Exploring the Effects of Vehicle Automation and Cooperative Messaging on Mixed Fleet Eco-Drive Interactions

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Highway Research Center

FOREWORD

In recent years, motor vehicle driving automation systems have undergone rapid growth and development. As the current vehicle fleet becomes increasingly more automated, vehicles with engaged driving automation features must be able to interact with roadway infrastructure. The Federal Highway Administration, in conjunction with the Intelligent Transportation Systems Joint Program Office Automation Program, funded research that investigates the safe operation of automated vehicles in relation to infrastructure. The project focuses on SAE International® Level 2™ and Level 3™, which apply to driving automation taxonomy.(1)

As part of this project, the research team explored the effects of automated driving and cooperative driving automation technology on the behavior and perceptions of drivers who followed a lead vehicle equipped with eco-driving strategies as it approached an intersection. This report will interest infrastructure owner–operators and other professionals who are examining how vehicle automation will interpret the roadsides and road users.

John A. Harding
Director, Office of Safety and Operations,
Research and Development

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16. Abstract

Driver assistance systems that facilitate economical driving (eco-driving) aim to reduce greenhouse gas emissions and improve vehicle efficiency. These systems reduce idling time at intersections and smooth acceleration and deceleration patterns. Eco-driving has the potential to improve driving comfort by smoothing speed profiles. This study explores the behavior of drivers who followed a lead vehicle that demonstrated eco-driving strategies, such as reducing speed ahead of a signal change to minimize idling time at the intersection. The participants received cooperative driving automation (CDA) messages about the upcoming signal change or that shared the intent of the lead vehicle. The participants drove under one of four conditions: without adaptive cruise control (ACC) or CDA enabled, with ACC enabled, with CDA messages enabled, or with CDA messages and ACC both enabled. The four levels of CDA messages were no message, vehicle-to-vehicle (V2V) lead vehicle intent sharing, vehicle-to-infrastructure (V2I) signal status message, and both messages. The field research vehicle recorded speed, braking variability, and following distance from each participant's vehicle. After each trial, the researchers asked the participants about their trust in the vehicle they had been following. The team analyzed speed and acceleration profiles to assess differences in fluctuation in different signal phasing conditions. Statistical analyses aimed to understand the impact of ACC status and CDA messages on driver behavior. The team used mid- and postexperiment questionnaires to evaluate the drivers' experiences and acceptance of lead vehicle, CDA messaging, and vehicle automation technology. The study's findings suggest that drivers in ACC-enabled vehicles could follow the eco-driving vehicle with more ease than drivers in conventional vehicles. The impact of CDA messages was not unanimous for all the scenarios. V2V messages helped ACC-enabled vehicle drivers, and V2I messages helped conventional vehicle drivers to some degree. The study found the participants had high trust ratings on lead vehicles and CDA messages. Overwhelming evidence of acceptance of vehicle automation was not observed, although the study showed slightly higher perceptions of safety gain than loss.

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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
ADS	automated driving system
C-ADS	cooperative automation driving system
CAN	controller area network
CDA	cooperative driving automation
eco-driving	economical driving
eco-mode	economical mode
FHWA	Federal Highway Administration
M2M	machine-to-machine
V2I	vehicle-to-infrastructure
V2V	vehicle-to-vehicle

CHAPTER 1. INTRODUCTION

Advanced vehicle technologies, such as driving automation and cooperative driving automation (CDA), are gradually being introduced to road users on public roadways.(2) Driver assistance (SAE International Levels® 0–2™) or automated driving features (Levels 3–5™) automate many specific driving functions.(1) Examples of such functions include using adaptive cruise control (ACC) to maintain speed and headway and using machine-to-machine (M2M) communication to enable two or more entities to wirelessly transmit electronic data.(1) Evaluating the interactions among drivers, surrounding vehicles, systems, and roadway infrastructure ensures safe and successful implementation of driving automation technologies. If the interactions are not considered, drivers may become disinterested in, or distrustful of, driving automation, which may cause drivers to risk their safety and the safety of others. Therefore, challenges remain in the ways to cultivate adequate benefits of automation technology.

Transportation practitioners design and develop the roadway infrastructure to accommodate human drivers. Effectively incorporating driving automation technology into roadway design can impose additional needs on the infrastructure, which can create challenges with safely and successfully introducing driving automation and CDA features.(3) Because transportation practitioners have designed roadways for human drivers, incorporating physical and digital infrastructure that can be reliably detected and processed by vehicle systems will take time.(4) In addition, advanced driving automation and CDA systems becoming common on public roadways will also take time. Consequently, the gradual introduction of infrastructure and automated vehicle technologies will result in vehicles equipped with advanced vehicle technologies sharing the roadway with conventional vehicles. Interacting with vehicles of varying driving automation levels and CDA capabilities may confuse drivers and lead to unpredictable behaviors, particularly when some of the automated vehicles operate based on information that is only available through CDA systems.

In January 2020, the Federal Highway Administration (FHWA) held a workshop with experts and stakeholders in automated and cooperative driving systems, infrastructure, and human factors. The workshop participants discussed key research areas related to safe and successful operation of automated driving systems (ADSs) on the roadways.(5) The most important research areas the participants identified are mixed fleet scenarios involving vehicles with varying levels of driving assistance, driving automation, and CDA technologies. Another important research area they identified for further exploration is the influence of varying levels of information and vehicles with and without M2M communication or CDA. The workshop participants prioritized these research areas because they are relevant in the near term, have a potential impact on roadway safety, and may influence user trust in and acceptance of driving automation and CDA. This study is designed to explore these research areas to support safe integration of advanced vehicle technologies with existing infrastructure.

Many vehicles have an economical mode, or eco-mode, to improve fuel economy. Eco-mode helps reduce the environmental impact of a vehicle. Strategies for economical driving, or eco-driving, are intended to reduce fuel use and the emission of harmful gases by optimizing speed profiles through efficient use of acceleration, deceleration, and idling at a stop.(6–8) Eco-driving strategies can result in optimizing acceleration and deceleration based on signal phase information.(9) Drivers can manually monitor and implement eco-driving strategies. However, drivers who monitor in-vehicle guidance, fuel use, and other vehicle feedback can increase the number of driving tasks and may compromise driver safety.(10,11) With advanced cooperative automation driving systems (C-ADSs), partially or fully automated eco-driving patterns can control acceleration and deceleration patterns based on optimized algorithms. In addition to maximizing the efficiency of eco-driving, a C-ADS removes the task of monitoring and controlling speed and fuel use from the driver. CDA also provides opportunities to improve the efficiency of eco-driving for larger traffic systems by coordinating behavior among multiple vehicles and roadway infrastructure via M2M communication. A study suggested that using M2M communication from the surrounding environment can reduce energy consumption by 54 percent.(12) Coordination with infrastructure becomes useful on signalized arterials where drivers are more likely to accelerate, decelerate, and idle in response to traffic signals than when driving on highways. On arterials, a C-ADS eco-driving can reduce idling time at signalized intersections by coordinating vehicle speed with the upcoming traffic signal phase.(6,7,13) Fuel savings and traffic flow are optimized by smoothing the acceleration and deceleration profiles of vehicles as the vehicles approach and depart the intersection. The smoothing of acceleration and deceleration profiles is referred to as eco-approach and departure.(7,14,15) In this report, the process is called eco-driving.

C-ADS eco-driving is likely to be deployed in some vehicles equipped with Level 3 ADS, as defined by SAE.(1) SAE Level 3 ADS is capable of independently performing the dynamic driving task in defined situations, although the driver may be required to resume control if the system leaves its intended operational design domain. Cooperative eco-driving further requires M2M communication between the signal infrastructure and the vehicle to harmonize vehicle speed on the approach to the intersection. In this case, the traffic controller at the intersection communicates a signal phase and timing message that is wirelessly transmitted to the C-ADS-equipped vehicle. The vehicle's ADS processes the signal message to either decelerate, maintain speed, or accelerate based on the vehicle's location and timing and the state of the upcoming signal phase.(7,15)

Whether automated, connected, or manual, eco-driving patterns are expected to influence the driving patterns of following vehicles. Research indicates that the behavior of a limited number of vehicles using eco-drive can lead to positive effects on surrounding traffic.(6) The car-following model predicts that vehicles lacking C-ADS technology will adopt the travel pattern of a C-ADS vehicle ahead of them.(6,16) For instance, vehicles that are following an eco-driving vehicle that is approaching and departing an intersection can also demonstrate a reduction in fuel usage and contribute to improved traffic flow. Simulations have suggested that at least 50 percent of vehicles in a traffic system need to be equipped with C-ADS to yield meaningful fuel savings and traffic flow benefits for surrounding vehicles.(17)

The influence of eco-driving on non-eco-driving vehicles may eventually lead to reduced fuel use, emissions, and road congestion; however, empirical investigations into how comfortable and willing drivers of non-eco-driving vehicles will be to follow a lead eco-driving vehicle are sparse. In addition to employing acceleration and deceleration profiles that are more conservative than those of typical human drivers, a C-ADS that is eco-driving near signalized intersections will likely engage in behavior that a conventional vehicle driver does not expect.(10,11) For example, a driver nearing an intersection with a green signal phase would likely expect to maintain speed or accelerate to pass through the intersection. A C-ADS-equipped vehicle that receives a signal message from the traffic controller that a red phase will begin before the vehicle reaches the intersection will decelerate early and come to a gradual stop at the red signal. Without access to the signal message or knowledge that the C-ADS-equipped vehicle ahead is employing ADS eco-drive strategies, a following vehicle may find the early deceleration inappropriate, frustrating, or inefficient.

In a field test examining driver responses to eco-driving vehicles, Ando and Nishihori conducted a preliminary experiment to determine how many drivers unaware of eco-driving behaviors would choose to follow a string of vehicles practicing manual eco-driving behaviors and for how long.(8) The results showed that cars followed the eco-driving vehicle string 75.8 percent of the total recorded time and that the string was passed 21 percent of the time. Compared with the average car-following time of 2.2 min, cars that overtook the eco-driving string followed for only 1.5 min. These results indicate that drivers of conventional vehicles may be more likely to overtake eco-driving vehicles than to adopt eco-driving travel patterns.

Driving automation technologies, such as ACC and M2M communication via CDA technologies, may alter driver following behaviors. For example, ACC automatically adjusts throttle and brake input to maintain a set speed and time gap to a vehicle ahead detected by forward-looking sensors.(18) Because speed and following distance are automated, ACC may encourage sustained following and acceptance of eco-driving strategies. Indeed, when asked to follow a lead vehicle, drivers using ACC have been observed driving at statistically significantly slower speeds than drivers without ACC.(19) Drivers also change lanes less frequently when using ACC.(20) On the other hand, drivers may find eco-driving travel patterns unappealing, even when using ACC, without knowing that the lead vehicle is directly communicating with the traffic controller to save fuel. Intent-sharing information from a C-ADS eco-driving vehicle or traffic signal controller can increase the awareness of surrounding vehicles and may support the adoption of eco-driving travel patterns by following vehicles.

This study seeks to address the concerns associated with following a C-ADS eco-driving vehicle when using driving automation and CDA technologies. Since no standardized CDA messages for traffic signal messages and lead vehicle intent messages are currently available (to the researchers' knowledge), the research team conducted a small-scale preliminary study to select effective CDA message designs. The team used the selected designs in a field study to investigate driver behavior and acceptance when following a lead vehicle performing simulated eco-driving behaviors at a signalized intersection. The researchers also explored the influence of using CDA messages and ACC. The results of the field study provided insight into the potential for conventional vehicles to adopt C-ADS eco-driving patterns and the level of driving automation and M2M communication needed to support appropriate compliance and adoption of eco-driving strategies. The team also evaluated driver trust in C-ADS and the vehicle's driving automation system by having an eco-driving vehicle perform signal violations. This evaluation required ACC-enabled vehicle drivers to manually override the ACC system to prevent an illegal maneuver. This research explored critical safety concerns identified by experts and stakeholders to support proper use of advanced vehicle technologies.

OBJECTIVES

This research study primarily explores the effects of automated driving and CDA technology on the behavior and perceptions of drivers who followed a simulated Level 3 C-ADS eco-driving vehicle to a signalized intersection. The research team also conducted a preliminary study to identify effective CDA vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) message designs to use in the field study.

The field study focused on the following four research objectives:

- Examine whether any speed fluctuation and following distance differences occur between drivers using ACC-enabled vehicles and drivers not using ACC.
- Examine whether any following distance differences between drivers using CDA messages and those not using CDA messages occur as a function of ACC use.
- Assess the stopping and acceleration or deceleration patterns ahead of the red light for different combinations of CDA messages and ACC.
- Investigate the level of driver trust in automation for different combinations of CDA messages.

Hypotheses

Based on the research objectives, the team investigated six hypotheses in the field study:

- Drivers in ACC-enabled vehicles will have fewer fluctuations in speed than drivers in conventional vehicles (objective 1).
- Drivers in conventional vehicles who receive CDA messages will exhibit shorter following distances than drivers who do not receive CDA messages as a function of ACC use (objective 2).
- Drivers in ACC-enabled vehicles will have less variability in following distance than drivers in conventional vehicles (objective 1).
- Drivers in conventional vehicles who receive CDA messages will show earlier preparation to stop than drivers who do not receive CDA messages (objective 3).
- Drivers in ACC-enabled vehicles who do not receive CDA messages will be more likely to run the red light when following the lead vehicle than those who receive the CDA messages (objective 3).
- Drivers who receive CDA messages will report higher levels of trust in vehicle automation technology than drivers who do not receive CDA messages (objective 4).

CHAPTER 2. PRELIMINARY STUDY

The research team conducted a preliminary study to determine which CDA message designs to use in the field study. This study was not intended to be an exhaustive investigation of in-vehicle CDA message designs, but rather it was conducted to select message designs that ensure participants in the field study understand the meaning of the V2I (traffic signal messages) and V2V (lead vehicle intent) CDA message designs.

METHODS

Participants

Twenty-four licensed drivers (12 males and 12 females) from the Washington, DC, area participated in the study. An equal number of males and females were aged 45 yr or younger and 46 yr or older.

Experimental Design

The team divided the 24 participants equally between the V2I and V2V message designs. The experimental design was a two-by-four-by-two mixed-factorial design with two messaging types (V2I, V2V), four CDA message designs, and two colors (green (go), red (stop)). Messaging type was manipulated between subjects, while message design and color were manipulated within subjects. Half of the participants answered questions about V2I stimuli, and the other half answered questions about V2V stimuli. The participants answered questions about each message design and color of their assigned stimuli group.

Apparatus

During the study, the researchers showed the participants pictures of message designs on a computer screen and asked them to answer questions and provide opinions. Experimental sessions took place via an Internet Web-conferencing session between each participant's computer and the computer used by the researcher. The team provided the participants with a code and a password to join a virtual meeting at the appointed session time.

Stimuli

The study used 16 message designs: eight V2I traffic signal message designs and eight V2V lead vehicle intent message designs. The V2I traffic signal designs used variations of traffic signal icons consisting of the following four styles:

- *Standard traffic signal* (showing the color to which the traffic signal will be changing).
- *Traffic signal with text* (same as standard but with the word UPCOMING displayed).
- *Traffic signals with a transition arrow* (showing two traffic signals separated by an arrow; the left signal is the current color, and the right signal shows the color to which the signal will be changing).

- *Countdown traffic signal* (displaying the current color with a countdown number).

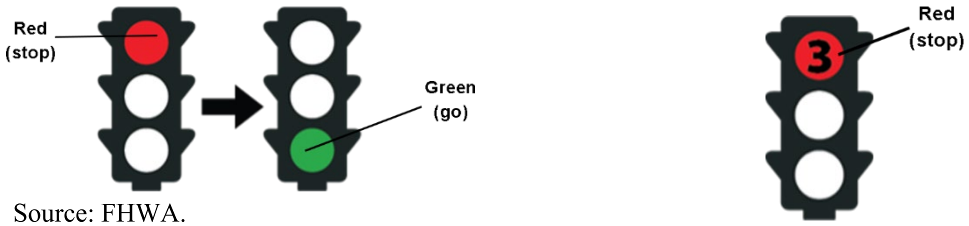
Figure 1 shows V2I message designs 1–4 for the red signal turning green scenario. The message designs are intended to convey the red traffic signal will turn green when the driver reaches the intersection.

Source: FHWA.

A. Design 1: Standard traffic signal.

Source: FHWA.

B. Design 2: Traffic signal with text.



Source: FHWA.

C. Design 3: Traffic signals with transition arrow.

Source: FHWA.

D. Design 4: Countdown traffic signal.

Figure 1. Illustrations. V2I message designs for traffic signal transitioning from red to green indication.

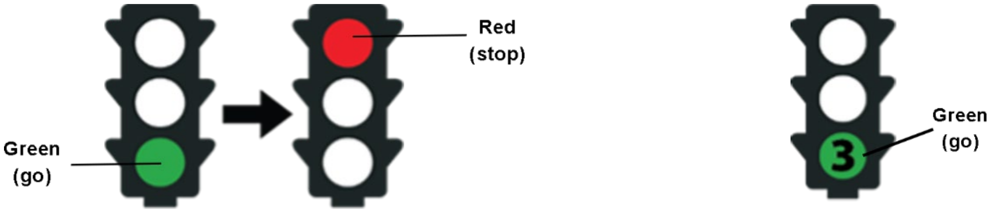
Figure 2 shows V2I message designs 5–8 for the green signal turning red scenario. They are intended to convey the green traffic signal will turn red when the driver reaches the intersection.

Source: FHWA.

A. Design 5: Standard traffic signal.

Source: FHWA.

