Cooperative Adaptive Cruise Control Human Factors Study: Experiment 4—Preferred Following Distance and Performance in an Emergency Event

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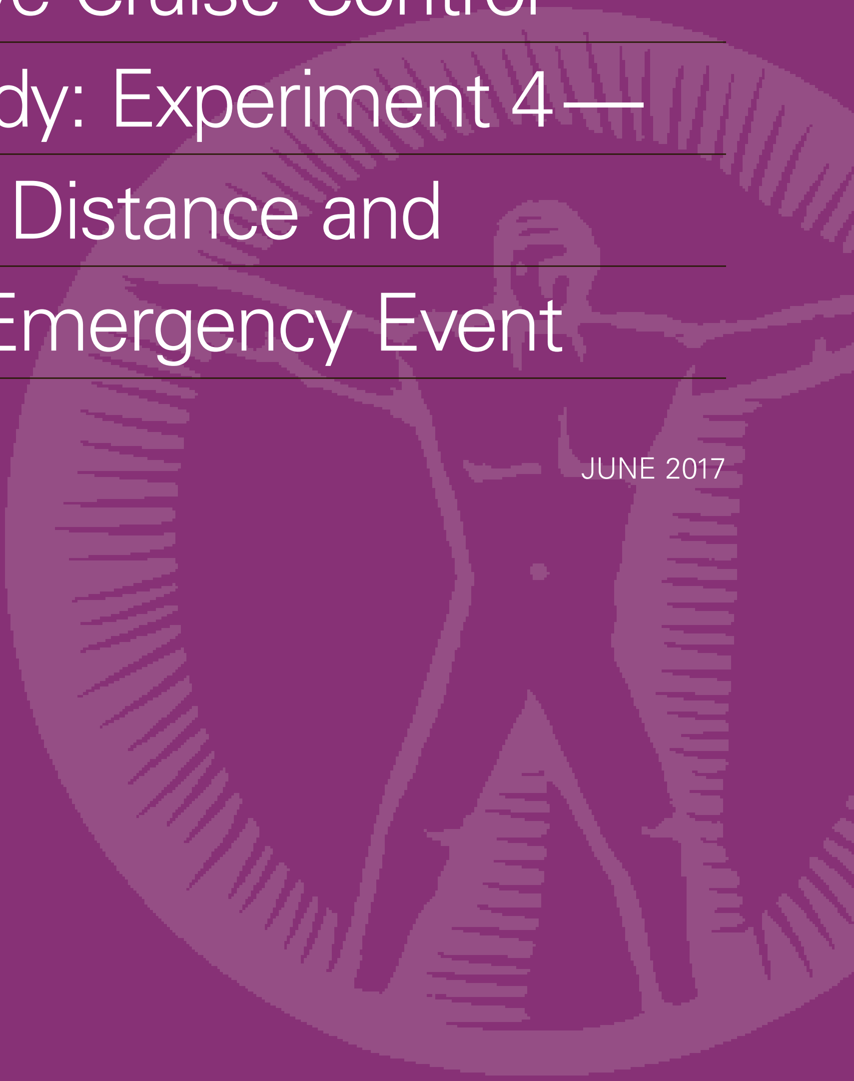

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Federal Highway Administration

Research, Development, and Technology
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FOREWORD

This report presents human factors research to examine the effects of cooperative adaptive cruise control (CACC) on driver performance in a variety of situations. It summarizes driving simulator experiments in which the driver was required to drive in a stream of vehicles. Participants experienced a vehicle merge in front of them as well as an emergency event that required driver intervention. The participants' preferred following time gap did not significantly affect collision avoidance. However, those participants following at shorter distances were more likely to intervene more rapidly that those following at a far distance.

These findings support the idea that performance depends more on overall CACC following distance settings than with drivers' personal preferences. This will allow CACC systems to implement a single following distance gap (or set of gaps based on vehicle physics). The results show that it is critical that drivers receive clear alerts when it is necessary to take over control of the vehicle. Without such measures, it is possible that CACC implementation may not result in improved roadway safety. This report should be useful to transportation professionals, State transportation departments, and researchers interested in the effects of automation on driver behavior and performance.

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Research and Development

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16. Abstract

This study is the fourth in a series of four experiments exploring human factors issues associated with the introduction of cooperative adaptive cruise control (CACC). Specifically, the goals of this experiment were as follows:

- Assess drivers' workloads under two different CACC following gaps (near and far).
- Assess drivers' reactions to a vehicle merging in front of them under different following gaps.
- Assess drivers' reactions to an emergency event that requires driver intervention to avoid collision.
- Determine whether preferred time gap following distance affects the first three goals.

As measured by the National Aeronautics and Space Administration Task Load Index, drivers' perceived workloads did not vary between the cruise period and after the vehicle merge. However, workloads were significantly greater after the emergency crash event. Workloads varied based on neither assigned following distance nor preferred following distance.

Those participants in driving in the assigned near distance were more likely to hover their foot over the brake during the merging event and to react faster to the emergency event. Preferred following distance did not affect performance. Throughout the study, participants' following distance preferences did not affect performance. In other words, one's abilities may not necessarily reflect his or her following preferences. This finding is promising for widespread implementation of CACC.

