Preferred Following Distance as a Function of Speed—Function-Specific Automation (Level 1) Applications

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FOREWORD

The use of adaptive cruise control (ACC) is becoming more prevalent on today's roadways, while the research and development in cooperative adaptive cruise control (CACC) is increasingly mature. These systems have the potential to increase the safety and operational capacity of the roadway. It is notable that the potential impact that these systems will have on roadways will depend largely on the specific parameters used in their implementation, and the extent to which drivers feel comfortable accepting those parameters.

This report documents an experiment aimed at identifying comfortable gap distances used in ACC and CACC systems. This study used a variety of speeds that could be used to help guide set speeds for these systems. Participants drove an experimental course that included nine test speeds. The participants comfortable and minimally safe following gaps were recorded as they drove manually, and they rated their comfort level with the ACC gap distance at the same locations and speeds. The result was a creation of a set of comfortable and minimally safe following gap curves that were compared to the gap distance curve of an ACC system currently on the market.

This report is of interest to transportation engineers and researchers, ACC developers, State and local transportation agencies, and other roadway safety professionals interested in understanding how ACC and CACC systems will affect drivers and roadway safety.

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16. Abstract The gap distances used on adaptive cruise control (ACC) and cooperative adaptive cruise control (CACC) systems have important implications for both driver safety and transportation operations The current study sought to identify comfortable or preferred following gaps under a variety of speeds that could be used to help guide set speeds for ACC and CACC. Participants drove an experimental course that included nine test speeds ranging from 25 to 65 mi/h, once using ACC and once while driving manually. For each of the nine test speeds, comfortable and minimally safe following gaps were recorded as the participants drove manually. The participants also rated their comfort with the ACC gap distance at the same locations and speeds. The result was a creation of a set of comfortable and minimally safe following gap curves that were compared to the gap distance curve of an ACC system currently on the market.		
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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 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 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 (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for 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
CAN	car area network
CDC	Centers for Disease Control
GPS	Global Positioning System
LOESS	locally estimated scatterplot smoothing
M	mean
OSHA	Occupational Safety and Health Administration
OHRP	Office for Human Research Protections
RMS	remote monitoring system

INTRODUCTION

Adaptive cruise control (ACC) is a commercially available SAE International Level 1 automated system that is growing in popularity. Traditional cruise control systems allow a vehicle to automatically maintain a selected speed set by the driver. ACC builds on this type of system in that when a vehicle with ACC approaches a vehicle moving slower than the selected speed, the vehicle with ACC uses radar or lidar sensors to automatically maintain a preselected gap between it and the vehicle ahead.(1) Cooperative adaptive cruise control (CACC) builds on ACC by using dedicated communications to transmit data to, and receive data from, surrounding vehicles. This dedicated communication allows the system to respond to changes in speed and location of other CACC vehicles more quickly, even when the driver cannot see them.(2)

ACC is generally marketed as a convenience system that reduces stress and workload by relieving the driver of the need to continuously regulate vehicle speed and following distance.(3,4) However, these convenience benefits have potential implications for road safety. First, when in use, ACC keeps a vehicle driving at a consistent speed, which is a potentially valuable effect because increased speed variability has been associated with increased crash rates.(5) Additionally, ACC ensures that drivers maintain a consistent gap distance with the vehicle ahead. Even at its shortest setting, the gap distance maintained by ACC tends to be equal to or greater than that typically maintained during manual driving.(7) If ACC allows drivers to maintain a more consistent speed and greater following distance, then ACC could have positive effects on driver safety. CACC could further increase safety by allowing the vehicle to alter its speed and following distance in response to position and safety information that is directly delivered to the vehicle by surrounding traffic.

ACC and especially CACC use also have the potential to influence road network operation. CACC has the potential to decrease congestion by reducing the size of gaps between vehicles, increasing string stability within a platoon of vehicles, and increasing the capacity of highways.(2) Based on Monte Carlo simulations, van der Werf et al. estimated that both ACC and CACC use could lead to increased roadway capacity and that CACC market penetration could lead to quadratic increases in highway capacity that represented up to a 203-percent increase in capacity at full market penetration.(7) However, these potential safety and operational advantages of ACC can only occur if drivers feel comfortable using the technology.

CACC and ACC automatically modulate vehicle speed to maintain a set time-based following distance behind a slower-moving lead vehicle. Utilizing a time-based following distance results in an instantaneous position-based following distance that is variable across a range of speeds. For example, a 1.1 s following distance is a greater positional distance at 60 mi/h than at 25 mi/h. The findings of Goodrich and Boer suggest that users will accept ACC and CACC more readily if the gap distances employed by the systems align to a user acceptance curve, adjusting time gap with speed to match empirically-derived gap versus speed preferences.(9) At lower speeds, drivers are hypothesized to perceive a close following distance (in time) as more comfortable than at higher speeds.

The objective of this research is to develop time gap curves that describe comfortable and minimally acceptable following distances over a range of speeds, both with and without ACC engaged. Specifically, we compared the comfort level and minimally acceptable following distances over a range of speeds rates, when driving with ACC, to those found when driving manually. The primary analysis evaluated time gap as a function of vehicle speed, regardless of road type or posted speed limit. Comfort ratings were obtained at approximately one-minute intervals under normal driving conditions. The study sought to suggest design guidelines for both ACC and CACC by identifying comfortable or preferred set distances under a variety of speeds.

The COVID-19 pandemic lockdown posed some challenges at the end of the data collection task. To address those challenges, part of the experiment was conducted utilizing a remote monitoring system (RMS) in lieu of the experimenter and the participant sharing a vehicle cabin. The team also followed several cautionary steps to reduce the exposure risks, which were based on guidance and information from the Centers for Disease Control (CDC), Occupational Safety and Health Administration (OSHA), and Office for Human Research Protections (OHRP).

METHOD

PARTICIPANTS

Twenty-six drivers from the Washington, D.C. metropolitan area participated in the study. However, data from two participants were later dropped due to data acquisition system failure for one participant and strong resistance to use of the ACC system for the other participant. As a result, our analysis was based on 24 participants. All participants were over the age of 18 and under the age of 66. Approximately equal numbers of male and female participants were recruited for the study. Within gender groups, approximately half the participants were 45 years or older. Table 1 displays the proportion of participants who were male or female divided by age group. All drivers had a valid driver's license and met the following safe driving record criteria.

- Have a minimum of 20/40 vision uncorrected or with contact lenses.
- No DUI citations in the preceding 3 yr.
- No more than one reported crash in the preceding 3 yr.
- No reported crashes in the preceding yr.
- No more than one moving violation in the preceding 2 yr.

Table 1. Participant demographics

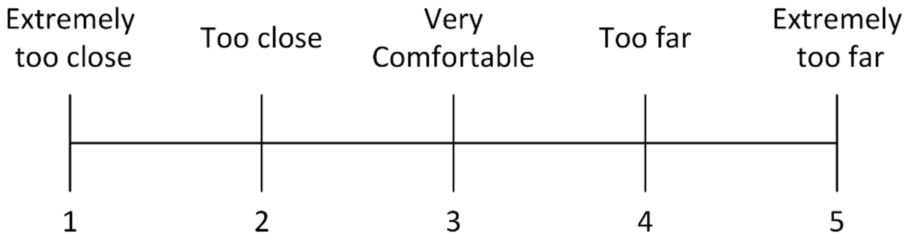
Age Groups	Female	Male
45 and older	6	5
Younger than 45	5	8
Total	11	13

EQUIPMENT

Participants drove two trips in a 2012 sedan. Participants followed a secondary lead vehicle that was also a sedan for the duration of the experiment. The participant vehicle was equipped with ACC. During the experimental drive, the ACC was set at the closest following distance and a system for recording car area network (CAN) data including following distance. Data was collected at a rate of at least 1 Hz.