B. Design 6: Traffic signal with text.



Source: FHWA.

C. Design 7: Traffic signals with transition arrow.

Source: FHWA.

D. Design 8: Countdown traffic signal.

Figure 2. Illustrations. V2I message designs for traffic signal transitioning from green to red indication.

The V2V message designs used variations of car icons consisting of the following four styles: dual vehicle in the same lane, dual vehicles with separating lines, dual vehicles with lead vehicle intention indicators, and dual vehicles with intention indicators and limit lines. Figure 3 shows V2V message designs 9–12 for the red traffic signal with the car-moving scenario. They are intended to convey that the front vehicle plans to continue through the intersection.

Source: FHWA.

A. Design 9: Dual vehicles.

Source: FHWA.

B. Design 10: Dual vehicles with separating lines.

Source: FHWA.

C. Design 11: Dual vehicles with intention.

Source: FHWA.

D. Design 12: Dual vehicles with intention and limit line.

Figure 3. Illustrations. V2V message designs for traffic signal transitioning to green with car-moving intention.

Figure 4 shows V2V message designs 13–16 for the green signal turning red scenario. They are intended to convey that the front vehicle plans to stop at the intersection.

Source: FHWA.

Source: FHWA.

A. Design 13: Dual vehicle.

B. Design 14: Dual vehicles with separating lines.

Source: FHWA.

Source: FHWA.

C. Design 15: Dual vehicles with intention.

D. Design 16: Dual vehicles with intention and limit line.

Figure 4. Illustrations. V2V message designs for traffic signal transitions to red with car-stopping intention.

Procedure

The research team scheduled a virtual conferencing session with participants to review the participant information sheet and indicate whether they wished to continue with the study. After the participants choose to continue, the research team asked them to indicate if they had a valid driver's license. The team gave the participants instructions about the task, and then data collection commenced.

During the experiment, the researchers provided the participants with a series of scenarios in which they imagined their vehicles approaching other vehicles at an intersection with either a red or green traffic signal. For each scenario, a questionnaire displayed a CDA message and asked multiple questions to investigate participants' understanding, situational expectations, and effectiveness of the design, as well as their opinions about their design preferences. The computer-based questionnaire included selected-response and free-response questions and explored four areas: message understanding, situational expectations, message effectiveness, and design preferences. The researchers remained in the live session throughout the study to answer questions, input verbal responses, and monitor for any issues. After the participants completed the test scenarios and questionnaire, the team emailed an electronic gift card to them, and they acknowledged receipt of the card using an electronic receipt. The research assistant debriefed the participants and thanked them for their time before ending the virtual session.

RESULTS

The analyses examined responses to the scenario-specific questions for the V2I and V2V message designs. Half of the participants (12) provided feedback for the V2I traffic signal designs, and the other half of participants (12) provided feedback for the V2V lead vehicle intent designs. The analysis of participant feedback from the study questionnaire for the V2I and V2V message designs are described next.

V2I Traffic Signal Designs

The V2I messages conveyed what the traffic signal would be changing to when the driver reaches the intersection (i.e., red traffic signal turning green when the driver reaches the intersection, or vice versa). The analysis examined the participants' understanding of the intended meaning, expectations, effectiveness, and design preferences (i.e., likes, dislikes, and possible improvements).

Message Understanding

The researchers showed the participants an image of the message that consisted of a traffic signal design and asked the participants, "What is the alert telling you?" Table 1 shows the percentage of correct responses for designs in the red signal turning green scenario (i.e., designs 1–4). Table 2 shows the percentage of correct responses for designs in the green signal turning red scenario (i.e., designs 5–8). Higher percentages reflect a higher proportion of participants who understood the intended meaning of the design. More than 90 percent of participants understood the meaning of designs 3, 5, and 7. Design 5 had the highest percentage of correct responses at 100 percent. Design 4 had the lowest percentage of correct responses at 58.3 percent.

The standard traffic signal style (designs 1 and 5) and the signals with transition arrow style (design 3 and 7) were tied for the highest average percentage of correct responses. The standard traffic signal style had 91.6 percent correct responses ((83 + 100) ÷ 2 = 91.5). The traffic signals with transition arrow style also had 91.6 percent correct responses. Both styles surpassed the traffic signal with text style of 83.3 percent correct responses and the countdown traffic signal style of 66.6 percent correct responses ((58.3 + 75) ÷ 2 = 66.6).

Table 1. Participants' understanding of V2I message designs—red signal turning green.

Design Number	Message Style	Percentage Correct
1	Standard traffic signal	83.3
2	Traffic signal with text	83.3
3	Traffic signals with transition arrow	91.6
4	Countdown traffic signal	58.3

Table 2. Participants' understanding of V2I message designs—green signal turning red.

Design Number	Message Style	Percentage Correct
5	Standard traffic signal	100.0
6	Traffic signal with text	83.3
7	Traffic signals with transition arrow	91.6
8	Countdown traffic signal	75.0

Situational Expectations

The team asked the participants questions about their expected actions or responses to receiving the message, and the participants selected from a list of response options.

The researchers examined the percentage of correct responses for the following questions:

- **What would you be most likely to do in response to this message?** Designs 5, 6, and 7 had the highest percentage of correct responses ("Slow down and prepare to stop") at 83.3, 91.7, and 83.3 percent, respectively. Design 8 had the lowest percentage of correct responses at 16.7 percent.

- **What would you expect to happen after receiving this message?** Designs 3 and 7 had the highest percentage of correct responses ("Traffic signal color will change") at 100 percent. Designs 2 and 8 had the lowest percentage of correct responses at 75 percent.

- **What would you expect the vehicle ahead to do after you and only you received this message?** Design 4 ("Vehicle ahead will speed up") and design 8 ("Vehicle ahead will slow down") had the highest percentage of correct responses at 91.7 percent. Designs 1, 3, and 6 had the lowest percentage of correct responses at 66.7 percent.

- **After receiving this message, would you expect to: continue through the intersection or stop at or before the intersection?** Designs 5 and 6 had the highest percentage of correct responses ("Stop at or before the intersection") at 91.7 percent. Design 8 had the lowest percentage of correct responses at 25 percent.

For the best overall situational expectation results, three styles had average scores within three percentage points of each other:

- Traffic signals with transition arrow (designs 3 and 7) with an average of 81.2 percent correct.

- Traffic signal with text (designs 2 and 6) with an average of 79.2 percent correct.

- Standard traffic signal (designs 1 and 5) with an average of 78.1 percent correct.

Table 3 shows the percentage of correct responses for the red signal turning green scenario (designs 1–4). Table 4 shows the percentage of correct responses for the green signal turning red scenario (designs 5–8).

Table 3. Participants' responses to V2I message design questions—red signal turning green.

	Message Design			
	Standard Traffic Signal (1)	Traffic Signal With Text (2)	Traffic Signals With Transition Arrow (3)	Countdown Traffic Signal (4)
Question	Percentage of Correct Responses			
What would you do?	58.3	66.7	58.3	50.0
Expect to happen?	83.3	75.0	100.0	83.3
Expect vehicle ahead to do?	66.7	75.0	66.7	91.7
Expect to continue or stop?	75.0	75.0	75.0	41.7

Table 4. Participants' responses to V2I message design questions—green signal turning red.

	Message Design			
	Standard Traffic Signal (5)	Traffic Signal With Text (6)	Traffic Signals With Transition Arrow (7)	Countdown Traffic Signal (8)
Question	Percentage of Correct Responses			
What would you do?	83.3	91.7	83.3	16.7
Expect to happen?	83.3	91.7	100.0	75.0
Expect vehicle ahead to do?	83.3	66.7	83.3	91.7
Expect to continue or stop?	91.7	91.7	83.3	25.0

Message Effectiveness

The research team gave the participants the intended meaning of the V2I message designs and asked them to rate the designs on clarity and ease of understanding. The team used a Likert scale of 1 (not at all clear and not easy to understand) to 5 (very clear and easy to understand). Designs 2, 3, 6, and 7 received a rating of 4 or higher, indicating the designs were somewhat clear and easy to understand. Design 3 had the highest rating at 4.17. Design 5 had the lowest rating at 3.0.

The traffic signals with transition arrow style (designs 3 and 7) had an average rating of 4.125 ((4.17 + 4.08) ÷ 2 = 4.125). The traffic signal with text style (designs 2 and 6) had an average rating of 4.04. The countdown traffic signal style (designs 4 and 8) had an average rating of 3.545. The standard traffic signal style (designs 1 and 5) had the lowest average rating with 3.04.

Table 5 shows the average ratings for the red signal turning green scenario (designs 1–4). Table 6 shows the average ratings for the green signal turning red scenario (designs 5–8).

Table 5. Participants' ratings for clear and easy-to-understand V2I message designs—red signal turning green.

Design Number	Message Style	Average Rating
1	Standard traffic signal	3.08
2	Traffic signal with text	4.08
3	Traffic signals with transition arrow	4.17
4	Countdown traffic signal	3.67

Table 6. Participants' ratings for clear and easy-to-understand V2I message designs—green signal turning red.

Design Number	Message Style	Average Rating
5	Standard traffic signal	3.0
6	Traffic signal with text	4.0
7	Traffic signals with transition arrow	4.08
8	Countdown traffic signal	3.42

The team asked the participants to choose the least and most effective designs for notifying drivers that the traffic signal will change when they reach the intersection. Table 7 shows the percentage of participants who selected the least effective and most effective designs for the red signal turning green scenario (designs 1–4). Table 8 shows the percentage of participants selecting the least effective and most effective designs for the green signal turning red scenario (designs 5–8).

The least effective style for the red signal turning green scenario was the standard traffic signal (design 1), chosen by 67 percent of participants. The most effective style was traffic signals with transition arrow (design 3) at 42 percent. The least effective style for the green signal turning red scenario was the standard traffic signal (design 5) at 33 percent. The most effective style was traffic signals with transitional arrow (design 7) at 58 percent.

The standard traffic signal (designs 1 and 5) had the highest average percentage of participants agreeing the style was least effective at 50 percent ((67 + 33) ÷ 2) = 50). The traffic signals with transition arrow (designs 3 and 7) had the highest average percentage of participants agreeing the designs were the most effective at 50 percent ((42 + 58) ÷ 2) = 50).

Table 7. Least and most effective V2I message designs—red signal turning green.

	Message Design			
	Standard Traffic Signal (1)	Traffic Signal With Text (2)	Traffic Signals With Transition Arrow (3)	Countdown Traffic Signal (4)
Choice	Percentage of Participants			
Least Effective	67.0	0.0	8.0	25.0
Most Effective	8.0	17.0	42.0	33.0

Table 8. Least and most effective V2I message designs—green signal turning red.

	Message Design			
	Standard Traffic Signal (5)	Traffic Signal With Text (6)	Traffic Signals With Transition Arrow (7)	Countdown Traffic Signal (8)
Choice	Percentage of Participants			
Least Effective	33.0	8.0	17.0	42.0
Most Effective	17.0	8.0	58.0	17.0

Design Preferences

The researchers asked the participants what they liked, what they disliked, and how they thought the designs could be improved. Table 9 summarizes the most frequently cited likes, dislikes, and improvements for the V2I message designs grouped by common styles (e.g., designs 1 and 5; designs 2 and 8).

Table 9. Most frequently cited likes, dislikes, and improvements for V2I message designs.

Message Style	Design Numbers	Likes	Dislikes	Improvements
Standard traffic signal	1, 5	Simplicity of the design.	Does not have a countdown timer; not enough information about when the signal will change color.	Add a timer (more information) to show a countdown when the signal will change color; ensure legibility and include driver education.
Traffic signal with text	2, 6	The text is more informative.	Wording is somewhat vague and does not indicate time or when the signal will change color.	Add a countdown timer to indicate when the signal will change.
Traffic signals with transition arrow	3, 7	Clear and easy-to-understand message.	Does not have a countdown timer.	Add a countdown timer so driver knows how long until light changes.

Message Style	Design Numbers	Likes	Dislikes	Improvements
Countdown traffic signal	4, 8	Provides a countdown timer.	Uncertain the number is a countdown timer; number is too small.	Legibility to make the number easier to see; driver education of design functionality and messaging.

V2V Vehicle Intention Designs

The V2V messages convey to the driver the current state of the traffic signal and whether the vehicle in front of the participant intends to stop or continue through the intersection. The analyses examined participants' understanding of the intended meaning, expectations, effectiveness, and design preferences (i.e., likes, dislikes, and possible improvements).

Message Understanding

The team showed the participants a message that consisted of a vehicle-based design and asked, "What is the alert telling you?" Table 10 shows the percentage of correct responses for the red traffic signal with car ahead moving scenario (designs 9–12). Table 11 shows the percentage of correct responses for the green traffic signal with car ahead stopping scenario (designs 13–16). The higher percentages reflect a higher proportion of the participants who understood the designs' meaning. Designs 11 and 16 had the highest percentage of correct responses with 67 percent. Designs 9 and 14 had the lowest percentage of correct responses with 33.3 percent.

Two styles, dual vehicles with intention (designs 11 and 15) and dual vehicles with intention and limit line styles (designs 12 and 16), tied for the highest average percentage of correct responses. Dual vehicles with intention had 58.5 percent correct responses ((67 + 50) ÷ 2 = 58.5). Dual vehicles with intention and a limit line also had 58.5 percent correct responses ((50 + 67) ÷ 2 = 58.5). These styles were higher than dual vehicle with separating lines style at 41.5 percent ((50 + 33.3)÷2 = 41.5 percent) and the dual vehicle style with 37.5 percent correct ((33.3 + 42) ÷ 2 = 37.5 percent).

Table 10. Participants' understanding of V2V message designs—red signal with car ahead moving.

Design Number	Message Style	Percentage Correct
9	Dual vehicle	33.3
10	Dual vehicles with separating lines	50.0
11	Dual vehicles with intention	67.0
12	Dual vehicles with intention and limit line	50.0

Table 11. Participants' understanding of V2V message designs—green signal with car ahead stopping.

Design Number	Message Style	Percentage Correct
13	Dual vehicle	42.0
14	Dual vehicles with separating lines	33.3
15	Dual vehicles with intention	50.0
16	Dual vehicles with intention and limit line	67.0

Situational Expectations

The research team asked the participants questions about their expected actions or responses to receiving the message about the front vehicle's intention, and the participants selected from a list of response options.

The team examined the percentage of correct responses for the following questions:

- **What would you be most likely to do in response to this message?** Design 16 had the highest percentage of correct responses at 91.7 percent. Design 9 had the lowest percentage of correct responses at 33.3 percent.

- **What would you expect to happen after receiving this message?** Design 12 had the highest percentage of correct responses at 91.7 percent. Design 15 had the lowest percentage of correct responses at 33.3 percent.

- **What would you expect the vehicle ahead to do after you and only you receive this message?** Designs 9, 10, 12, and 13 had the highest percentage of correct responses at 41.7 percent. Design 15 had the lowest percentage of correct responses at 8.3 percent.

- **After receiving this message, would you expect to: continue through the intersection or stop at or before the intersection?** Designs 15 and 16 had the highest percentage of correct responses at 91.7 percent. Design 10 had the lowest percentage of correct responses at 50 percent.

For the best overall situational expectation results, three styles had average scores within four percentage points of each other:

- Dual vehicles with separating lines (designs 10 and 14) with an average of 64.6 percent correct.

- Dual vehicle (designs 9 and 13) with an average of 62.5 percent correct.

- Dual vehicles with intention and limit line (designs 12 and 16) with an average of 60.5 percent correct.

The dual vehicles with intention style (designs 11 and 15) had the lowest percentage correct at 52.1 percent. Table 12 shows the percentage of correct responses for the red signal turning green with car ahead moving intent (designs 9–12). Table 13 shows the percentage of correct responses for the green signal turning red with car heading stopping intent (designs 13–16).

Table 12. Participants' responses to V2V message design questions—red signal turning green with car ahead moving.

	Message Design			
	Dual Vehicle (9)	**Dual Vehicles With Separating Lines (10)**	**Dual Vehicles With Intention (11)**	**Dual Vehicles With Intention and Limit Line (12)**
Question	**Percentage of Correct Responses**			
What would you do?	33.3	41.7	50.0	50.0
Expect to happen?	58.3	50.0	66.7	91.7
Expect vehicle ahead to do?	41.7	41.7	33.3	41.7
Expect to continue or stop?	58.3	50.0	75.0	66.7

Table 13. Participants' responses to V2V message design questions—green signal turning red with car ahead stopping.

	Message Design			
	Dual Vehicle (13)	**Dual Vehicles With Separating Lines (14)**	**Dual Vehicles With Intention (15)**	**Dual Vehicles With Intention and Limit Line (16)**
Question	**Percentage of Correct Responses**			
What would you do?	66.7	83.3	75.0	91.7
Expect to happen?	66.7	66.7	33.3	41.7
Expect vehicle ahead to do?	41.7	33.3	8.3	16.7
Expect to continue or stop?	75.0	75.0	91.7	91.7

Message Effectiveness

The researchers gave the participants the intended meaning of the V2V message designs and asked them to rate the designs on clarity and ease of understanding. A Likert scale of 1 (not at all clear and not easy to understand) to 5 (very clear and easy to understand) was used. Table 14 shows the average ratings for the red signal turning green scenario (designs 9–12). Table 15 shows the average ratings for the green signal turning red scenario (designs 13–16). The ratings ranged from 2.83 to 3.58, indicating the participants thought the designs were neither "very clear and easy to understand" nor "not at all clear and not easy to understand." Designs 9 and 11 had the highest ratings at 3.58. Design 10 had the lowest rating at 2.83.