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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

CACC	cooperative adaptive cruise control
LCD	liquid crystal display
NASA-TLX	National Aeronautics and Space Administration Task Load Index
SSQ	simulator sickness questionnaire

CHAPTER 1. INTRODUCTION

This report describes the fourth and final experiment in a series of four studies that explore cooperative adaptive cruise control (CACC). CACC combines three driver assist systems: (1) conventional cruise control, which automatically maintains the speed a driver has set, (2) adaptive cruise control, which uses radar or lidar 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 will 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 physical amount of roadway. However, shorter following gaps lead to problematic human factors issues.

At 104.6 km/h (65 mi/h), a 1-s gap leaves approximately 28.96 m (95 ft) between vehicles. Previous studies have shown that drivers feel both comfortable and safe travelling at gaps shorter than 1 s. For example, in an on-road study testing drivers' choices in following distances, drivers regularly used gap settings shorter than 1 s.(2) In fact, overall, when following another vehicle, drivers elected to set the gap at 0.7 or 0.6 s 80 percent of the time. However, with a 0.6-s gap, there was only approximately 17.37 m (57 ft) between vehicles. If an average vehicle length is assumed to be around 6.10 m (20 ft), then this leaves less than 5.64 m (18.5 ft) of buffer on either side for a merging vehicle. As a result of these shorter distances, drivers may not feel comfortable merging or having a vehicle merge in front of them in a CACC platoon. Furthermore, gap-based discomfort may vary from person to person.

It is possible that individual differences in preferred following time gap may influence performance in the event that a driver needs to overtake the CACC system and regain manual control of the vehicle. For this reason, preferred following distance as it relates to performance is considered.

Another important assumption made in this study is that the CACC system will require dedicated infrastructure in its early implementation. This infrastructure requires that the CACC lane (or lanes) is physically separated from "normal" travel. This is important for several reasons. CACC will be of the most use in congested regions. This congestion often leads to lower travelling speeds and a great deal of speed variation (i.e., stop-and-go or slow-and-go traffic). Because CACC-equipped vehicles travelling in a separate lane will travel at fairly constant speeds with standard gap distances, the lane will be less susceptible to speed variability. As a result, vehicles in the CACC lane are likely to be travelling at speeds greater than the normal travel lanes. The speed differential between the two types of lanes will introduce problems reaching speeds great enough to transfer from one type of lane to the other. Instead, drivers will be required to enter the lane from a separate on ramp (much like drivers entering and exiting dedicated high-occupancy vehicle lanes). The physical separation between the two types of lanes also prevents non-CACC-equipped vehicles from entering the CACC lane and disrupting travel flow stability. To mimic this anticipated initial early implementation of CACC, participants drove in a dedicated and physically separated lane.

Current cruise control systems, both conventional and adaptive, 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.(3,4) The desired effect of stress reduction is to optimize 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) As a result, a less favorable CACC outcome might be to reduce driver arousal below the optimum level and 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. This can be especially problematic in the case of system failure or an emergency event (e.g., a crash upstream).

This study (the fourth in a series of four experiments) explored driver performance while using CACC. The goal of this research was to address some of the critical human factors issues for CACC usage related to the abilities and limitations of the drivers using the system.

In CACC experiment 1, the CACC system was effective in preventing crashes.(6) Participants rated their workload as low. However, the gap (the time gap is the distance between the front bumper of the host to the rear bumper of the preceding vehicle) was 1.1 s. For a CACC system to greatly increase highway capacity, it would need to maintain smaller gaps. The question then arises whether (1) drivers would accept smaller gaps, (2) drivers' preferred following distance influences crash avoidance performance, and (3) preferred following distance influences perceived workload.

As previously noted, many drivers already accept gaps smaller than 1.1 s. For instance, Taieb-Maimon and Shinar reported a study in which the perceived minimum safe gaps were 0.7 s or less, and comfortable perceived gaps were less than 1 s.(7) It is possible and likely that acceptable gap perception varies greatly between drivers and driving environments. The present experiment will explore the gap acceptability and driving performance in a driving simulator experiment.

This experiment was divided into two parts. The goal of part 1 was to determine median preferred following distance. That median distance was then used to determine whether participants would be classified as near or far preferred followers in part 2.

The goals of part two were as follows:

- Assess drivers' workloads under two different CACC following gaps (near and far).
- Assess drivers' reactions to a vehicle merging in front of them under different following gaps.

- Assess drivers’ reactions to an emergency event that requires driver intervention to avoid collision.
- Determine whether preferred time gap following distance affects the first three goals.

CHAPTER 2. PART 1

EQUIPMENT

The National Advanced Driving Simulator $^1/_4$ cab miniSim™ was used. The simulator uses three 182.88-cm (42-inch) 720p plasma screens to display the forward roadway and side and rearview mirrors. An additional 30.48-cm (12-inch)-wide screen was used to display dashboard information. The simulator operated without a motion base (i.e., it was stationary) but was equipped with a subwoofer underneath the driver's seat that generated appropriate rumble road feel.

