Lane-Change Response to Infrastructure Warning About Lane Closure in a Mixed Vehicle Fleet

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FOREWORD

Rapid advances in vehicle automation are underway that may broadly affect the transportation landscape once widescale deployment occurs. While automated driving systems (ADS; i.e., driving systems capable of performing the driving task) have received much attention in the field, cooperative driving automation (CDA) is also being developed and provides a means for ADS and roadway infrastructure to communicate safety messages. Currently, drivers can receive information about roadway conditions from the infrastructure via traffic control devices (TCDs) like dynamic message signs. However, how drivers will respond to in-vehicle CDA messaging is currently unknown.

This report documents a driving simulator experiment that explores drivers' behaviors in response to receiving roadway information from either a TCD sign, an in-vehicle CDA alert, or a combination of the two message sources. This report may interest personnel at State and local transportation agencies who want to better understand the potential safety benefits of vehicle-to-infrastructure CDA messaging.

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Director, FHWA Office of Safety and Operations
Research and Development

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Fostering the safe and efficient operation of road networks that include vehicles equipped with SAE International® Level 3™ (L3) automation and a cooperative automated driving system (C-ADS) requires an examination of these systems' ability to interpret and correctly respond to infrastructure that was designed for human drivers (SAE International, 2020). Changeable message signs (CMSs) are one of the infrastructure elements that may be problematic for L3 automation systems. This research study used a driving simulator to assess the potential value of adding cooperative driving automation (CDA) alerts to a CMS. The study team manipulated whether the participants were equipped with a simulated L3 automation system; the source of information (CDA alert only, CMS only, or both the CDA alert and CMS); and the message type (informational or instructional). The results suggest drivers who received messaging from both a CDA alert and the CMS displayed "smoother" lane changes, as indicated by longer lane-change times, longer distances traveled, and less variability in their steering wheel angle in comparison to drivers who received the messaging only via the CMS. Of the drivers equipped with L3 automation capabilities, the majority (65 percent) disengaged the automation just before and during the lane-change maneuver. In contrast to conventional drivers, those equipped with the L3 automation capabilities displayed "less smooth" lane changes, as indicated by shorter lane-change times, shorter distances traveled, and more variability in their steering wheel angle. Drivers exposed to the informational message tended to initiate a lane changes soon after passing the CMS, relative to drivers who viewed the instructional message. The research team observed several interaction effects among all three experimental factors, and the authors review those observations in more detail in the Discussion section of this report. The overall findings support incorporating CDA alerts in tandem with CMS.</td></tr>
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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

ADS	automated driving system
C-ADS	cooperative automated driving system
CDA	cooperative driving automation
CI	confidence interval
CMS	changeable message sign
FHWA	Federal Highway Administration
I2V	infrastructure-to-vehicle
L3	Level 3
LL	lower limit
Message	message type
MUTCD	*Manual on Uniform Traffic Control Devices for Streets and Highways*
OR	odds ratio
Ref	reference
SE	standard error
Source	source of information
SSQ	simulator sickness questionnaire
TCD	traffic control device
TMC	traffic management center
UL	upper limit

CHAPTER 1. INTRODUCTION

The transportation system is expected to see dramatic advances in vehicle technology in the near future. Safety engineers are currently testing vehicles equipped with automated driving systems (ADSs), or systems capable of performing the driving task without the aid of a human driver. Engineers are also developing cooperative driving automation (CDA) technologies, which allow ADS and infrastructure to send and receive cooperative safety messages (SAE International®, 2020). Vehicles equipped with ADS and cooperative-ADS (C-ADS) will soon be deployed onto roadway systems that were designed and built to accommodate human drivers. Fostering the safe and efficient operation of road networks that include vehicles equipped with ADS requires an examination of these systems' ability to comprehend and correctly respond to current infrastructure. Where appropriate, novel infrastructure elements and changes in existing infrastructure features may be needed to support the operation of ADS- and C-ADS-equipped vehicles.

Conventional drivers use traffic control devices (TCDs), including various types of signage, to help them navigate the roadway. ADSs have shown some success in their ability to use computer vision and sensors to detect signs (Snyder et al., 2018). Standardizing sign shape and color aids ADSs in correctly classifying and responding to warning, regulatory, and temporary traffic control signing. However, changeable message signs (CMSs) may be more problematic for ADSs to interpret. CMSs, also referred to as variable or dynamic message signs, are programable, electronic message signs used to convey up-to-the-moment traveler information to drivers (Dudek & Ullman, 2006). The *Manual on Uniform Traffic Control Devices for Streets and Highways* (MUTCD) provides basic guidelines for CMS operators regarding message length, color, and phase timing (Federal Highway Administration, 2023). However, messages presented on CMSs do not conform to the same level of standardization seen for other sign types. Individual traffic management centers (TMCs) typically determine the specific messages presented on CMSs (Schroeder & Demetsky, 2010). As a result, the specific phrases used will often vary across States, regions, and event types. Even within the same TMC, different CMS operators may use different CMS messages to describe similar events (Schroeder & Demetsky, 2010). Human drivers tend to be able to correctly interpret and respond to CMS messages despite these variations (Lerner et al., 2009). However, the lack of standardization is likely to hamper the ability of ADSs to interpret, and therefore benefit from, CMS messages.

CMSs have been shown to benefit conventional drivers by reducing driver stress and increasing traffic throughput, especially during unexpected, nonrecurring events (Lappin & Bottom, 2001; Lerner et al., 2009). More than 90 percent of transportation agencies report using CMSs to disseminate traveler information (Robinson et al., 2012). However, from a regulatory perspective, the information presented on a CMS is not strictly necessary for vehicle operation. CMSs are frequently used to convey information about incidents that slow or block traffic. Drivers who view this information can choose to divert to an alternate route to avoid the event, reduce speed to help prevent traffic shockwaves and alleviate incident-related congestion, or simply be on greater alert to prevent secondary collisions, such as those incidents that can occur when drivers traveling at higher speeds reach unexpected, slower moving traffic. However, these reactions are a choice and not a requirement. CMS information can help inform drivers about unexpected events, but drivers are required to respond appropriately to these events regardless of whether they receive a CMS warning. So, while the messaging has been shown to be beneficial to drivers, neither conventional drivers nor ADS-equipped vehicles are required to respond to information on CMSs. As a result, ensuring that ADSs are capable of acquiring information from or responding to CMSs may not be a priority to ADS developers.

One way that transportation agencies could help ensure the information presented on a CMS is acquired and correctly interpreted by C-ADS-equipped vehicles is to install CDA devices on their CMSs. When installed on infrastructure, CDA devices could use infrastructure-to-vehicle (I2V) communication to directly communicate the traveler information displayed on a CMS to C-ADS-equipped vehicles and the travelers inside.

CDA technology provides a mechanism by which traveler information could be transferred directly to C-ADS-equipped vehicles. However, this technology is likely to be expensive, particularly in the early phases of C-ADS deployment. Research examining how this technology could affect the safety and operation of the roadway will be valuable in allowing transportation agencies to assess the value of such an investment. In a meeting of experts on human factors, infrastructure, and ADSs, researchers identified three issues as critical for the successful integration of ADSs (Roldan et al., 2020):

1. Researchers need to review situations where an ADS has different information than that available in the external environment (information mismatch).

2. Engineers need to ensure that ADSs can communicate information to human drivers (ADS communication).

3. Researchers need to analyze how humans react to TCDs designed specifically for ADSs (ADS-specific TCDs).

INFORMATION MISMATCH

If ADS-equipped vehicles are not able to interpret CMS messages, a mismatch between the information that the ADS is acting on and the information available in the external environment would occur. Specifically, the ADS would have less information than is available to conventional drivers when traveling in a mixed fleet. As noted in the previous section, information presented on a CMS is not required for safe vehicle operation. However, having up-to-date information about the road directly ahead can be valuable. For example, studies show that providing drivers with customized traveler information about a work zone downstream from required work zone signage decreases aggressive maneuvers among drivers, reduces collisions, and decreases travel delays (Datta et al., 2004; McCoy & Pesti, 2001; Meyer, 2000; Tudor et al., 2003). This same information may be less critical to ADS safety since aggressive driving and driver inattention are not possible for an ADS.

If traditional CMSs are not able to convey traveler information to an ADS, a situation in which the ADS has less information than is available to a human traveling inside the vehicle would occur. How drivers inside an ADS-equipped vehicle would react to this situation is unclear. Would an ADS that does not appear to respond to a CMS message impact drivers’ trust and subsequent use of the system? Would drivers choose to override the system after viewing the CMS to comply with the presented message? Driver reactions may depend on the specific information presented on the CMS. That is, drivers may be more likely to mistrust or override a system after seeing an ADS fail to respond to a CMS message that explicitly requests a change in vehicle behavior compared with a CMS message that simply provides information about an upcoming event.

ADS COMMUNICATION

If transportation agencies choose to equip CMSs with CDA devices capable of transmitting information to C-ADSs, then both the ADS and the driver would have access to the same traveler information. However, the driver may be unaware that the ADS has access to the information, especially if it does not appear to trigger an immediate change in vehicle behavior. ADSs could potentially reduce this confusion by communicating with the driver. To operate at SAE International Level 3™ (L3), ADS will need to be capable of issuing takeover requests (SAE International, 2014; SAE International, 2020). These same in-vehicle alert systems could be used to present information received from the CMS to the driver. Previous studies show that in-vehicle alerts improve driving behavior among conventional drivers (Craig et al., 2017; Davis et al., 2018). However, how the information would affect drivers traveling in an ADS-equipped vehicle is unclear. Drivers who receive in-vehicle alerts may see the alerts as evidence that the ADS has access to the information available in the environment (via a CMS) and be less likely to override the system as a result. Conversely, drivers may view the alert as a type of takeover request, such that they would be more likely to override the system. Drivers' interpretation may depend on whether the ADS system appears to be responding to the information in the alert.

ADS-SPECIFIC TCD

In the future, personnel at transportation agencies will likely consider the potential value of equipping CMSs with CDA devices. However, as C-ADS-equipped vehicles become more prevalent on the roadways, personnel at transportation agencies who have had success in their use of CDA to disseminate traveler information may wish to understand whether that success results from the CMS–CDA combination, or whether similar results can be achieved by CDA alone. That is, personnel at transportation agencies who wish to disseminate traveler information at new locations, but that have a limited budget to do so, may need to decide between constructing a traditional CMS to disseminate information to conventional drivers or constructing a CDA device to disseminate information to C-ADS-equipped vehicles. A CDA constructed to transmit traveler information to C-ADS-equipped vehicles would be an example of a TCD designed specifically for ADS, and understanding how drivers would react to such a device is important.

CURRENT STUDY

Overall, this study investigates the potential value of using CDA technology to distribute traveler information messages that are traditionally disseminated using a CMS. The current study sought to address the potential issues of information mismatch, ADS communication, and ADS-specific TCD as related to CDA technology. The following statements describe this study's main hypotheses:

1. Drivers who experience both the traditional CMS and CDA messages are expected to be more likely to modify their driving behaviors in response to the messages than the other message source conditions (i.e., a CMS only or a CDA only).

2. Compared with conventional driving, while merging, drivers with an L3 automation system are expected to be associated with safer and more efficient driving, as measured by driving metrics (e.g., slower driving speeds, lower lane position variability) and eye-tracking metrics (e.g., quicker to fixate on the TCD or CDA warning).

3. The instructional message will be associated with slower average driving speeds after passing the CMS than the informational message.

4. The informational message will be associated with an earlier and "smoother" change into the left lane of the highway than the instructional message.

In addition to the aforementioned hypotheses, the study sought to determine the patterns of L3 automation use and trust in the system. For instance, those drivers who experienced the L3 automation system may report the highest level of general trust in automation. The outcome of this research should help personnel at transportation agencies assess the impacts of equipping CMSs with CDA technology while also providing broader insight into the potential for distributing traveler information to a mixed fleet through I2V communication.

CHAPTER 2. METHOD

PARTICIPANTS

In the Washington, DC, metropolitan area, the research team recruited 96 participants who met the inclusion criteria of being 18 yr of age or older, holding a valid U.S. driver's license, and having a visual acuity of 20/40 or better in both eyes, based on the Bailey-Lovie eye chart (Bailey & Lovie, 1976). The researchers balanced the groups based on sex (male and female) and age (split as younger than and older than 46 yr of age). They also compensated the participants for their time at a rate of $40 per hour. The researchers collected the data during May and June 2024.

EXPERIMENTAL DESIGN

The study utilized a two (vehicle automation: no automation, simulated L3 automation) by three (messaging source: CMS only, CDA only, CMS+CDA) by two (message type: instructional, informational) between-sample design resulting in 12 unique conditions. Table 1 shows the experimental matrix for the design.

Table 1. Experimental design matrix.

Vehicle Automation	Message Source	Message Type
No automation	CMS only	Instructional
No automation	CMS only	Informational
No automation	CDA only	Instructional
No automation	CDA only	Informational
No automation	CMS+CDA (both)	Instructional
No automation	CMS+CDA (both)	Informational
L3 automation	CMS only	Instructional
L3 automation	CMS only	Informational
L3 automation	CDA only	Instructional
L3 automation	CDA only	Informational
L3 automation	CMS+CDA (both)	Instructional
L3 automation	CMS+CDA (both)	Informational

The research team manipulated vehicle automation between subjects and included two levels: (1) does not have L3 automation, and (2) has L3 automation. The participants in the no-automation condition operated a conventional vehicle and drove the vehicle manually. The participants in the L3 automation condition operated the Federal Highway Administration (FHWA) Highway Driving Simulator using a simulated L3 automation system capable of performing lane centering, adaptive cruise control, and automated lane changes. All events that occurred within the study were within the operational design domain of the L3 ADS, such that participants would not be required to do anything other than monitor the system during the study.