Two styles tied for the highest average ratings for clear and easy to understand: dual vehicles with intention (designs 11 and 15) with an average rating of 3.5 ((3.58 + 3.42) ÷ 2 = 3.5), and dual vehicles with intention and a limit line (designs 12 and 16) with an average rating of 3.5 ((3.5 + 3.5) ÷ 2 = 3.5). The dual vehicle style (designs 9 and 13) had an average rating of 3.33 ((3.58 + 3.08) ÷ 2 = 3.33), and the dual vehicles with separating lines style (designs 10 and 14) had the lowest average rating with 3.08 ((2.83 + 3.33) ÷ 2 = 3.08).

Table 14. Participants' ratings for clear and easy-to-understand V2V message designs—red signal turning green with car ahead moving.

Design Number	Message Style	Mean Rating
9	Dual vehicle	3.58
10	Dual vehicles with separating lines	2.83
11	Dual vehicles with intention	3.58
12	Dual vehicles with intention and limit line	3.50

Table 15. Participants' ratings for clear and easy-to-understand V2V message designs—green signal turning red with car ahead stopping.

Design Number	Message Style	Mean Rating
13	Dual vehicle	3.08
14	Dual vehicles with separating lines	3.33
15	Dual vehicles with intention	3.42
16	Dual vehicles with intention and limit line	3.50

The team asked the participants to choose the least and most effective designs for notifying drivers that the traffic signal will change and what the lead vehicle intends to do. Table 16 shows the percentage of participants selecting the least and most effective designs for the red traffic signal turning green scenario with the lead vehicle intending to continue through the intersection (designs 9–12). Table 17 shows the percentage of participants selecting the least and most effective design for the green traffic signal turning red scenario with the lead vehicle stopping at the intersection (designs 13–16). The participants chose two designs as both the least effective and most effective. Designs 11 and 12 were chosen by 42 percent of participants as least effective; these designs were also chosen by 50 and 42 percent of participants, respectively, as most effective. Design 9 was chosen by 8 percent of participants as least effective; none of the participants chose design 9 as most effective. Design 13 had the highest percentage of participants agreeing the style was least effective, at 58 percent. Designs 14 and 15 received 17 and 25 percent, respectively. Design 16 was chosen by 75 percent of the participants as the most effective; none of the participants chose design 16 as the least effective.

The dual vehicle with intention style (designs 11 and 15) had the highest average percentage of participants agreeing the style was least effective at 33.5 percent ((42 + 25) ÷ 2 = 33.5). The dual vehicle style (designs 9 and 13) was a close second, with 33.0 percent of participants choosing it as least effective. The dual vehicles with intention and limit line style (designs 12 and 16) had the highest average percentage of participants agreeing the designs were the most effective at 58.5 percent ((42 + 75) ÷ 2 = 58.5). The dual vehicles with intention style (designs 11 and 15) had the second highest average percentage for most effective at 29 percent ((50 + 8) ÷ 2 = 29).

Table 16. Least and most effective V2V message designs—red signal turning green with car ahead moving.

Choice	Dual Vehicle (9)	Dual Vehicles With Separating Lines (10)	Dual Vehicles With Intention (11)	Dual Vehicles With Intention and Limit Line (12)
	Percentage of Participants			
Least Effective	8.0	8.0	42.0	42.0
Most Effective	0.0	8.0	50.0	42.0

Table 17. Least and most effective V2V message designs—green signal turning red with car ahead stopping.

Choice	Dual Vehicle (13)	Dual Vehicles With Lines (14)	Dual Vehicles With Intention (15)	Dual Vehicles With Intention and Line (16)
	Percentage of Participants			
Least Effective	58.0	17.0	25.0	0
Most Effective	8.0	8.0	8.0	75.0

Design Preferences

The research team asked the participants what they liked, what they disliked, and how they thought the designs could be improved. Table 18 summarizes the most frequently cited likes, dislikes, and improvements for the V2V message designs grouped by common styles. In general, the participants liked the simple design and use of color. Many participants were confused because the design colors did not match the traffic light color and thought the meaning of the lines and arrows was unclear. The most suggested improvements were to add words or text to clarify the message.

Table 18. Most frequently cited likes, dislikes, and improvements for V2V message designs.

Message Style	Design Numbers	Likes	Dislikes	Improvements
Dual vehicle	9, 13	Simple and clear design; red car is straightforward and simple.	Confusing design (unclear message) when the color does not match traffic signal color.	Add words/text consistent with traffic light; clarify message by adding traffic signal or adding arrow or text.
Dual vehicle with separating lines	10, 14	Red color, simple and clear design; lines indicate to be cautious of front car.	Color does not match traffic signal and it is unclear; meaning of lines is confusing and open to interpretation.	Add traffic light/words/text to clarify message and convey what participant should be doing.
Dual vehicles with intention	11, 15	Simple design but message is unclear given the scenario; red color provides clear indication vehicle in front is braking.	Colors conflict with traffic signal color because it is confusing and unclear what the front vehicle is doing.	Show information that does not conflict with traffic light; add text or symbol to clarify if front car is stopping or stopped; convey what participant should be doing.
Dual vehicles with intention and limit line	12, 16	Simple design; liked red car lights for simplicity, and showing red means stop.	Unsure what the green arrow with the red traffic signal means; when color conflicts with traffic signal, it is misleading and confusing.	Change graphics, add text, or add traffic signal to clarify message.

DISCUSSION

The research team conducted this preliminary study to determine which CDA message designs to use in the field study. The team investigated two message types (i.e., V2I and V2V) and 16 total designs (i.e., 8 V2I traffic signal message designs, 8 V2V lead vehicle intent message designs). The researchers showed V2I and V2V message types to the participants to investigate their understanding of the message, expected actions, perceived effectiveness, and overall preferences.

The participants viewed four V2I message designs styles:

- Standard traffic signal (showing the color to which the traffic signal will be turning).
- Traffic signal with text (same as the standard traffic signal, but with the word UPCOMING also displayed).
- Traffic signals with a transition arrow (showing two traffic signals separated by an arrow, with the left signal the current color and the right signal the color to which it will be turning).
- Countdown traffic signal (showing the current color with a countdown number).

Of the eight V2I designs, the team chose four for use in the field study based on participants' scores and an examination of ratings and comments. The standard traffic signal style (designs 1 and 5, shown in figure 5) and traffic signals with transition arrow style (designs 3 and 7, shown in figure 6) were selected primarily due to their scores in message understanding (e.g., the traffic signal was changing from green to red) and overall situational expectation results (e.g., slow down and prepare to stop). All four designs had the highest percentage of message understanding (ranging from 83 to 100 percent). The standard traffic signal style and traffic signals with transitions arrow style both had the highest average percentage of correct responses (91.6 percent) compared with the traffic signal with text (designs 2 and 6) and countdown traffic signal (designs 4 and 8) styles (which had an average percentage of correct responses of 83.3 and 66.6 percent, respectively). Both styles also were among the top three overall situational expectation results, with an average score of 78.1 and 81.2 percent, respectively. This result indicated that when participants viewed designs 1, 3, 5, and 7, they often knew what action or response should be expected after receiving the message.

The design's ability to convey the desired message was weighed more heavily than participants' subjective assessments. Consequently, the standard traffic signal designs 1 and 5 were chosen, despite participants giving the lowest Likert-scale ratings for clear and easy to understand and despite being selected the least effective design (see figure 5). The participants had a more favorable view of designs 3 and 7 for traffic signals with a transition arrow, as shown in figure 6. The participants gave these designs the highest average rating for clear and easy to understand (4.1), and the highest average percentage of participants agreed these designs were the most effective (50 percent).

Source: FHWA.

Source: FHWA.

A. Design 1: Standard traffic signal.

B. Design 5: Standard traffic signal.

Figure 5. Illustrations. Selected V2I designs 1 and 5.

Source: FHWA.

Source: FHWA.

A. Design 3: Traffic signals with transition arrow.

B. Design 7: Traffic signals with transition arrow.

Figure 6. Illustrations. Selected V2I designs 3 and 7.

The participants viewed four styles of V2V message designs:

- Dual vehicle in the same lane.
- Dual vehicles with separating lines.
- Dual vehicles with intention.
- Dual vehicles with intention and limit line.

The research team chose the dual vehicles with intention style (design 11) and the dual vehicles with intention and a limit line style (design 16), shown in figure 7, for use in the field study to notify participants of the lead vehicle's intention to either move ahead or stop. The team selected these designs due to their top scores (67 and 67 percent, respectively) in message understanding (i.e., the traffic signal changing color and the car ahead intending to move or stop), high ratings for message effectiveness (3.6 and 3.5, respectively), and high participant agreement on being the most effective (50 and 75 percent, respectively).

Source: FHWA.

Source: FHWA.

A. Design 11: Dual vehicles with intention.

B. Design 16: Dual vehicles with intention and limit line.

Figure 7. Illustrations. Selected V2V designs 11 and 16.

This preliminary study provided insights into which designs best convey the desired message to participants and elicit the desired situational expectation and action, as well as participants' perceptions and perspectives. These insights contributed to the selection process for the field study.

CHAPTER 3. FIELD STUDY

This field study investigated the participants' driving behaviors and perceptions of automated driving and CDA technology. The study used the traffic signal and lead vehicle intent message designs identified in the preliminary study. This chapter describes the participants, experiment design, apparatus, procedures used during data collection, and questionnaires conducted during data collection.

METHOD

Participants

Eighty licensed drivers from the Thornburg, VA, area, who were between the ages of 18 and 75 yr, participated in this study. Forty participants were male, and 40 participants were female, with all participants having a visual acuity of at least 20/40 in one eye, based on the Snellen eye chart.(21) In each group, 20 participants were aged 46 yr or younger, and 20 participants were aged more than 46 yr.

Experimental Design

The team divided the 80 participants equally between the conventional vehicle condition and the ACC condition. Within each vehicle condition, the researchers assigned the participants to one of four CDA message types (no message, signal message, lead vehicle message, and both messages), resulting in 10 participants in each message type condition. Table 19 displays the breakdown of the participant distribution in each condition.

Table 19. Field study experimental design.

Condition	Vehicle Automation	CDA Message Type	Number of Participants
1	Conventional	No messages	10
2		Signal message	10
3		Lead vehicle message	10
4		Both messages	10
5	ACC enabled	No messages	10
6		Signal message	10
7		Lead vehicle message	10
8		Both messages	10

The 80 participants each drove 18 trials over 9 loops on the test site, experiencing 5 different scenarios: (A) gradually stopped at the intersection on a red signal, (B) maintained speed and cleared the intersection on a green signal, (C) decelerated on a green signal in anticipation of an upcoming red signal, (D) maintained speed during a red signal in anticipation of an upcoming green signal, and (E) performed an illegal maneuver by maintaining speed through an intersection during a red signal. Due to certain limitations, all participants completed the trials in identical order, as presented in table 20.

Table 20. Order of trials.

Loop	Trial	Scenario	Signal at Approach	Signal at Crossing	Lead Vehicle Action
1	1	A	Red	Red	Stops
1	2	B	Green	Green	Maintains speed
2	3	C	Green	Red	Slows early
2	4	D	Red	Green	Maintains speed
3	5	A	Red	Red	Stops
3	6	C	Green	Red	Slows early
4	7	E	Red	Red	Maintains speed (runs light)
4	8	D	Red	Green	Maintains speed
5	9	B	Green	Green	Maintains speed
5	10	A	Red	Red	Stops
6	11	C	Green	Red	Slows early
6	12	D	Red	Green	Maintains speed
7	13	E	Red	Red	Maintains speed (runs light)
7	14	B	Green	Green	Maintains speed
8	15	D	Red	Green	Maintains speed
8	16	C	Green	Red	Slows early
9	17	B	Green	Green	Maintains speed
9	18	A	Red	Red	Stops

Apparatus

During the study, the participants operated a vehicle equipped with CDA features and ACC capabilities. The researchers mounted cameras within the vehicle, and they streamed controller area network (CAN) bus data—including speed, steering wheel angle, brake force, ACC status and following distance—from the vehicle's electronic system. This procedure allowed the researchers to monitor the drivers' physical states and interactions with the steering wheel and dashboard and verify the participants' vehicle speeds and ACC status in realtime. The participants and researchers communicated through a two-way audio system during the testing. Collision warning and mitigation features in the participant research vehicle were enabled at the nearest possible setting. Figure 8 shows the CAN data collection setup of the lead vehicle.

Source: FHWA.

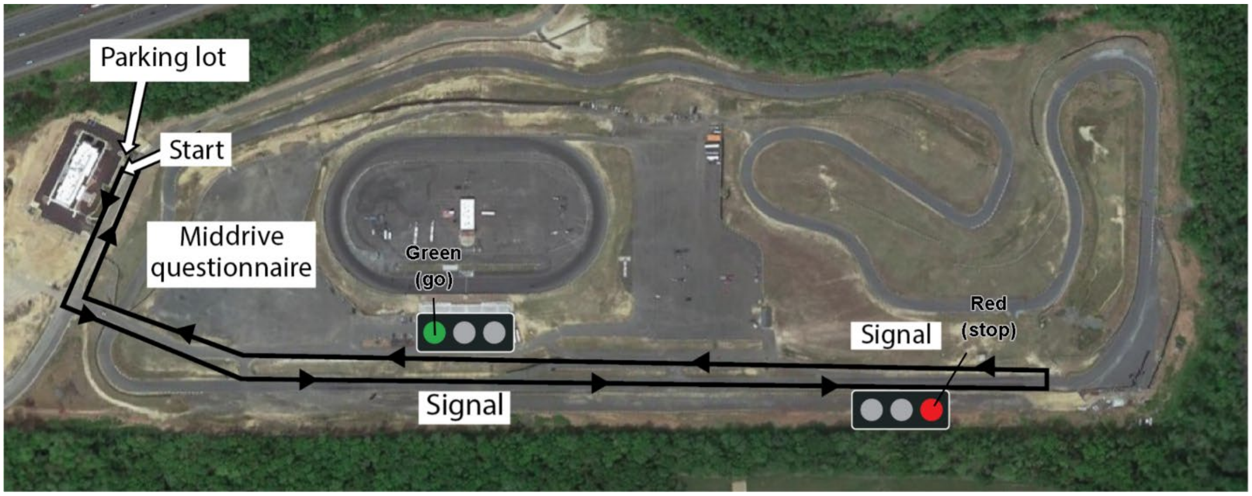
Figure 8. Photo. Data collection setup of the research vehicle.

The research team equipped the lead vehicle with SAE Level 2 driving automation systems supported by visible external sensors. The researchers told the participants that the lead vehicle was equipped with advanced SAE Level 3 C-ADS technology. The following features were included in the lead vehicle's acceleration and deceleration patterns:

- Gentle start from the stop line: spending more than 5 s to accelerate to approximately 12 mph.(8)
- Advanced deceleration: vehicle braking approximately 365 ft upstream of the intersection; applying gentle brake force approximately 200 ft upstream of the intersection at a rate of no more than 7.65 mph/s.(9)
- General operation: changes in speed limited to no more than ±6.7 mph/s).(9)

Test Site

The research team chose a commercial, closed-course racetrack in Virginia as the site for conducting the experiment. The team installed two portable traffic signal heads of standard size and color scheme on a 2,500-ft road on both directions, as shown in figure 9. Arrows mark the direction of travel in the looped racetrack.



© 2023 Google® Earth™. Map modifications by FHWA (see Acknowledgments section).

Figure 9. Photo. Test site marked with route and locations of the signal heads.[(22)]

Stimuli

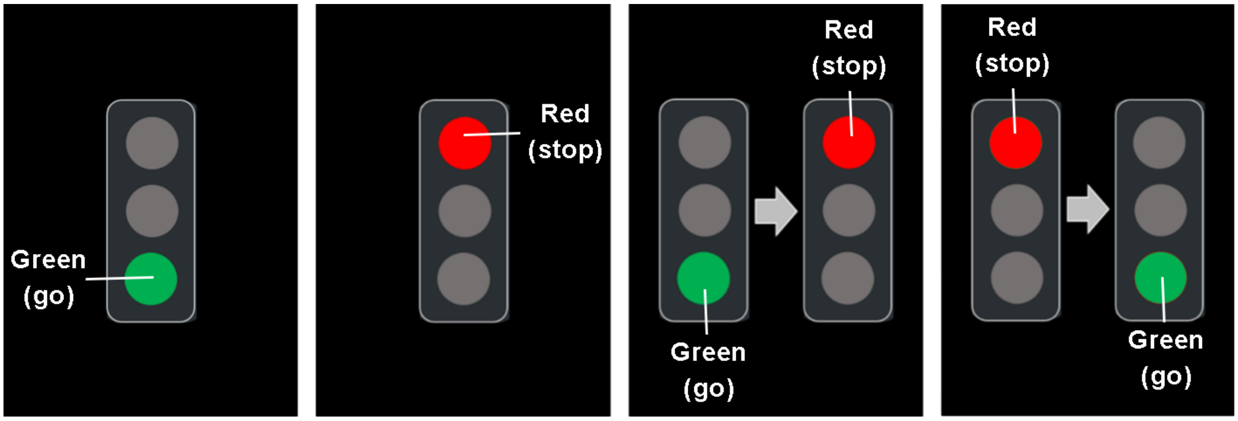
The researchers used three types of simulated connected vehicle messages in the study. A researcher at a designated point on the drive 1,200 ft upstream of the signal remotely triggered the messages. The messages were displayed on a smartphone mounted on the dashboard of the participant vehicle, as shown in figure 10.

Source: FHWA.