The researchers sat in an adjacent room separated by pocket doors. The participants and researchers were easily able to communicate if needed. The researchers were able to monitor the system and the participants' well-being from this position.

SIMULATION SCENARIO

Participants drove in a dedicated center lane on a simulated eight-lane interstate highway (four lanes in each direction). Entrance to the dedicated center lane was accessed from the left side of the roadway from a ramp. The dedicated center lane was separated from other lanes with a jersey barrier. The environment was similar to suburban-rural interstate driving with a mix of trees and buildings along the roadway.

The simulation began with the participant vehicle as the only vehicle on the roadway. This time period was provided for participants to become accustomed to the feel of the driving simulator, including the steering, acceleration, and braking capabilities. After a few minutes, the participant came upon another vehicle. That vehicle acted as a lead vehicle and drove at 88.5, 104.6, 112.7, and 88.5 km/h (55, 65, 70, and 55 mi/h) for 3 min each. (The participant following task is described in more detail in the Procedure section.)

CALIBRATION OF LEAD VEHICLE SIZE

In the first experiment, the vehicle size was scaled in order for participants to accurately perceive the correct following distance.(6) This same vehicle scaling was used in the remainder of the studies. Given that the present experiment took place in a different simulator, the vehicle reduction scaling (to 75 percent of the original scale) was verified to ensure that the same following distance perception was attained.

PARTICIPANTS

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

PROCEDURE

Upon arrival at the research center, participants were asked to review and sign an informed consent form. This was followed by a health screening to ensure that the participants were not at an 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 Bailey-Lovie eye chart was used to verify a minimum of 6/12 (20/40) visual acuity with correction if necessary. An overview of the experiment was provided, and participants were given a chance to familiarize themselves with the driving simulator.

All participants completed two separate drives. The goal of the first drive was to assess the participants' comfortable driving gap distance. In other words, under a normal low-traffic environment, how much space would the participants leave between themselves and the lead vehicle? Specifically participants were asked to "drive at what you consider a comfortable distance. In other words, follow that vehicle at a distance that you would normally follow another car in the real world." Participants were reminded that the lead vehicle would change speed several times and that speed would need to be adjusted in order to maintain following distance. As previously mentioned, the lead vehicle drove at 88.5, 104.6, 112.7, and 88.5 km/h (55, 65, 70, and 55 mi/h) for 3 min each. The entire drive lasted 14–17 min.

After the completion of the first drive, participants completed a simulator sickness questionnaire (SSQ) and were provided with a break if necessary.(8) The goal of the second drive was to assess drivers' perceived minimum safe following distance. The drive was identical to the first drive. The only component that varied was the instructions to participants. Participants were told the following:

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

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

After the completion of the second drive, participants completed a second SSQ. Participants were provided time to ask any questions about the study, debriefed, thanked, and paid for their time. In total, participation lasted 45–60 min.

RESULTS

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

While the data from the first comfortable following task are not used to inform part 2, those data are presented here for descriptive purposes. To provide participants with sufficient time to adjust the following gap for each speed change (88.5, 104.6, 112.7, and 88.5 km/h (55, 65, 70, and 55 mi/h)), the first 30 s of vehicle following at each speed were excluded from analysis. Table 1 presents participants' following time gap distributions by speed averaged across all 14 participants during the comfortable following distance drive.

Table 1. Participant following time gaps (s) by speed during comfortable following drive.

Speed (km/h)	Minimum (s)	Quartile 1 (s)	Quartile 2 (s)	Quartile 3 (s)	Maximum (s)	Mean (s)
88.5	1.26	2.04	2.50	2.71	7.93	2.68
104.6	1.18	2.25	2.64	2.83	6.08	2.76
112.7	1.08	2.08	2.48	3.88	11.84	3.36
88.5	0.92	1.80	2.56	2.79	7.36	2.79

1 km/h = 0.62 mi/h.

Data from the second drive were initially explored to look for outlying following distances. Time gaps from a single participant were greater that 3 standard deviations away from the mean (2.74 s) and were subsequently excluded from further analyses. Once again, to provide participants with sufficient time to adjust following gap for each speed change (88.5, 104.6, 112.7, and 88.5 km/h (55, 65, 70, and 55 mi/h)), the first 30 s of vehicle following at each speed were excluded from analysis. Table 2 presents drivers' following time gap distributions by speed averaged across 13 participants during the comfortable following distance drive.

Table 2. Participant following time gaps (s) by speed during close following drive.

Speed (km/h)	Minimum (s)	Quartile 1 (s)	Quartile 2 (s)	Quartile 3 (s)	Maximum (s)	Mean (s)
88.5	0.55	0.65	0.92	1.02	1.43	0.89
104.6	0.41	0.60	0.86	1.10	1.51	0.88
112.7	0.38	0.64	0.90	1.28	1.70	0.94
88.5	0.52	0.69	1.03	1.23	1.88	1.04
Mean	**0.38**	**0.64**	**0.91**	**1.15**	**1.88**	**0.94**

1 km/h = 0.62 mi/h.

The median overall following distance time gap was 0.91 s. This value was used to assign participants as near or far followers.

CHAPTER 3. PART 2

EQUIPMENT

The Driving Simulator

The same driving miniSim™ driving simulator setup as in part 1 was used.