The researchers manipulated the message source between subjects and included three levels: CMS only, CMS+CDA, and CDA only. The team provided all the participants with information about a traffic incident on the road ahead. The participants in the CMS only condition received the information via a traditional TCD in the form of a permanent, overhead CMS. The participants in the CMS+CDA condition received the information via an overhead CMS and an in-vehicle CDA alert in the dashboard of the vehicle. An alert tone would sound as the in-vehicle alert appeared. To prevent the CDA alert from distracting participants from receiving information via the overhead CMS, the team issued the alert 323 ft (98.45 m) before the vehicle reaching the CMS, a timing that would be within the range of I2V transmission of a CMS equipped with a CDA. The participants in the CDA only condition received information about the traffic incident from the in-vehicle CDA alert and the alert tone.

The research team also manipulated the message type between subjects and included two levels: (1) instructional messages and (2) informational messages. The researchers presented the participants in the instructional message condition with the message:

“Traffic Incident

Ahead

Slow Down”

When the instructional message was transmitted via CDA (in either the CMS+CDA or CDA only conditions) to a vehicle currently being controlled by the L3 automation, the system would respond by gradually reducing the speed of the vehicle from 55 mph (88.51 kph) to 50 mph (80.47 kph). The team presented the participants in the informational message condition with the message:

“Traffic Incident

Ahead

Right Lane Closed”

Vehicles being controlled by the L3 automation would not change speed in response to the CMS message as with the instructional message condition. Figure 1-A shows the instructional message as it is displayed on the CMS, and figure 1-B shows the instructional message on the instrument cluster via the CDA alert.

Source FHWA.

A. The CMS with CDA capabilities displaying the instructional message.

Source FHWA.

B. The instrument cluster displaying the instructional message via the CDA.

Figure 1. Photos. Text displayed on the CMS and instrument cluster of the informational message type.

APPARATUS AND MATERIALS

Apparatus

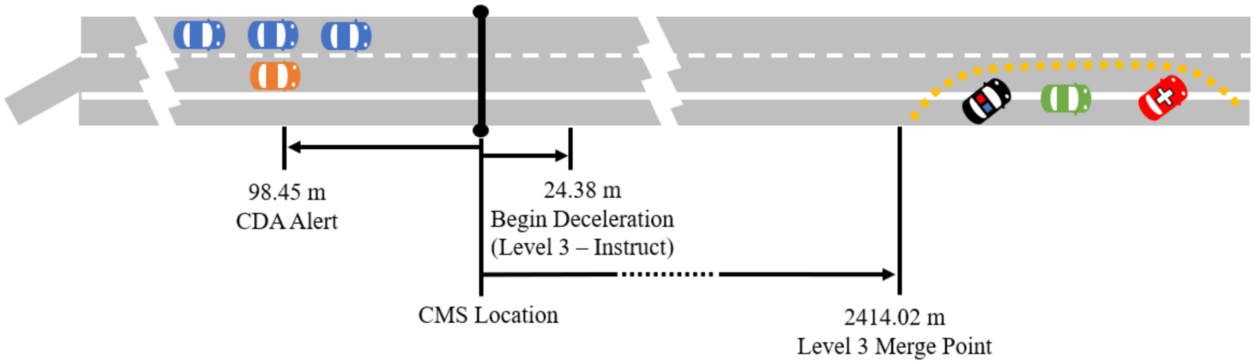
The researchers conducted the study in the FHWA Highway Driving Simulator at the Turner-Fairbank Highway Research Center. The simulator consists of a full automobile chassis surrounded by a semicircular projection screen (radius of 8.5 ft. (2.6 m)). Seven high-definition projectors render a seamless 200° view (motorists' field of view) of high-fidelity, computer-generated roadway scenes. Three LCD (liquid-crystal display) panels are used to simulate the vehicle's rearview and side mirrors. The simulator has a six-degree-of-freedom motion base that provides pitch and surge (for acceleration and braking), lateral, roll, yaw (for curve and turning forces), and heave (for bumps) cues in concert with the visual environment. The simulator's sound system provides engine, wind, tire noises, auditory alerts, and other environmental sounds.

Training materials

The research team prepared four separate training slideware presentation decks for this study. These slide decks explained the vehicle technologies and features associated with L3 automation and CDA. Specifically, the team designed the four slide decks to familiarize the participants with vehicles equipped with L3 automation and CDA, L3 automation without CDA, no automation and CDA, and no automation without CDA. The researchers only showed a given slide if it matched the participant's experimental condition. Each set also reminded participants to observe all posted signage, obey the speed limit, and interact with other vehicles as they normally would, as well as to take all the exits on the right-hand side of the road. In addition, the two sets of slides that had information about L3 automation showed participants how to engage and disengage the automation and stated that "the autonomous mode is designed to assist the driver to autonomously drive the vehicle with minimum intervention."

Experimental Drive

The roadway the team used in the experiment was approximately 20 mi (32.19 km) long and included multiple locations where the participants would exit and reenter the highway. The section of interest for the current study was 4 mi (6.44 km) long and took place after a participant had driven for either 2 mi (3.22 km) or 16 mi (25.74 km), with the specific location counterbalanced between participants. Figure 2 depicts a diagram of the relevant portion of the drive. The participants began the section of interest by taking an onramp onto the highway. Three vehicles traveling in the left lane prevented the drivers from leaving the right lane before passing a CMS. At approximately 1.5 mi (2.41 km) after entering the highway, all the participants encountered the CMS. However, a message would only display on the CMS if a participant was in the CMS only or in the CMS+CDA condition.



Source: FHWA.

Figure 2. Illustration. Roadway diagram showing locations of the CDA alert, CMS, and deceleration merge point and the traffic incident.

The research team programmed the simulator to display audiovisual alerts through the dashboard, but only those participants who traveled near CDA capable devices and whose vehicle were equipped with CDA capabilities received in-vehicle alerts (i.e., in the CDA only and CMS+CDA conditions). Approximately 321.52 ft (98 m) before reaching the location of the CMS, an in-vehicle alert was issued to participants in the CMS+CDA and CDA only conditions. The same traveler information message was displayed on the CMS (see figure 1-A) and in the vehicle's dashboard during the in-vehicle alert in the CMS+CDA condition (see figure 1-B). The specific message used varied, depending on whether the participants were in the instructional or the informational message condition. At approximately 78.75 ft (24 m) after passing the location of the CMS, the vehicles being controlled by ADS that received the instructional message (via either CDA only or CMS+CDA) began to gradually reduce their speeds from 55 mph (88.51 kph) to 50 mph (80.47 kph). The ADS maintained a speed of 50 mph (80.47 kph) for the remainder of road section of interest, unless the driver overrode the speed. The team presented the participants in the informational message condition with the message:

"Traffic Incident

Ahead

Right Lane Closed"

Vehicles controlled by ADS did not change speed or change lanes in response to this message. All the participants in the L3 automation condition would be able to turn off the automated system at any time or override the automated functions by moving the steering wheel or braking.

At approximately 1.5 mi (2,414 m) after the location of the CMS, the participants encountered a traffic incident that blocked the right lane. The incident included two police cars, one stationary vehicle, and an ambulance located in the right travel lane. The police car and ambulance were in a fend-off position, as recommended by the *2010 Traffic Incident Management Handbook Update* (Owens et al., 2010). The vehicles were parked at a 30° angle with their rear doors facing away from traffic. The temporary traffic control zone surrounding the incident was consistent with MUTCD recommendations for an intermediate traffic incident management area, without signing, to create an advanced warning area (Federal Highway Administration, 2023). Cones served as channelizing devices. Vehicles controlled by the ADS as they approached the traffic incident merged into the left lane at the start of the shoulder taper and engaged their blinker for 2 s before changing lanes. The participants in the no-automation condition could choose when to merge to avoid the incident. At approximately 0.5 mi (0.81 km) after passing the incident, the ADS-controlled vehicles signaled and then merged back to the right lane. The participants in the no-automation condition could choose when to merge back to the right lane after passing the incident.

Before the experimental drive began, the experimenter read the following scenario to the participants: "For this drive, I would like you to imagine yourself in the following scenario. You are on your way to an important doctor's appointment. It took a while to schedule. If you miss this appointment, you will not be able to reschedule anytime soon, and there will be a late fee. The appointment is in approximately 20 minutes from now. Please stay diligent and try to get to the doctor's office as soon as possible. However, please still take all exits on the right and obey all posted traffic signs and speed limits." The researchers designed this backstory to put participants in the mindset of needing to go somewhere with a sense of urgency.

Postdrive Questionnaires

The research team used a demographic questionnaire to collect participants' age, gender, years of driving experience, typical car that they drove (sedan, pickup truck, SUV (sports utility vehicle), etc.), and familiarity with vehicle features, such as cruise control, adaptive cruise control, automated emergency braking, lane departure warning, lane keeping, parking assist, and autopilot. The researchers used a trust questionnaire to collect the participants' general trust between people and automation. They asked the participants to rate their agreement on statements about ADSs on a scale of 1 to 5 where 1 meant "not at all true" and 5 meant "extremely true." Appendix A lists the 10 statements in the trust questionnaire.

The third part of the postdrive questionnaire asked about participants' experience driving through the scenarios in the simulator. Appendix B lists these feedback questions; the researchers asked the participants to answer "yes" or "no" to each statement and to further explain their answer if they answered "no."

PROCEDURES

The research team asked the participants to review and sign an informed consent form when they arrived at the research center. Next, the experimenter asked the participants to verify their age and licensure by showing their driver's licenses. The team then checked the participants' visual acuity via a Bailey-Lovie eye chart (Bailey & Lovie, 1976) and required a minimum of 6/12 (20/40), with correction, if necessary, for participation.

Next, the research team provided the participants with study instructions as well as information about the ADS and CDA technologies and in-vehicle alerts. They gave the participants assigned to each condition a slideware presentation that contained all the information needed for their particular condition to review. Once the participants understood the instructions, they responded to the simulator sickness questionnaire (SSQ) to provide a symptoms baseline (Kennedy et al., 1993).

The experimenter then walked the participant to the driving simulator and provided an orientation to the simulation system (e.g., the turn signals, hard brake). Once seated inside the driving simulator, the participant could adjust the seat and put on the seatbelt. The experimenter then calibrated the eye-tracker, including adjusting the focus and aperture of its four cameras to participant's eyes. Once the calibration was verified, participants completed a brief practice drive to become familiar with the simulator. During the practice drive, the experimenter asked the participants to accelerate, brake, and change lanes. The participants assigned to the L3 automation condition practiced engaging, monitoring, and disengaging the ADS. After completing the practice drive, the participants exited the simulator and completed the SSQ a second time to screen for any simulator sickness symptoms before beginning the experimental drive.

Once participants sat back in the simulator, the research team provided them with further instructions about the upcoming driving task. The researchers told the participants a backstory about going to a doctor's appointment. During the experimental drive, the participants drove on a simulated four-lane divided (two lanes in either direction) highway with a posted speed limit of 55 mph (88.51 kph). The experimenter reminded the participants of the condition in which they were assigned to participate. For the participants in the L3 automation condition, the ADS system performed continuous lane centering, automated speed and following distance control, and automated speed and lane changes. The participants in the no-automation condition were responsible for performing these functions manually.

After the experimental drive, the participants exited the simulator and completed the SSQ a final time to monitor for symptoms of simulator sickness. The participants then completed the postdrive questionnaire, and the experimenter thanked them and compensated them for their time.

ANALYTIC PLAN

The study's goal was to investigate the potential benefits of CDA alerts on driver behavior. The researchers used a driving simulator, eye-tracking software, and questionnaire data to assess this goal. Using the driving simulator, the research team examined the following variables:

- L3 automation disengagement.
- Lane-change location in relation to the vehicle platoon.
- Lane-change location in relation to the traffic incident.
- Time taken to initiate the lane change.
- Time taken to complete the lane change, and distance traveled to complete the lane change.
- Steering wheel angle variability during the lane change.
- Average driving speed.
- Driving speed variability.
- Driving acceleration variability.
- Vehicle collisions.

Using the eye-tracking software, the research team examined the total duration of fixations and the fixation frequency per second for the following areas of interest:

- TCD sign.
- Emergency vehicle at the traffic incident.
- Instrument cluster.
- Left mirror.

The researchers used *t*-tests, linear regressions, logistic regressions, multinomial logistic regressions, and gamma-generalized linear models, as appropriate, to test the associations between the experimental variables and the dependent variables.

The team identified four distinct data windows in the experimental roadway section of interest:

- Data window 1 (pre-CMS/CDA message phase): between 1,600 ft (487.68 m) and 800 ft (243.84 m) before the CMS. The researchers were able to use this data window to capture the driving characteristics before the message information.

- Data window 2 (CMS/CDA message phase): between 800 ft (243.84 m) before the CMS up to the CMS location. The researchers chose this distance in accordance with the MUTCD's recommendation that messages displayed on CMSs' should be legible from 800 ft (243.84 m) in daytime conditions (Federal Highway Administration, 2023). The researchers were able to use this data window to capture driving behavior characteristics when information from the CMS should be legible to all drivers.