Figure 10. Photo. CDA message displayed on a smartphone mounted on the vehicle's dashboard.

Signal Messages

The researchers selected the signal messages based on the findings from the preliminary study discussed in chapter 2. Figure 11 shows the V2I signal messages for the green, red, green-to-red, and red-to-green scenarios. The team intended for the V2I signal messages to display the status of the signal at the upcoming intersection.

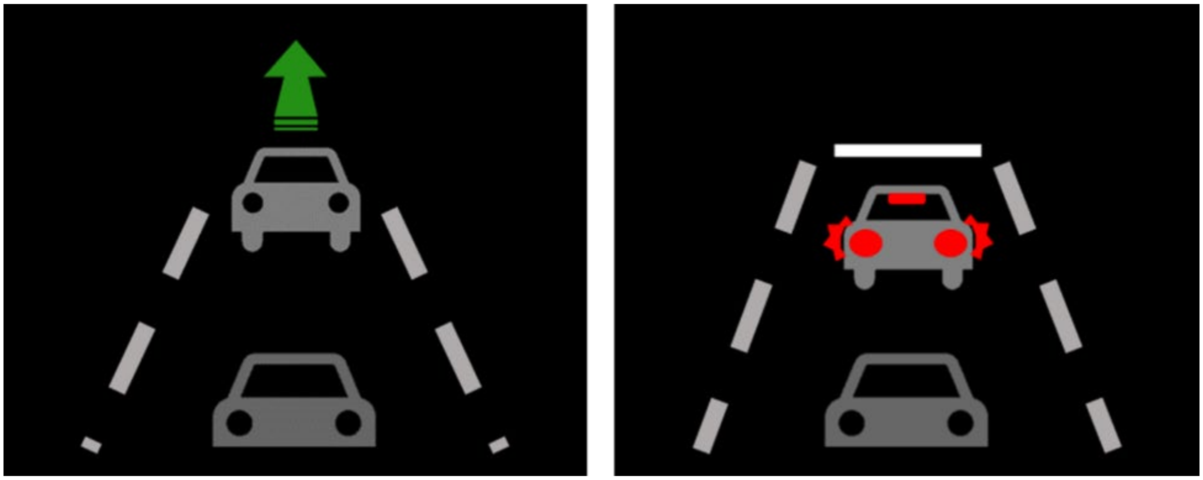


Source: FHWA.

Figure 11. Illustrations. CDA signal messages.

Lead Vehicle Intent Messages

Figure 12 shows the V2V lead vehicle intent messages. The team intended for the V2V messages to show whether the vehicle would continue through the intersection (i.e., signal was green) or if the lead vehicle was stopping (i.e., signal was turning red).

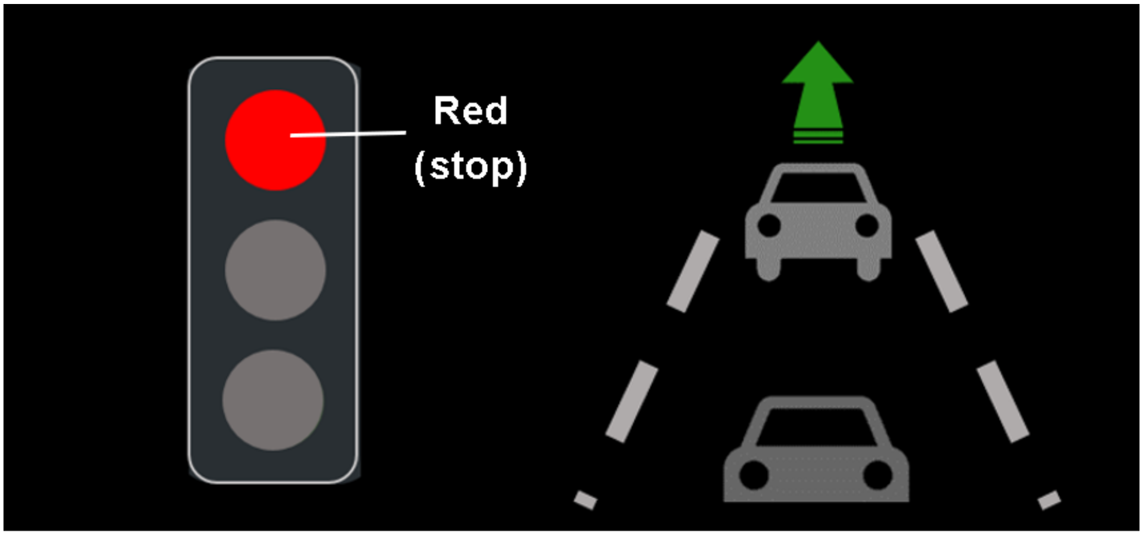


Source: FHWA.

Figure 12. Illustrations. Lead vehicle intent messages.

Both Messages

Figure 13 shows an example of the combined V2I and V2V messages condition. The team designed these messages to communicate the status of the upcoming signal on the left and the intent of the lead vehicle in response to the signal status. In the example shown, the message is intended to display a signal status of red when the vehicles arrive at the intersection and that the lead vehicle intends to run the red light.



Source: FHWA.

Figure 13. Illustration. Combined V2I and V2V messages.

Procedures

The researchers instructed the participants to meet at the commercial racetrack. Upon arrival, the team asked the participants to indicate whether they had a valid driver's license. Next, the research team verified that the participants' visual acuity was at least 20/40, based on a Snellen eye chart.(21) The participants entered their assigned vehicle and were presented with a prerecorded instructional video familiarizing them with the vehicle's controls, connected message displays, and ACC conditions as applicable to their group condition. The researchers then explained lane centering and eco-driving travel patterns before the data collection. The researchers led the participants through the test route as a practice trial to become familiar with the route. The participants started the route from the parking lot and traveled east toward the first signal, following the lead vehicle. During the experimental trials, the eco-drive vehicle maintained a consistent speed of 30 mph whenever possible and as aided by conventional cruise control. When approaching an intersection that required slowing to a stop, the lead vehicle decelerated and stopped at the defined distances from the intersection in coordination with the upcoming traffic signal state. After passing the first signal, the researchers instructed the participants to turn around and follow the lead vehicle west toward the second signal. After passing the second signal, the participants continued toward the parking lot, where they completed a loop and turned around in preparation for a next loop. After completing each loop, the team asked the participants to answer the middrive questions. After completing nine loops, the participants completed a postexperiment questionnaire. After the participants finished the questionnaire, the research team sent them an electronic gift card via email, and the participants acknowledged receipt of the card using an electronic receipt. Finally, the team debriefed the participants and thanked them for their time.

Trust and Safety Questionnaire

The research team verbally asked the participants questions during and after the experimental drive. During the experiment, the team asked the questions after the participants completed each experimental loop. The researchers asked the participants the following three questions:

On a scale of 0–100 percent, how much do you trust:

1. The lead vehicle?
2. The adaptive cruise control in your vehicle?
3. The in-vehicle messages?

The team did not ask the participants in conventional vehicles to rate their level of trust in the ACC system. The participants who did not receive any CDA messages were not asked to rate their level of trust in CDA messages. The researchers questioned participants after the experiment to assess driver perception of vehicle automation technology safety on the roadway.

The postexperiment questionnaire asked participants in all groups to rate, on a scale of 1–5, how much they agreed with the following eight statements:

1. The presence of automated driving systems on the roadway increases road safety.
2. The presence of automated driving systems on the roadway prevents traffic violations.
3. Automated driving systems support drivers' ability to detect hazards in time.
4. The presence of automated driving systems on the roadway contributes to reduced crash risk.
5. Automated driving systems distract drivers from detecting hazards in time.
6. I drive safer than vehicles that use automated driving system.
7. Automated driving systems are vulnerable for new hazards like hacker attack and issues with data safety and to me.
8. New risks that emerge from the presence of automated driving systems on the roadway appear to be more serious than the decrease in crash risk due to the systems.

The research team framed the first four statements in a positive way toward the presence of automation on the roadway. The ratings on these statements indicated participants' opinions on the improvement of safety due to the presence of ADS on the roadway. This rating was defined as a safety gain in this research. The last four statements focused on the negative attributes of the presence of ADS on the roadway. The team defined the ratings on these statements as safety loss because they provide a measurement of the participants' sense of negative impact on safety.

RESULTS

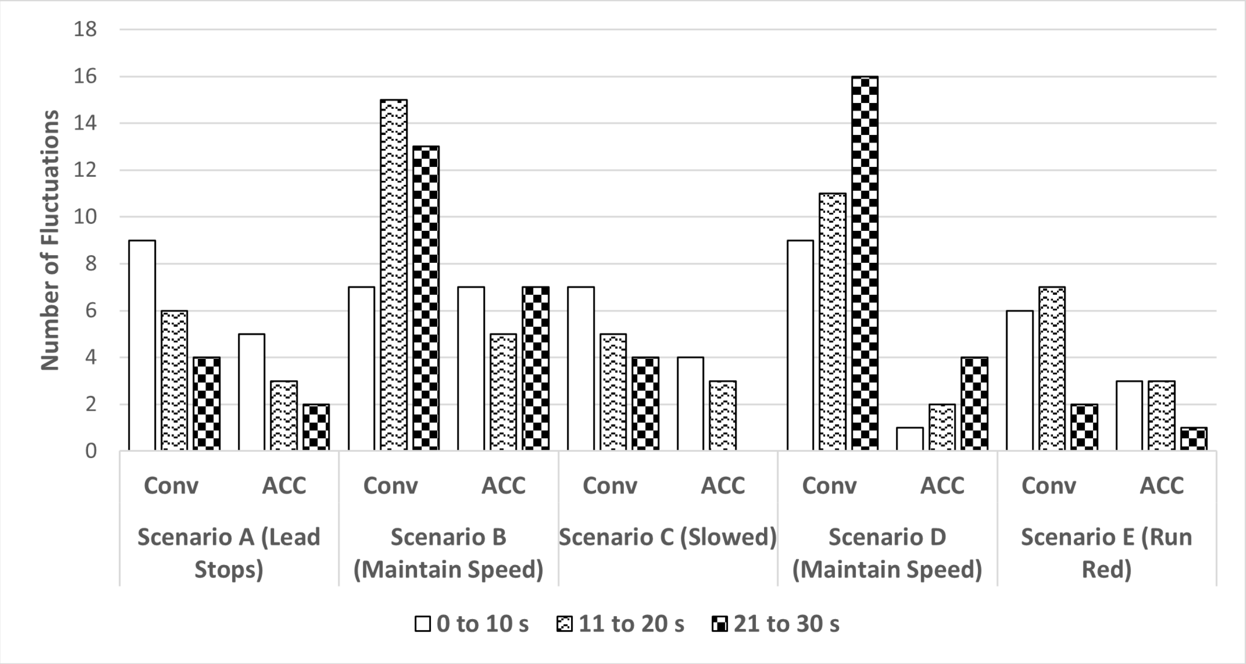
The analysis assessed driver behavior and perspectives for automated driving and CDA technology when following a simulated Level 3 C-ADS eco-driving vehicle to a signalized intersection. The researchers investigated: speed fluctuation and following distance differences between drivers using ACC-enabled vehicles and driver not using ACC, following distance differences between drivers using CDA messages and those not using CDA messages as a function of ACC use, stopping and acceleration or deceleration patterns ahead of the red light for different combinations of CDA messages and ACC, and participant perspectives on trust and safety. The data analysis included examining driver performance metrics (i.e., speed fluctuation, following distance) and ratings from the trust in automation technology questionnaire and ratings from the drivers' perspectives on safety postexperiment questionnaire.

Objective 1: Speed Fluctuation and Following Distance

Drivers in ACC-enabled vehicles will have fewer fluctuations in speed than drivers in conventional vehicles (hypothesis 1). To test this hypothesis, the research team examined driving performance for five driving scenarios in which the lead vehicle: (A) gradually stopped at the intersection on a red signal, (B) maintained speed and cleared the intersection on a green signal, (C) decelerated on a green signal in anticipation of an upcoming red signal, (D) maintained speed during a red signal in anticipation of an upcoming green signal, and (E) performed an illegal maneuver by maintaining speed through an intersection during a red signal. The team examined the number of fluctuations, speed, speed variability, and brake pedal position to assess how ACC status and CDA messages affected the behavior of drivers.

Number of Fluctuations

The researchers used the participants' speed profiles to examine the number of vehicle speed fluctuations. The team defined fluctuation as an increase and a decrease in speed in a short duration of time. Figure 14 shows the number of speed fluctuations, in 10-s intervals, for vehicles that approached the intersection for each scenario. Across all scenarios, the drivers with conventional vehicles had a total of 121 fluctuations versus 50 for drivers in ACC-enabled vehicles. Within all scenarios, conventional drivers also had more total fluctuations (15–36) than participants in ACC vehicles (7–19). Two-sample *t*-tests revealed that the difference in number of speed fluctuations for conventional and ACC-enabled vehicle drivers was statistically significant for scenarios A, B, C, and D (p = 0.006, 0.029, 0.057, and 0.011, respectively). For scenario E, the difference in number of speed fluctuations for conventional and ACC-enabled vehicle drivers was not statistically significant.



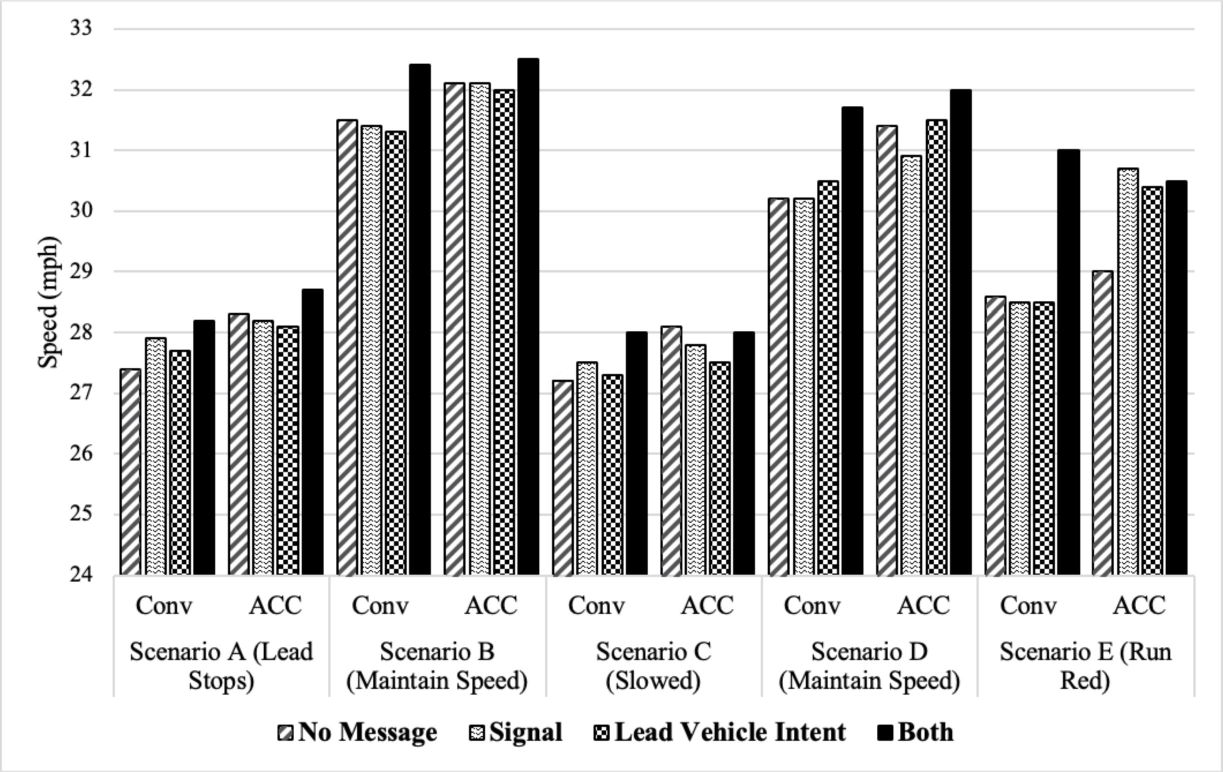
Source: FHWA.
Conv = conventional.

Figure 14. Bar chart. Number of speed fluctuations by scenario, vehicle type, and fluctuation group.

Speed

The researchers examined vehicle speed to identify if vehicle automation (ACC enabled or not) and CDA message types had any effect on vehicle speed for the five different signal scenarios. Figure 15 shows the average speed as a function of vehicle automation, CDA message type, and scenario. Within each scenario, the participants with ACC tended to have a higher average speed than the participants with conventional vehicles (ranging from 0.1 mph to 2.2 mph). The researchers conducted statistical analyses using linear mixed-effects models and descriptive statistics. They included the genders and ages of the participants in the statistical model for their possible confounding effect. The participants in scenario B (when the lead vehicle maintained speed and cleared the intersection on a green signal) with ACC had statistically higher speeds than those in conventional vehicles ($p < 0.050$). Similarly, in scenario E (when the lead vehicle maintained speed and ran the red light), the participants with ACC also had higher speeds than those in conventional vehicles ($p < 0.001$). No significant interaction effects between ACC and CDA messages were found.

In scenario D (when the lead car maintained speed while signal was changing from red to green), the linear mixed-effects model indicated a significant interaction effect between ACC and CDA message on speed was found ($p < 0.010$). This outcome indicated that the effect of ACC on speed would depend on the type of CDA messages received.