Multifunction Display

A 17.78-cm (7-inch) (11.43- by 19.05-cm (4.5- by 7.5-inch)) liquid crystal display (LCD) touch-screen display was mounted just to the right of the steering wheel in the driving simulator, which was similar to where the center console would be in a full cab vehicle. The display was used to turn on the CACC system at the beginning of the drive and if the driver used the brake. For all conditions, the screen displayed the vehicle's set speed (always set to 112.7 km/h (70 mi/h)), the following distance (always set to near), and the status of the CACC system (engaged or not engaged). The engage button on the right side of the display could be used by the participants to engage CACC. When the system was engaged, the text and icons appeared green; when the system was not engaged, the text and icons appeared red.

SIMULATION SCENARIOS

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

The participants began stopped on an on-ramp in the third position of a four-car platoon. As the scenario began and the ramp meter turned green, the platoon proceeded down the ramp and accelerated to 112.65 km/h (70 mi/h) while maintaining the appropriate gap (0.6 or 1.1 s (described in more detail later)). Approximately 5 min into the drive, another CACC vehicle merged into the platoon directly in front of the participant and halfway (9.33 or 17.07 m (30.6 or 56 ft)) between the participant's vehicle and the vehicle the participant had been following. The CACC system adjusted the gaps of the affected vehicles back to the assigned gap. If the participant braked in this situation, then the CACC system disengaged and needed to be reengaged.

Approximately 20 min into the drive, a vehicle sped down an on-ramp, merged in front of the platoon, and crashed. (The crash was animated but was not in the participant's line of sight if driving centered in the travel lane.) The crash avoidance event began when the lead vehicle in the platoon decelerated at 9.75 m/s^2 (32 ft/s^2). One tenth of a second after the lead vehicle began braking, all of the CACC vehicles behind it simultaneously began to decelerate at 3.90 m/s^2 (12.8 ft/s^2) and illuminated their brake lights. The engine noise was set up to exaggerate the engine revolutions per minute to more adequately cue 3.90 m/s^2 (12.8 ft/s^2) deceleration.

GAP ASSIGNMENT

Participant assignment to gap groups was based on mean gap maintained during the second drive. Based on the median following distance of part 1 (0.91 s), participants' preferred following distance was determined. Participants were assigned as near or far preference group based on whether their preferred gap fell above or below the median. Next, participants were assigned to either a congruent or incongruent following preference group (see table 3). Those participants who completed the second drive with a mean following gap of less than 0.91 s were determined to have a preferred near following distance. Of the 59 drivers with a preferred near following distance, 29 were assigned to the congruent (0.6 s near) gap in drive 3, and 30 were assigned to the incongruent (1.1 s far) gap in drive 3. Those participants who completed the second drive with a mean following gap greater than 0.91 s were determined to have a preferred far following distance. Of the 39 drivers with a preferred far following distance, 20 were assigned to the congruent (1.1 s far) gap in drive 3, and 19 were assigned to the incongruent (0.6 s near) gap in drive 3.

Table 3. Participant following distance group assignments.

Group Assignment	Gap Following Distance (Drive 2) (s)	Assigned Following Distance (Drive 3) (s)
Congruent	< 0.91 (Near)	0.6 (Near)
Incongruent	< 0.91 (Near)	1.1 (Far)
Incongruent	> 0.91 (Far)	0.6 (Near)
Congruent	> 0.91 (Far)	1.1 (Far)

Gap following distances were selected based on quartiles 1 and 3 following distances during the close drive. A 0.6-s gap (quartile 1) was used as the near following distance, and a 1.1-s gap (quartile 3) was used as the far following distance.

WORKLOAD ASSESSMENT

Driver workload was assessed by administration of the National Aeronautics and Space Administration Task Load Index (NASA-TLX) and was measured three times.(9) The first assessment was approximately 5 min into the drive. It was administered after the vehicle merged in front of the participant at about 30 s after the platoon had stabilized. The second assessment was administered approximately 10 min into the drive and was intended to assess the workload associated with driving in a stable, unchanging state (i.e., a baseline index). At this point, participants were between merging events and were likely to feel comfortable with the driving task in general. The third and final NASA-TLX was administered immediately after the final collision avoidance event.

PARTICIPANTS

Participants included 98 licensed drivers recruited from the Washington, DC, metropolitan area. Participants were required to be at least 18 years of age and were screened for susceptibility to motion and simulator sickness. Out of the 98 participants, 49 were male and 49 were female. The participants' ages ranged from 21 to 73 years with a mean age of 43.3 years (median 43.5 years).

Roughly equal numbers of participants under and over the age of 45 were recruited (see table 4). Data from five participants were excluded from analyses because of corrupt data files.

Table 4. Total number of participants included in each condition.

Preferred Gap	**Assigned Gap**		
	Near	**Far**	**Total**
Near	27 (14 males)	30 (15 males)	57 (29 males)
Far	17 (9 males)	19 (9 males)	36 (18 males)
Total	**44 (23 males)**	**49 (24 males)**	**93 (47 males)**

PROCEDURE

Participants experienced the same welcome and screening and were provided with the first two drive procedures as those participants in part 1. After the completion of the second drive and SSQ, a slideshow presentation was shown to all participants. The presentation provided an overview of the experimental instructions and familiarized participants with the NASA-TLX questions. The participants assigned to the CACC conditions were also shown videos that explained the CACC concept.