- Data window 3 (lane-change planning phase): between the CMS location and the start of the lane-change maneuver. The researchers were able to use this data window to capture driving behaviors just before a lane change and capture the planning stage of a lane change.

- Data window 4 (lane-change maneuver phase): between the first instance of a negative headway angle of the vehicle (indicating the vehicle is heading toward the left lane) and the first instance the headway angle returned to 0° (indicating the vehicle is heading straight forward in its lane). This data window constitutes the actual lane-change maneuver (Macuga et al., 2007; Tehran et al., 2016; van Winsum et al., 1999).

CHAPTER 3. RESULTS

DRIVING DATA

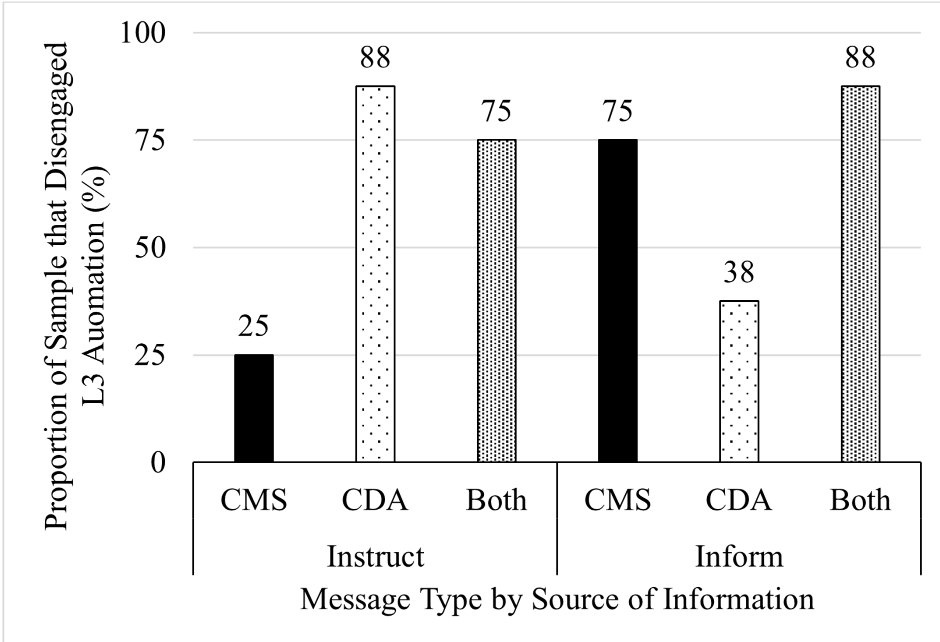
The research team derived the following results from the data collected from the subject vehicle and the interaction between the participant and vehicle capabilities.

Patterns of L3 Automation Use

Main Result(s): Most of the participants who were equipped with L3 automation capabilities disengaged the automation system during and just before the lane-change maneuver. Additionally, the effect of viewing information via a CDA alert only on the disengagement of the L3 automation system during the lane change was dependent on whether the driver viewed an informational message.

This particular data analysis focuses on the 48 participants who were equipped with L3 automation functionality. Ten (20.83 percent) participants never took over the L3 automation for manual control across the four data windows of interest. Among the other 38 participants, some took over the L3 automation system multiple times in a single data window. The number of attempted takeovers by data window is as follows: 3 in data window 1, 8 in data window 2, 37 in data window 3, and 37 in data window 4. During the planning stage and during the lane-change maneuver, the participants disengaged the L3 automation system more often. Some participants attempted to reengage the L3 automation system after the takeover. The number of attempted reengagements of the L3 automation system by data window is as follows: 2 in data window 1, 13 in data window 2, and 16 in data window 3.

Each participant experienced a lane closure in the right lane that required a lane-change maneuver into the left lane. The research team conducted a further examination of the manual takeover only during the window of the lane change (i.e., data window 4). Overall, 31 (65 percent) of the participants with L3 automation took over for manual control during the lane change (figure 3). The researchers performed a logistic regression to determine whether the source of information, message type, age, and gender influenced the likelihood of a takeover event (table 2). The team observed a significant interaction effect between the source of information (dubbed as "source" in all tables and figures) and the message type. The seemingly positive effects on the likelihood of disengaging an L3 automation system, when the source of information was a CDA alert only, decreased when the message was informational, odds ratio (OR) = 0.01, 95-percent confidence interval (CI) [0.00, 0.28].



Source: FHWA.

Figure 3. Chart. Proportion of the sample equipped with an L3 automation system that disengaged the L3 automation during the lane change (data window 4 only) by message type and source of information grouping (*n* = 48).

Table 2. ORs with 95-percent CI from the logistic regression predicting whether a manual takeover event occurred during the lane-change maneuver (data window 4 only) among drivers equipped with the L3 automation system (*n* = 48).

Predictor	OR	95% CI LL	95% CI UL
Main Effects:			
Source: CDA alert (ref: CMS only)	19.78	1.37	285.02
Source: both (ref: CMS only)	8.78	0.90	85.71
Message type: inform (ref: instruct)	9.50	0.94	96.16
Age (ref: older)	0.98	0.24	4.08
Gender (ref: female)	1.35	0.29	6.40
Interactions:			
Source: CDA alert x message type: inform	0.01	0.00	0.28
Source: both x message type: inform	0.26	0.01	9.09

LL = lower limit; message = message type; ref = reference; source = source of information; UL = upper limit.
Note: The x indicates an interaction between the two listed variables.

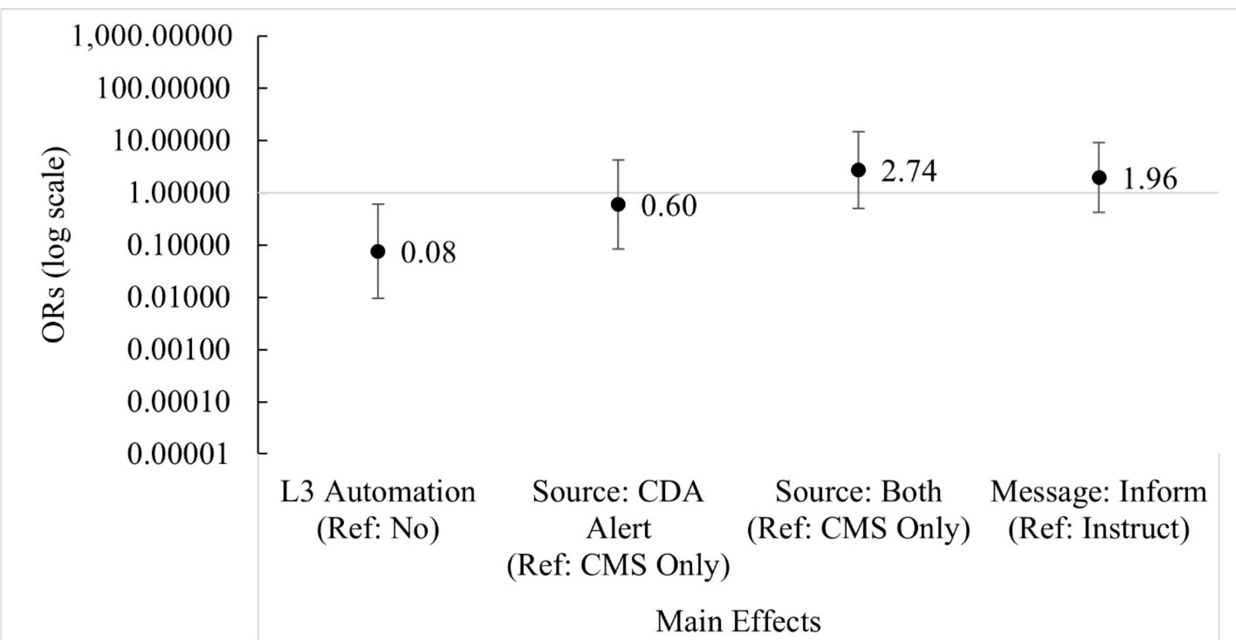
Lane-Change Location in Relation to the Vehicle Platoon

Main Result(s): Most of the participants merged behind the vehicle platoon. The drivers who were equipped with an L3 automation system were more likely to merge behind the vehicle platoon than conventional drivers. The drivers who received information from both a CMS and a

CDA alert were more likely than drivers who received information only via a CMS to merge ahead of the vehicle platoon then behind the platoon.

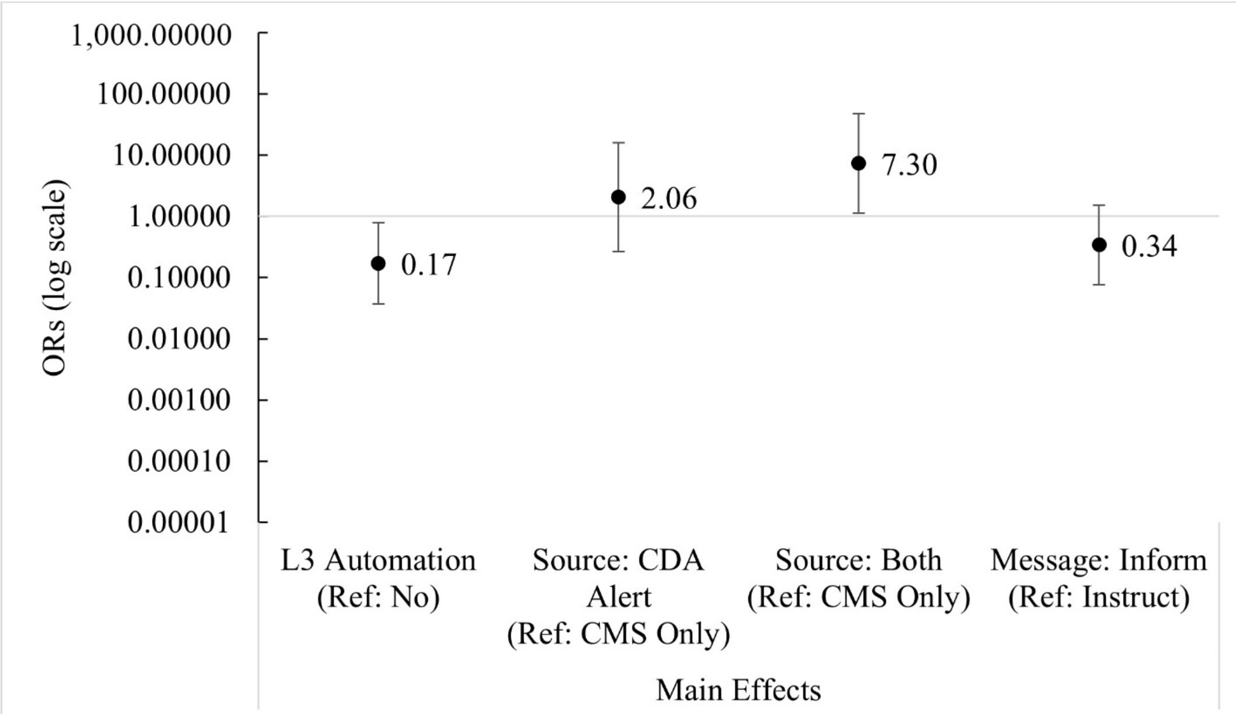
All the participants predominantly merged behind the vehicle platoon (77.08 percent), followed by merging ahead of the vehicle platoon (12.5 percent), and, lastly, by merging in the middle of the vehicle platoon (10.42 percent). The research team conducted a multinomial logistic regression to determine the likelihood of changing lanes ahead of, in the middle of, and before the vehicle platoon.

As shown in figure 4, the findings indicate the presence of L3 automation, OR = 0.08, 95-percent CI [0.01, 0.61], was associated with a lower likelihood of merging between the vehicle platoon than behind. All other factors were associated with merging between the vehicle platoon in comparison to behind the vehicle platoon. As likewise shown in figure 5, the findings indicate the presence of L3 automation, OR = 0.17, 95-percent CI [0.04, 0.80], was associated with a lower likelihood of merging ahead of the vehicle platoon than behind. However, participants who received messaging from both the CDA alert and the TCD sign were more likely to merge ahead of the vehicle fleet than behind, OR = 7.30, 95-percent CI [1.12, 47.50]. All other factors associated with merging ahead of the vehicle platoon in comparison to behind the vehicle platoon were not statistically significant.



Source: FHWA.

Figure 4. Graph. ORs with 95-percent CI (adjusted for age and gender) from the multinomial logistic regression predicting the likelihood of a lane change occurring (data window 4 only) between the vehicle platoon compared with behind the vehicle platoon (*n* = 96).



Source: FHWA.