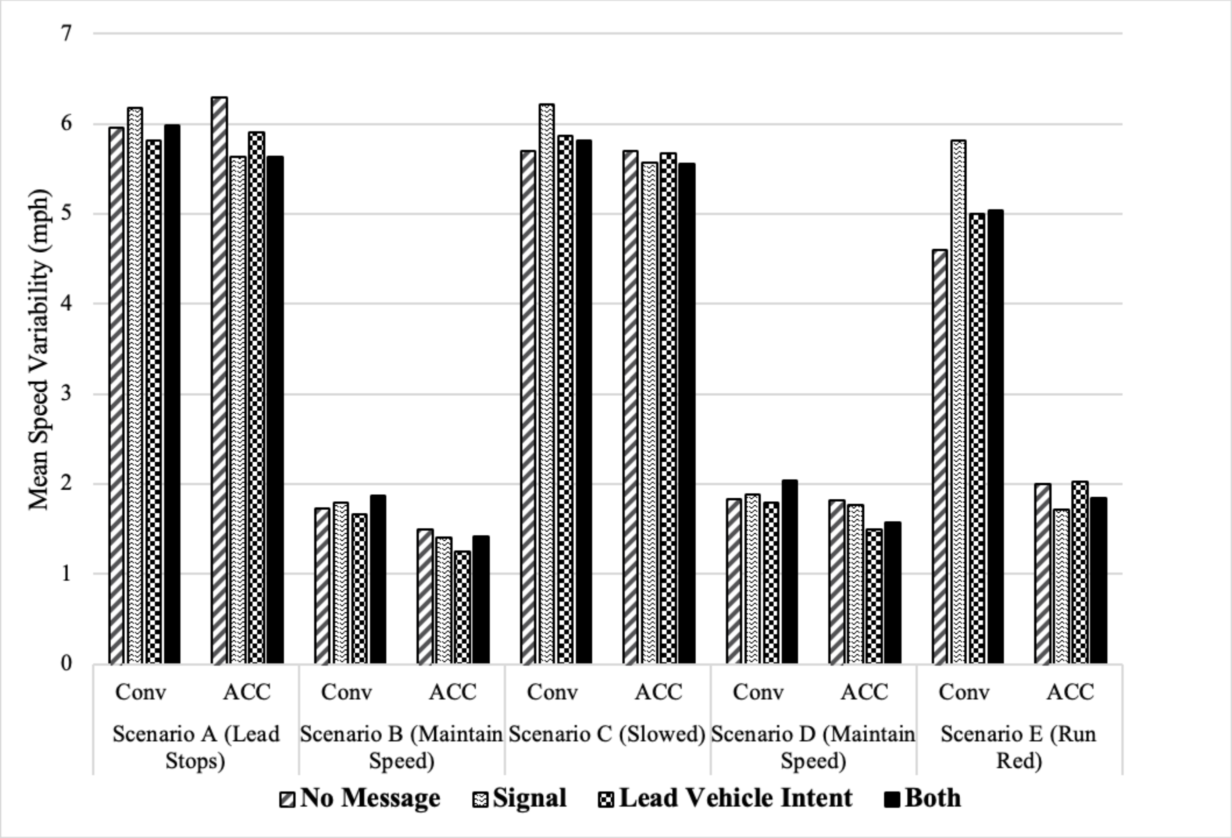


Source: FHWA.

Figure 15. Bar chart. Average speed by scenario, vehicle automation, and message type.

Speed Variability

In conjunction with the speed analyses, the research team investigated speed variability to examine how vehicle automation, CDA message type, or scenario type may be reflected in speed variability. Figure 16 shows the mean speed variability as a function of vehicle automation, CDA message type, and scenario. In most scenarios and message types, the drivers in conventional vehicles tended to have slightly higher variability than their ACC counterparts (ranging from −0.33 mph to 4.1 mph). The difference was most apparent in scenario E (when the lead vehicle maintained speed and ran the red light), for which the participants in conventional vehicles had the highest speed variability (ranging from 4.6 mph to 5.8 mph) compared with ACC drivers with signal messages (1.7–2.0 mph). The team conducted statistical analyses using Type II Wald *F* tests and descriptive statistics. ACC, CDA message type, gender, and age of the participants were included in the statistical model. The participants with ACC had statistically lower speed variability than those in conventional vehicles ($p < 0.001$). CDA message type, gender, and age were not statistically significant.

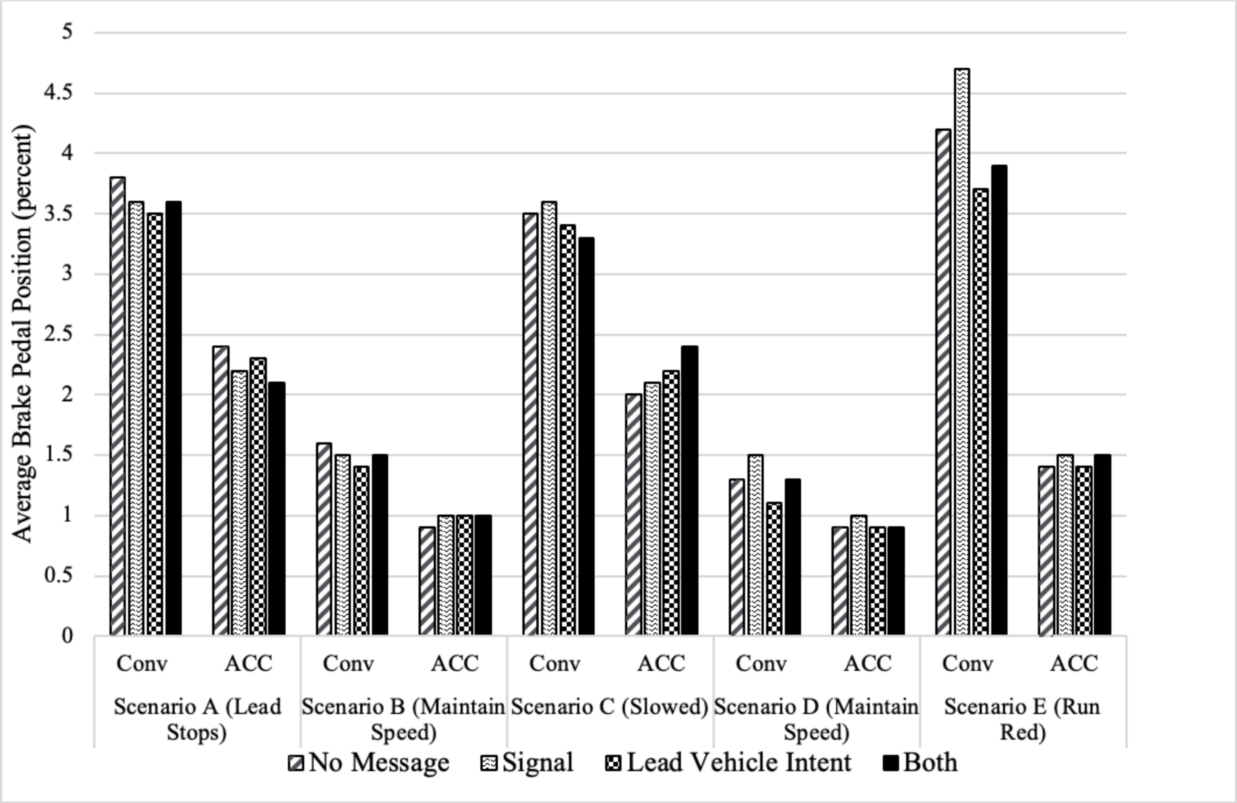


Source: FHWA.

Figure 16. Bar chart. Mean speed variability by scenario, vehicle type, and message type.

Brake Pedal Position

The research team investigated brake pedal position to analyze braking behavior. Brake pedal position, expressed as a percentage out of 100, reflects how much the position of the brake pedal changes. Higher percentages indicate more brake pedal usage and vehicle deceleration. Figure 17 shows the average brake pedal positions as a function of vehicle automation, CDA message type, and scenario. In general, within each scenario, the participants in conventional vehicles tended to apply the brakes more often than the participants with the same message types in ACC vehicles (0.2–3.2 percent more). For example, in scenario A (when the lead vehicle stops), the participants in conventional vehicles with no messages had higher brake pedal positions (3.8 percent) than ACC drivers with no messages (2.4 percent). Similar results for message types were observed within the other scenarios (B–E). These results indicate that for any given message type, the participants with conventional vehicles will tend to decelerate more than participants with ACC vehicles. The team conducted statistical analyses using Type II Wald *F* tests and descriptive statistics. They included ACC, CDA message type, gender, and age of the participants in the statistical model. In all scenarios, the participants in conventional vehicles used the brake pedal more than those with ACC ($p < 0.001$). CDA message type, gender, and age were not statistically significant.



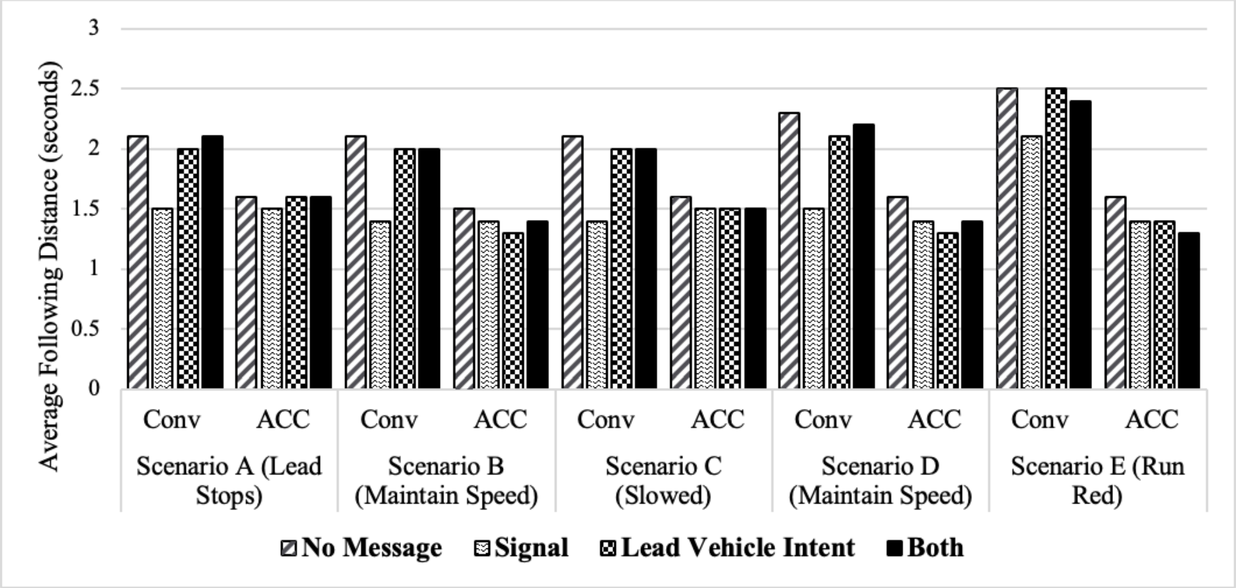
Source: FHWA.

Figure 17. Bar chart. Average variation in brake pedal position.

Objective 2: Following Distance

Drivers in conventional vehicles who receive CDA messages will have shorter following distances than drivers who do not receive CDA messages as a function of ACC use (hypothesis 2). The research team measured following distance in seconds. The team used linear mixed-effects models to evaluate the significance and impact of ACC status and CDA messages on following distance. The team included age and gender in the model as potential confounding variables. Figure 18 presents the average following distances by scenario, vehicle type, and message type. In general, the participants with ACC vehicles tended to have shorter following distances than participants with conventional vehicles (0.1–1.1 s shorter). The linear mixed-effects model revealed that the following distance difference for conventional and ACC-enabled vehicle drivers was statistically significant for scenarios A, B, C, D, and E ($p = 0.001$ for all scenarios).

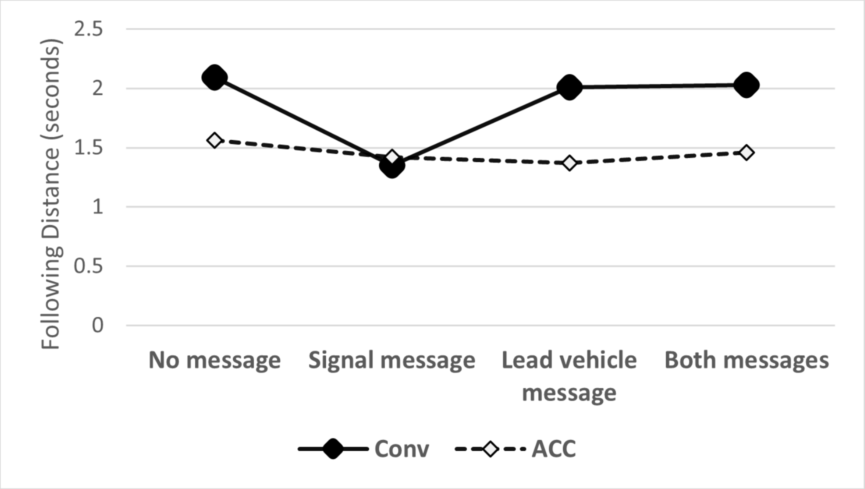
In scenario A, not only was the effect of ACC on following distance significant ($p = 0.001$), but CDA messages ($p = 0.033$) and age ($p = 0.018$) were also statistically significant; however, gender was not. ACC-enabled vehicle drivers had a 0.3-s shorter following distance than conventional vehicle drivers. Drivers aged 45 yr or younger had a 0.2-s longer following distance than drivers aged 46 yr or older.



Source: FHWA.

Figure 18. Bar chart. Average following distances by scenario, vehicle type, and message type.

In scenario B, the effect of ACC ($p < 0.001$) and CDA messages ($p < 0.050$) and their interaction ($p < 0.050$), as well as gender, on following distance were significant. The use of ACC was associated with a shorter following distance except for the traffic signal message. Similarly, the effect of CDA messages on following distance depended on whether ACC was in use. The effect of ACC on following distance, CDA messages ($p = 0.022$), gender ($p = 0.016$), and interaction of ACC status and CDA messages ($p = 0.045$) were significant. The interaction of ACC status and CDA messages were significant, and the statistical estimates of following distance and their differences across different CDA messages are shown in figure 19.



Source: FHWA.

Figure 19. Line graph. Interaction of automation and CDA messages on following distances in scenario B.

In scenario C, the effects of ACC ($p < 0.001$), CDA messages ($p = 0.022$), and gender ($p = 0.049$) on following distance were significant. ACC-enabled vehicle drivers had a 0.4-s shorter following distance than conventional vehicle drivers. Male drivers had a 0.2-s longer following distance than female drivers. In scenario D the effects of ACC status ($p = 0.001$) and CDA messages ($p = 0.020$) on following distance were significant. ACC-enabled vehicle drivers had a 0.7-s shorter following distance than conventional vehicle drivers. In scenario E, ACC status ($p = 0.001$), age ($p = 0.007$) and interaction between age and ACC ($p = 0.026$) were significant. Younger drivers in ACC-enabled vehicles had a 1.3-s shorter following distance than younger drivers in conventional vehicles. Older drivers in ACC-enabled vehicles had a 0.7-s shorter following distance than older drivers in conventional vehicles.

Variability in Following Distance

Drivers in ACC-enabled vehicles will have less variability in following distance than drivers in conventional vehicles (hypothesis 3). In conjunction with the following distance analyses, the research team investigated following distance variability to examine how vehicle automation, CDA message type, or scenario type may be reflected in following distance variability. Figure 20 shows the following distance variability as a function of vehicle automation, CDA message type, and scenario. In terms of the effects of ACC, drivers with ACC vehicles often had slightly more following distance variability in scenarios A, B, C, and D than participants in conventional vehicles (ranging from 0.19 more to 0.04 fewer seconds). The linear mixed-effects model revealed that the differences in scenarios A and C were statistically significant ($p < 0.001$ and $p < 0.050$, respectively). The differences in scenarios B and D were not statistically significant ($p = 0.490$ and $p = 0.970$, respectively). In scenario E, the participants in conventional vehicles had more following distance variability (1.05 s) than the participants in ACC vehicles ($p < 0.001$).