After being provided with a time to answer questions and clarify the use and functionality of the CACC system, participants were escorted back to the driving simulator. The use of the multifunction LCD display was explained and demonstrated as necessary. Next, participants drove the third scenario while using the CACC system. If at any time the participants used the brake or otherwise disengaged the CACC, then they were reminded to use the multifunction display to reengage the system.

After the completion of the third drive, participants completed a second SSQ. They were given time to ask any questions about the study, debriefed, thanked, and paid for their time. In total, participation lasted 60–90 min.

RESULTS

Drives 1 and 2

Participants in part 2 completed the same two drives as those participants in part 1. The data from the first comfortable following task were not used to determine following distance preference; those data are presented here for descriptive purposes. To provide participants with sufficient time to adjust following gap for each speed change (88.5, 104.6, 112.7, and 88.5 km/h (55, 65, 70, and 55 mi/h)), the first 30 s of vehicle following at each speed were excluded from analysis. Table 5 presents drivers' following time gap distributions by speed averaged across participants during the comfortable following distance drive.

Table 5. Participant following time gaps (s) by speed during comfortable following drive in part 2.

Speed (km/h)	Minimum (s)	Quartile 1 (s)	Quartile 2 (s)	Quartile 3 (s)	Maximum (s)	Mean (s)
88.5	0.69	1.63	2.17	2.80	6.66	2.33
104.6	0.62	1.54	2.15	3.09	21.90	2.82
112.7	0.41	1.57	2.21	3.08	21.04	2.94
88.5	0.34	1.51	1.83	2.57	7.44	2.18

1 km/h = 0.62 mi/h.

Data from the second drive were used to classify drivers as having a near or far following distance preference. Once again, in order to provide participants with sufficient time to adjust following gap for each speed change (88.5, 104.6, 112.7, and 88.5 km/hr; 55, 65, 70, 55 mi/hr), the first 30 s of vehicle following at each speed were excluded from analysis. Table 6 presents drivers' following time gap distributions by speed averaged across all participants during the comfortable following distance drive.

Table 6. Participant following time gaps (s) by speed during close following drive in part 2.

Speed (km/h)	Minimum (s)	Quartile 1 (s)	Quartile 2 (s)	Quartile 3 (s)	Maximum (s)	Mean (s)
88.5	0.30	0.64	0.79	1.12	3.96	0.99
104.6	0.27	0.59	0.80	1.18	5.25	1.06
112.7	0.28	0.58	0.82	1.20	6.93	1.08
88.5	0.35	0.61	0.90	1.27	14.61	1.29
Mean	**0.30**	**0.60**	**0.83**	**1.19**	**7.69**	**1.10**

1 km/h = 0.62 mi/h.

The median following distance for the participants in part 2 dropped 0.08 s from 0.91 to 0.83 s. However, the overall distribution of scores remained relatively consistent.

Workload

The NASA-TLX was administered verbally at three points during the third drive: shortly after the first merge, during a cruise period, and after the final crash event. The effects of CACC following distance on workload were tested using generalized estimating equations (normal response distribution and identity link function) with NASA-TLX as a repeated measure and experimental treatment conditions (preferred gap and assigned following gap) as the between-group factors of interest (see figure 1).

