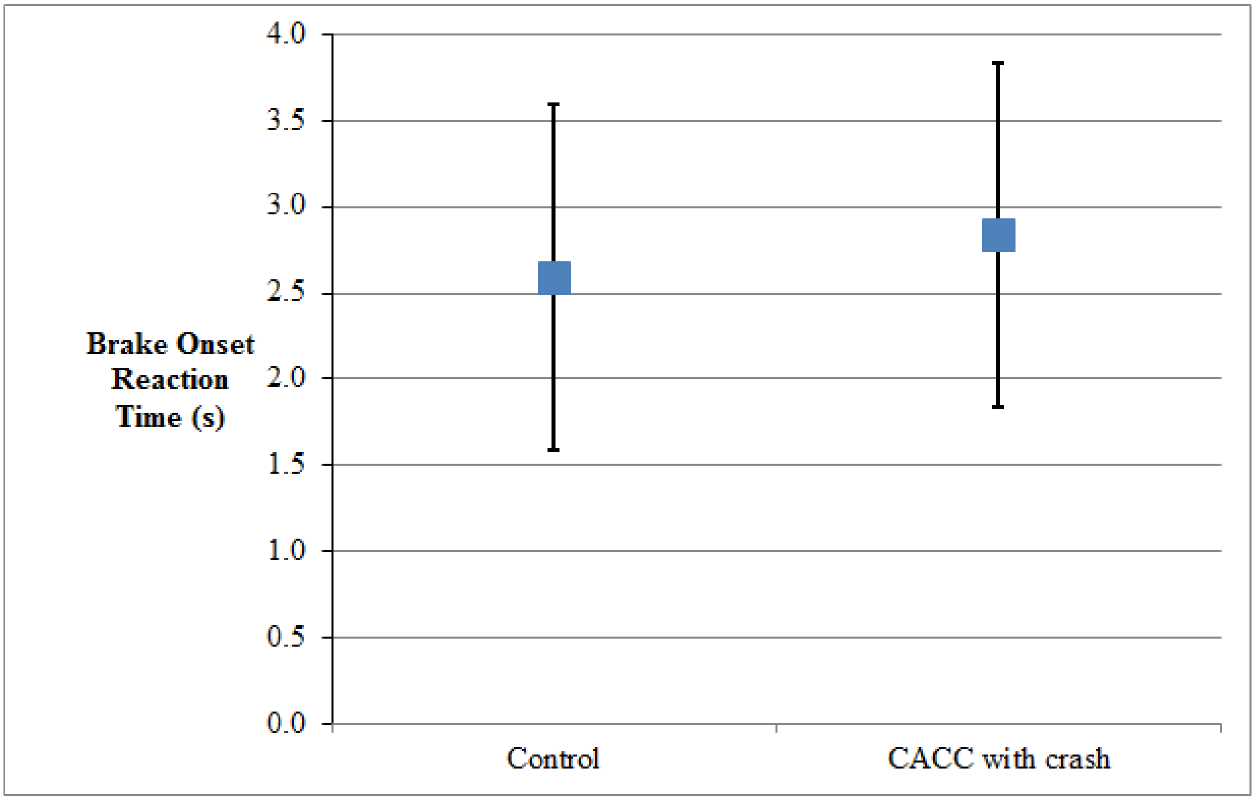
Note: Error bars represent estimated 95-percent confidence limits of the means.

Figure 12. Graph. Estimated adjusted mean TTC.

Minimum TTC depends in part on the driver's reaction time. In the next section, driver reaction time to the crash event is examined.