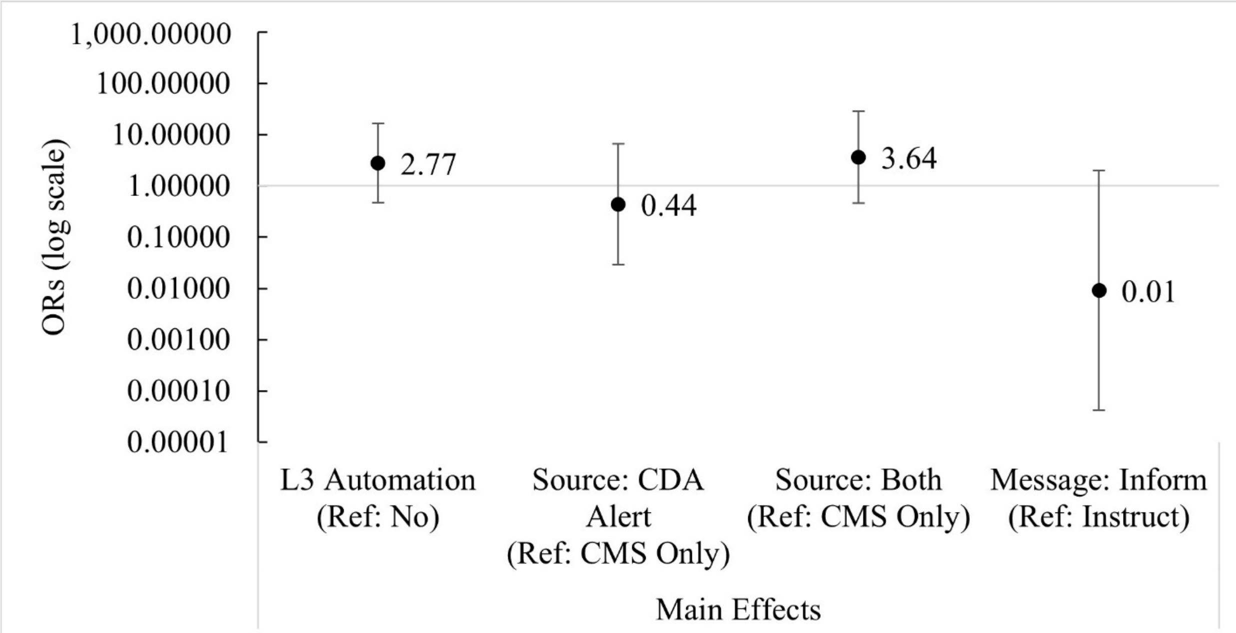
Figure 5. Graph. ORs with 95-percent CI (adjusted for age and gender) from the multinomial logistic regression predicting the likelihood of a lane change occurring (data window 4 only) ahead of the vehicle platoon compared with behind the vehicle platoon (*n* = 96).

Lane-Change Location in Relation to the Traffic Incident

Main Result(s): Most of the participants changed lanes near the traffic incident. The drivers who were equipped with an L3 automation system were more likely to change lanes nearer to the traffic incident than farther away from it. In contrast, the drivers who were presented with an informational message were more likely to merge near the CMS than near the traffic incident.

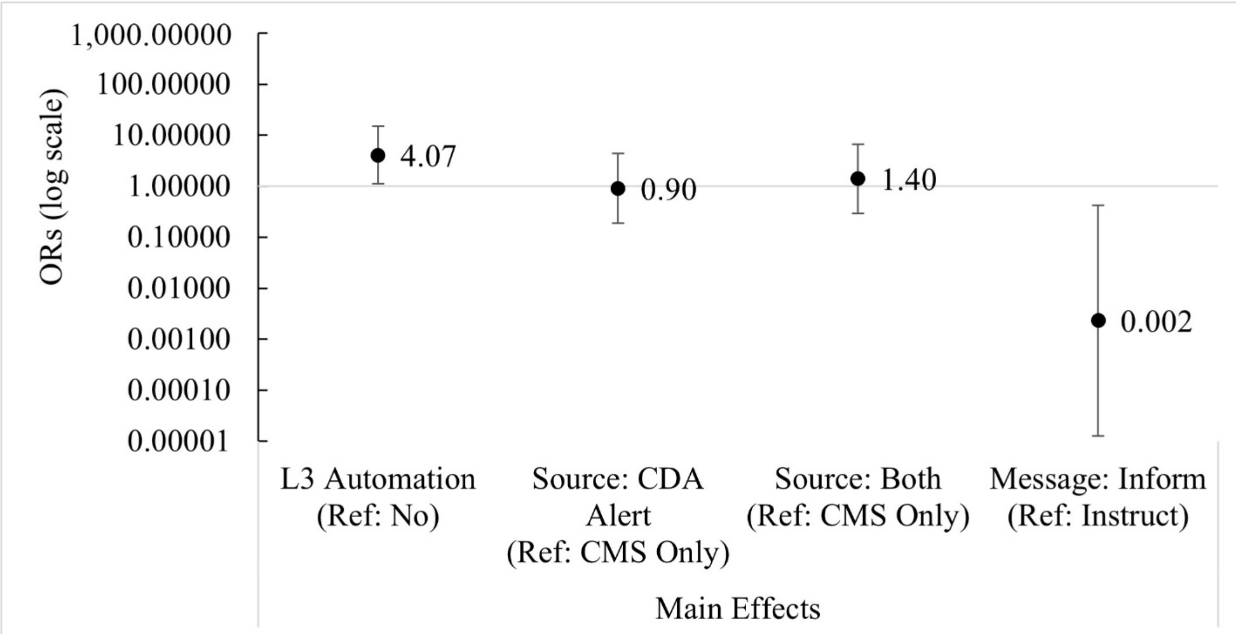
The participants predominantly merged into the left lane near the traffic incident (69 percent; within 0.5 mi (0.81 km)of the traffic incident), followed by merging far from the traffic incident (23 percent; within 0.5 mi (0.81 km) after passing the CMS), and, lastly, merging midway to the traffic incident (8 percent; between 0.5 mi (0.81 km) after passing the CMS and 0.5 mi (0.81 km) before the traffic incident). The research team conducted a multinomial logistic regression to determine the likelihood of changing lanes far from, midway to, and near to the traffic incident.

The findings shown in figure 6 indicate no factor significantly differentiated whether a participant changed lanes midway compared with far from the traffic incident. Figure 7 shows the presence of L3 automation, OR = 4.07, 95-percent CI [1.12, 14.81], was associated with a higher likelihood of changing lanes near the traffic incident than far away. Compared with drivers who received the instructional message, those participants exposed to the informational message were less likely to change lanes near the incident compared with far away, OR = 0.002, 95-percent CI [0.00, 0.43]. All other factors associated with changing lanes near the traffic incident compared with far from the traffic incident were not statistically significant.



Source: FHWA.

Figure 6. Graph. ORs with 95-percent CI (adjusted for age and gender) from the multinomial logistic regression predicting the likelihood of a lane change occurring (data window 4 only) midway to the roadway incident compared with far from the roadway incident (*n* = 96).



Source: FHWA.

Figure 7. Graph. ORs with 95-percent CI (adjusted for age and gender) from the multinomial logistic regression predicting the likelihood of a lane change occurring (data window 4 only) near the roadway incident compared with far from the roadway incident (*n* = 96).

Time Taken To Initiate the Lane After the CMS Became Visible

Main Result(s): The drivers who were equipped with an L3 automation system took longer to initiate a lane change than the drivers without L3 automation. In contrast, the drivers who were presented with an informational message tended to initiate a lane change sooner than drivers who received an instructional message.

On average, across all the participants, the drivers took 75 s to initiate the lane-change maneuver after the CMS became visible. The research team conducted a linear regression to determine the effects of the experimental design factors on the time taken to initiate the lane change (table 3). When compared with drivers without L3 automation, those with L3 automation took 18.56 s longer to initiate a lane change ($p = .001$). In contrast, participants who received the informational message tended to initiate a lane change 38.04 s sooner than those who received the instructional message ($p < .001$). All the other factors associated with the time taken to initiate a lane change were not statistically significant ($p > .05$).

Table 3. Estimates from a linear regression predicting the time (s) taken to initiate a lane change after the CMS became visible (data windows 2 and 3; *n* = 96).

Predictor	Estimate	SE	*p*
Main Effects:			
L3 automation (ref: no)	18.56	5.56	.001
Source: CDA alert (ref: CMS only)	1.55	6.70	.817
Source: both (ref: CMS only)	−2.94	6.70	.662
Message: inform (ref: instruct)	−38.04	5.54	<.001
Age (ref: older)	−3.09	5.50	.576
Gender (ref: female)	4.52	5.60	.422

p = *p*-value; SE = standard error.

Time Taken To Complete the Lane Change

Main Result(s): The drivers who were equipped with an L3 automation system took less time to complete a lane change than the drivers without L3 automation. In contrast, the drivers who were presented with information via both a CDA alert and the CMS took longer to complete a lane change than the drivers who viewed information only via a CMS. These effects persisted in a sensitivity analysis.

On average, across all the participants, the drivers took 8.33 s to complete a lane-change maneuver. The research team conducted a linear regression to determine the effects of the experimental design factors on the time taken to complete the lane change (table 4). Compared with drivers without L3 automation, those drivers with L3 automation took 4.56 s less to complete a lane change ($p < .001$). In contrast, the participants who received the messages from both a CDA alert and the CMS took 2.46 s longer to complete a lane change than participants who only received information from the CMS ($p = .005$). All the other factors associated with the time taken to complete a lane change were not statistically significant ($p > .05$).

Table 4. Estimates from a linear regression predicting the time (s) taken to complete a lane change (data window 4 only; *n* = 96).

Predictor	Estimate	SE	*p*
Main Effects:			
L3 automation (ref: no)	−4.56	0.67	<.001
Source: CDA alert (ref: CMS only)	0.37	0.81	.647
Source: both (ref: CMS only)	2.36	0.81	.005
Message: inform (ref: instruct)	0.26	0.67	.696
Age (ref: older)	−0.39	0.66	.563
Gender (ref: female)	0.52	0.68	.448

The research team conducted a sensitivity analysis to determine whether the results changed as a consequence of removing the 17 participants who did not disengage the L3 automation system during the lane change. The researchers observed no differences in the significance of the predictors in the sensitivity analysis. On average, across all the participants, the drivers took

8.64 s to complete a lane-change maneuver. The researchers conducted a linear regression to determine the effects of the experimental design factors on the time taken to complete the lane change (table 5). Compared with drivers without L3 automation, those drivers with L3 automation took 4.00 s less to complete a lane change ($p < .001$). In contrast, the participants who received the messages from both a CDA alert and from the CMS took 2.27 s longer to complete a lane change than participants who only received information from the CMS ($p = .022$). All the other factors associated with the time taken to complete a lane change were not statistically significant ($p > .05$) in this sensitivity analysis.

Table 5. Estimates from a linear regression predicting the time (s) taken to complete a lane change—sensitivity analysis (data window 4 only; *n* = 79).

Predictor	Estimate	SE	*p*
Main Effects:			
L3 automation (ref: no)	−4.00	0.82	<.001
Source: CDA alert (ref: CMS only)	0.55	1.00	.585
Source: both (ref: CMS only)	2.27	0.97	.022
Message: inform (ref: instruct)	0.49	0.81	.546
Age (ref: older)	−0.50	0.79	.532
Gender (ref: female)	0.75	0.81	.357

Distance Traveled To Complete the Lane Change

Main Result(s): The drivers who were equipped with an L3 automation system drove less distance during the lane change than drivers without L3 automation; this effect persisted in a sensitivity analysis. In contrast, the drivers who were presented with information via both a CDA alert and the CMS drove a longer distance to complete a lane change than drivers who viewed information only via a CMS; this effect disappeared in a sensitivity analysis.

On average, across all participants, the drivers traveled 621.75 ft (189.51 m) to complete a lane-change maneuver. The research team conducted a linear regression to determine the effects of the experimental design factors on the distance traveled to complete the lane change (table 6). Compared with drivers without L3 automation, those drivers with L3 automation traveled 331.69 ft (101.10 m) less to complete a lane change ($p < .001$). In contrast, the participants who received the messages from both a CDA alert and from the CMS traveled 158.17 ft (48.21 m) longer to complete a lane change than participants who only received information from the CMS ($p = .018$). All the other factors associated with the distance traveled to complete a lane change were not statistically significant ($p > .05$).

Table 6. Estimates from a linear regression predicting the distance traveled (m) to complete a lane change (data window 4 only; *n* = 96).

Predictor	Estimate	SE	*p*
Main Effects:			
L3 automation (ref: no)	−101.10	16.51	<.001
Source: CDA alert (ref: CMS only)	5.89	19.92	.768
Source: both (ref: CMS only)	48.21	19.92	.018
Message: inform (ref: instruct)	5.16	16.45	.755
Age (ref: older)	−5.64	16.33	.731
Gender (ref: female)	21.65	16.65	.197

The research team conducted a sensitivity analysis to determine whether the results changed as a consequence of removing the 17 participants who did not disengage the L3 automation system during the lane change. The researchers observed a slight difference in the significance of the predictors in the sensitivity analysis. On average, across all the participants, the drivers traveled 641.47 ft (195.52 m) to complete a lane-change maneuver. The team conducted a linear regression to determine the effects of the experimental design factors on the distance traveled to complete the lane change (table 7). Compared with drivers without L3 automation, those drivers with L3 automation traveled 296.29 (90.31 m) less to complete a lane change ($p < .001$). The primary analysis (table 6) indicated that receiving messaging from both a CDA alert and the CMS was associated with a greater distance being traveled during the lane change. However, the researchers did not observe this effect in the present sensitivity analysis, $b = 47.40$, standard error (SE) = 24.05, $p = .053$. All the other factors associated with the distance traveled to complete a lane change were not statistically significant ($p > .05$).

Table 7. Estimates from a linear regression predicting the distance traveled (m) to complete a lane change—sensitivity analysis (data window 4 only; *n* = 79).

Predictor	Estimate	SE	*p*
Main Effects:			
L3 automation (ref: no)	−90.31	20.34	<.001
Source: CDA alert (ref: CMS only)	10.93	24.76	.660
Source: both (ref: CMS only)	47.40	24.05	.053
Message: inform (ref: instruct)	10.12	20.06	.615
Age (ref: older)	−7.65	19.62	.698
Gender (ref: female)	29.06	20.07	.152

Steering Wheel Angle Variability During the Lane Change

Main Result(s): The drivers who were equipped with an L3 automation system displayed more variability in their steering wheel angle during a lane change than drivers without L3 automation. In contrast, the drivers who were presented with information via both a CDA alert and the CMS displayed less variability in their steering wheel angle during a lane change than the drivers who viewed information only via a CMS. These effects persisted in a sensitivity analysis.

