Cooperative Adaptive Cruise Control Human Factors Study: Experiment 3—The Role of Automated Braking and Auditory Alert in Collision Avoidance Response

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FOREWORD

This final report presents human factors experimental results that examine the effects of cooperative adaptive cruise control (CACC) on driver performance in a variety of situations. The experiment was conducted in a driving simulator 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 his or her alertness and attention.

The experiment explored the interaction effect of the presence or absence of an auditory warning with the presence or absence of automated braking on drivers' responses to a maximum deceleration crash avoidance event. The CACC system was effective in assisting drivers in avoiding collisions when both automated braking and an auditory warning were present. Braking or auditory warning alone were not effective in reducing the probability of a collision.

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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16. Abstract This report is the third in a series of four human factors experiments to examine the effects of cooperative adaptive cruise control (CACC) on driver performance in a variety of situations. The experiment reported here was conducted in a driving simulator scenario in which the subject driver was embedded in a platoon of CACC-equipped vehicles. The experiment explored the interaction effect of the presence or absence of an auditory warning with the presence or absence of automated braking on drivers' responses to a maximum deceleration crash avoidance event. The subject was in the fourth position in a five-car platoon. Dependent measures were crash avoidance (yes/no), manual brake reaction time (seconds), and adjusted time to collision (seconds). The results indicated that a crash avoidance safety benefit was achieved with full CACC (warning and automated braking) but not otherwise. Brake reaction times were longer when automated braking was present, but without the auditory alarm, about half the drivers took too long to react.		

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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)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		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)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		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
CACC-A	cooperative adaptive cruise control with alarm when engine braking authority is exceeded
CACC-AB	cooperative adaptive cruise control with automated braking and alarm when automated braking authority is exceeded
CACC-B	cooperative adaptive cruise control with automated braking but no auditory alarm
CL	confidence limit
FHWA	Federal Highway Administration
GLM	generalized linear model
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 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 enables 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.(2)

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 CACC human factors study, of which the present experiment was a part, 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 may be required to model the influence of human drivers on overall CACC performance.

The present experiment was the third in the human factors study and is a follow-up to the first experiment. Experiment 1 included two conditions in which a crash occurred ahead of the platoon that the participant driver was in.(3) 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 event was called a "crash avoidance event," and the CACC group that experienced the event was labeled "CACC with crash avoidance." The other group that experienced the crash avoidance event did not have any type of cruise control and was provided a multifunction display to assist in maintaining a 1.1-s gap. This other group was labeled "control."

Out of the 11 participants in the control group, 5 collided with the vehicle ahead. Out of the 12 participants in the CACC with crash avoidance group, only 1 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. However, there were several factors that may have contributed to the difference between 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 0.4-g deceleration 0.1 s after the platoon lead vehicle initiated 1-g deceleration. Simultaneous with the onset of 0.4-g deceleration, the CACC-equipped vehicles sounded an audio alarm. The first indication of a need to respond for control drivers was the looming of the vehicle ahead as it began to decelerate at 0.4 g. The brake lights of the vehicle ahead did not come on until 1.9 s later, when the vehicle ahead began decelerating at 1 g. The control group had no auditory alarm, and the control group vehicle did not decelerate at 0.4 g, although the other vehicles in the platoon did. Thus, the only indication for the control group that there was a problem prior to the brake lights illuminating on the vehicle ahead was the looming (i.e., the increase in size and decrease in distance of the simulated vehicle ahead). In addition to looming, the CACC group had an audible alarm that came on at the same time the vehicle ahead and their own vehicle began to decelerate.

The original intent for experiment 1 was that the vehicle ahead would have its brake lights come on simultaneous with the 0.4-g deceleration and that the 1-g deceleration of all CACC-equipped vehicles (except the participant's vehicle) would commence 1 s after the lead vehicle began its 1-g deceleration. If the original intent had been implemented, then the CACC group would have had 0.8 s less time to react than it did. Also, under the original intent, both the control and CACC groups would have had the cue of the brake lights of the vehicle ahead coming on at the same time the 0.4-g deceleration began.