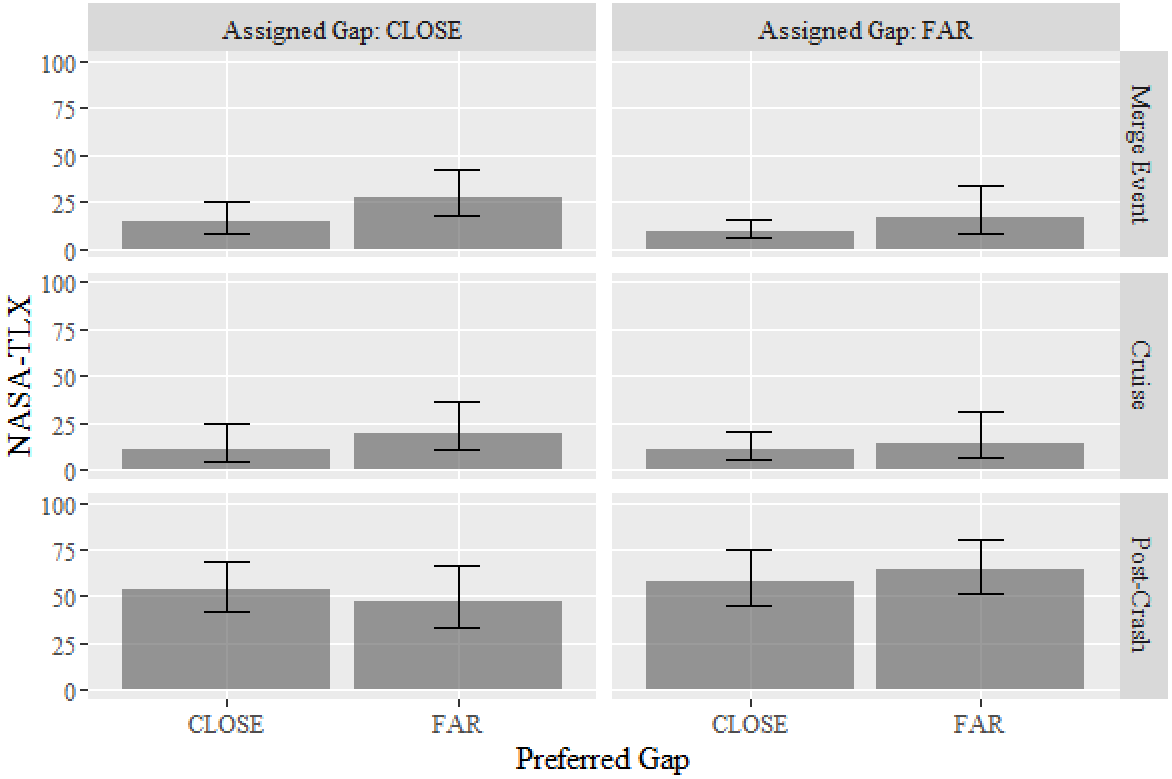

Figure 1. Graph. Mean NASA-TLX scores by preferred time gap, assigned time gap, and assessment location.

As expected, the location of the NASA-TLX assessment significantly affected perceived workload ($\chi^2(2) = 129.81$, $p < 0.001$). The mean NASA-TLX score after the first merge ($M = 15.76$) was not significantly different than during the cruise period (M = 13.11). However, mean workload was significantly greater after the final crash event (M = 55.44) than at the two previous times.

Merging Vehicle Response

To assess trust and comfort in the CACC system, participants' responses to the merging event was evaluated. After approximately 5 min of driving, a vehicle traveled down an on-ramp and merged directly in front of the participant vehicle. The CACC system was programmed in such a way that it was not necessary to interfere with or override the vehicle speed during the merge. Nonetheless, three older participants (two males and one female) pressed the brake pedal. Table 7 shows participants' preferred and assigned following distances along with the time until the brake pedal was depressed during the merging event. Time is relative to the merging vehicle entering half way into the travel lane. As such, the participant with the negative value anticipated the vehicle merge and braked in advance. Because only three participants pressed the brake pedal during this merge event, braking was not further analyzed.

Table 7. The time from merging vehicle entrance into lane until brake press.

Preferred Following Distance	Assigned Following Distance	Time from Merging Vehicle Entering Travel Lane to Driver Depressing the Brake Pedal (s)
Far	Near	0.01
Far	Near	−2.00
Far	Far	1.20

Despite few participants using the brake pedal, the speed and short distance between the participant's vehicle and the merging vehicle may have made the participants uncomfortable. As a result, foot position immediately prior to and during the vehicle merge was explored.

Foot pedal video data were coded beginning at 30 s immediately preceding the merge event. Each participant's foot position was noted. Foot movement to the brake pedal into a hovering position in anticipation of the merging vehicle was coded. Those participants following at the near following distance were significantly more likely to hover over the brake pedal than those at the longer distance ($\chi^2(1) = 5.27, p = 0.022$). This is not surprising given the short distance between the participant's vehicle and the merging vehicle, which was likely to generate some mild discomfort in following distance. Participants appeared to be readying themselves to apply the brake if necessary.

No difference in foot hovering over the brake was found based on preferred following distance ($\chi^2(1) = 0.29, p > 0.05$). Further, no significant interaction between preferred following distance and assigned following distance was found ($\chi^2(1) = 0.00, p > 0.05$). In other words, those participants who preferred to drive at a shorter following distance were just as likely to hover their foot over the brake pedal as those who preferred a longer following distance.

Crash Event Reaction

Given that it is possible that participants may have anticipated a collision event or some other nonrecurring traffic event, participant foot hovering prior to the final crash event was explored. Only three participants hovered their foot over the brake prior to the crash. Lateral position within the lane could also have the potential to influence participant reaction time. However, in this study, lateral position within the lane was not found to significantly affect reaction time ($p > .05$). Taken together, it is supposed that participants did not anticipate a crash or other abnormal driving event.

All but three of the participants depressed the brake pedal during the final event. Next, participant reaction time for those who used the brake pedal was explored. Participant reaction time was calculated as the time between when the principal other vehicle entered the line of traffic and when the participant first depressed the brake pedal (see figure 2). Participants who drove at the close distance depressed the brake pedal ($M = 2.77$ s) significantly faster than the participants who drove at the far distance ($M = 4.88$ s) ($\chi^2(1) = 14.34, p < 0.001$). No difference in reaction time based on preferred following distance was found ($\chi^2(1) = 0.00, p > 0.05$). Similarly, no interaction between preferred and assigned following distance was found ($\chi^2(1) = 1.08, p > 0.05$).