On average, for all the participants, the steering wheel angle varied by 4.63° during the lane-change maneuver. The research team conducted a linear regression to determine the effects of the experimental design factors on the variability in the steering wheel angle during the lane change (table 8). Compared with drivers without L3 automation, those drivers with L3 automation displayed greater variability in their steering wheel angle, $b = 1.04$, SE = 0.11, $p < .001$. In contrast, the participants who received the messages from both a CDA alert and the CMS displayed less variability in their steering wheel angle during the lane change than participants who received information from the CMS only, $b = -0.32$, SE = 0.13, $p = .018$. All the other factors associated with steering wheel angle variability during the lane change were not statistically significant ($p > .05$).

Table 8. Estimates from a linear regression predicting the steering wheel angle variability during a lane change (data window 4 only; *n* = 96).

Predictor	Estimate	SE	*p*
Main Effects:			
L3 automation (ref: no)	1.04	0.11	<.001
Source: CDA alert (ref: CMS only)	0.02	0.13	.901
Source: both (ref: CMS only)	−0.32	0.13	.018
Message: inform (ref: instruct)	−0.02	0.11	.844
Age (ref: older)	−0.05	0.11	.656
Gender (ref: female)	−0.22	0.11	.053

The research team conducted a sensitivity analysis to determine whether the results changed as a consequence of removing the 17 participants who did not disengage the L3 automation system during the lane change. The researchers observed no differences in the significance of the predictors in the sensitivity analysis. On average, for all the participants, the steering wheel angle varied by 4.70° during the lane-change maneuver. The team conducted a linear regression to determine the effects of the experimental design factors on the variability in steering wheel angle during the lane change (table 9). Compared with the drivers without L3 automation, those drivers with L3 automation displayed greater variability in their steering wheel angle, $b = 0.97$, SE = 0.13, $p < .001$. In contrast, the participants who received the messages from both a CDA alert and the CMS displayed less variability in their steering wheel angle during the lane change than participants who only received information from the CMS, $b = -0.34$, SE = 0.16, $p = .033$. All other factors associated with steering wheel angle variability during the lane change were not statistically significant ($p > .05$).

Table 9. Estimates from a linear regression predicting the variability in steering wheel angle during a lane change—sensitivity analysis (data window 4 only; n = 79).

Predictor	Estimate	SE	p
Main Effects:			
L3 automation (ref: no)	0.97	0.13	<.001
Source: CDA alert (ref: CMS only)	−0.03	0.16	.858
Source: both (ref: CMS only)	−0.34	0.16	.033
Message: inform (ref: instruct)	−0.05	0.13	.712
Age (ref: older)	−0.06	0.13	.627
Gender (ref: female)	−0.21	0.13	.114

Average Driving Speed

The research team examined the average driving speed during all four data windows (see the Analytic Plan section earlier in this technical report).

Main Result(s): The drivers who were equipped with an L3 automation system drove faster than the drivers without L3 automation only when they were within 800 ft (243.84 m) of the CMS (data window 2). Some evidence supported that younger drivers drove faster when the CMS was legible (data window 2) and just before the lane change (data window 3).

Data Window 1

The average driving speed across all the participants during data window 1 was 57.79 mph (93 kph).

Data Window 2

The average driving speed across all the participants during data window 2 was 56.93 mph (91.62 kph). The research team conducted a linear regression to determine the effects of the experimental design factors on the average driving speed during data window 2 (table 10). Compared with drivers without L3 automation, those drivers with L3 automation displayed slower average driving speeds, $b = -1.57$, SE = 0.79, p = .050 (the p-value equaled .0498, but due to rounding, the p-value appears nonsignificant at .050). Compared with older drivers, the younger driver group tended to drive faster, b = 2.33, SE = 0.78, p = .004. All the other factors associated with driving speed in data window 2 were not statistically significant (p > .05).

Table 10. Estimates from a linear regression predicting the average driving speed during data window 2 (n = 96).

Predictor	Estimate	SE	p
Main Effects:			
L3 automation (ref: no)	−1.57	0.79	.050
Source: CDA alert (ref: CMS only)	1.33	0.96	.171
Source: both (ref: CMS only)	0.44	0.96	.650
Message: inform (ref: instruct)	−0.68	0.79	.397
Age (ref: older)	2.33	0.78	.004
Gender (ref: female)	−1.02	0.80	.205

Data Window 3

The average driving speed across all the participants during data window 3 was 55.12 mph (88.71 kph). The research team conducted a linear regression to determine the effects of the experimental design factors on the average driving speed during data window 3 (table 11). Compared with older drivers, the younger driver group tended to drive faster, $b = 1.70$, SE = 0.67, $p = .013$. All the other factors associated with driving speed in data window 3 were not statistically significant ($p > .05$).

Table 11. Estimates from a linear regression predicting the average driving speed during data window 3 (n = 96).

Predictor	Estimate	SE	p
Main Effects:			
L3 automation (ref: no)	−0.46	0.67	.497
Source: CDA alert (ref: CMS only)	−1.08	0.81	.189
Source: both (ref: CMS only)	−1.14	0.81	.164
Message: inform (ref: instruct)	1.06	0.67	.116
Age (ref: older)	1.70	0.67	.013
Gender (ref: female)	−0.10	0.68	.886

The research team conducted a sensitivity analysis to determine whether the results changed as a consequence of removing the 17 participants who did not disengage the L3 automation system during the lane change. The researchers observed no differences in the significance of the predictors in the sensitivity analysis. The average driving speed across all the participants during data window 3 was 55.51 mph (89.33 kph). The team conducted a linear regression to determine the effects of the experimental design factors on the average driving speed during data window 3 (table 12). Compared with older drivers, the younger driver group tended to drive faster, $b = 2.69$, SE = 0.94, $p = .006$. All the other factors associated with driving speed in data window 3 were not statistically significant ($p > .05$).

Table 12. Estimates from a linear regression predicting the average driving speed during data window 3—sensitivity analysis 1 ($n = 79$).

Predictor	Estimate	SE	*p*
Main Effects:			
L3 automation (ref: no)	−0.27	0.98	.782
Source: CDA alert (ref: CMS only)	−1.04	1.19	.386
Source: both (Ref: CMS Only)	−0.94	1.15	.419
Message: inform (ref: instruct)	0.68	0.96	.482
Age (ref: older)	2.69	0.94	.006
Gender (ref: female)	−0.11	0.96	.913

The research team conducted a second sensitivity analysis to determine whether the results changed as a consequence of including data window 1 driving speed as a covariate. The researchers observed changes in the significance of the predictors from the main analysis in the sensitivity analysis (table 11 and table 13). The team conducted a linear regression to determine the effects of the experimental design factors and data window driving speed on the average driving speed during data window 3 (table 13). As the average driving speed in data window 1 increased, the average driving speed in data window 3 increased as well, $b = 0.80$, SE = 0.09, $p < .001$. After controlling for the data window 1 driving speed, the effect of age disappears, $b = 0.67$, SE = 0.72, $p = .360$. Additionally, the drivers who received information from both the CDA alert and CMS displayed slower driving speeds, $b = -2.44$, SE = 0.86, $p = .006$. All the other factors associated with driving speed in data window 3 were not statistically significant ($p > .05$).

Table 13. Estimates from a linear regression predicting the average driving speed during data window 3—sensitivity analysis 2 ($n = 96$).

Predictor	Estimate	SE	*p*
Main Effects:			
L3 automation (ref: no)	0.91	0.75	.230
Source: CDA alert (ref: CMS only)	−1.48	0.86	.090
Source: both (ref: CMS only)	−2.44	0.86	.006
Message: inform (ref: instruct)	1.13	0.72	.118
Age (ref: older)	0.67	0.72	.360
Gender (ref: female)	0.54	0.72	.459
Average driving speed in data window 1	0.80	0.09	<.001

Data Window 4

The average driving speed across all the participants during data window 4 was 51.45 mph (82.80 kph). The research team conducted a linear regression to determine the effects of the experimental design factors on the average driving speed during data window 4 (table 14). No factor associated with driving speed in data window 4 was statistically significant ($p > .05$).

Table 14. Estimates from a linear regression predicting the average driving speed during data window 4 (n = 96).

Predictor	Estimate	SE	p
Main Effects:			
L3 automation (ref: no)	0.90	1.50	.550
Source: CDA alert (ref: CMS only)	−0.74	1.82	.686
Source: both (ref: CMS only)	−1.04	1.82	.570
Message: inform (ref: instruct)	1.27	1.50	.399
Age (ref: older)	1.86	1.49	.215
Gender (ref: female)	1.45	1.52	.342

The research team conducted a sensitivity analysis to determine whether the results changed as a consequence of removing the 17 participants who did not disengage the L3 automation system during the lane change. The researchers observed no differences in the significance of the predictors in the sensitivity analysis. The average driving speed across all the participants during data window 3 was 50.75 mph (81.67 kph). The team conducted a linear regression to determine the effects of the experimental design factors on the average driving speed during data window 4 (table 15). No factor associated with driving speed in data window 4 was statistically significant ($p > .05$).

Table 15. Estimates from a linear regression predicting the average driving speed during data window 4—sensitivity analysis 1 (n = 79).

Predictor	Estimate	SE	p
Main Effects:			
L3 automation (ref: no)	−0.37	1.85	.842
Source: CDA alert (ref: CMS only)	−0.12	2.26	.958
Source: both (ref: CMS only)	−0.05	2.19	.983
Message: inform (ref: instruct)	1.37	1.83	.456
Age (ref: older)	2.44	1.79	.177
Gender (ref: female)	1.72	1.83	.349

The research team conducted a second sensitivity analysis to determine whether the results changed as a consequence of including data window 1 driving speed as a covariate. The researchers observed no changes in the significance of the predictors from the main analysis in the sensitivity analysis (table 14 and table 16). The team performed a linear regression to determine the effects of the experimental design factors and data window driving speed on the average driving speed during data window 4 (table 16). As the average driving speed in data window 1 increased, the average driving speed in data window 4 increased as well, $b = 0.47$, SE = 0.18, $p = .010$. All the other factors associated with driving speed in data window 4 were not statistically significant ($p > .05$).

Table 16. Estimates from a linear regression predicting the average driving speed during data window 4—sensitivity analysis 2 (n = 96).

Predictor	Estimate	SE	p
Main Effects:			
L3 automation (ref: no)	2.16	1.53	.162
Source: CDA alert (ref: CMS only)	−0.89	1.76	.615
Source: both (ref: CMS only)	−1.13	1.76	.522
Message: inform (ref: instruct)	1.74	1.46	.237
Age (ref: older)	1.09	1.47	.459
Gender (ref: female)	1.62	1.47	.274
Average driving speed in data window 1	0.47	0.18	.010

Driving Speed Variability

The research team examined the driving speed variability during all four data windows (see the Analytic Plan section earlier in this technical report).

Main Result(s): The researchers observed a significant three-way interaction effect between the presence of L3 automation, source of information, and message type during data windows 2 (when the CMS was legible) and 4 (during the lane-change maneuver). The seemingly negative effects on driving speed variability when the driver was equipped with an L3 automation system and the source of information was a CDA alert only during data windows 2 and 4 were less pronounced when the message type was informational. Some evidence supported that drivers equipped with an L3 automation system displayed less variability in their driving speed than drivers without an L3 automation system just before the lane-change maneuver (data window 3).

Data Window 1

On average, across all the participants, the driving speed varied by 0.58 mph.

Data Window 2

On average, across all the participants, the driving speed varied by 1.06 mph (1.71 kph). The research team conducted a gamma-generalized linear model with a log link adjusted for zero inflation to determine the effects of the experimental design factors on the driving speed variability during data window 2 (table 17). The researchers observed an interaction effect. While the effect of having an L3 automation system and receiving the message via a CDA alert seemed to have a negative effect on driving speed variability, the effect was less negative when the message type was informational, OR = 790.21, 95-percent CI [8.12, 76,930.98]. The team did not observe a three-way interaction when the mode of information was from both a CDA alert and CMS, OR = 80.63, 95-percent CI [0.90, 7,214.07].

Table 17. Estimates from a gamma-generalized linear model with a log link adjusting for zero inflation predicting the driving speed variability during data window 2 (*n* = 96).

Predictor	OR	95% CI LL	95% CI UL
Main Effects:			
L3 automation (ref: no)	4.87	0.21	110.55
Source: CDA alert (ref: CMS only)	0.68	0.15	3.06
Source: both (ref: CMS only)	1.31	0.30	5.78
Message: inform (ref: instruct)	0.54	0.11	2.53
Age (ref: older)	0.67	0.26	1.70
Gender (ref: female)	0.52	0.22	1.25
Interactions:			
L3 automation x source: CDA alert	0.04	0.00	1.56
L3 automation x source: both	0.37	0.01	14.57
L3 automation x message: inform	0.01	0.00	0.23
Source: CDA alert x message: inform	1.59	0.18	14.32
Source: both x message: inform	2.92	0.34	25.15
L3 automation x source: CDA alert x message: inform	790.21	8.12	76,930.98
L3 automation x source: both x message: inform	80.63	0.90	7,214.07

Data Window 3

On average, across all the participants, the driving speed varied by 1.56 mph (2.51 kph). The research team conducted a gamma-generalized linear model with a log link adjusted for zero inflation to determine the effects of the experimental design factors on the driving speed variability during data window 3 (table 18). Compared with the drivers without L3 automation, those drivers with L3 automation displayed less variability in their driving speed, OR = 0.42, 95-percent CI [0.20, 0.87]. All the other factors associated with driving speed variability in data window 3 were not statistically significant.