DESIGN

Each participant completed two drives. First, the participant followed the lead vehicle normally without cruise control. Speed was dictated by the lead vehicle (manual). Then, the participant followed the lead vehicle with the ACC set with a close time gap. This, following condition, served as a within-subject independent variable. The order in which each following condition was driven was counterbalanced. Speed was also manipulated within subjects and ranged from 25 to 65 mi/h. Specifically, the nine test speeds were 25 mi/h, 30 mi/h, 35 mi/h, 40 mi/h, 45 mi/h, 50 mi/h, 55 mi/h, 60 mi/h and 65 mi/h. Dependent variables of interest included gap time and participant comfort level. Participant comfort level was assessed on the scale of 1–5 (figure 1).



Source: FHWA.

Figure 1. Illustration. Scale for rating comfort with the current following distance.

PROCEDURE

Each session began with participants reviewing and signing the informed consent form. Participants were then asked to show a valid driver's license and complete a brief visual screening to ensure a minimum 20/40 acuity (with correction if needed), which is the minimum visual acuity required to obtain a driver's license in most States. After these preliminary procedures, the participant was escorted to the research vehicle where they were introduced to its controls and displays.

Participants were instructed to follow the lead vehicle. If a nonlead vehicle cut in between the participant and the lead, the participant would then follow the cut-in vehicle as long as it remained in the same lane as the lead vehicle. When traffic was congested, cut-ins were more likely. The dependent and independent following distance variables were related to the vehicle directly ahead, and not necessarily the lead experimenter vehicle. When the participant vehicle fell behind because of a cut-in, the lead driver continued to the next planned roadway. The lead driver would then find a safe place to park on the side of the road, wait for the participant to appear, and then merge into traffic ahead of them.

Figure 2 contains a map of the test route where the participants followed the lead vehicle. It also contains the estimated prompt locations. Segments marked as "transition" required the participants to make potentially hazardous driving maneuvers, such as changing lanes and entering/exiting highways. Therefore, the transition segments did not contain prompts, and the participants were not instructed to use ACC. In figure 2, the transition segments are marked with a thin black line, and the text segments are marked with a thick blue line.

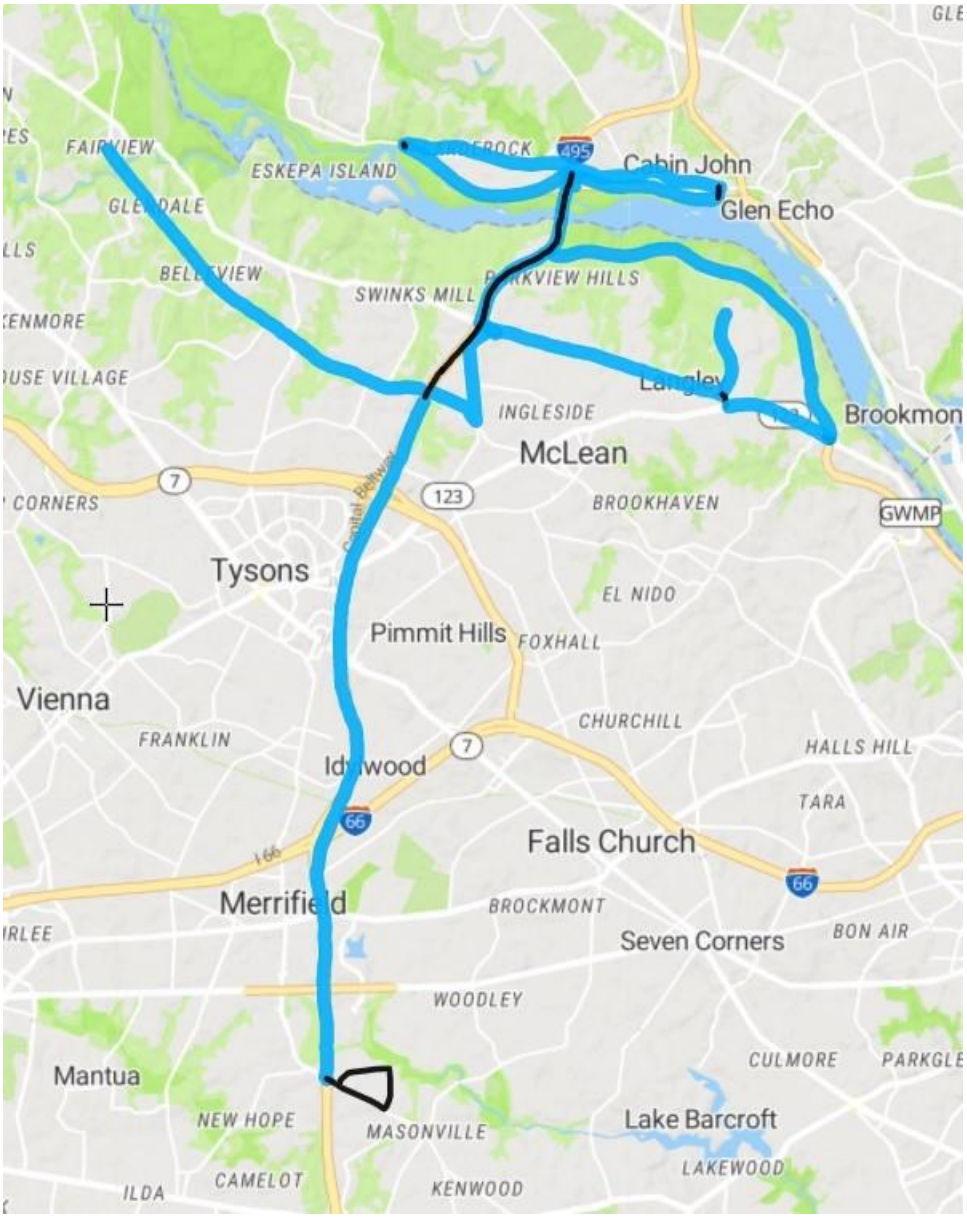


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Figure 2. Map. Experimental route.

The participants started the first trial at the Turner-Fairbank Highway Research Center (TFHRC), McLean, Virginia. They traveled west on Dolly Madison Boulevard to Old Dominion Drive, then turned around and drove back on Old Dominion Drive to I–495 south. While on I–495 south, they were asked to enter the I–495 express lanes and continue until they reached the Gallows Road exit, where they turned around and returned to the I–495 north express lanes. From the I–495 express lanes, they drove to the George Washington Parkway until they reached Dolly Madison Boulevard and exited the parkway. They traveled on Dolly Madison Boulevard until they reached Georgetown Pike, which they turned onto, followed immediately by a right turn onto Colonial Farm Drive. They then drove on Colonial Farm until just before the TFHRC entrance. This point marked the end of trial 1.

During the drive, the lead vehicle dictated the speed by driving ±5 mi/h the posted speed limits. The result was the creation of nine different speed segments during each drive. Table 2 contains detailed information on the test route segments, such as distance, posted speed limits, and test speed.

Table 2. Test route.