In addition to the lack of an alarm and the lack of 0.4-g deceleration of their vehicle, the control drivers could have conceivably been distracted by the in-vehicle display that showed their following (gap) distance. After 31 min of driving, it was expected that the distraction factor from the in-vehicle display would be minimal. However, the finding that the control group looked at the forward roadway only 90 percent of the time compared with the CACC group, which looked at the forward roadway 95 percent of the time suggests that distraction could be an alternative explanation of why the control group was more likely to crash.

The advantage that the CACC-equipped vehicles had in avoiding collisions would diminish with shorter following distances. Experiment 1 examined only 1.1-s gaps because this was believed to be the shortest gap that manufacturers would allow until there is more experience with these systems. With gaps less than 1.1 s, CACC users might maintain greater alertness (e.g., hovering their feet over the brake pedal). Therefore, the point at which driver intervention would become irrelevant is not necessarily linearly related to gap size. Driver reaction times might be less with smaller gaps. In experiment 3, the 1.1-s gap was maintained in all four experimental conditions.

To address whether an auditory alarm and automated braking at 0.4 g were necessary and sufficient for the crash avoidance benefit observed in experiment 1, the braking and alarm features were factorially combined in CACC experiment 3, as shown in table 1. The ACC control group did not have automated braking in the same sense as the CACC with automated braking but no auditory alarm (CACC-B) and CACC with automated braking and alarm when automated braking authority was exceeded (CACC-AB) groups. However, it did have engine braking with about 0.2 g of deceleration. The ACC group deceleration was delayed in onset by 0.3 s from when the vehicle ahead began braking at 0.4 g. The CACC with alarm when engine braking authority was exceeded (CACC-A) group had neither engine braking nor automated braking.

Table 1. Factorial design of experiment 3.

Factor	**0.4-g Automated Braking**	
Auditory Alarm	No	Yes
No	ACC Control	CACC-B
Yes	CACC-A	CACC-AB

In experiment 3, the original intent of experiment 1 was implemented (i.e., the brake lights of the vehicle ahead came on at the same time that the 0.4-g deceleration commenced, and the vehicle ahead began braking with 1-g deceleration 1 s after the onset of the 0.4-g deceleration).

CHAPTER 2. METHODS

PARTICIPANTS

A total of 112 participants completed the study, 28 in each of 4 groups. Participants in 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. Table 2 provides the mean, minimum, and maximum ages of the participants in each of the experimental groups. Each group shown in table 2 had 14 males and 14 females.

Table 2. Age distribution within the experimental groups.

Age Group	Experimental Group	Mean Age (Years)	Minimum Age (Years)	Maximum Age (Years)
Younger	CACC-AB	34	20	45
	CACC-B	34	19	45
	CACC-A	35	18	46
	ACC	34	19	45
Older	CACC-AB	57	47	75
	CACC-B	65	47	86
	CACC-A	60	47	76
	ACC	58	48	74

SIMULATOR

The experiment was conducted in the Federal Highway Administration (FHWA) Highway Driving Simulator. The simulator consisted of a compact sedan mounted on a 6-degree of freedom motion base placed within a cylindrical projection screen with a radius of 8.9 ft (2.7 m). Three projectors were used to provide a 200- by 40-degree (horizontal by vertical) field of view. Each projector provided a nominal resolution of 4,096 by 2,400 pixels. The motion base was tuned to optimize realistic perceptions of longitudinal acceleration and deceleration and minimize false lateral acceleration cues. Prior to the experiment, a panel of six drivers rated the acceptability of the motion cues to be 6, where 1 represented “totally unacceptable” and 7 represented “very acceptable.” The simulator’s steering was also tuned prior to the experiment so that constant steering corrections were not required to maintain a straight path.

The simulated vehicle was equipped with a hands-free 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.

SCENARIO

Participants drove in a dedicated center lane on a simulated eight-lane interstate highway (four lanes in each direction). The center lane in the participants’ direction of travel was separated from the other lanes by F-type barriers, which are shown in figure 1. Entrance to 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, merged into the dedicated lane, and cruised at 70 mi/h (113 km/h). Vehicles in CACC mode were set to maintain a 1.1-s gap. For the first 5.8 mi (9.4 km) or 5 min, the platoon proceeded as formed. At 5.8 mi (9.3 km), a CACC vehicle merged into the platoon from the left in front of the participant. The merge was from a ramp identical to the initial ramp. The initial gap between the participant and the merging vehicle was about 0.5 s or 51 ft (15.5 m). The CACC or ACC systems immediately responded by decelerating to restore a 1.1-s gap.