Table 18. Estimates from a gamma-generalized linear model with a log link adjusting for zero inflation predicting the driving speed variability during data window 3 (*n* = 96).

Predictor	OR	95% CI LL	95% CI UL
Main Effects:			
L3 automation (ref: no)	0.42	0.20	0.87
Source: CDA alert (ref: CMS only)	1.99	0.86	4.58
Source: both (ref: CMS only)	2.29	0.98	5.32
Message: inform (ref: instruct)	0.67	0.34	1.29
Age (ref: older)	1.23	0.62	2.43
Gender (ref: female)	1.15	0.57	2.33

The research team conducted a sensitivity analysis to determine whether the results changed as a consequence of removing the 17 participants who did not disengage the L3 automation system during the lane change. The researchers observed differences in the significance of the predictors in the sensitivity analysis (table 18 and table 19). On average, across all the participants, the driving speed varied by 1.80 mph (2.9 kph). The research team conducted a gamma-generalized linear model with a log link adjusted for zero inflation to determine the effects of the experimental design factors on driving speed variability during data window 3 (table 19). After the team removed the 17 participants who did not disengage the L3 automation system, the effect of automation on driving speed variability from the main analysis disappeared, OR = 0.70, 95-percent CI [0.48, 1.03]. However, the message type emerged as a significant predictor. The participants who received the informational message displayed less variability in their driving speed than those participants who received the instructional message, OR = 0.63, 95-percent CI [0.43, 0.92]. All the other factors associated with driving speed variability in data window 3 were not statistically significant.

Table 19. Estimates from a gamma-generalized linear model with a log link adjusting for zero inflation predicting the driving speed variability during data window 3—sensitivity analysis 1 (*n* = 79).

Predictor	OR	95% CI LL	95% CI UL
Main Effects:			
L3 automation (ref: no)	0.70	0.48	1.03
Source: CDA alert (ref: CMS only)	1.51	0.94	2.42
Source: both (ref: CMS only)	1.57	0.99	2.48
Message: inform (ref: instruct)	0.63	0.43	0.92
Age (ref: older)	1.16	0.80	1.69
Gender (ref: female)	1.02	0.69	1.49

The research team conducted a second sensitivity analysis to determine whether the results changed as a consequence of including data window 1 driving speed variability as a covariate. The researchers observed no changes in the significance of the predictors from the main analysis in the sensitivity analysis (table 18 and table 20). The team conducted a gamma-generalized linear model with a log link adjusted for zero inflation to determine the effects of the experimental design factors on driving speed variability during data window 1 on the driving speed variability during data window 3 (table 20). Compared with drivers without L3 automation, those drivers with L3 automation displayed less variability in their driving speed, OR = 0.39, 95-percent CI [0.19, 0.79]. Additionally, as driving speed variability in data window 1 increased, the driving speed variability in data window 3 increased, OR = 1.50, 95-percent CI [1.00, 2.25]. All the other factors associated with driving speed variability in data window 3 were not statistically significant.

Table 20. Estimates from a gamma-generalized linear model with a log link adjusting for zero inflation predicting the driving speed variability during data window 3—sensitivity analysis 2 (n = 96).

Predictor	OR	95% CI LL	95% CI UL
Main Effects:			
L3 automation (ref: no)	0.39	0.19	0.79
Source: CDA alert (ref: CMS only)	2.03	0.90	4.55
Source: both (ref: CMS only)	1.93	0.86	4.32
Message: inform (ref: instruct)	0.55	0.28	1.07
Age (ref: older)	1.28	0.66	2.50
Gender (ref: female)	1.50	0.73	3.06
Driving speed variability in data window 1	1.50	1.00	2.25

Data Window 4

On average, across all the participants, the drivers' speed varied by 1.51 mph (2.43 kph). The research team conducted a gamma-generalized linear model with a log link adjusted for zero inflation to determine the effects of the experimental design factors on the driving speed variability during data window 4 (table 21). The team observed an interaction effect: While the effect of having an L3 automation system and receiving the message via a CDA alert seemed to have a positive effect on driving speed variability, the effect became negative when the message type was informational, OR = 0.03, 95-percent CI [0.00, 0.45]. The team did not observe a three-way interaction when the mode of information was from both a CDA alert and CMS, OR = 0.31, 95-percent CI [0.02, 4.87].

Table 21. Estimates from a gamma-generalized linear model with a log link adjusting for zero inflation predicting the driving speed variability during data window 4 (n = 96).

Predictor	OR	95% CI LL	95% CI UL
Main Effects:			
L3 automation (ref: no)	0.18	0.05	0.70
Source: CDA alert (ref: CMS only)	1.71	0.43	6.78
Source: both (ref: CMS only)	1.12	0.29	4.30
Message: inform (ref: instruct)	0.79	0.21	3.02
Age (ref: older)	0.75	0.42	1.34
Gender (ref: female)	1.60	0.84	3.02
Interactions:			
L3 automation x source: CDA alert	2.81	0.38	20.57
L3 automation x source: both	4.39	0.60	31.92
L3 automation x message: inform	5.54	0.81	37.91
Source: CDA alert x message: inform	0.75	0.11	5.12
Source: both x message: inform	0.93	0.14	6.16
L3 automation x source: CDA alert x message: inform	0.03	0.00	0.45
L3 automation x source: both x message: inform	0.31	0.02	4.87

The research team conducted a sensitivity analysis to determine whether the results changed as a consequence of removing the 17 participants who did not disengage the L3 automation system during the lane change. The researchers observed differences in the significance of the predictors in the sensitivity analysis (table 21 and table 22). On average, across all the participants, the drivers' speed varied by 1.73 mph (2.78 kph). The team conducted a gamma-generalized linear model with a log link adjusted for zero inflation to determine the effects of the experimental design factors on the driving speed variability during data window 4 (table 22). The researchers did not observe main or interaction effects after they removed the 17 participants who did not disengage the L3 automation system.

Table 22. Estimates from a gamma-generalized linear model with a log link adjusting for zero inflation predicting the driving speed variability during data window 4—sensitivity analysis 1 (*n* = 79).

Predictor	OR	95% CI LL	95% CI UL
Main Effects:			
L3 automation (ref: no)	0.98	0.65	1.46
Source: CDA alert (ref: CMS only)	1.10	0.68	1.80
Source: both (ref: CMS only)	1.15	0.71	1.84
Message: inform (ref: instruct)	0.79	0.53	1.17
Age (ref: older)	0.76	0.52	1.12
Gender (ref: female)	1.38	0.93	2.05

The research team conducted a second sensitivity analysis to determine whether the results changed as a consequence of including data window 1 driving speed variability as a covariate. The researchers observed no changes in the significance of the predictors from the main analysis in the sensitivity analysis (table 21 and table 23). The team performed a gamma-generalized linear model with a log link adjusted for zero inflation to determine the effects of the experimental design factors and driving speed variability during data window 1 on the driving speed variability during data window 4 (table 23). While the effect of having an L3 automation system and receiving the message via a CDA alert seemed to have a somewhat positive effect on driving speed variability, the effect became negative when the message type was informational, OR = 0.03, 95-percent CI [0.00, 0.42]. The team did not observe a three-way interaction when the mode of information was from both a CDA alert and CMS, OR = 0.21, 95-percent CI [0.01, 3.31]; nor did they observe an effect of driving speed variability during data window 1, OR = 1.28, 95-percent CI [0.89, 1.83].

Table 23. Estimates from a gamma-generalized linear model with a log link adjusting for zero inflation predicting the driving speed variability during data window 4—sensitivity analysis 2 (*n* = 96).

Predictor	OR	95% CI LL	95% CI UL
Main Effects:			
Automation (ref: no)	0.24	0.06	1.00
Source: CDA alert (ref: TCD only)	1.82	0.46	7.24
Source: both (ref: TCD only)	1.19	0.31	4.56
Message: inform (ref: instruct)	0.84	0.22	3.18
Age (ref: older)	0.80	0.45	1.42
Gender (ref: female)	1.81	0.94	3.49
Driving speed variability in data window 1	1.28	0.89	1.83
Interactions:			
Automation x source: CDA alert	2.35	0.32	17.42
Automation x source: both	3.47	0.47	25.79
Automation x message: inform	4.85	0.71	33.13
Source: CDA alert x message: inform	0.74	0.11	4.94
Source: both x message: inform	0.96	0.15	6.28
Automation x source: CDA alert x message: inform	0.03	0.00	0.42
Automation x source: both x message: inform	0.21	0.01	3.31

Driving Acceleration Variability

The research team examined the driving speed variability during all four data windows (see the Analytic Plan section earlier in this technical report).

Main Result(s): The researchers observed a significant three-way interaction effect between the presence of L3 automation, source of information, and message type during data window 2 (when the CMS was legible). The seemingly negative effects on acceleration variability, when the driver was equipped with an L3 automation system and the source of information was both a CMS and a CDA alert during data window 2, became positive when the message type was informational. The team did not observe the clear effects of the experimental factors on acceleration variability in both the main and sensitivity analyses for data windows 3 and 4.

Data Window 1

On average, across all the participants, the drivers' rate of acceleration varied by 0.10 mph^2 (0.16 kph^2).

Data Window 2

On average, across all the participants, the drivers' rate of acceleration varied by 0.16 mph^2 (0.26 kph^2). The research team conducted a gamma-generalized linear model with a log link adjusted for zero inflation to determine the effects of the experimental design factors on the driving acceleration variability during data window 2 (table 24). The team observed an interaction effect: While the effect of having an L3 automation system and receiving the messaged via a CDA alert seemed to have a negative effect on driving acceleration variability, the effect became positive when the message type was informational, OR = 12,759.10, 95-percent CI [39.24, 4,148,892.55]. The researchers did not observe a three-way interaction when the mode of information was from a CDA alert only, OR = 215.21, 95-percent CI [0.36, 1,29,672.07].

Table 24. Estimates from a gamma-generalized linear model with a log link adjusting for zero inflation predicting the driving acceleration variability during data window 2 (*n* = 96).

Predictor	OR	95% CI LL	95% CI UL
Main Effects:			
L3 automation (ref: no)	1.12	0.05	26.35
Source: CDA alert (ref: CMS only)	1.45	0.09	24.51
Source: both (ref: CMS only)	2.19	0.14	33.97
Message: inform (ref: instruct)	2.14	0.12	37.91
Age (ref: older)	3.73	0.63	22.15
Gender (ref: female)	0.66	0.14	3.03
Interactions:			
L3 automation x source: CDA alert	0.29	0.00	25.90
L3 automation x source: both	0.09	0.00	5.60
L3 automation x message: inform	0.00	0.00	0.14
Source: CDA alert x message: inform	0.90	0.02	48.73
Source: both x message: inform	0.42	0.01	22.84
L3 automation x source: CDA alert x message: inform	215.21	0.36	129,672.07
L3 automation x source: both x message: inform	12,759.10	39.24	4,148,892.55

Data Window 3

On average, across all the participants, the drivers' rate of acceleration varied by 0.23 mph^2 (0.37 kph^2). The research team conducted a gamma-generalized linear model with a log link adjusted for zero inflation to determine the effects of the experimental design factors on the driving acceleration variability during data window 3 (table 25). No factor associated with driving acceleration variability in data window 3 was statistically significant.

Table 25. Estimates from a gamma-generalized linear model with a log link adjusting for zero inflation predicting the driving acceleration variability during data window 2 (*n* = 96).

Predictor	OR	95% CI LL	95% CI UL
Main Effects:			
L3 automation (ref: no)	0.98	0.65	1.46
Source: CDA alert (ref: CMS only)	1.10	0.68	1.80
Source: both (ref: CMS only)	1.15	0.71	1.84
Message: inform (ref: instruct)	0.79	0.53	1.17
Age (ref: older)	0.76	0.52	1.12
Gender (ref: female)	1.38	0.93	2.05

The research team conducted a sensitivity analysis to determine whether the results changed as a consequence of removing the 17 participants who did not disengage the L3 automation system during the lane change. The researchers observed differences in the significance of predictors in the sensitivity analysis (table 25 and table 26). On average, across all the participants, the drivers' acceleration varied by 0.27 mph^2 (0.44 kph^2)The researchers performed a gamma-generalized linear model with a log link adjusted for zero inflation to determine the effects of the experimental design factors on the driving acceleration variability during data window 3 (table 26). An interaction effect emerged when the researchers removed the 17 identified participants: While the effect of having an L3 automation system and receiving the message via a CDA alert seemed to have a somewhat positive effect on driving acceleration variability, the effect was more positive when the message type was informational, OR = 29.42, 95-percent CI [4.56, 189.95]. The team did not observe a three-way interaction when the mode of information was from a CDA alert only, OR = 5.56, 95-percent CI [0.78, 39.65]; nor did they observe an effect of driving speed variability during data window 1, OR = 1.28, 95-percent CI [0.89, 1.83].

Table 26. Estimates from a gamma-generalized linear model with a log link adjusting for zero inflation predicting the driving acceleration variability during data window 3—sensitivity analysis 1 (*n* = 79).