Segment	Road Name	Start Point	End Point	Distance (mi)	Posted Speed Limit (mi/h)	Test Speed (mi/h)
1	Colonial Farm Rd.	TFHRC	Georgetown Pike	0.768	25	25
2	Georgetown Pike	Colonial Farm Rd.	Balls Hill Rd.	2.25	35	35
3	Balls Hill Rd.	Georgetown Pike	Old Dominion Blvd.	0.893	35	30
4	Old Dominion Dr.	Balls Hill Rd.	Falls Run Rd.	4.35	40	40
Transition	Falls Run Rd.	Old Dominion Dr.	Old Dominion Blvd.	0.217	n/a	n/a
5	Old Dominion Dr.	Falls Run Rd.	Balls Hill Rd.	4.35	40	45
6	Balls Hill Rd.	Old Dominion Dr.	Georgetown Pike	0.977	35	35
Transition	I–495 inner loop	Georgetown Pike	Clara Barton Pkwy.	1.93	n/a	n/a
7	Clara Barton Pkwy.	I–495	Macarthur Blvd.	1.22	50	50
Transition	Clara Barton Pkwy.	Clara Barton Pkwy.	Macarthur Blvd.	0.457	n/a	n/a
8	Macarthur Blvd.	Clara Barton Pkwy.	I–495 Overpass	1.55	30	30
9	Macarthur Blvd.	I–495 overpass	Seven Locks Rd.	0.951	30	25
Transition	Macarthur Blvd.	Seven Locks Rd.	Clara Barton Pkwy.	0.728	n/a	n/a
10	Clara Barton Pkwy.	Macarthur Blvd.	I–495 outer-loop	1.05	50	50
Transition	I–495 outer-loop	Clara Barton Pkwy.	I–495 outer-loop express lanes	2.96	n/a	n/a
11	I–495 outer-loop express lanes	I–495 outer-loop	Gallows Rd	6.48	65	65

Segment	Road Name	Start Point	End Point	Distance (mi)	Posted Speed Limit (mi/h)	Test Speed (mi/h)
Transition	Gallows Rd./Holmes Rd.	Gallows Rd.	I–495 inner loop express lanes	1.15	n/a	n/a
12	I–495 inner-loop express lanes	Gallows Rd.	I–495 end of express lanes	6.25	65	60
Transition	I–495 inner-loop	I–495 end of express lanes	GW Pkwy.	2.18	n/a	n/a
13	GW Pkwy.	I–495 inner-loop	CIA Bridge	2.06	50	50
14	GW Pkwy.	CIA Bridge	GW Pkwy. Chain Bridge exit	1.53	50	55
Transition	Chain Bridge Rd.	GW Pkwy.	GW Pkwy.	0.338	n/a	n/a
15	GW Pkwy.	Chain Bridge Rd.	CIA Bridge	1.21	50	55
Transition	CIA Bridge	GW Pkwy.	GW Pkwy.	0.613	n/a	n/a
16	GW Pkwy.	CIA Bridge	Dolly Madison Blvd.	1.18	50	55
Transition	GW Pkwy. exit ramp	GW Pkwy.	Dolly Madison Blvd.	0.131	n/a	n/a
17	Dolly Madison Blvd.	GW Pkwy. exit ramp	Georgetown Pike	0.874	45	45
Transition	Georgetown Pike	Dolly Madison Blvd.	Colonial Farm Rd.	0.126	n/a	n/a
18	Colonial Farm Rd.	Georgetown Pike	GW Pkwy. entrance ramp	0.768	25	25
—	—	—	Transition Total	10.83	—	—
—	—	—	Segment Total	38.711	—	—
—	—	—	Trip Total	49.541	—	—

—No data.
Blvd. = Boulevard; CIA = Central Intelligence Agency; Dr. = Drive; GW = George Washington; n/a = not applicable; Pkwy. = Parkway; Rd. = Road.

The participants completed the experimental route twice, once with ACC engaged and once while driving manually. At predesignated points along the route, the experimenter would make comfort and minimally acceptable speed ratings. During the ACC trial, the remote experimenter asked the participants, on a scale of 1–5, how comfortable they were with the following distance. The ratings were obtained at approximately 1-minute intervals under normal driving conditions, but always at the same prompt locations along the route (i.e., rating responses will be prompted by location rather than time). The participants reviewed the rating scale before the drive began and provided verbal responses that were recorded by a research assistant. The time and location of participants' rating responses were synchronized with vehicle, radar, and Global Positioning System (GPS) data by entering responses into a unified recording stream.

During the manual driving trial, participants' comfort ratings were not recorded. Instead, for half of the prompt locations, the experimenter flagged the following distance data at the prompt locations. The time gaps at these locations were assumed to be the participants' comfortable or preferred following distances during manual driving. For the other half of the prompt locations, the experimenter prompted the drivers to approach the lead vehicle and briefly follow the lead vehicle at the closest following distance they felt was safe and then resume following at a comfortable distance. This distance was flagged as the minimally acceptable following distance. Thus, the minimally acceptable and comfortable following distance observations occurred at approximately the same prompt locations as in the ACC trials. Each of the nine speed segments contained two minimum safe distance observations and two comfortable observations.

After the drive, participants completed a brief questionnaire wherein they indicated how familiar they were with ACC before the drive, how familiar they were with the experimental route, how long they have had their license, and how frequently they drove. The participants were then debriefed and compensated for their time.

Table 3 shows the target test speeds used in the study along with the distance that the participants were expected to drive at that speed. Test speed ranged from 25 mi/h to 65 mi/h in 5 mi/h increments. Note that table 3 only includes the cumulative distance for test segments that contain prompts. Transition segments are excluded from table 3.

Table 3. Cumulative distance (mi) traveled on test segments as a function of test speed limit (mi/h).

Speed (mi/h)	Distance (mi)
25	2.49
30	2.44
35	3.23
40	4.35
45	5.22
50	4.33
55	3.92
60	6.25
65	6.48
Total	38.71

Data collection occurred both before and after the COVID-19 pandemic lockdown. Data collection was suspended for several months when the pandemic began. When data collection resumed, the research team took several steps to reduce the risk of disease transmission based on guidance from CDC, OSHA, and OHRP. All study equipment and common touch surfaces were sanitized both before and after each data collection session. Participants and research personnel wore face masks during data collection and engaged in social distancing as much as possible. Before the lockdown, an experimenter rode in the backseat of the participant vehicle, where they provided instructions and recorded participants' responses. After the lockdown, the team utilized an RMS in lieu of the experimenter and the participant sharing a vehicle cabin. The RMS leveraged three inputs to monitor the participant and vehicle: cameras, a microphone, and a vehicle CAN connection. This allowed the experimenter to monitor and communicate with the participant from a remote location.

ANALYSIS

Time gap data for each of the nine test speeds were binned according to recorded vehicle speed rather than posted speed limit. Thus, for both test conditions, time gaps and comfort ratings were binned into the mi/h categories shown in table 4. This binning approach enabled several analyses to be conducted.

Table 4. Speed in mi/h categories for binning following distance and following distance comfort ratings.

Test Speed (mi/h)	Speed (mi/h) Greater Than	Speed (mi/h) Less Than Or Equal To
25	22.5	27.5
30	27.5	32.5
35	32.5	37.5
40	37.5	42.5
45	42.5	47.5
50	47.5	52.5
55	52.5	57.5
60	57.5	62.5
65	62.5	67.5
70	67.5	—

—No data.

The maximum possible number of observations per participant was 72 (36 ACC, 36 manual), but uncontrollable factors related to testing on public roads, such as slower moving traffic that prevented the participant vehicle from reaching its target speed, reduced the number of participant observations that were recorded. During data collection, there were 816 (Mean (*M*) = 34 observations per participant) ACC trial observations and 829 (*M* = 34.5 observations per participant) manual trial observations captured from the participants.