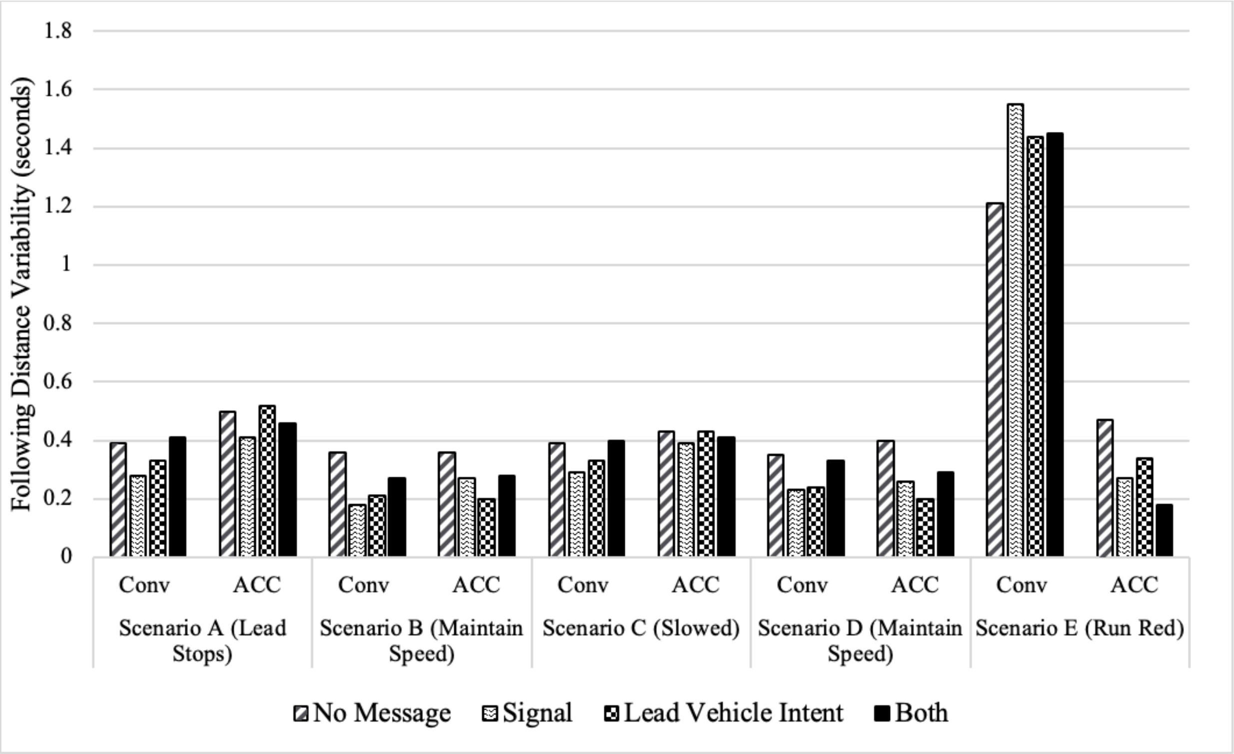
In scenario A (lead vehicle stops), the Type II Wald F tests found age ($p < 0.050$) to be significant, with younger drivers estimated to have slightly more variability (about 0.1 s) than older drivers. CDA messages and gender were not significant ($p = 0.240$ and 0.680, respectively).

In scenario B (lead vehicle maintains speed), the Type II Wald F tests found the effect of CDA messages ($p < 0.050$) and gender ($p < 0.001$) were significant. Drivers receiving the signal, lead vehicle intent, and both CDA messages had less variability than drivers with no CDA messages, with an estimated 0.12, 0.15, and 0.08 less seconds, respectively. For gender, male drivers had 0.12-s less following distance variability than female drivers.

In scenario C (lead vehicle slows in anticipation of an upcoming red signal, the Type II Wald F tests found age ($p < 0.050$) to be significant, with younger drivers estimated to have slightly more following distance variability (about 0.07 s) than older drivers. CDA messages and gender were not significant ($p = 0.440$ and $p = 0.150$, respectively).

In scenario D (lead vehicle maintains speed with red light changing to green), the Type II Wald F tests found the effects of CDA messages ($p < 0.050$) and gender ($p < 0.050$) to be significant. Drivers receiving the signal, lead vehicle intent, and both CDA messages had less variability than drivers with no CDA messages, with an estimated 0.13, 0.15, and 0.06 fewer seconds, respectively. For gender, male drivers had 0.09-s less following distance than females. Age was not significant ($p = 0.950$).

In scenario E (lead vehicle runs the red signal), the Type II Wald F tests found age ($p < 0.050$) to be significant with younger drivers estimated to have slightly more following distance variability (about 0.2 s) than older drivers. CDA messages and gender were not significant ($p = 0.920$ and $p = 0.260$, respectively).



Source: FHWA.

Figure 20. Bar chart. Standard deviation of following distances for scenarios A–E.

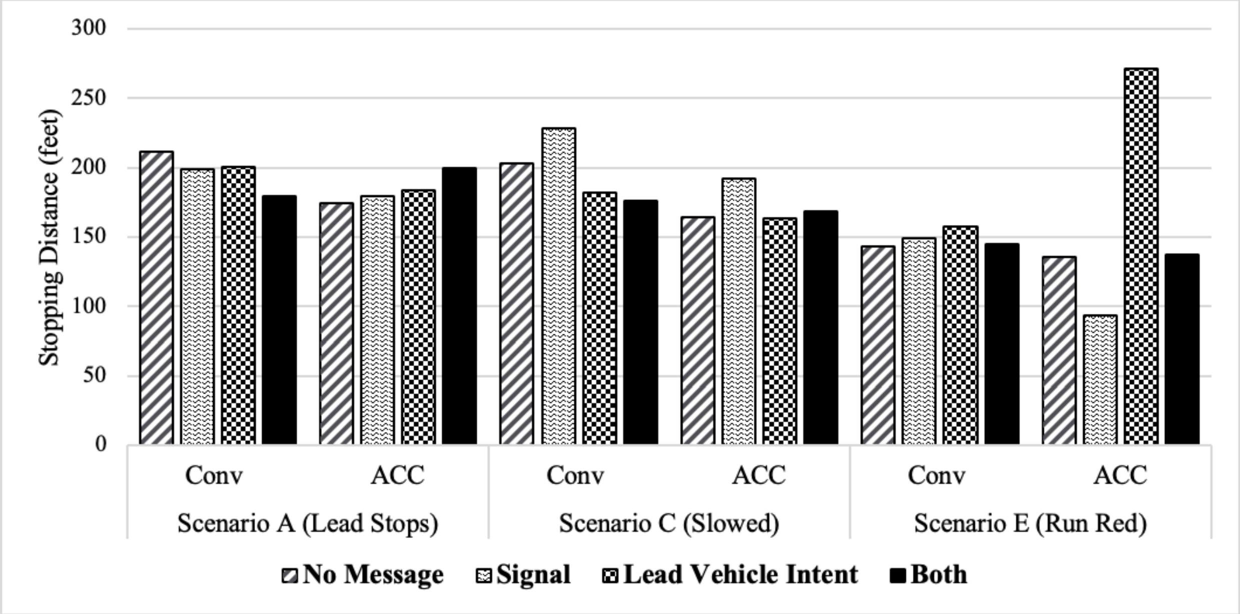
Objective 3: Stopping Patterns

Drivers in conventional vehicles who receive CDA messages will show earlier preparation to stop than drivers who do not receive CDA messages (hypothesis 4). The research team assessed stopping distance to examine when drivers in different groups showed preparation to stop. Stopping distance was defined as the distance from the intersection at which the driver started to brake that eventually progressed to stopping. Among scenarios A–E, scenarios A, C, and E required stopping. Figure 21 shows the average stopping distances as a function of vehicle automation, CDA message type, and scenario. In general, the participants in conventional vehicles with CDA messages did not always begin to stop earlier than those who did not receive CDA messages. In scenario A (when the lead vehicle stopped), the conventional vehicle drivers who received messages stopped 11–32 ft later than the drivers who received no messages (211 ft from the intersection versus 179–200 ft). In scenario C (when the lead vehicle slowed in anticipation of a red signal), the conventional vehicle driver who received the signal message stopped earliest (228 ft from the intersection). The drivers who received no messages stopped second earliest (about 200 ft). The drivers who received the lead vehicle intent and both messages were the latest to stop (181 and 176 ft from the intersection, respectively). In scenario E (when the lead vehicle ran the red light), conventional vehicle drivers who received no message were the latest to stop (143 ft) compared with drivers who received traffic signal (148 ft), lead vehicle intent (157 ft), and both messages (144 ft).

The participants in conventional vehicles generally tended to stop earlier than the participants in ACC-enabled vehicles with the same message type. In scenario A, the conventional vehicle drivers had longer stopping distances than the ACC-enabled vehicle drivers when no CDA messages were displayed. This outcome was similar when signal and lead vehicle messages were displayed. Conventional vehicle drivers had shorter stopping distances than ACC-enabled vehicle drivers when both messages were displayed. A series of two-sample *t*-tests revealed the differences in stopping distance for conventional vehicle drivers and ACC-enabled vehicle drivers for no messages ($p = 0.005$), signal messages ($p = 0.050$), lead vehicle messages ($p = 0.010$), and both messages ($p = 0.050$) were statistically significant. Among the CDA message levels, no statistical difference was observed.

In scenario C, the conventional vehicle drivers had longer stopping distances than the ACC-enabled vehicle drivers for all CDA message levels. A series of two-sample *t*-tests revealed the differences in stopping distance among conventional vehicle drivers and ACC-enabled vehicle drivers for no messages ($p < 0.001$) and lead vehicle messages ($p < 0.001$) were statistically significant.

In scenario E, the conventional vehicle drivers had longer stopping distances than the ACC-enabled vehicle drivers when no CDA messages were displayed. This outcome was similar when signal messages and both messages were displayed. The conventional vehicle drivers had shorter stopping distances than the ACC-enabled vehicle drivers when lead vehicle messages were displayed. A series of two-sample *t*-tests revealed the difference in stopping distances among conventional vehicle drivers and ACC-enabled vehicle drivers for signal message ($p = 0.006$) was statistically significant.



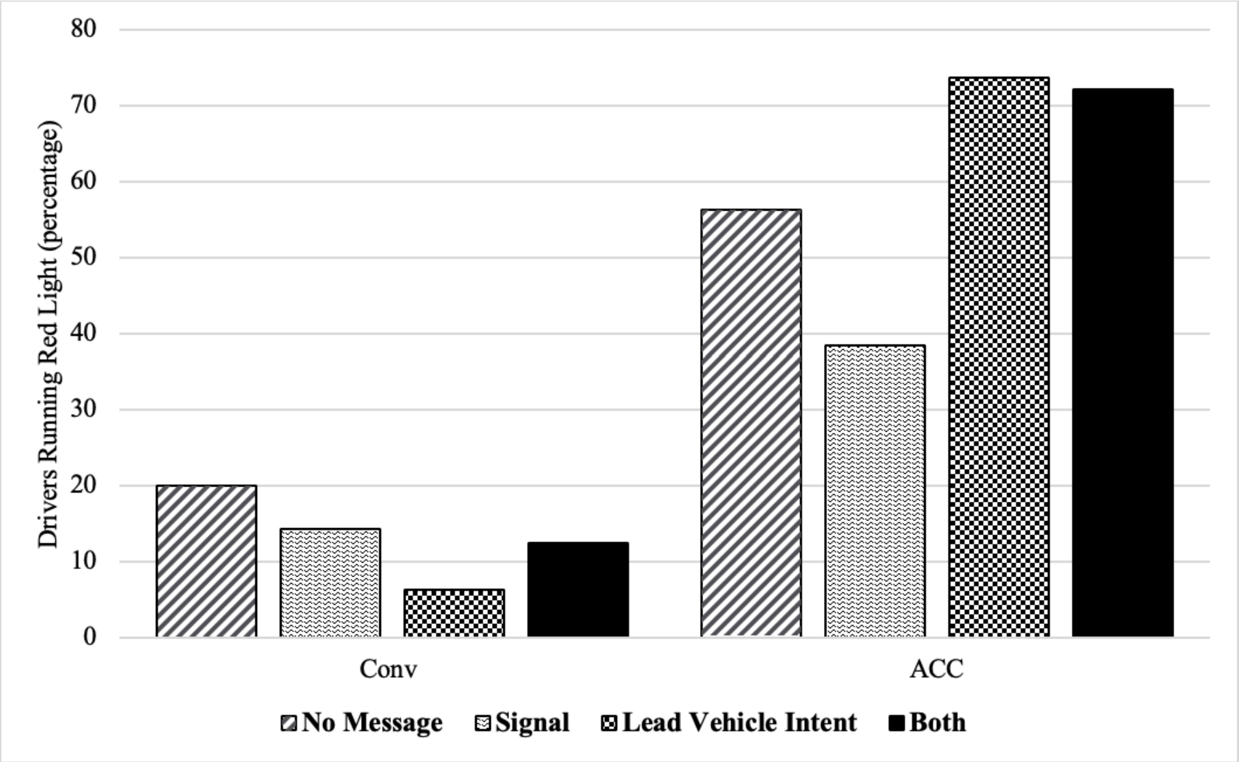
Source: FHWA.

Figure 21. Bar chart. Stopping distances by ACC status and CDA messages for scenarios A, C, and E.

Red Light Running

Drivers in ACC-enabled vehicles who do not receive CDA messages will be more likely to run the red light when following the lead vehicle than those who receive the CDA messages (hypothesis 5). In scenario E, the lead vehicle maintained vehicle speed and ran the red light, and the participant had to decide whether to stop at the light or proceed through the red light. Figure 22 shows the percentage of drivers following the lead vehicle who ran the red light. Only the participants in ACC-enabled vehicles with the signal message ran the red lights less often than drivers who did not receive CDA messages, suggesting that receiving traffic signal information was helpful for understanding the signal phase and timing and determining whether to proceed or stop. The team found that participants in ACC-enabled vehicles who received the lead vehicle intent or both message types ran the red light more frequently than participants in the conventional vehicle who received no messages.

Overall, the participants with ACC-enabled vehicles tended to run the red light more frequently than participants with conventional vehicles. Participants with ACC vehicles ran the red light about 40–75 percent of the time, whereas participants with conventional vehicles ran the red light between 6 and 20 percent. The research team used a mixed-effect logistic regression model to assess the influence of ACC status and CDA messages on drivers running the red light. The effect of ACC status was statistically significant ($p < 0.001$), but CDA messages were not. The team found no other statistically significant effects.



Source: FHWA.

Figure 22. Bar chart. Percentage of drivers who ran the red light.

Objective 4: Driver Trust in Automation

Drivers who receive CDA messages will report higher levels of trust in vehicle automation technology than drivers who do not receive CDA messages (hypothesis 6). The research team investigated the participants' ratings from the midexperiment trust questions and postexperiment safety questions.

Midexperiment Trust Questions

The midexperiment questions explored driver trust in automation based on the participants' ratings of their trust in the lead vehicle, the ACC in their vehicle, and the CDA messages. The results for participants in conventional and ACC-enabled vehicles are provided in the following sections.

Question 1: Trust in the Lead Vehicle

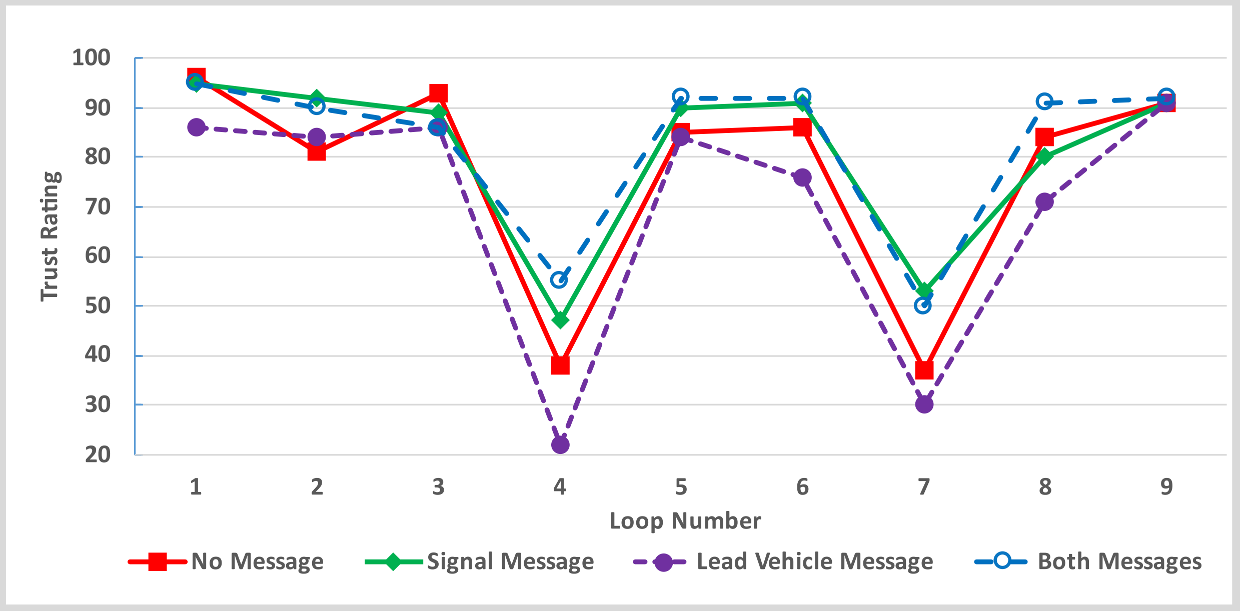
The research team asked the participants to rate their level of trust in the lead vehicle. As previously described in table 20, the participants drove nine loops, each consisting of different driving scenarios (i.e., lead vehicle stopping, maintaining speed, slowing early, and running red light driving scenarios). After completing each loop, the researchers asked the participants to rate their trust (from 0 to 100) in the lead vehicle. The data analysis indicated that drivers with ACC-enabled vehicles had a higher average trust rating for the lead vehicle than drivers in conventional vehicles (82 versus 78). The analyses also found that drivers who received CDA messages had a slightly lower average trust rating for the lead vehicle than drivers who did not receive CDA messages (77 versus 81). However, Type II Wald Chi-square tests revealed a statistically significant three-way interaction between vehicle automation, CDA message type, and loop ($p < 0.001$) and two-way interactions for CDA message type by loop ($p < 0.001$) and vehicle automation by loop ($p < 0.001$). To better understand the results, the following sections describe the participants' ratings of trust in the lead vehicle for conventional and ACC-enabled vehicles as a function of message type and loop.

Conventional Vehicles

The researchers examined the conventional vehicle drivers' ratings as a function of message type and loop. As shown in figure 23, trust in the lead vehicle ratings were above 75, except after loops 4 and 7 (after the lead vehicle ran the red light). In loops 4 and 7, the average trust ratings dropped, indicating a reduction in trust for the lead vehicle. However, after each reduction in trust event, the ratings rebounded on subsequent loops (i.e., loops 5 and 6 and loops 8 and 9).