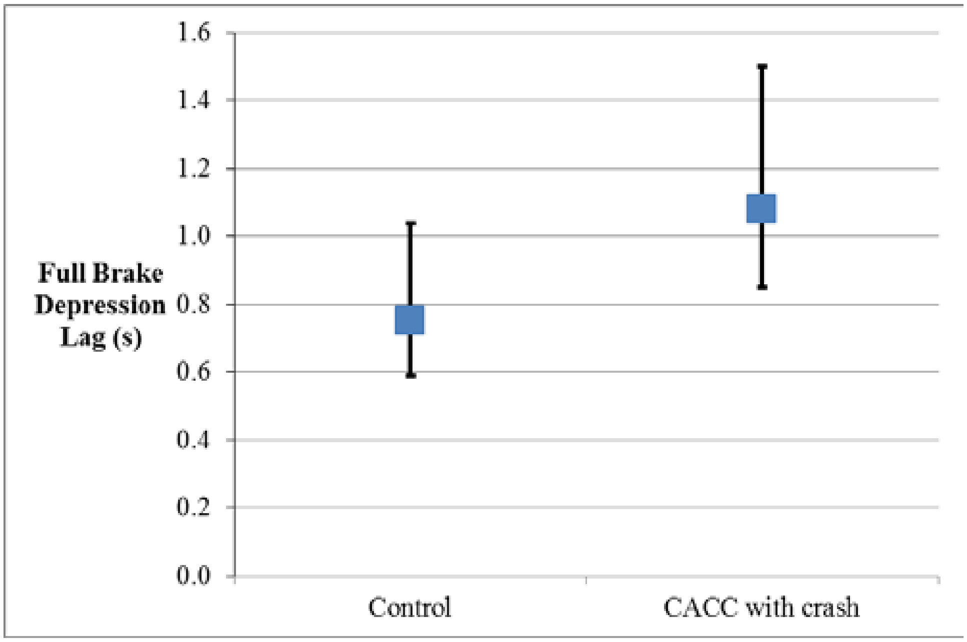
REACTION TIME

Brake reaction time is 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 either never braked or swerved out of the travel lane before braking. Despite the large difference in TTC between the control group and the CACC crash avoidance group, which responded to the same event as the control group, there was no significant difference in brake reaction time between these groups; a GLM with a gamma response distribution and inverse link function yielded a Wald $\chi^2(1) = 0.42$, $p = 0.52$. The brake reaction times for these two groups are shown in figure 13. 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 can be 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 14 shows the time taken to move the brake pedal position from off to full braking. The difference between groups was not significant; a GLM with a gamma response distribution and inverse link function produces Wald $\chi^2(1) = 3.07$, $p = 0.08$.



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

Figure 13. 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 14. Graph. Estimated mean time to from beginning of brake pedal depression to full braking.

TRUST IN THE CACC SYSTEM

About 6.8 min into the drive (the moment where period 1 ended and period 2 began), 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 the merge event. One measure of trust in the system is 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.

CHAPTER 4. DISCUSSION

This study set out to examine the following diverse number of questions regarding CACC use:

- Does CACC reduce driver workload relative to manual gap control?
- Does CACC increase the probability of driver distraction relative to manual gap control?
- Does CACC result in reduced driver arousal relative to 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?

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

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 multipurpose display. The original intent of the gap display was to ensure that the gap maintained by the control group would be similar to that maintained by the CACC groups. It was assumed that control participants would not need to refer to the gap display for more than a few minutes of driving because they would learn what the desired gap looked like on the roadway. Contrary to this assumption, the control group looked at the multipurpose display as frequently at the end of the drive as they did at the beginning. This finding could provide an alternate explanation for the workload difference between CACC and control groups as well as account for the difference in diversionary activities. As a result of this finding, a second experiment has been proposed in which the control group is equipped with ACC rather than CACC so that a gap display would not be required.

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 the readings should not be relied on. 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.

The results of the crash avoidance event that the control and CACC with crash avoidance groups were exposed to suggest that CACC does provide 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 is the 0.4-g braking that the system engaged 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 (recall these slight differences were not statistically significant) yet be much less likely to have a collision.

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, they did not appear to over trust the system; all but one CACC driver responded appropriately to the crash avoidance critical event.

ACKNOWLEDGEMENTS

This research was sponsored by the FHWA Exploratory Advanced Research Program under contract DTFH61-13-D-00024.

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