In the analysis, ratings with gap distances greater than 6 s were removed because they were deemed not informative. Removing this data reduced the data to 804 ACC observations and 816 manual observations. In addition, the reduced data showed most of the observations had gap distances less than 3 s (90th percentile = 2.97 s.) Thus, an additional analysis on this majority group, including 761 ACC observations and 789 manual observations, was further conducted.

For comfort ratings, few participants used the extreme ends of the rating scale. Too close ratings made up only 6.9 percent of total responses, whereas too far ratings made up only 0.9 percent. Therefore, participant responses were regrouped from five into three rating levels: Extremely too close and too close ratings were combined, and extremely too far and too far ratings were combined.

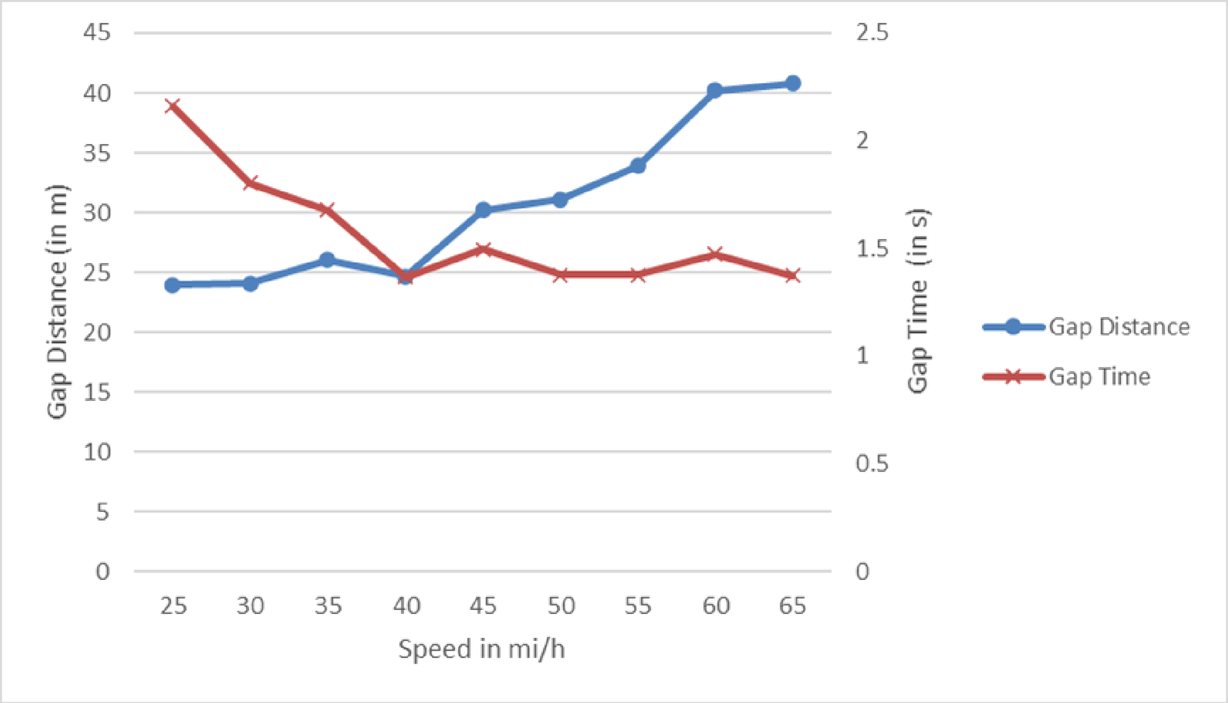
RESULTS

To address the research goal, the following three scenarios were considered from the data:

1. ACC trial comfort ratings with respect to time gap and speed.
2. Manual trial gap distances (comfortable/minimum safe) with respect to speed.
3. "Comfortable" ACC and manual driving with respect to time gap and speed.

ACC TRIAL

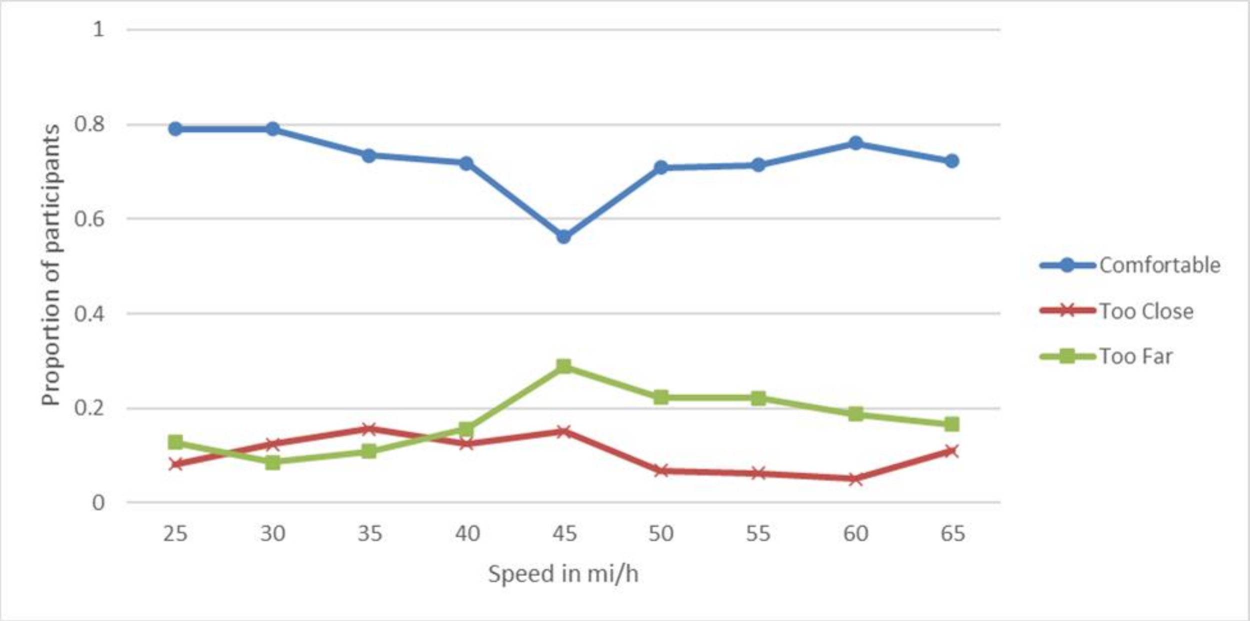
ACC is designed to keep the participant vehicle at a set distance from the vehicle ahead. The distance is generally based on time, such that as speed increases or decreases. The distance between the participant and the lead vehicle will also vary, but the following time gap will remain roughly the same. To test this assumption, the analysis was initiated by assessing the actual time and distance gaps recorded across the test speeds (figure 3). In figure 3, the ACC appears to shift from use of a stable gap distance to stable gap time at approximately 40 mi/h. That is, at speeds 40 mi/h and greater, gap time remains relatively stable at approximately 1.4 s, while gap distance increases as expected to maintain the stable time gap. However, at speeds less than 40 mi/h, gap distance remains relatively stable at approximately 24 m, while gap time increases with reduced speed to maintain the stable gap distance. It seems that the manufacturer of the ACC system used in this study used 24 m as a minimum allowable safe gap, and only transitioned to dictating following speed based on gap time once that distance had been surpassed (at approximately 40 mi/h).



Source: FHWA.

Figure 3. Chart. ACC gap distance and time as a function of speed.

Figure 4 shows the proportion of participants who rated the gap they experienced during the ACC trial as comfortable, too far, and too close as a function of speed. Most of the participants rated the gap provided by the ACC as comfortable consistently across speeds. A small dip in comfort ratings was found at approximately 45 mi/h. At this speed, more participants felt that the set gap was too far from the lead vehicle. It is noteworthy, that even at this speed, when approximately one-third of the participants felt the gap distance was too far, another 15 percent of the participants reported that same distance to be too close.