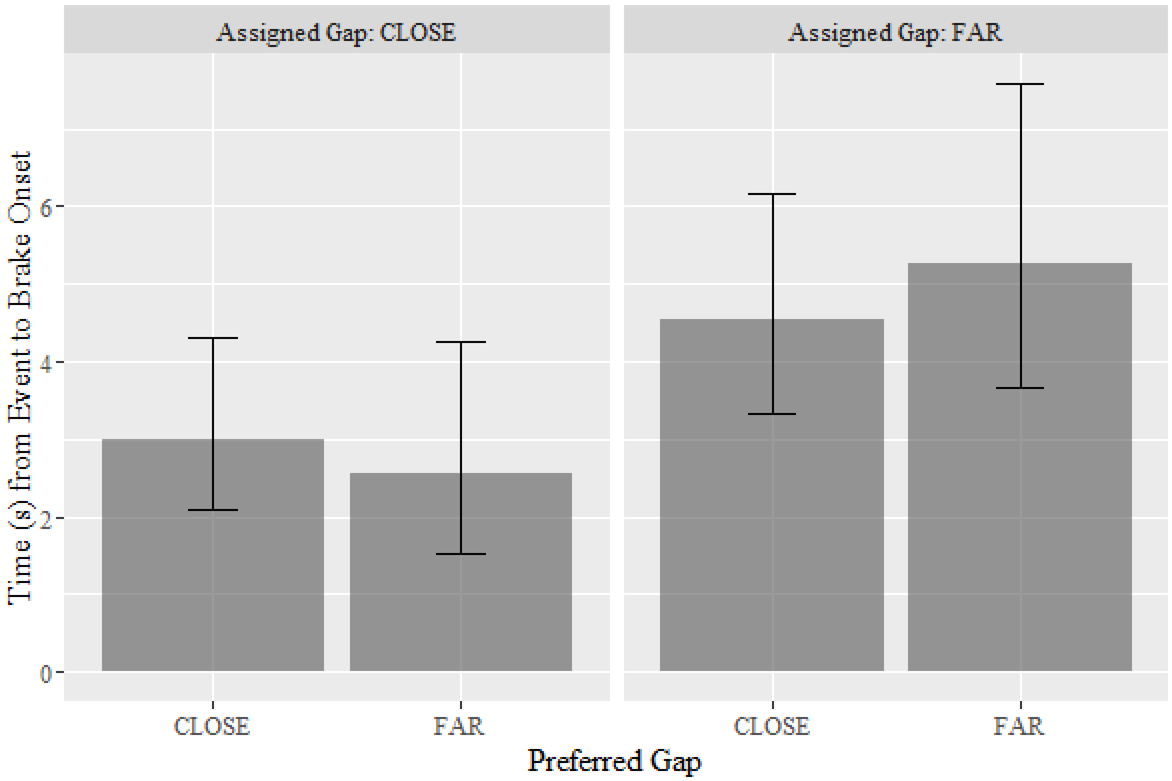

Figure 2. Graph. Time (s) from principal other vehicle entering the traffic flow to participant brake pedal onset based on preferred and assigned time gaps.

Another manner in which brake pedal response was examined was through maximum pedal depression. The time from initial brake pedal press until the maximum pedal depression was explored. Preferred following distance approached significance in an interesting way ($\chi^2(1) = 3.54$, $p = 0.059$). Those participants who preferred to follow at a far distance reached maximum pedal depression ($M = 1.28$ s) faster than those who preferred to follow at a near following distance ($M = 2.05$ s). While the difference was not significant, the trend shows that those participants who were more comfortable following at a greater distance may have been more likely to react with full brake pedal force more rapidly. No significant difference in assigned following distance was found ($\chi^2(1) = 0.69$, $p > 0.05$). Similarly, the interaction between preferred and assigned following gap was not significant ($\chi^2(1) = 0.82$, $p > 0.05$).

Crashes

Next, participant crashes during the final crash event were examined. A *crash* was defined as the participant vehicle colliding with the immediately preceding vehicle. Participants that drove at the close distance experienced significantly more crashes ($M = 0.82$) than those who drove at the far distance ($M = 0.61$) ($\chi^2(1) = 4.32$, $p = 0.038$) (see figure 3). No difference in collision rate based on preferred following distance was found ($\chi^2(1) = 0.49$, $p > 0.05$). Similarly, no interaction between preferred and assigned following distance was found ($\chi^2(1) = 1.27$, $p > 0.05$). Table 8 shows the total number of crashes by preferred and assigned gaps. Because there were an uneven number of participants in each group, table 9 shows the number of participants who did not crash by preferred and assigned following gaps.

Table 8. Total number of crashes by preferred and assigned gaps.

Gap	**Assigned**	
Preferred	**Near**	**Far**
Near	20	19
Far	15	11

Table 9. Total number of non-crashes by preferred and assigned gaps.