The Type II Wald Chi-square tests indicated that a statistically significant two-way interaction occurred between CDA message type and loop ($p < 0.001$). The researchers examined pairwise comparisons of differences in conventional vehicle drivers' trust in lead vehicle ratings between the CDA message types *within each loop*. Overall, within each loop, only one statistically significant difference occurred between CDA message types. Within loop 4, conventional vehicle drivers who received the lead vehicle message had statistically lower trust in the lead vehicle ratings than those who received both messages ($p < 0.050$). This finding was the only statistically significant trust in the lead vehicle rating difference that the researchers found when comparing CDA message types within a loop. The team found no other statistically significant pairwise differences in trust ratings between CDA message types within loops.

The researchers examined pairwise comparisons of differences in the conventional vehicle drivers' trust in lead vehicle ratings for the CDA message types *between each loop*. The results indicated that regardless of the CDA message type (no message, signal, lead vehicle, or both), conventional vehicle participants' trust in the lead vehicle ratings decreased when the lead vehicle ran the red light on loops 4 and 7 and increased on loops 5 and 8. The pairwise comparisons found that the decreases between loops 3 and 4 and loops 6 and 7 and the increases between loops 4 and 5 and loops 7 and 8 were significant ($p < 0.001$ for all). Overall, the results did not indicate a higher trust rating for conventional vehicle drivers receiving CDA messages versus drivers not receiving messages within each loop.



Source: FHWA.

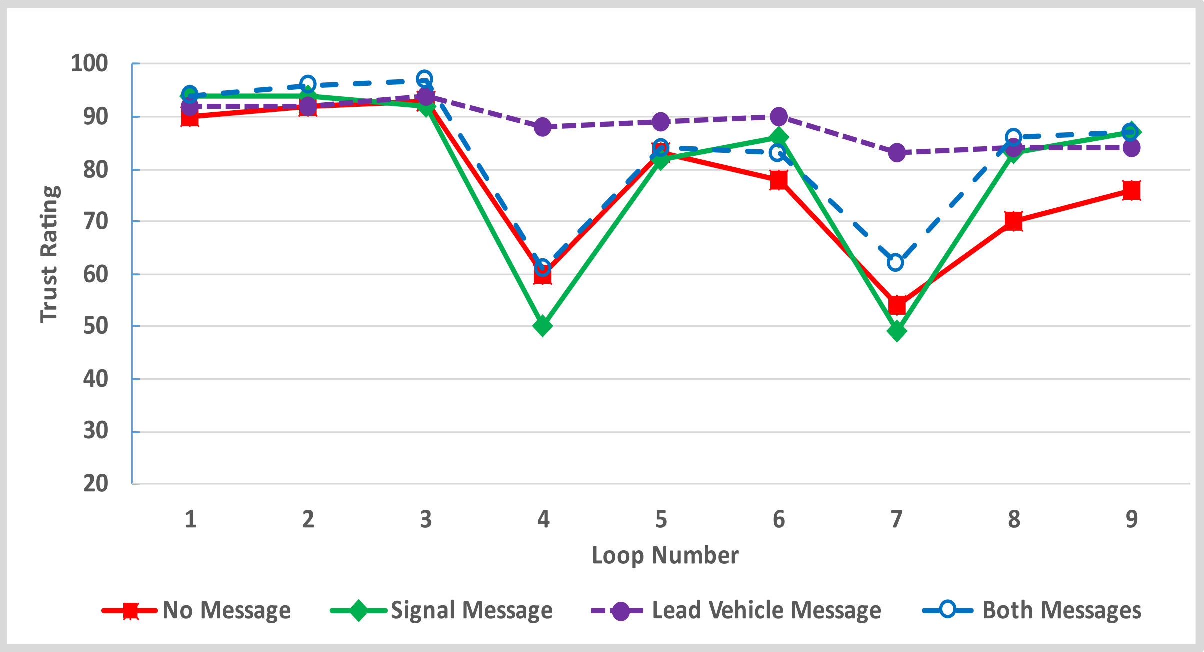
Figure 23. Line graph. Conventional vehicle participant lead vehicle trust ratings.

ACC-Enabled Vehicles

The researchers examined the ACC-enabled vehicle drivers' ratings as a function of message type and loop. As shown in figure 24, trust in the lead vehicle ratings was above 70 percent, except when a reduction in trust for the lead vehicle was again observed on loops 4 and 7 (after the lead vehicle ran the red light). In loops 4 and 7, the average trust ratings tended to drop then rebound in loops 5 and 8. However, the participants who received the lead vehicle message had a smaller change in lead vehicle trust ratings after the lead vehicle ran the red light in loops 4 and 7.

The Type II Wald Chi-square tests indicated a statistically significant two-way interaction occurred between CDA message type and loop ($p = 0.001$). The researchers then examined pairwise comparisons of differences in ACC-enabled vehicle drivers' trust ratings between the CDA message types *within each loop*. Overall, within each loop, only one statistically significant difference occurred between CDA message types. Within loop 3, ACC-vehicle drivers who received the signal message had statistically lower trust ratings than those receiving both messages ($p < 0.050$). The team found no other statistically significant pairwise differences in trust ratings within loops.

The researchers examined pairwise comparisons of differences in the conventional vehicle drivers' trust in lead vehicle ratings for the CDA message types *between each loop*. The results indicated that regardless of the CDA message type (no message, signal, lead vehicle, or both), ACC-enabled vehicle participants' trust in the lead vehicle ratings decreased when the lead vehicle ran the red light on loops 4 and 7 and increased on loops 5 and 8. The pairwise comparisons found that the decreases between loops 3 and 4 and loops 6 and 7 and the increases between loops 4 and 5 and loops 7 and 8 were significant for all ($p < 0.001$), except for the drivers receiving lead vehicle messages. For the drivers receiving lead vehicle messages, the decreases on loops 4 and 7 were small and significant ($p < 0.001$) but the increases in loops 5 and 8 were not significant ($p = 0.930$ and $p < 1.000$, respectively). Overall, the results did not indicate a higher trust rating for drivers in ACC-enabled vehicles receiving CDA messages versus drivers not receiving messages within each loop.



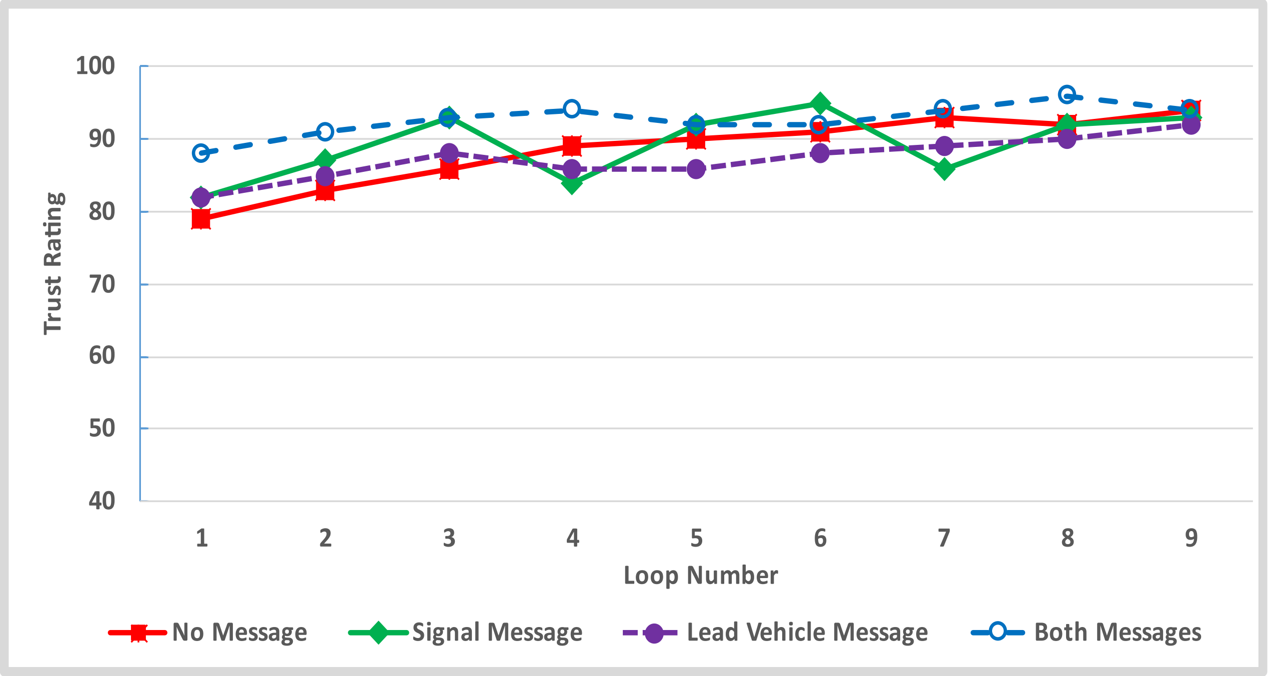
Source: FHWA.

Figure 24. Line graph. ACC-enabled vehicle participant lead vehicle trust ratings.

Question 2: Trust in the ACC System

The research team asked the participants in ACC-enabled vehicles to rate their level of trust in the ACC system. As shown in figure 25, all participants in ACC-enabled vehicles had a relatively high level of trust in the ACC system, with ratings between 79 and 96 out of 100. Type II Wald Chi-square tests indicated a statistically significant two-way interaction occurred for CDA message type by loop ($p < 0.001$). The researchers then examined pairwise comparisons of differences in ACC-enabled vehicle drivers' trust ratings between the CDA message types *within each loop*. The pairwise comparisons for only the ACC-vehicle drivers who received the signal message on loops 4 and 7 were significant. Within loop 4, ACC-vehicle drivers who received the signal message had statistically lower trust ratings than those receiving both messages ($p < 0.050$). Within loop 7, ACC-vehicle drivers who received the signal message had statistically lower trust ratings than those receiving both messages ($p < 0.050$). The team found no other statistically significant pairwise differences in trust ratings within loops.

The researchers examined pairwise comparisons of differences in conventional vehicle drivers' trust in lead vehicle ratings for the CDA message types *between each loop*. The pairwise comparisons found that only the drivers receiving the signal message had statistically reliable changes in trust in the ACC system ratings. The ACC-enabled vehicle participants' trust in the ACC system ratings decreased when the lead vehicle ran the red light on loops 4 and 7 and increased on loops 5 and 8. The pairwise comparisons found that the decreases between loops 3 and 4 and loops 6 and 7 and the increases between loops 4 and 5 and loops 7 and 8 were all significant ($p < 0.001$ for all). Overall, the results did not indicate a higher trust rating for drivers in ACC-enabled vehicles receiving CDA messages versus drivers not receiving messages within each loop.



Source: FHWA.

Figure 25. Line graph. Level of trust in the ACC system.

Question 3: Trust in the CDA Messaging System

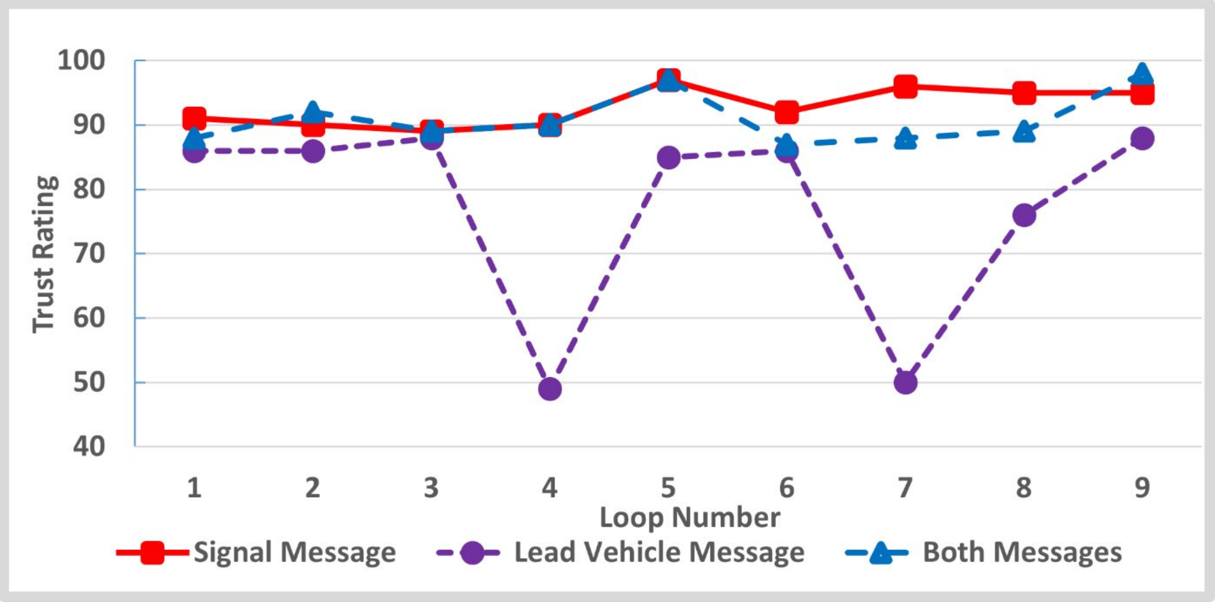
The research team asked the participants in conventional and ACC-enabled vehicles to rate their level of trust in the CDA messages. The participants drove nine loops and after completing each loop, the team asked them to rate their trust (from 0 to 100) in the CDA message system. The data analysis indicated that drivers with ACC-enabled vehicles had a higher average trust rating for the CDA message system than drivers in conventional vehicles (92 versus 87). Type II Wald Chi-square tests indicated a statistically significant two-way interaction occurred for CDA message type by loop ($p < 0.001$) and vehicle automation by loop ($p < 0.001$). The following sections describe the participants' ratings of trust in the CDA messaging system for conventional and ACC-enabled vehicles as a function of message type and loop.

Conventional Vehicles

The researchers investigated the ratings of participants in conventional vehicles as a function of message type and loop. As shown in figure 26, trust in the CDA messaging system was higher than 75, except for drivers receiving lead vehicle messages on loops 4 and 7 (after the lead vehicle ran the red light). In loops 4 and 7, the average trust ratings dropped to about 50 and rebounded in loops 5 and 8.

The Type II Wald Chi-square tests indicated a statistically significant two-way interaction occurred between CDA message type and loop ($p < 0.001$). The researchers examined pairwise comparisons of differences in the conventional vehicle drivers' trust ratings between the CDA message types *within each loop*. Overall, within each loop, only one statistically significant difference occurred between CDA message types. Within loop 4, conventional vehicle drivers who received the lead vehicle message had statistically lower trust in the lead vehicle ratings than those receiving both messages ($p < 0.050$). This finding was the only statistically significant trust in the lead vehicle rating difference that the researchers found when comparing CDA message types within a loop. The team found no other statistically significant pairwise differences in trust ratings between CDA message types within loops.

The researchers examined pairwise comparisons of differences in the conventional vehicle drivers' trust in CDA message system ratings for the CDA message types *between each loop*. When the conventional vehicle participants received signal messages, trust ratings remained high when the lead vehicle ran the red light on loops 4 and 7 and even increased slightly after loop 4. The pairwise comparisons found no differences between loops 3 and 4, but loops 4 and 5 were significant ($p = 0.001$). The pairwise comparisons also found that the trust rating increase between loops 6 and 7 was significant ($p < 0.050$) but not between loops 7 and 8 ($p = 0.950$). The participants who received the lead vehicle messages had large reductions in trust (from about mid 80s down to 49 and 50) after the lead vehicle ran the red light. A pairwise comparison of the differences found that the trust rating decreased between loops 3 and 4, and loops 6 and 7 were both statistically significant ($p < 0.001$ for both). A similar outcome occurred for the rating increases between loops 4 and 5 and loops 7 and 8 ($p < 0.001$ for both). The participants who received both messages also had generally high trust ratings (87–98). When participants received both messages, the trust ratings remained high on loops 4 and 7 (when the lead vehicle ran the red light) and increased slightly after loop 4. The pairwise comparisons found no differences between loops 3 and 4 ($p = 0.990$), but loops 4 and 5 were significant ($p < 0.001$). The pairwise comparisons also found that the trust rating did not change between loops 6 and 7 ($p = 1.000$) or between loops 7 and 8 ($p = 0.940$). Overall, the results did show that conventional vehicle drivers receiving signal and both messages had consistently high trust for the CDA message system versus drivers receiving the lead vehicle messages.



Source: FHWA.

Figure 26. Line graph. Level of trust in CDA messaging systems when participants drove the conventional vehicle.