Predictor	OR	95% CI LL	95% CI UL
Main Effects:			
L3 automation (ref: no)	1.73	0.52	5.82
Source: CDA alert (ref: CMS only)	1.89	0.86	4.15
Source: both (ref: CMS only)	1.24	0.58	2.69
Message: inform (ref: instruct)	1.47	0.67	3.22
Age (ref: older)	1.11	0.78	1.59
Gender (ref: female)	0.89	0.61	1.30

Predictor	OR	95% CI LL	95% CI UL
Interactions:			
L3 automation x source: CDA alert	0.55	0.13	2.37
L3 automation x source: both	0.55	0.13	2.40
L3 automation x message: inform	0.10	0.02	0.45
Source: CDA alert x message: inform	0.39	0.13	1.15
Source: both x message: inform	0.28	0.09	0.83
L3 automation x source: CDA alert x message: inform	5.56	0.78	39.65
L3 automation x source: both x message: inform	29.42	4.56	189.95

The research team conducted a second sensitivity analysis to determine whether the results changed as a consequence of including data window 1 driving acceleration variability as a covariate. The researchers observed no changes in the significance of predictors from the main analysis in the sensitivity analysis (table 25 and table 27). The team conducted a gamma-generalized linear model with a log link adjusted for zero inflation to determine the effects of the experimental design factors and driving speed variability during data window 1 on the driving speed variability during data window 3 (table 27). No factor associated with driving acceleration variability in data window 3 was statistically significant.

Table 27. Estimates from a gamma-generalized linear model with a log link adjusting for zero inflation predicting the driving acceleration variability during data window 3—sensitivity analysis 2 (*n* = 96).

Predictor	OR	95% CI LL	95% CI UL
Main Effects:			
L3 automation (ref: no)	0.62	0.35	1.13
Source: CDA alert (ref: CMS only)	1.48	0.75	2.91
Source: both (ref: CMS only)	1.21	0.60	2.45
Message: inform (ref: instruct)	0.62	0.36	1.08
Age (ref: older)	1.27	0.73	2.20
Gender (ref: female)	1.05	0.59	1.88
Driving acceleration variability in data window 1	4.63	0.88	24.48

Data Window 4

On average, across all the participants, the drivers' rate of acceleration varied by 0.31 mph^2 (0.5 kph^2). The research team conducted a gamma-generalized linear model with a log link adjusted for zero inflation to determine the effects of the experimental design factors on the driving acceleration variability during data window 4 (table 28). Compared with older drivers, the younger drivers displayed less variability in their driving acceleration, OR = 0.49, 95-percent CI [0.27, 0.87]. No other factor associated with driving acceleration variability in data window 4 was statistically significant.

Table 28. Estimates from a gamma-generalized linear model with a log link adjusting for zero inflation predicting the driving acceleration variability during data window 4 (n = 96).

Predictor	OR	95% CI LL	95% CI UL
Main Effects:			
L3 automation (ref: no)	0.64	0.35	1.17
Source: CDA alert (ref: CMS only)	1.16	0.57	2.34
Source: both (ref: CMS only)	1.01	0.51	2.01
Message: inform (ref: instruct)	0.75	0.43	1.34
Age (ref: older)	0.49	0.27	0.87
Gender (ref: female)	1.19	0.67	2.10

The research team conducted a sensitivity analysis to determine whether the results changed as a consequence of removing the 17 participants who did not disengage the L3 automation system during the lane change. The team observed differences in the significance of the predictors in the sensitivity analysis (table 28 and table 29). On average, across all the participants, the drivers' acceleration varied by 0.31 mph^2 (0.5 kph^2). The researchers conducted a gamma-generalized linear model with a log link adjusted for zero inflation to determine the effects of the experimental design factors on the driving acceleration variability during data window 4 (table 29). When the researchers removed the 17 identified participants, the effect of age disappeared, OR = 0.57, 95-percent CI [0.33, 1.01]. All the other factors associated with driving acceleration variability in data window 4 were not statistically significant.

Table 29. Estimates from a gamma-generalized linear model with a log link adjusting for zero inflation predicting the driving acceleration variability during data window 4—sensitivity analysis 1 (n = 79).

Predictor	OR	95% CI LL	95% CI UL
Main Effects:			
L3 automation (ref: no)	1.08	0.60	1.92
Source: CDA alert (ref: CMS only)	1.14	0.56	2.31
Source: both (ref: CMS only)	0.81	0.41	1.62
Message: inform (ref: instruct)	0.77	0.44	1.37
Age (ref: older)	0.57	0.33	1.01
Gender (ref: female)	1.07	0.60	1.89

The research team performed a second sensitivity analysis to determine whether the results changed as a consequence of including data window 1 driving acceleration variability as a covariate. The researchers observed no changes in the significance of predictors from the main analysis in the sensitivity analysis (table 28 and table 30). The researchers conducted a gamma-generalized linear model with a log link adjusted for zero inflation to determine the effects of the experimental design factors and driving acceleration variability during data window 1 on the driving speed variability during data window 4 (table 30). Compared with older drivers, the younger drivers displayed less variability in their driving acceleration, OR = 0.51, 95-percent CI [0.28, 0.91]. No other factor associated with driving acceleration variability in data window 4 was statistically significant.

Table 30. Estimates from a gamma-generalized linear model with a log link adjusting for zero inflation predicting the driving acceleration variability during data window 3—sensitivity analysis 2 (n = 96).

Predictor	OR	95% CI LL	95% CI UL
Main Effects:			
L3 automation (ref: no)	0.65	0.36	1.19
Source: CDA alert (ref: CMS only)	1.10	0.54	2.21
Source: both (ref: CMS only)	0.94	0.47	1.87
Message: inform (ref: instruct)	0.74	0.42	1.31
Age (ref: older)	0.51	0.28	0.91
Gender (ref: female)	1.32	0.73	2.39
Driving acceleration variability in data window 1	2.15	0.52	8.94

Likelihood of a Collision During the Lane Change

Main Result(s): Few participants experienced a collision with another vehicle during the lane-change maneuver (data window 4). The participants who were equipped with L3 automation capabilities tended to experience fewer collisions during the lane change than drivers without L3 automation capabilities.

Of the 96 participants, 12 (12.5 percent) experienced a collision with another vehicle during their lane change in the left lane. The research team conducted a logistic regression to determine whether experimental design factors predicted the occurrence of crashes. Figure 8 shows the presence of L3 automation, OR = 0.16, 95-percent CI [0.03, 0.78], was associated with a lower likelihood of a crash occurring during the lane-change event. The researchers observed no effects on the occurrence of crashes for CDA alerts, OR = 0.69, 95-percent CI [0.13, 3.66], CDA alerts and the TCD, OR = 1.36, 95-percent CI [0.31, 6.10], or informational messages, OR = 2.22, 95-percent CI [0.58, 8.56].

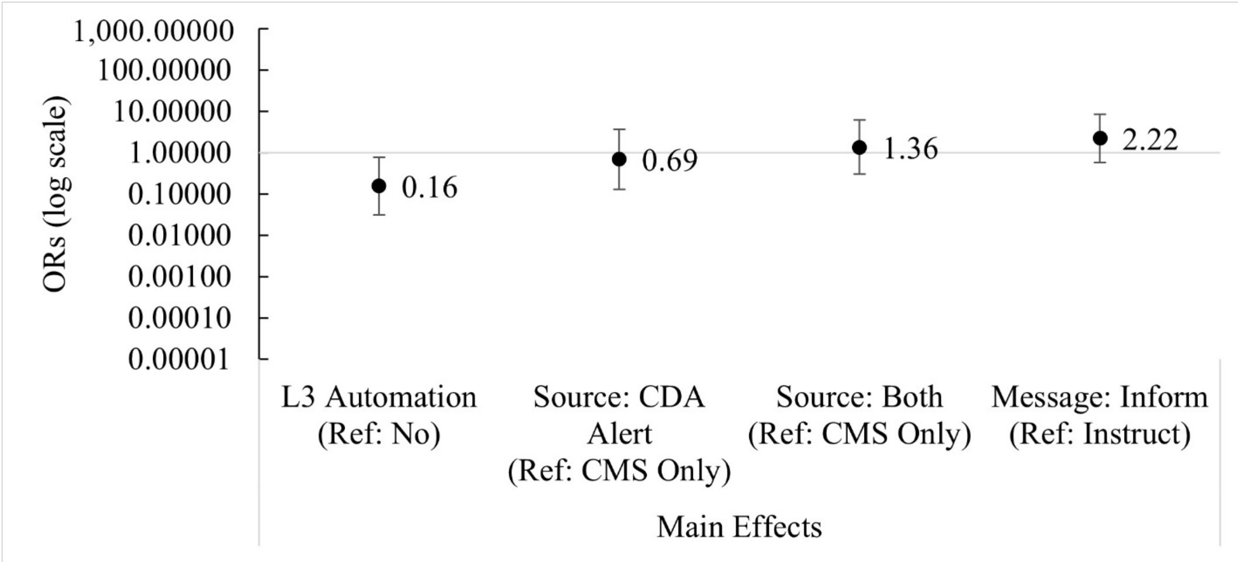


Figure 8. Graph. ORs with 95-percent CI (adjusted for age and gender) from the logistic regression predicting the likelihood of a crash occurring during the lane-change event.

EYE-TRACKING DATA

The research team derived the following results from the eye-tracking data collected during the study.

CMS

Main Result(s): Few participants observed the CMS. The researchers observed a significant three-way interaction effect between the presence of L3 automation, source of information, and message type during data window 2 (when the CMS was legible) on the total fixation duration. While drivers equipped with an L3 automation system received information from both a CMS and a CDA alert tended to view the CMS longer, the effect was somewhat stronger for those drivers who viewed an informational message instead of an instructional message. However, the study found only a two-way interaction regarding the number of fixations on the CMS per second. Although it seemed the effects of viewing information via a CDA alert and, separately, the effects of viewing an informational message, were associated with fewer fixations on the CMS per second, the drivers who received an informational message via a CDA alert only seemed to make more fixations on the CMS per second.

Of the 96 participants, only 35 (36.46 percent) drivers viewed the CMS when they were within 800 ft (243.84 m) of the CMS (i.e., data window 2).

Total Fixation Duration

On average, the drivers fixated on the CMS for approximately 1.55 s during data window 2. The research team conducted a gamma-generalized linear model with a log link to determine the effects of the experimental design factors on the total fixation duration during data window 2 (table 31). The researchers observed an interaction effect: While the effect of having an L3 automation system and receiving the message via a CDA alert seemed to have a positive effect on total fixation duration on the CMS, the effect was more positive when the message type was informational, OR = 231.18, 95-percent CI [9.85, 5,427.84]. The team did not observe a three-way interaction when the mode of information was from a CDA alert only, OR = 5.90, 95-percent CI [0.21, 162.81]. Given the reduced sample size (n = 35) in the present analysis, the findings should be interpreted with caution.

Table 31. Estimates from a gamma-generalized linear model with a log link predicting the total duration of fixations on the CMS during data window 2 (n = 35).

Predictor	OR	95% CI LL	95% CI UL
Main Effects:			
L3 automation (ref: no)	5.67	1.75	18.39
Source: CDA alert (ref: CMS only)	4.71	1.26	17.55
Source: both (ref: CMS only)	2.87	0.63	12.98
Message: inform (ref: instruct)	1.30	0.28	6.10
Age (ref: older)	0.48	0.19	1.20
Gender (ref: female)	0.80	0.38	1.70
Interactions:			
L3 automation x source: CDA alert	0.03	0.00	0.23
L3 automation x source: both	0.15	0.02	1.02
L3 automation x message: inform	0.26	0.03	2.44
Source: CDA alert x message: inform	5.38	0.38	75.85
Source: both x message: inform	0.03	0.00	0.45
L3 automation x source: CDA alert x message: inform	5.90	0.21	162.81
L3 automation x source: both x message: inform	231.18	9.85	5,427.84

Fixation Frequency Per Second

On average, the drivers made 0.39 fixations on the CMS per second during data window 2. The research team performed a gamma-generalized linear model with a log link to determine the effects of the experimental design factors on the fixation frequency per second on the CMS during data window 2 (table 32). The researchers observed an interaction effect: The drivers who received information from the CDA alert only and received the informational message tended to have more fixations on the CMS per second, OR = 5.43, 95-percent CI [1.84, 16.05]. No other factor was statistically significantly associated with the fixation frequency per second on the CMS in data window 2. Given the reduced sample size (n = 35) in the present analysis, the findings should be interpreted with caution.

Table 32. Estimates from a gamma-generalized linear model with a log link predicting the fixation frequency per second on the CMS during data window 2 (n = 35).

Predictor	OR	95% CI LL	95% CI UL
Main Effects:			
L3 automation (ref: no)	1.23	0.83	1.82
Source: CDA alert (ref: CMS only)	0.72	0.33	1.61
Source: both (ref: CMS only)	1.48	0.89	2.45
Message: inform (ref: instruct)	0.56	0.27	1.16
Age (ref: older)	0.74	0.50	1.09
Gender (ref: female)	0.80	0.53	1.20
Interactions:			
Source: CDA alert x message: inform	5.43	1.84	16.05
Source: both x message: inform	1.41	0.56	3.57

Instrument Cluster

Main Result(s): Nearly all the participants observed the instrument cluster during data windows 2–4. No experimental factor was associated with the total duration of fixations on the instrument cluster. However, the research team observed three-way interaction effects regarding the number of fixations on the instrument cluster per second. While the drivers who were equipped with an L3 automation system and received information from a CDA alert only made more fixations per second on the instrument cluster, the positive effect was lessened when viewing an informational message compared to an instructional message. The team observed this same pattern in the case of drivers receiving information from both a CDA alert and a CMS.