Figure 1. Screenshot. A typical section of the simulated roadway.

There were left access and exit ramps for the dedicated lane every 2 mi (3 km). At the 11th access ramp, a vehicle traveled rapidly down the ramp and entered the dedicated lane ahead of the platoon's lead vehicle and overturned. The overturn event was occluded from view by the three platoon members ahead of the participant. As the overturning began, the platoon's lead vehicle began a constant deceleration of 32 ft/s^2 (9.8 m/s^2). After a 0.1-s delay, all the remaining CACC vehicles in the platoon began a constant deceleration of 0.4 g. All the CACC vehicles except the participant's vehicle began 1-g deceleration 1 s after the 0.4-g deceleration began. The participant vehicle in the ACC condition began decelerating at 0.2 g 0.4 s after the platoon lead vehicle began hard braking (0.3 s after the vehicle directly ahead began its 0.4-g deceleration).

The CACC groups that received the auditory warning were presented 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. The alarm was triggered at the same time as the automated braking. The CACC groups that had automated braking enabled braked at the same time and with the same 0.4-g rate of deceleration as the other CACC vehicles that responded to the lead vehicle braking event.

DEPENDENT MEASURES

The dependent measures were as follows:

- Participant crashes (collision yes/no) at the final crash event.
- Reaction time to the final event (onset of brake pedal depression).
- Minimum time to collision (TTC).

A crash was recorded if the participant's gap to the preceding vehicle decreased to zero and the lateral position with respect to the preceding vehicle was less than the width of the design vehicle. That is, if the participant vehicle either braked sufficiently to avoid contact with the vehicle ahead or successfully swerved to avoid contact, then there was no crash.

Reaction time was calculated for either a braking response or a steering response, whichever came first after the onset of the platoon leader braking. A braking response was scored if the brake pedal position exceeded 0.02 on a scale from 0 to 100. A steering wheel reaction time was recorded if the steering wheel torque exceeded 1.125 lbf (5 N).

Minimum TTC is the adjusted minimum TTC described by Brown and also described in the experiment 1 report.(3,4) This measure has the advantage of being interpretable even if a crash occurs; positive values indicate severity of the near crash event, whereas negative values indicate the severity of crashes. In all cases, smaller values are more severe. More accurately, positive values indicate how much extra time the participant had available to react, and negative values indicate how much shorter the reaction time needed to be to avoid a collision. If the deceleration of the following vehicle is less than the deceleration of the lead vehicle, which is still moving, then adjusted TTC goes to negative infinity and precludes its use in estimating group means.

CHAPTER 3. RESULTS

CRASHES

Table 3 shows the number of crashes, the number of crashes avoided by each group, the maximum likelihood estimates of crash probability, and the 95-percent confidence limit (CL) for those estimates. The probability of a crash was reduced for the full CACC system (both braking and alarm enabled) compared to the other groups. This effect was tested using a generalized linear model (GLM) with a binomial distribution and logit link function. The effect of condition was significant ($\chi^2(3) = 10.6$, $p = 0.01$). Post hoc testing showed that only the CACC-AB significantly differed from the ACC control ($p = 0.003$).

Table 3. Crash results by experimental group.

Condition	No. of Avoided Crash	No. of Crashed	Crash Probability	Lower 95-Percent CL	Upper 95-Percent CL
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 2, which displays the mean reaction times and 95-percent CLs about the means for the four conditions. Three participants in the CACC-B group never reacted and therefore were not included in the reaction time analysis. A GLM with normal response distribution and identity link function showed the condition effect significant ($\chi^2(3) = 59.2$, $p < 0.0001$). Post hoc testing showed that the ACC group mean reaction time did not differ significantly from the CACC-AB group mean but that all the other group mean comparisons yielded significant differences.