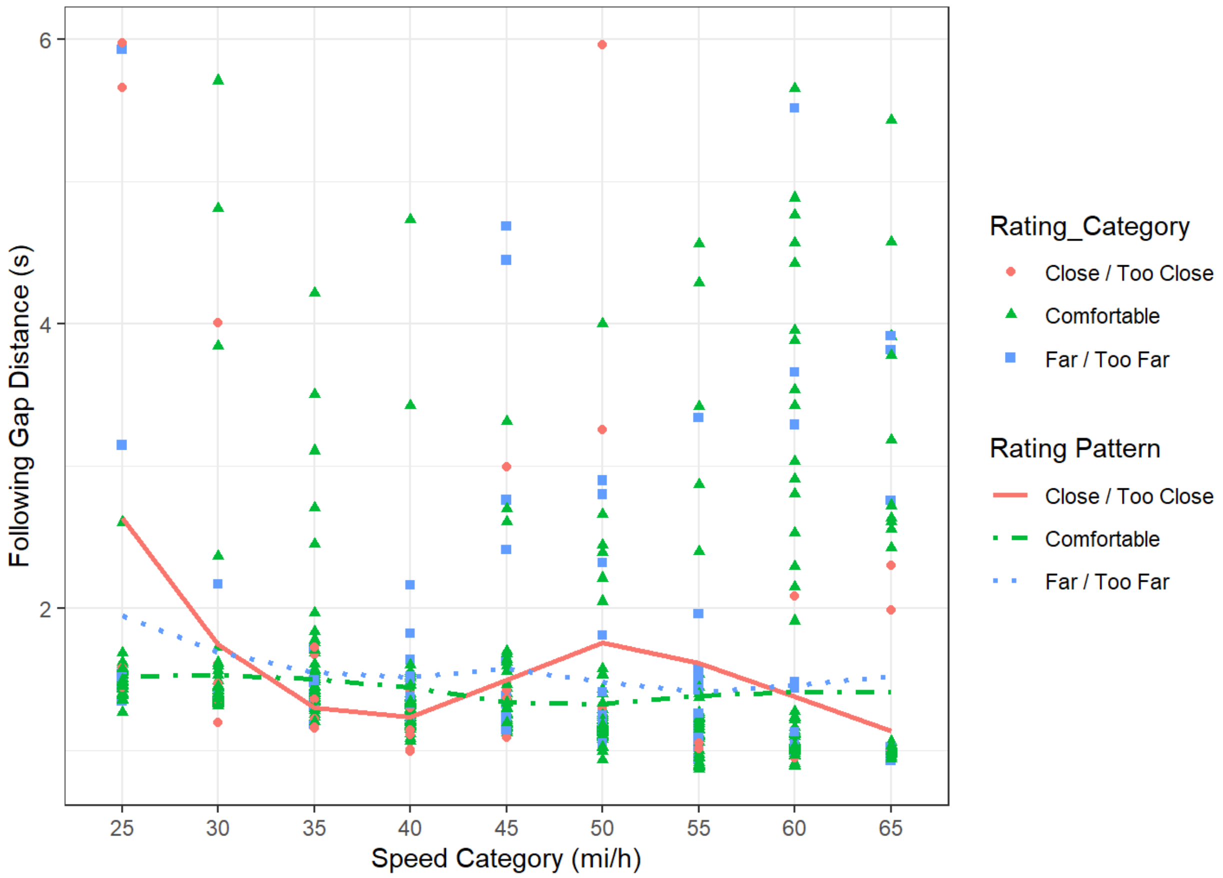


Source: FHWA.

Figure 4. Chart. Proportion of participants who rated the ACC gap distance as comfortable, too close, or too far as a function of speed.

Since actual gap distance varied slightly across participants, comfortable gap curves were created using both speed and following distances. Figure 5 contains a graph of the comfort ratings from the ACC trial as a function of speed (mi/h) and following distance (s). The far/too far curve contains 137 observations, the comfortable curve contains 584 observations, and the close/too close category contains 83 observations.

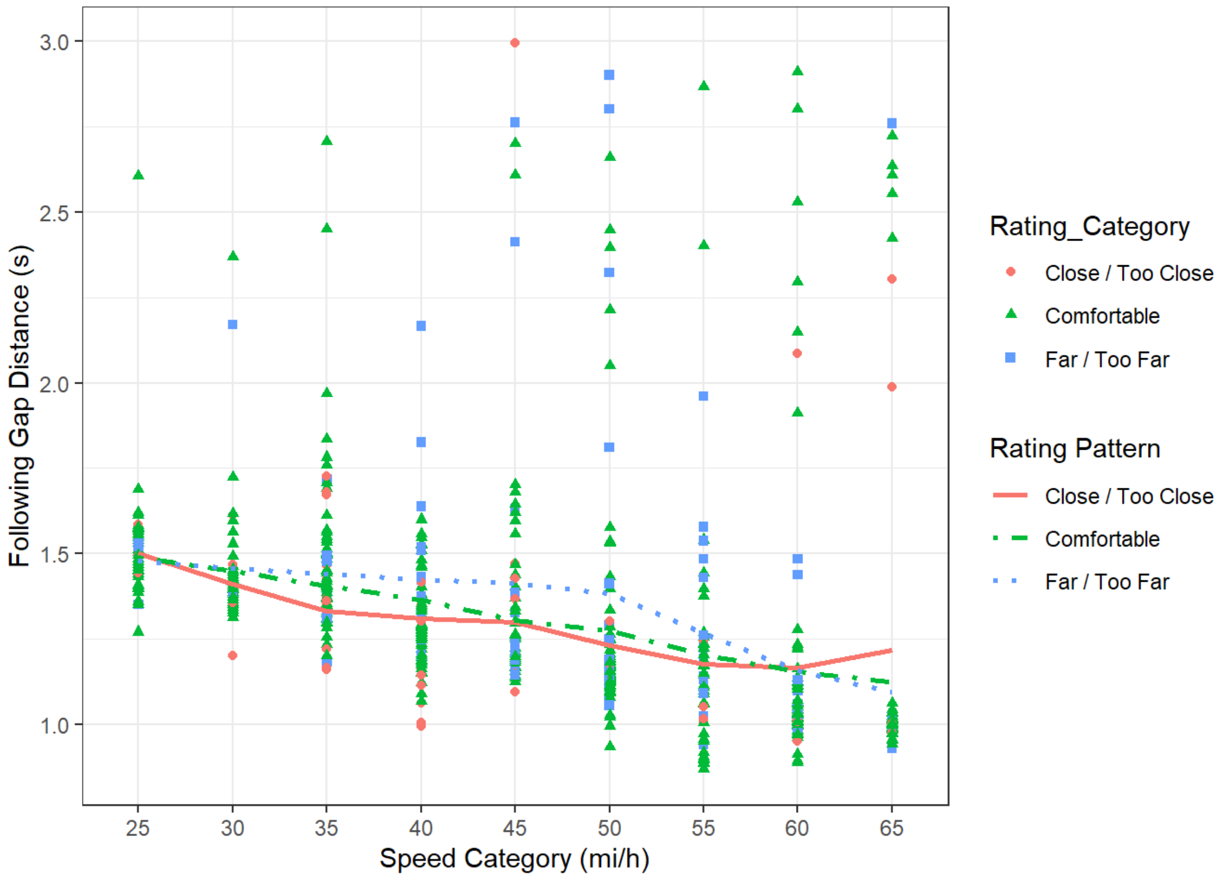
Figure 6 was created under the same setting as figure 5 but based on the observations with gap distances less than 3 s. In this subset, the far/too far curve contains 127 observations, the comfortable curve contains 556 observations, and the close/too close category contains 78 observations.