Gap	**Assigned**	
Preferred	**Near**	**Far**
Near	7	11
Far	2	8

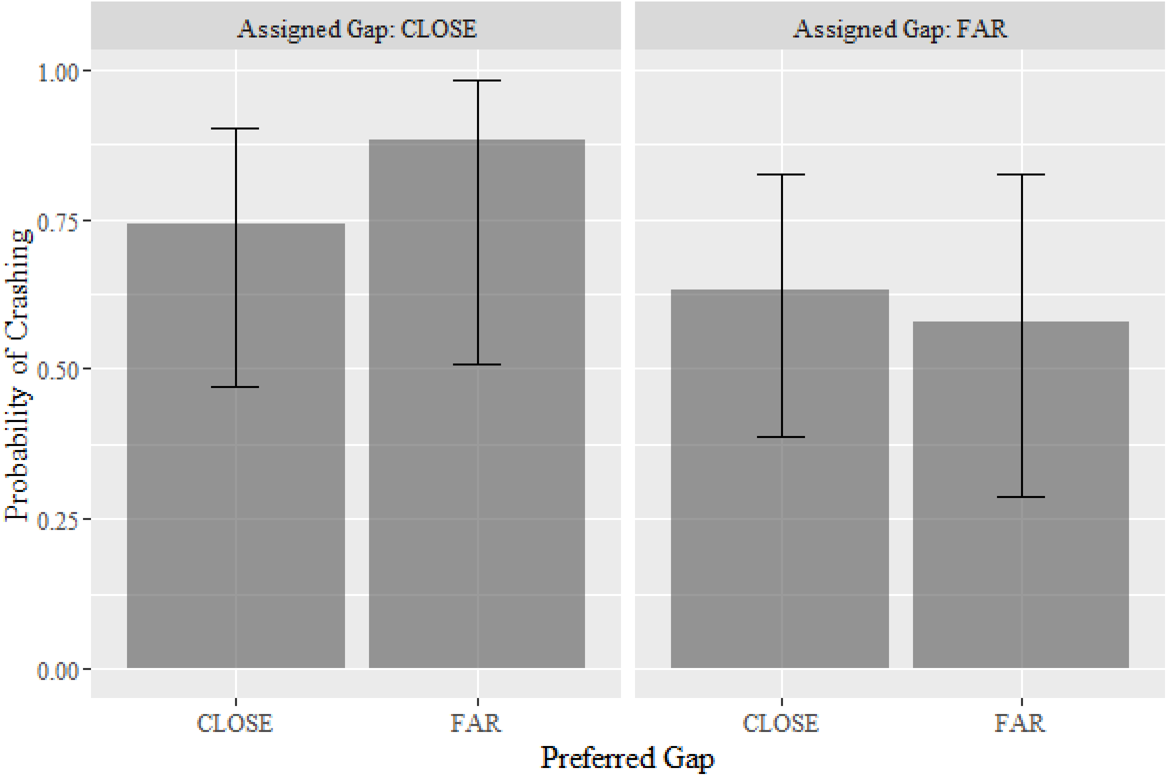

Figure 3. Graph. Probability of experiencing a crash based on both preferred and assigned following time gap.

CHAPTER 4. DISCUSSION

There were many goals of this study. The first part of this study sought to determine the typical range of the shortest time gap that drivers feel comfortable following. Participants drove in two scenarios where they were asked to follow a lead vehicle at a comfortable distance and at a minimally safe distance. The median gap from the minimum safe drive was used to classify participants in the second study as near or far preference followers.

In the second part, participants first drove in the two scenarios used in part one. The mean following distance from the minimum safe drive was used to determine participants' preferred following gap. Those who drove with a shorter gap than the median value from the first study were determined to be close (or near) followers, and those with longer time gaps were determined to be far followers.

Next, participants drove in a scenario with CACC engaged with either a near (0.6 s) or far (1.1 s) time gap. During that drive, a vehicle merged directly in front of the participant. Later, a vehicle out of direct line of sight crashed, which required the participant to take action to avoid collision. Driver performance during these two events and perceived workload were assessed.

As one might expect, drivers' perceived workload (as assessed by the NASA-TLX) varied by location at which it was administered. Not surprisingly, workload was the greatest after the final crash event. However, no significant variation between the workload after the initial merge event and a relaxed cruise time period was found. This provides evidence that participants felt that the CACC system was adequately able to allow space for a merging vehicle.

At the first vehicle merge event, only three people depressed the brake. While this highlights an overall trust in the system, foot hovering behavior highlighted that those people following at the near CACC setting were prepared to override the system if necessary as the other vehicle merged. This was independent of preferred following distance. That is, those participants who preferred to follow at closer time gaps were as likely to hover their foot over the brake pedal in anticipation of potentially overriding the CACC system as those who preferred to follow at longer time gaps.

During the emergency event, those participants assigned to drive at the closer following distance both reacted faster and had more crashes. Given that participants following closer had physically less distance to react to avoid a collision, it is not surprising that more of these participants experienced a collision.

Throughout the study, participants' following distance preference did not affect performance. In other words, participants' abilities may not necessarily reflect their following preferences. This is a promising finding for widespread implementation of CACC. While overall comfort level may vary across drivers, these findings support the idea that performance will depend more on overall CACC following distance settings than with drivers' personal preferences. This will allow CACC systems to implement a single following distance gap (or set of gaps based on vehicle physics). These results also highlight the need to implement well-designed human factors-based systems that clearly indicate to drivers when it is necessary to take over control of the vehicle.

Without such measures, it is possible that CACC implementation may not result in roadway safety improvements.

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