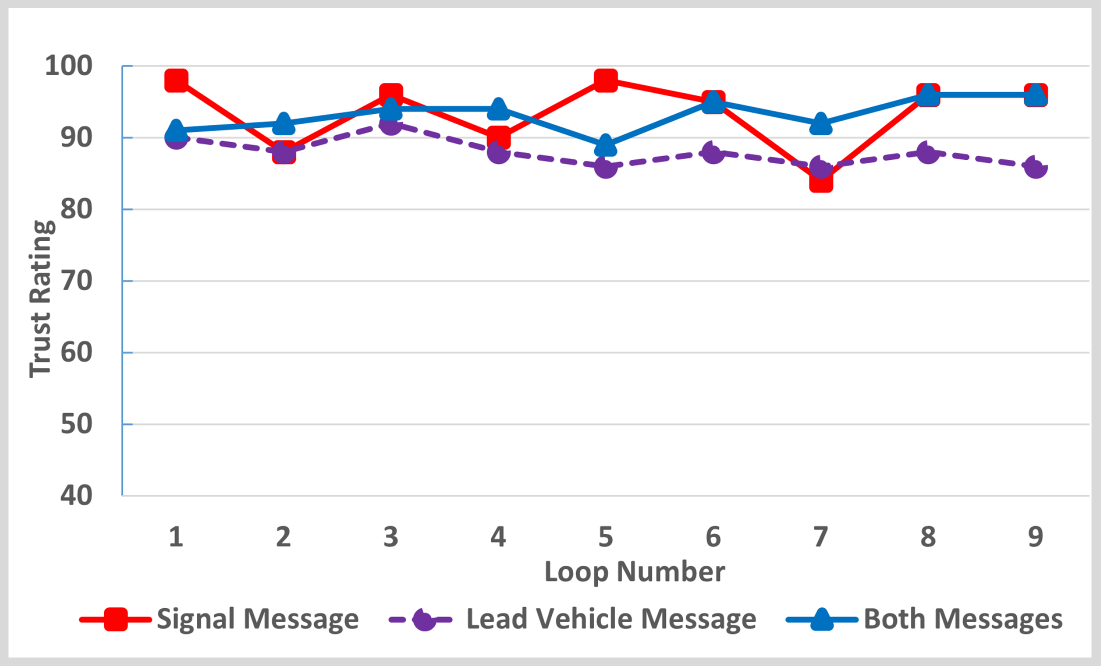
ACC-Enabled Vehicles

The researchers investigated the ratings of participants in ACC-enabled vehicles as a function of message type and loop. Figure 27 shows trust ratings of participants in ACC-enabled vehicles. In general, the participants' trust in the CDA messaging system was higher than 80, even after loops 4 and 7 (when the lead vehicle ran the red light).

The Type II Wald Chi-square tests indicated a statistically significant two-way interaction occurred between CDA message type and loop ($p < 0.001$). The researchers examined pairwise comparisons of differences in conventional vehicle drivers' trust ratings between the CDA message types *within each loop*. Overall, within each loop, no statistically significant differences occurred between any of the CDA message types ($p > 0.050$ for all).

The research team examined pairwise comparisons of differences in the conventional vehicle drivers' trust in CDA message system ratings for the CDA message types *between each loop*. Overall, ACC-enabled vehicle participants who received signal messages generally had higher trust ratings (84–98). When the participants received signal messages, the trust ratings remained high when the lead vehicle ran the red light but decreased on loop 4 and loop 7. The pairwise comparisons found significant differences between loops 3 and 4 ($p < 0.001$) and loops 4 and 5 ($p < 0.001$). Similarly, pairwise comparisons also found that the trust rating differences between loops 6 and 7 ($p < 0.001$) and between loops 7 and 8 ($p < 0.001$) were significant. The participants who received the lead vehicle messages had smaller changes in trust after the lead vehicle ran the red light. Between loops 3 and 4 and loops 6 and 7, the lead vehicle message participants' ratings decreased from 92 to 88 and 88 to 86, respectively. A pairwise comparison of the differences found that the trust rating decrease between loops 3 and 4 was statistically significant ($p < 0.050$). The rating change between loops 4 and 5 was not significant ($p < 0.990$).

The changes between loops 6 and 7 and loops 7 and 8 were not significant ($p = 0.690$ and $p = 0.920$, respectively). The participants who received both messages also had generally high trust ratings (89–96). When the participants received both messages, the trust ratings remained high on loops 4 and 7 (when the lead vehicle ran the red light) but decreased slightly after loop 4 and increased slightly on loop 7. The pairwise comparisons found no differences between loops 3 and 4 ($p = 0.990$), but the decrease between loops 4 and 5 were significant ($p < 0.001$). The pairwise comparisons also found that the trust rating did not change between loops 6 and 7 ($p = 0.070$) but did increase significantly between loops 7 and 8 ($p < 0.050$). Overall, the analyses showed that despite fluctuations between loops, the drivers with ACC-enabled vehicles had consistently high trust for the CDA message system.



Source: FHWA.

Figure 27. Line graph. Level of trust in CDA messaging systems when participants drove the ACC-enabled vehicle.

Postexperiment Vehicle Automation Safety Questions

The researchers also examined the participants' postexperiment ratings to assess their perception of vehicle automation technology safety on the roadway. Based on participants' responses to the postexperiment questionnaire, the research team calculated their perception of safety gain and loss associated with each statement. The team designed the statements to identify the net total safety (where net total safety equals average safety gain minus average safety loss) when driving on a roadway where some vehicles are driven manually and other vehicles are driven by ADS.

Table 21 shows the net total safety by vehicle type and CDA message type. Overall, the participants viewed the use of vehicle automation as a safety gain more than a safety loss for all CDA messages in conventional vehicles and all but one in ACC-enabled vehicles. The participants in conventional vehicles indicated that receiving signal messages resulted in the largest net total safety gain (0.8) compared with receiving no messages and both messages (0.6 and 0.5, respectively) and a lead vehicle message (0.1). Participants in ACC-enabled vehicles indicated that receiving the lead vehicle or both messages resulted in the largest net total safety gain (both 0.5) compared to receiving the signal message (0.4) or no messages (0.1). The researchers used a linear regression model to test whether vehicle automation or CDA message types affected the derived net total safety. The team found no significant differences for vehicle automation (*p* = 0.750), signal messages (*p* = 0.390), lead vehicle (*p* = 0.970), or both messages (*p* = 0.590).

Table 21. Net total safety by vehicle type and message type.

Vehicle Automation	CDA Message	Average Safety Gain	Average Safety Loss	Net Total Safety
Conventional	No message	3.9	3.3	0.6
	Signal message	3.6	2.8	0.8
	Lead vehicle message	3.1	3.0	0.1
	Both messages	3.2	2.7	0.5
ACC enabled	No message	3.0	2.9	0.1
	Signal message	3.3	2.9	0.4
	Lead vehicle message	3.5	2.9	0.5
	Both messages	3.6	3.1	0.5

CHAPTER 4. GENERAL DISCUSSION

This research consisted of a preliminary study that examined CDA V2I and V2V message designs to be used in the field study. The field study examined the behavior of drivers who followed a lead vehicle that demonstrated eco-driving strategies and drivers' perceptions of automated driving and CDA technology.

The preliminary study considered 16 designs. The research team selected four V2I and two V2V designs to use in the field study based on participants' understanding of the messages, expected actions, perceived effectiveness, and overall preferences. The team chose four V2I designs based on the participants' scores and an examination of ratings and comments. They selected the standard traffic signal style (designs 1 and 5, shown in figure 5) and traffic signals with the transition arrow style (designs 3 and 7, shown in figure 6) because of their scores in message understanding (e.g., the traffic signal was changing from green to red) and overall situational expectation results (e.g., slow down and prepare to stop). All four designs had the highest percentage of message understanding (from 83 to 100 percent). The researchers chose two V2V designs to notify the participants of the lead vehicle's intention to either move or stop. They selected the dual vehicles with intention (design 11, shown in figure 7) and dual vehicles with intention and line (design 16, also shown in figure 7) styles because of their top scores (67 and 67 percent) in message understanding (i.e., the traffic signal was changing color and the car ahead was intending to move/stop), high message effectiveness ratings (clear and easy to understand) (3.58 and 3.5, respectively), and high participant agreement on being the most effective designs (50 and 75 percent, respectively).

The field study used the traffic signal and lead vehicle intent styles identified in the preliminary study. Eighty participants drove a research vehicle nine loops around a test track where each loop consisted of two trials through a traffic signal. The participants drove either an ACC-enabled vehicle or a conventional vehicle (i.e., no ACC) and received one of four message conditions (i.e., no messages, signal only, lead vehicle intent, or both signal and lead vehicle intent). During each loop, the participants followed a lead vehicle while approaching a traffic signal where the signal phase and timing and the lead vehicle's action created one of five signal scenarios: (A) gradually stopping at the intersection on a red signal, (B) maintaining speed and clearing the intersection on a green signal, (C) decelerating on a green signal in anticipation of an upcoming red signal, (D) maintaining speed during a red signal in anticipation of an upcoming green signal, and (E) performing an illegal maneuver by maintaining speed through an intersection during a red signal.

The study examined driver behavior in four areas: speed fluctuation and following distance differences between drivers using ACC-enabled vehicles and drivers not using ACC, following distance differences between drivers using CDA messages and those not using CDA messages as a function of ACC use, stopping and acceleration or deceleration patterns ahead of the red light for different combinations of CDA messages and ACC, and participant perspectives on trust and safety.

Based on the research objectives, the team investigated the following six hypotheses:

1. **Drivers in ACC-enabled vehicles will have fewer fluctuations in speed than drivers in conventional vehicles.** The statistical analyses *supported* this hypothesis. Consistent with Howard,(18) the participants in ACC-enabled vehicles had statistically significant fewer total fluctuations (50) than the participants with conventional vehicles (121). The participants in ACC-enabled vehicles tended to have statistically significant higher average speeds (0.1–2.2 mph greater) and smaller speed variability (0.1–1.1 mph less) than the participants in conventional vehicles. These findings are reasonable given that the ACC-enabled drivers adapted their speeds by following the automated lead vehicle with a smooth speed profile. Within every scenario, the drivers in ACC-enabled vehicles had less fluctuations than participants in conventional vehicles. The statistical analyses also *supported* this outcome, showing that within each scenario, in general, the participants in conventional vehicles tended to apply the brakes more often (1.5–5.4 percent) than participants with the same message types in ACC vehicles (thus indicating more deceleration).

2. **Drivers in ACC-enabled vehicles will have less variability in following distances than drivers in conventional vehicles.** The statistical analyses *partially supported* this hypothesis. In most cases, the participants in conventional vehicles who received CDA messages had shorter following distances (0.1–0.4 s) than those who did not receive CDA messages; however, this difference was not always significant. The conventional vehicle drivers with both messages had (statistically) the same (or slightly greater) following distance in scenarios A, B, and D (lead vehicle stops, lead vehicle maintains speed through green light, lead vehicle maintains speed with red light changing to green). Within each scenario, the participants in conventional vehicles who received no messages tended to have higher variability than the participants who received the signal message and a lead vehicle intent message. Consistent with Howard,(18) the statistical comparisons of participants in conventional vehicles versus those in ACC-enable vehicles indicated that within each scenario, the participants in conventional vehicles had higher following distance variability (0.1–0.6 s more) than participants in ACC vehicles with the same message types.

3. **Drivers in conventional vehicles who receive CDA messages will exhibit shorter following distances than drivers who do not receive CDA messages as a function of ACC use.** The statistical analyses *supported* this hypothesis. Across all scenarios, the participants in ACC vehicles had statistically significant shorter following distances than the participants with conventional vehicles (0.1–1.1 s shorter). Among the CDA messages, the drivers who received signal messages had the shortest following distances. Their following distances were similar to the ACC-enabled vehicle drivers' following distances. The research team observed a small (significant) following distance difference among drivers who received no messages, lead vehicle messages, and both messages. Pulvirenti et al.(12) suggested that the use of M2M communication (CDA messages) can be successful in propagating eco-driving strategy, and that suggestion was supported in the observed following distances. Communicating with infrastructure through signal messages tended to sustain close following distances more than other sources of CDA

messages (i.e., lead vehicle intent and both messages), as suggested in the findings of Rakha, Kamalanathsharma, and Ahn.(13)

4. **Drivers in ACC-enabled vehicles who do not receive CDA messages will be more likely to run the red light when following the lead vehicle than those who receive the CDA messages.** The statistical analyses *did not support* this hypothesis. Only the participants in ACC-enabled vehicles who received the signal message ran the red light less than drivers who did not receive CDA messages. This outcome suggests that receiving traffic signal information was helpful for understanding the signal phase and timing and determining whether to proceed or stop. Statistical testing indicated that the participants in ACC-enabled vehicles who received the lead vehicle intent or both message types ran the red light more frequently than the participants in conventional vehicles who received no messages. The participants in conventional vehicles ran the red light between 6 and 20 percent, whereas the participants in ACC vehicles ran the red light about 40–75 percent of the time. Whether this outcome was due to the participants overtrusting the lead vehicle technology, driver complacency due to the closed track experiment, or some other reason is unclear.

5. **Drivers in conventional vehicles who receive CDA messages will show earlier preparation to stop than drivers who do not receive CDA messages.** The statistical analyses *did not support* this hypothesis. In general, the participants in conventional vehicles with CDA messages did not always prepare to stop earlier than those who did not receive CDA messages. In only one scenario (scenario E, when the lead vehicle ran the red light) did the statistical testing indicate that the participants in conventional vehicles who received messages stopped sooner than the participants who did not receive messages. In scenario A (when the lead vehicle stopped), statistical testing indicated that the participants in conventional vehicles who received messages stopped 11–32 ft later than the participants who received no messages (211 ft from the intersection versus 179–200 ft). In scenario C (when the lead vehicle slowed), statistical testing indicated that the participants in conventional vehicles who received the signal message stopped earliest (228 ft from the intersection). The participants who received no messages stopped second earliest (about 200 ft). The participants who received the lead vehicle intent and both messages were the latest to stop (181 and 176 ft from the intersection, respectively).

6. **Drivers who receive CDA messages will report higher levels of trust in vehicle automation technology than drivers who do not receive CDA messages.** The statistical analyses *did not support* this hypothesis. The results indicated that drivers with ACC-enabled vehicles and non-ACC vehicles both had relatively high trust in the lead vehicle regardless of whether the drivers were receiving CDA messages (77 versus 81, respectively, out of 100). In terms of trust in the lead vehicle, within each loop (i.e., lead vehicle stopping, maintaining speed, slowing early, and running red light driving scenarios) the drivers' trust in the lead vehicle was not statistically different between drivers who did and did not receive CDA messages. Although statistically reliable differences occurred in trust ratings between the loops (driving scenarios), especially when the lead vehicle ran the red light, the changes in trust in the lead vehicle were not statistically different between drivers who did and did not receive CDA messages.

In terms of trust in the ACC system, all the participants in ACC-enabled vehicles had relatively high levels of trust in the ACC system, with ratings between 79 and 96 out of 100. In terms of trust in the ACC system, within each loop, the drivers' trust in the ACC system was not statistically different between drivers who did and did not receive CDA messages. Although statistically reliable differences in trust ratings occurred between the loops (driving scenarios), especially when the lead vehicle ran the red light, the changes in trust in the ACC system was not statistically different between drivers who did and did not receive CDA messages.

In terms of trust in the CDA message system, the participants in conventional vehicles were affected by the type of CDA message they received. The participants who received signal messages had relatively high trust (higher than 75). Within each loop, the drivers' trust in the CDA message system was not statistically different between CDA message types, except within loop 4 (when the lead vehicle ran the red light) with conventional vehicle drivers. In loop 4, the conventional vehicle drivers who received the lead vehicle message had statistically lower trust in the lead vehicle ratings than those who received both messages. The team found no other statistically significant pairwise differences in trust ratings between CDA message types within loops. Overall, these analyses found that despite fluctuations between loops, drivers with ACC-enabled and conventional vehicles had consistently high trust for the CDA message system.

In terms of the perception of vehicle automation technology safety on the roadway, the participants generally had a positive view of the use of vehicle automation. When comparing safety gains to safety losses, all CDA messages in conventional vehicles and ACC-enabled vehicles had a positive net safety gain. For the participants in conventional vehicles, those who received signal messages had the largest net safety gain (0.8). For the participants in ACC-enabled vehicles, those who received the lead vehicle or both messages had the largest net safety gain (0.5 for both).

Through these hypotheses, the research team assessed whether the eco-driving strategies implemented by the lead vehicle were propagated into the behavior of the following vehicle. Ensuring stable, smooth driving is important for successful implementation of eco-driving strategies. The team found that participants in ACC-enabled vehicles had smoother speed profiles than participants in conventional vehicles. A smooth speed profile indicates less abrupt acceleration and deceleration, resulting in eco-friendly driving patterns. The participants in ACC-enabled vehicles had shorter following distances and more consistent following distances than the participants in conventional vehicles. The participants in conventional vehicles who received V2I signal messages also had shorter and more consistent following distances than the participants who were in other conventional vehicles. Achieving a short and stable following distance was important to ensure that the vehicles operated in a platoon. The research team hypothesized that receiving CDA messages would prompt participants to prepare to stop earlier at the intersection, but this expectation was not the case. The participants in ACC-enabled vehicles showed late preparation to stop, except when they received V2V messages about the lead vehicle running the red light. The participants took a significantly longer gap from the lead vehicle anticipating the event. Overall, ACC-enabled following vehicles and V2I CDA messages about upcoming signal changes were helpful in the successful implementation of eco-driving strategies.

This study provided insight into the implementation of eco-driving strategies among following drivers and how CDA messages can affect that implementation. This study also provided insight into driver acceptance of an eco-driving lead vehicle and overall driver trust in vehicle automation technology. The research team observed that if the following vehicle is adaptive or automated to some degree, then following the eco-driving lead vehicle is easier. V2I signal status CDA messages and V2V intent-sharing CDA messages showed an advantage for eco-driving strategies. V2V messages had a potential of prompting unsafe driving behaviors among the following drivers. This study was limited in the ability to determine if that outcome was because of overtrusting the technology or because of complacency due to driving on a closed test track. Future studies could help provide a better understanding of driver behaviors and attitudes when following an eco-driving vehicle in short (and larger) platoons of vehicles or at higher vehicle speeds and the reasons behind driver decisionmaking and rebuilding trust in technology.

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The photo in figure 9 in this report has been modified. The original map is the copyright property of Google Earth and can be accessed from https://www.google.com/earth/.(22) The map overlays show the test site markings that were developed for this research project. The overlays include white text boxes showing the specific route and locations of the signal heads.

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