Source: FHWA.

Note: Each dot represents a data point. A local regression (locally estimated scatterplot smoothing (LOESS)) smoothing technique is used to create the overall patterns of following gap distance in seconds over speed.

Figure 5. Graph. Plot of ACC comfort rating time gap versus speed curves.



Source: FHWA.

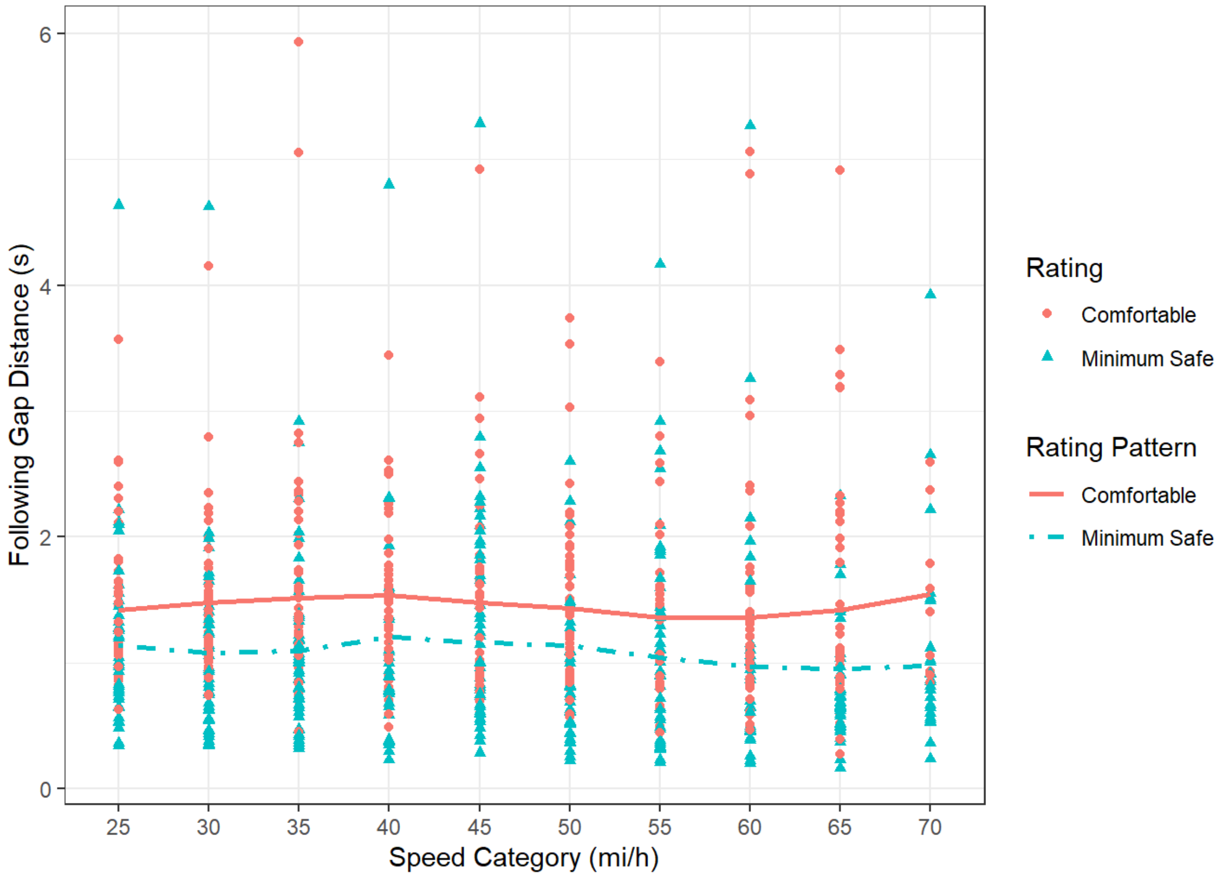
Note: Each dot represents a data point. A local regression (LOESS) smoothing technique is used to create the overall patterns of following gap distance in seconds over speed.

Figure 6. Graph. Plot of ACC comfort rating time gap versus speed curves for gap distances 3 s or less.

MANUAL TRIAL

Figure 7 contains a graph of comfortable and minimum safe ratings from the manual driving trial as a function of speed (mi/h) and following gap distance (s). Observations were binned into 10 speed range categories. There is a total of 394 minimum safe following distance observations and 422 comfortable following distance observations.

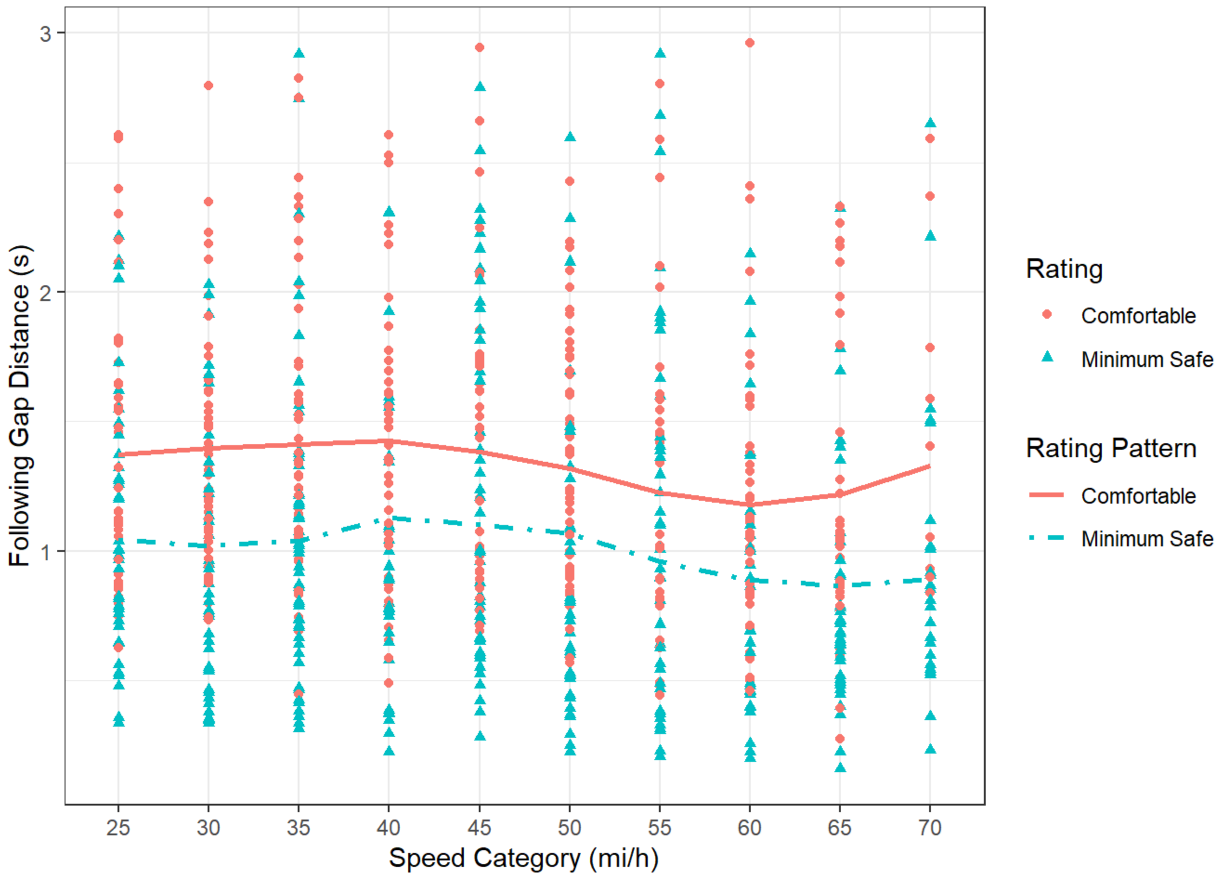
Figure 8 was created under the same setting as figure 7 but based on the observations with gap distances less than 3 s. In this subset, there were 386 minimum safe following distance observations and 403 comfortable following distance observations. As displayed in figure 7 and figure 8, the average distance between drivers' comfortable following distance and minimum safe following distance are approximately 0.39 s and 0.35 s, respectively, and that distance remains relatively stable across speeds.