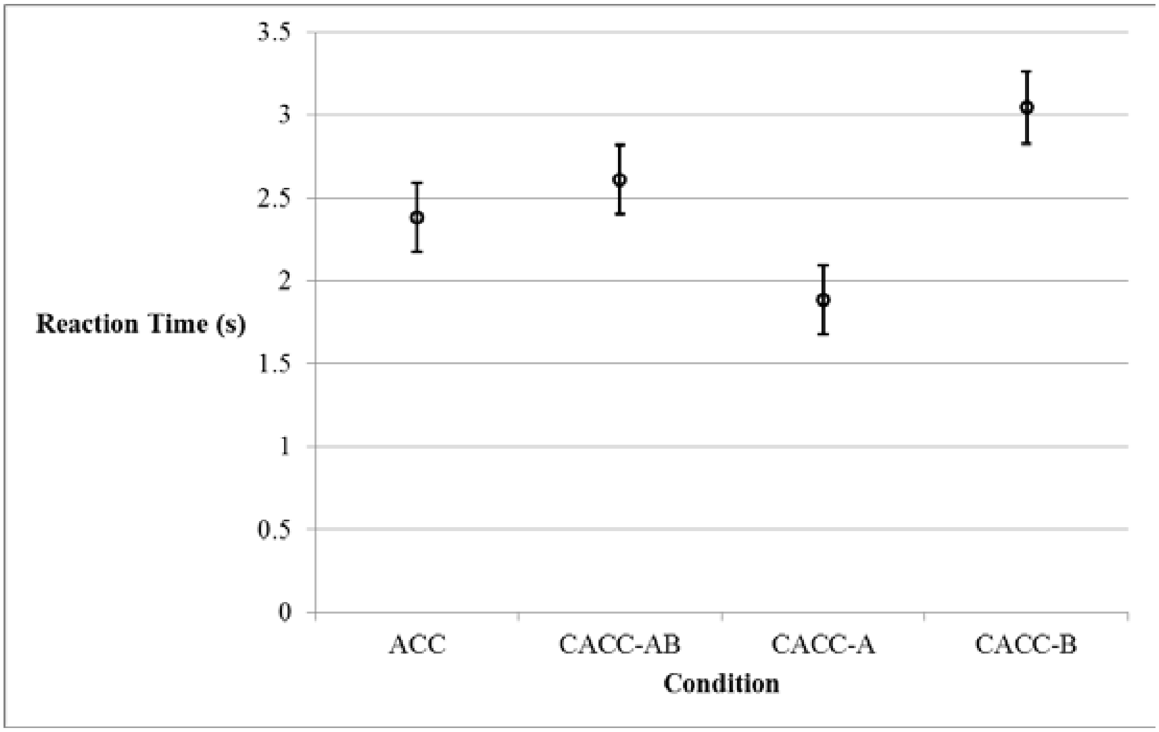

Figure 2. Graph. Reaction time from onset of braking by platoon-lead vehicle.

ADJUSTED TTC

The TTC findings are displayed in figure 3, which shows the adjusted TTC means and 95-percent CLs about the means for the four conditions. Figure 3 is based on a sample size of 92 participants. The remaining 20 participants had uninterpretable adjusted TTC estimates; 3 of those 20 are the same participants who had no reaction time 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. Table 4 shows that the ACC and CACC-A groups had the highest frequency of such values. Although the frequency of negative infinity occurrence is too low to enable meaningful statistical tests for group differences, the trend seems to suggest that automated braking contributed to mitigating the probability of inadequate braking responses.