Source: FHWA.

Note: Each dot represents a data point. A local regression (LOESS) smoothing technique is used to create the overall patterns of following gap distance in seconds over speed.

Figure 7. Graph. Plot of manual driving minimum safe and comfortable time gap versus speed curves.



Source: FHWA.

Note: Each dot represents a data point. A local regression (LOESS) smoothing technique is used to create the overall patterns of following gap distance in seconds over speed.

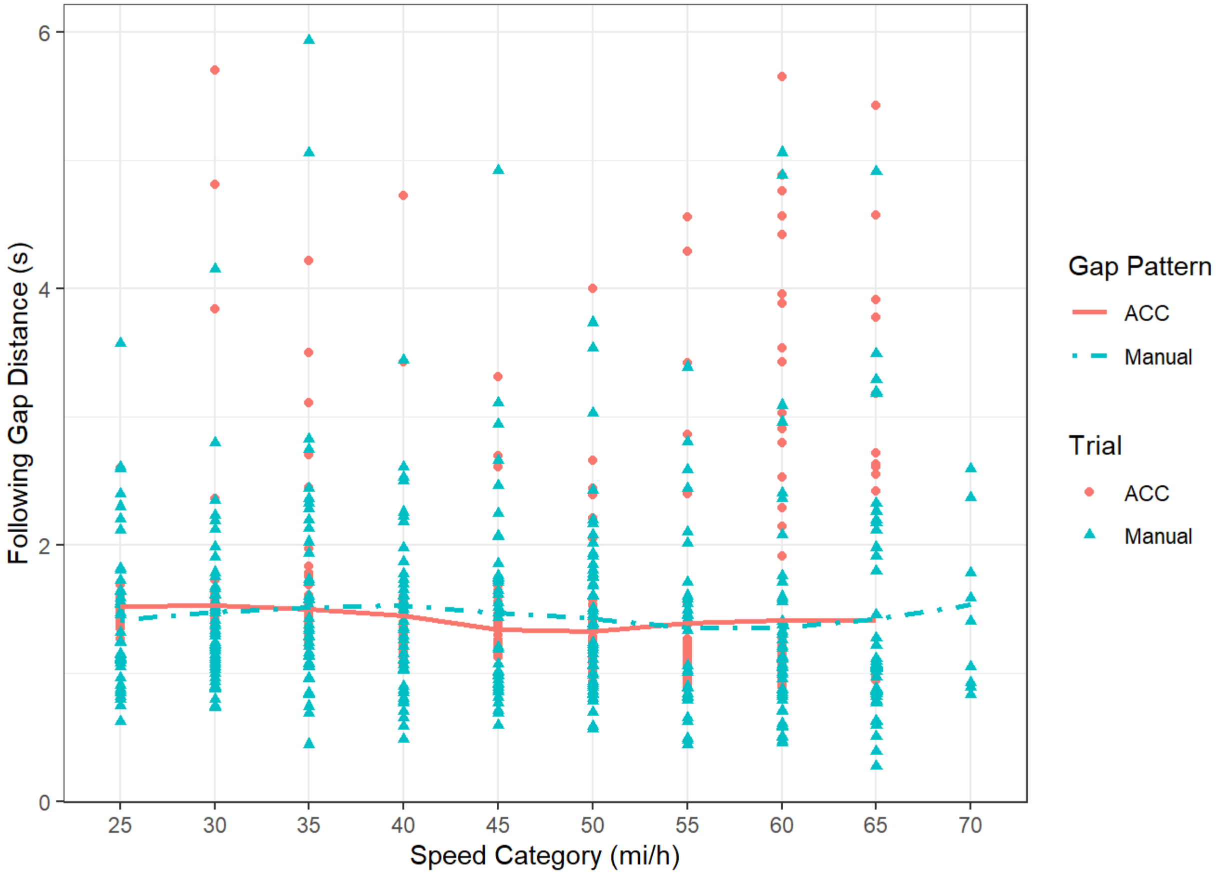
Figure 8. Graph. Plot of manual driving minimum safe and comfortable time gap versus speed curves for gap distances 3 s or less.

COMFORTABLE ACC AND MANUAL TRIALS

Finally, the research team assessed the extent to which the distances rated as “comfortable” during the ACC trial matched the following distances recorded during the manual condition when participants were driving at their preferred following distance. Figure 9 contains the observations rated as “comfortable” for both ACC and manual trials as a function of speed (mi/h) and following gap distance (s). Close and far observations from the ACC trials and minimum safe observations from the manual trials were removed in addition to any observations with a following distance greater than 6 s.

Figure 10 was created under the same setting as figure 9 but based on the observations with gap distances less than 3 s. As is displayed in figure 9 and figure 10, ACC gap distances tended to be rather similar to the gap distances maintained by participants when driving manually. At the lowest speeds (25–30 mi/h), ACC seems to select a more conservative gap distance than participants driving manually. The opposite pattern is seen within the 40–45 mi/h speed range, where the ACC maintains a slightly closer gap distance than participants driving manually.