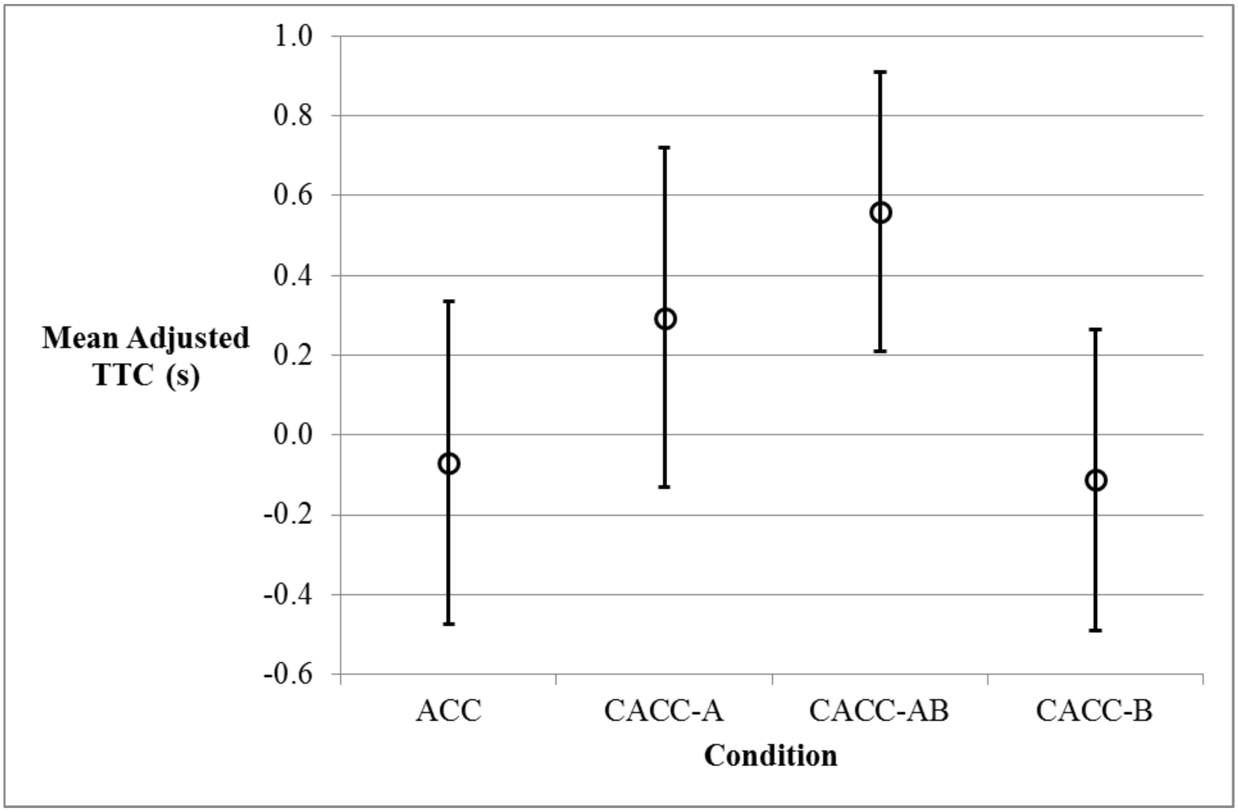

Figure 3. Graph. TTC results.

Table 4. Frequency of drivers for whom precise values of adjusted TTC could not be calculated.

Group	Number of Subjects with Minimum TTC Values of Negative Infinity
ACC	7
CACC-AB	0
CACC-A	9
CACC-B	1

GLM models with normal response distribution and identity link function showed the effect of condition significant ($\chi^2(3) = 8.54$, $p = 0.04$). As can be seen in figure 3, the CACC-AB group had a substantial positive adjusted TTC (i.e., on average, members of this group have almost 0.6 s extra 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.

CHAPTER 4. DISCUSSION

Experiment 3 reinforces the main conclusion of experiment 1: the full CACC system (i.e., as configured in condition CACC-AB) has the potential to provide for 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, which are two potential explanations for the high crash rate of the experiment 1 control condition. Nonetheless, the crash rate for the ACC control condition in experiment 3 was nearly identical to that in experiment 1. This suggests that it was CACC automated braking and an alarm that provided the apparent safety benefit in both experiments. Removing either the alarm or the automated braking from the CACC system appears to diminish or eliminate 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 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 overtrust in the system. The CACC-B braking force was twice that of the ACC braking (0.4 versus 0.2 g), so it is conceivable that the CACC-B group felt the system responding and trusted the automatic response until it was too late to recover. The mild braking in the ACC condition may been easier to perceive as inadequate than 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 of the other groups but still had a high crash rate. The extra time the 0.4-g automated braking provided 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 the extra time available.

In conclusion, it appears that the CACC system alarm may mitigate overtrust, while the automated braking feature provides drivers with the extra time they need to respond to an emergency condition. Whether this combination of alarm and automated braking will be effective with other CACC implementations (e.g., with shorter gaps between vehicles or different automated braking deceleration rates) remains to be explored.

ACKNOWLEDGEMENTS

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