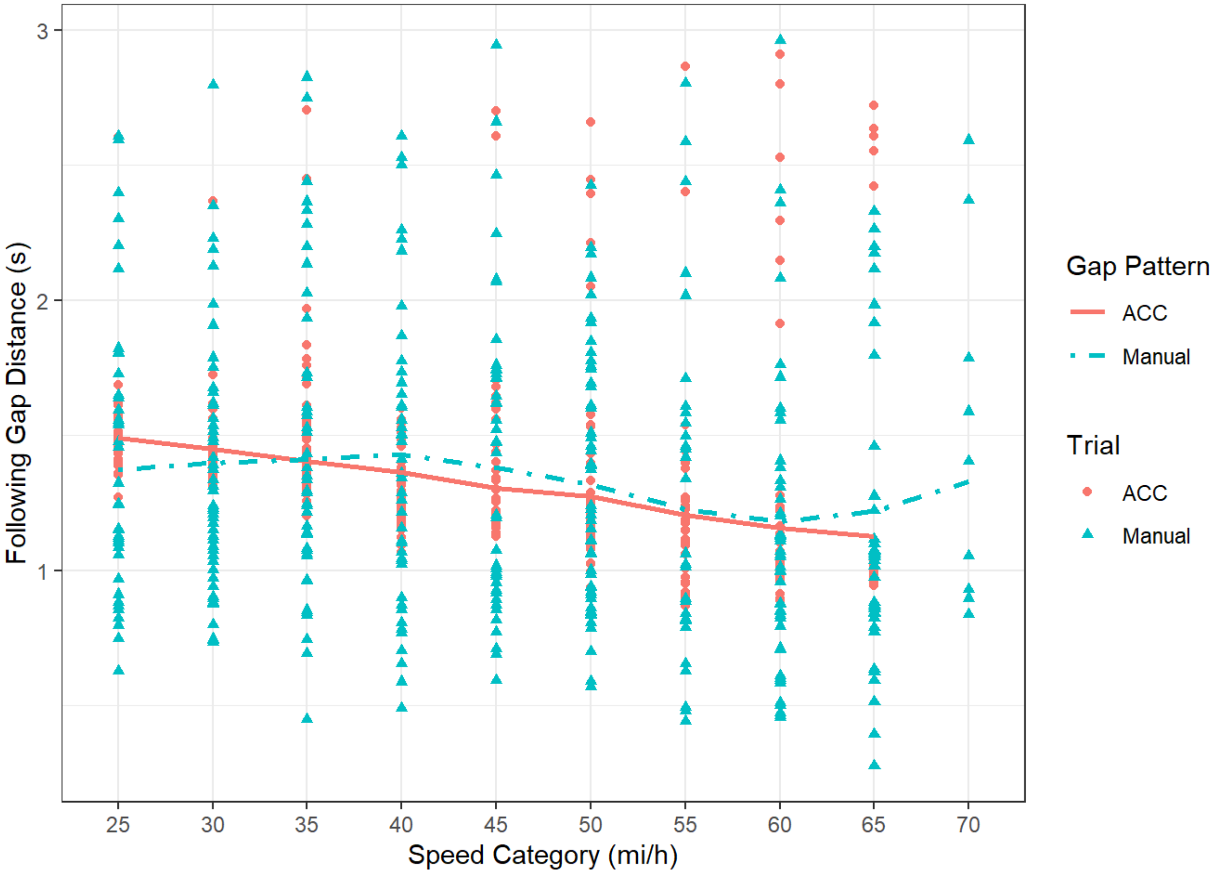
Manual drivers also selected a greater time gap than the ACC at the highest test speed (65 mi/h), when examining only following distances that were less than 3 s.



Source: FHWA.

Note: Each dot represents a data point. A local regression (LOESS) smoothing technique is used to create the overall patterns of following gap distance in seconds over speed.

Figure 9. Graph. ACC and manual trial comfortable observations as a function of time gap versus speed.



Source: FHWA.

Note: Each dot represents a data point. A local regression (LOESS) smoothing technique is used to create the overall patterns of following gap distance in seconds over speed.

Figure 10. Graph. ACC and manual trial comfortable observations as a function of time gap versus speed for gap distances 3 s or less.

DISCUSSION

The current study sought to identify comfortable or preferred following gaps under a variety of speeds that could be used to help guide set speeds for ACC and CACC. Participants drove an experimental course that included nine test speeds ranging from 25 to 65 mi/h, once using ACC and once while driving manually. For each of the nine test speeds, comfortable and minimally safe following gaps were recorded as the participants drove manually. The participants also rated their comfort with the ACC gap distance at the same locations and speeds. The study enabled the creation of a set of comfortable and minimally safe following gap curves that could be compared to the gap distance curve of an ACC system currently on the market.

Gap distance can be measured using either time or distance. The size of the distance gap between vehicles has the potential to influence fuel economy, since short distances can reduce drag.(9) As a result, it is sometimes hypothesized that freight vehicles, particularly freight vehicles using CACC or automated driving systems, may utilize distance gaps rather than time gaps to improve fuel economy on long haul drives.(10) However, ACC and CACC systems utilized by passenger vehicles tend to be based on time gaps, rather than distance gaps, as time gaps tend to more closely mirror the following distances used by drivers.(11)

Examination of the gap distances generated by the ACC in the current study found that the system used a combination of distance and time gaps, depending on the speed at which the vehicle was traveling. Specifically, at slower speeds (i.e., those less than 40 mi/h), the ACC system tended to use a set gap distance (near 24 m), whereas for speeds 40 mi/h and higher, the gap distance appeared to be based on a set gap time (near 1.4 s). It is likely that at slow speeds, the physical gap distance that would be generated by maintaining the 1.4 s gap time was deemed too close to be safe, such that a minimum gap distance was implemented. This change in the ACC setting from gap time to gap distance at the low speeds could explain why the comfortable gap distances that manual drivers maintained at low speeds were closer than the gap distances maintained by the ACC.

When asked to rate the gap distance provided by the near setting of the ACC, most of the participants in the current study rated the gap distances maintained by the ACC system as comfortable, across all of the tested speeds. Even at 45 mi/h, when the proportion of participants who rated the ACC's gap distance as comfortable was the lowest, more than half (56 percent) of participants felt comfortable with the assigned speed. The results suggest that the ACC system is likely to be valued and used by participants.

When participants were not comfortable with the speed of the ACC, they tended to rate the ACC distance as being too far from the lead vehicle. This tendency was especially prevalent for high speeds (i.e., 45 mi /h and higher). This finding is consistent with previous work on gap distances. For example, when given a choice of a range of CACC gap settings, Nowakowski et al. found that drivers elected to set the gap at 0.7 or 0.6 s 80 percent of the time.(6) Similarly, when Xiong, and Boyle allowed drivers with ACC to select between three gap sizes, participants selected the shortest gap size more often on the highway than during nonhighway driving.(12) Drivers appear to be comfortable using the gap sizes established by ACC but may sometimes express a preference for shorter distances when driving at high speeds.

The current study generated gap distance curves for both comfortable and minimally safe following distances. In general, the distance at which participants felt comfortable following a vehicle was about a third of a second farther than the minimum safe distance at which they were willing to follow the vehicle. Previous work has noted that preferred gap distance can be influenced by factors such as speed, road type, and congestion level.(12) The current study builds on previous work by helping to define the boundary conditions of drivers' comfort. The gap curve generated in the current study could be used to guide ACC and CACC manufacturers as they attempt to determine the parameters of their systems.

It is interesting to note that when ACC gaps and comfortable manual gaps were compared, the two curves were fairly similar, with the largest variations occurring at the extreme ends of the speed profile. As noted in the results section, at very low speeds, the participants tended to maintain gap distances that were closer to the vehicle ahead than the gap distances set by the ACC system. However, for the remaining speeds, the participants' chosen gap distances were slightly farther away than that maintained by the ACC system. While the actual differences in gap size were small, the finding contrasts with previous work noting drivers' preferences for shorter gap distances (particularly at high speeds) and even with the comfort level ratings expressed in the current study.(7,12) However, that drivers' subjective opinions about gap size may not always match their objective behavior is not surprising. Previous work has noted that a driver's preferred following distance is not correlated with their ability to respond during emergency situations.(11,13) The finding highlights the importance of using objective driving metrics when making decisions about gap distance parameter design.

The gap distances used on ACC and CACC systems have important implications for both driver safety and transportation operations. ACC systems have potential safety benefits.(4,9,12) However, these benefits will only occur if drivers feel comfortable utilizing the system. The gap distances maintained by the system can influence driver comfort, and ultimately driver use. ACC gap distances also have implications for transportation operations. ACC has the potential to increase string stability within a platoon of vehicles, thereby increasing traffic flow and reducing emissions.(2) However, ACC systems that use following distances that are greater than those used by manual drivers can still lead to increased congestion, particularly when ACC penetration rates increase.(14) Therefore, ACC and CACC systems will provide their greatest benefit if they use the minimum following distance at which drivers' safety and comfort can be maintained. The gap speed curves generated by the current study can help guide manufacturers as they strive to select ACC and CACC parameters that optimize both the safety and operation impacts of these systems on the road network.

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