Of the 96 participants, 94 (97.92 percent) drivers viewed the instrument cluster during data windows 2–4.

Total Fixation Duration

On average, the drivers fixated on the instrument cluster for approximately 3.81 s during data windows 2–4. The research team conducted a gamma-generalized linear model with a log link to determine the effects of the experimental design factors on the total fixation duration on the instrument cluster during data windows 2–4 (table 35). Males tended to view the instrument cluster longer than females, OR = 1.84, 95-percent CI [1.01, 3.34]. No other factor associated with total fixation duration on the instrument cluster during data windows 2–4 was statistically significant.

Table 33. Estimates from a gamma-generalized linear model with a log link predicting the total duration of fixations on the instrument cluster during data windows 2–4 (*n* = 94).

Predictor	OR	95% CI LL	95% CI UL
Main Effects:			
L3 automation (ref: no)	1.25	0.69	2.26
Source: CDA alert (ref: CMS only)	2.04	0.99	4.19
Source: both (ref: CMS only)	1.34	0.66	2.73
Message: inform (ref: instruct)	0.78	0.43	1.41
Age (ref: older)	0.86	0.48	1.54
Gender (ref: female)	1.84	1.01	3.34

Fixation Frequency Per Second

The research team observed and removed seven outliers from the analysis of the number of fixations per second on the instrument cluster. On average, the drivers made 3.89 fixations on the instrument cluster per second during data windows 2–4. The researchers performed a gamma-generalized linear model with a log link to determine the effects of the experimental design factors on the fixation frequency per second on the instrument cluster during data windows 2–4 (table 36). The researchers observed an interaction effect: While the effect of having an L3 automation system and receiving the message via a CDA alert seemed to have a positive effect on the number of fixations per second on the instrument cluster, the effect was more positive when the message type was instructional, OR = 0.75, 95-percent CI [0.65, 0.86]. The team found a similar interaction when drivers received information from both a CDA alert and the CMS, OR = 0.43. 95-percent CI [0.37, 0.50].

Table 34. Estimates from a gamma-generalized linear model with a log link predicting the fixation frequency per second on the instrument cluster during data windows 2–4 (*n* = 87).

Predictor	OR	95% CI LL	95% CI UL
Main Effects:			
L3 automation (ref: no)	4.63	2.24	9.56
Source: CDA alert (ref: CMS only)	0.50	0.22	1.12
Source: both (ref: CMS only)	0.48	0.23	1.01
Message: inform (ref: instruct)	1.88	0.98	3.61
Age (ref: older)	2.85	2.07	3.91
Gender (ref: female)	2.47	1.72	3.56
Interactions:			
L3 automation x source: CDA alert	0.89	0.30	2.62
L3 automation x source: both	0.31	0.10	0.90
L3 automation x message: inform	0.07	0.03	0.19
Source: CDA alert x message: inform	0.53	0.16	1.77
Source: both x message: inform	0.30	0.10	0.84
L3 automation x source: CDA alert x message: inform	1.99	0.43	9.31
L3 automation x source: both x message: inform	28.25	6.73	118.59

Left Mirror

Main Result(s): Most of the participants observed the left mirror during data windows 3 and 4. The research team observed several three-way interaction effects regarding the total duration of fixations and the number of fixations on the left mirror per second. While drivers who were equipped with an L3 automation system and received information from a CDA alert only seemingly viewed the left mirror for less time, the effect became positive when drivers viewed informational messages instead of instructional messages. In contrast, for those drivers who received the messages via CDA alerts and the CMS, the negative effect intensified (i.e., less time spent viewing the left mirror) when the driver received an instructional message. The team found a similar trend regarding the number of fixations on the left mirror per second.

Of the 96 participants, only 70 (72.92 percent) drivers viewed the left mirror during data windows 3 and 4.

Total Fixation Duration

On average, the drivers fixated on the left mirror for approximately 3.81 s during data windows 3 and 4. The research team performed a gamma-generalized linear model with a log link to determine the effects of the experimental design factors on the total fixation duration on the left mirror during data windows 3 and 4 (table 37). While the effect of having an L3 automation system and receiving the message via a CDA alert seemed to have a negative effect on total fixation duration on the left mirror, the effect became positive when the message type was informational, OR = 0.04, 95-percent CI [0.00, 0.52]. The researchers found another three-way interaction: While the effect of having an L3 automation system and receiving the message via a CDA alert seemed to have a somewhat negative effect on total fixation duration on the left mirror, the effect was more negative when the message type was informational, OR = 0.0001, 95-percent CI [0.0000, 0.0011].

Table 35. Estimates from a gamma-generalized linear model with a log link predicting the total duration of fixations on the instrument cluster during data windows 3 and 4 (*n* = 70).

Predictor	OR	95% CI LL	95% CI UL
Main Effects:			
L3 automation (ref: no)	0.34	0.12	0.94
Source: CDA alert (ref: CMS only)	0.32	0.11	0.92
Source: both (ref: CMS only)	0.11	0.04	0.31
Message: inform (ref: instruct)	0.01	0.00	0.03
Age (ref: older)	0.81	0.50	1.32
Gender (ref: female)	1.60	0.96	2.65

Predictor	OR	95% CI LL	95% CI UL
Interactions:			
L3 automation x source: CDA alert	2.40	0.55	10.52
L3 automation x source: both	25.77	5.48	121.25
L3 automation x message: inform	686.44	121.89	3,865.72
Source: CDA alert x message: inform	24.29	3.63	162.37
Source: both x message: inform	576.95	98.93	3,364.73
L3 automation x source: CDA alert x message: inform	0.04	0.00	0.52
L3 automation x source: both x message: inform	0.0001	0.0000	0.0011

Fixation Frequency Per Second

The research team observed and removed five outliers from the analysis on the number of fixations per second on the left mirror. On average, the drivers made 1.82 fixations on the left mirror per second during data windows 3 and 4. The researchers conducted a gamma-generalized linear model with a log link to determine the effects of the experimental design factors on the fixation frequency per second on the left mirror during data windows 3 and 4 (table 38). The researchers observed an interaction effect: While the effect of having an L3 automation system and receiving the message via a CDA alert seemed to have a negative effect on the number of fixations per second on the left mirror, the effect became positive when the message type was informational, OR = 0.13, 95-percent CI [0.06, 0.28]. The team found another three-way interaction: While the effect of having an L3 automation system and receiving the message via a CDA alert seemed to have a somewhat positive effect on the number of fixations per second on the left mirror, the effect became negative when the message type was informational, OR = 0.0005, 95-percent CI [0.0002, 0.0010].

Table 36. Estimates from a gamma-generalized linear model with a log link predicting the fixation frequency per second on the left mirror during data windows 3 and 4 (*n* = 65).

Predictor	OR	95% CI LL	95% CI UL
Main Effects:			
L3 automation (ref: no)	4.63	2.24	9.56
Source: CDA alert (ref: CMS only)	0.50	0.22	1.12
Source: Both (ref: CMS only)	0.48	0.23	1.01
Message: Inform (ref: instruct)	1.88	0.98	3.61
Age (ref: older)	2.85	2.07	3.91
Gender (ref: female)	2.47	1.72	3.56

Predictor	OR	95% CI LL	95% CI UL
Interactions:			
L3 automation x source: CDA alert	0.89	0.30	2.62
L3 automation x source: both	0.31	0.10	0.90
L3 automation x message: inform	0.07	0.03	0.19
Source: CDA alert x message: inform	0.53	0.16	1.77
Source: both x message: inform	0.30	0.10	0.84
L3 automation x source: CDA alert x message: inform	1.99	0.43	9.31
L3 automation x source: both x message: inform	28.25	6.73	118.59

QUESTIONNAIRE DATA

The research team derived the following results from subjective responses given by the participants in a questionnaire that was given to them after the experimental trials.

Trust in ADSs

The possible trust scores ranged from 10 to 50, with 50 indicating the highest amount of trust. The average trust score was 32.49. The drivers without the L3 automation system had a score of 32.08, and the drivers who experienced the L3 automation system had a score of 32.90. No statistical differences occurred between the two groups, $t(94) = -0.64$, $p = .521$.

Awareness and Trust of CMS

The researchers asked the participants, "During the drive, did you notice the black overhead sign prior to the lane closure?" Overall, 49 (51.04 percent) of the 96 participants noticed the CMS. The research team observed no group differences between the drivers with L3 automation (n = 23; 47.92 percent) and those drivers without L3 automation (n = 26; 54.17 percent) in terms of noticing the CMS, $X^2(1) = 0.17$, $p = .683$.

The researchers asked the participants, "Do you typically trust the information provided by overhead changeable message signs on the highway?" The majority of participants indicated trusting the information presented in the CMS (n = 95; 98.96 percent).

Awareness and Attitudes Toward the L3 Automation System

The researchers asked the participants, "Was the vehicle you drove today equipped with L3 automation capabilities?" Of those participants who experienced the L3 automation, 46 (95.83 percent) were aware that they experienced the L3 automation. Of the conventional drivers, 14 (29.17 percent) believed the vehicle they drove had L3 automation capabilities.

The team assessed the following items for those 46 participants who both experienced and were aware of the L3 automation system.

Perceived Comfort

The researchers asked the participants, "Were you comfortable using the L3 automation?" The majority (n = 36; 78.26 percent) reported feeling comfortable with the L3 automation system. The participants who reported feeling uncomfortable gave the following common reasons:

- Not being used to giving up control of the vehicle.
- Being unsure how the vehicle would respond to certain situations.
- Having differences in preferred driving styles (i.e., the L3 automated system drives differently than how the participant drives).

Perceived Understanding

The researchers asked the participants, "Did you feel like you fully understood how to operate the L3 automation?" The majority (n = 37; 80.43 percent) reported feeling they understood the L3 automation system. The participants who reported feeling they did not understand the system gave the following common reasons:

- Needing more time to practice with the system.
- Being unsure how the vehicle would respond to certain situations (e.g., interact with hazards or exiting the highway).

System Expectations

The researchers asked the participants, "Did the L3 automation behave like you expected it to behave?" The majority (n = 32; 69.57 percent) reported the system behaved as they expected. The participants who reported feeling the system did not behave as expected gave the following common reason: Expecting the system to react sooner (e.g., engage the time signal sooner, exit the highway sooner, merge onto the highway sooner, etc.).

The researchers asked the participants, "Did the L3 vehicle adjust its speed like you thought it would?" The majority (n = 30; 65.22 percent) reported the system adjusted its speed as they expected. The participants who reported feeling the system did not adjust its speed as expected gave the following common reason: When speed was adjusted, the adjustment was faster and more abrupt than anticipated.

Awareness and Attitudes Toward CDA Alerts

To reiterate, the full simulated drive was 20 mi (32.19 km). The simulated drive included two experimental segments of interest. In each experimental segment, exposure to a CDA alert was possible. As it was possible to experience a CDA alert in either or both experimental condition, 80 participants were exposed to a CDA alert.

The researchers asked the participants, “Did you drive a vehicle that received in-vehicle CDA messages at all during the drive?” Of those participants who experienced a CDA alert, 66 (82.50 percent) were aware that they received a CDA alert during the full simulated drive. Of the participants who did not experience any CDA alert during the full drive, one (5 percent) believed they had received a message.

Trust

The researchers asked the participants who received V2I CDA alerts and were aware of them, “Did you trust the connected in-vehicle messages from infrastructure on the roadway?” The majority (n = 37; 94.87 percent) reported trusting the CDA alerts. The two participants who reported not trusting the CDA alerts gave the following common reasons:

- Not noticing the alerts.
- Needing more time practicing with the system.

Awareness and Attitudes Toward Both the L3 Automation System and the CDA Alerts

The researchers asked the participants, “Did you receive both in-vehicle messages from infrastructure on the roadway (such as the lane closure message)?” Of those participants who experienced both systems, 36 (90.00 percent) were aware that they had L3 automation functionality and received a CDA alert during the full simulated drive. Of the participants who did not experience both systems, 15 (27.78 percent) believed they experienced both systems.

System Expectations

The researchers asked the participants who correctly answered “yes” to receiving both messages (n = 36), “Did the L3 vehicle behave or respond as you expected after receiving an in-vehicle CDA message?” The majority (n = 27; 75.00 percent) reported the system behaved as they expected. The participants who reported feeling the system did not behave as expected gave the following common reason: Unsure how the vehicle would respond to certain situations (e.g., interact with hazards or exiting the highway). Some expected the vehicle to or desired it to merge sooner.

CHAPTER 4. DISCUSSION

This study's goal was to examine the potential benefit of using CDA technology to communicate traveler information messages to drivers. Specifically, the research team examined the lane-changing behavior of drivers in response to a lane closure. Half of the drivers received an instructional message (participants were instructed to slow down), and the other half received an informational message (participants were informed of a closure in the right lane). The mechanism for displaying messaging varied among the drivers between receiving a CMS, getting an in-vehicle CDA alert, or receiving information via both a CMS and CDA alert.

This study found receiving a CDA alert in isolation did not affect the participants. However, the research team did find some evidence to support a positive effect on safe driving behavior when the participants received information from both a CDA alert and a CMS. The participants in the current study who received information from both message sources tended to travel a longer distance during the lane change (although this effect disappeared in the sensitivity analysis), took longer to complete the lane change, and displayed less variability in steering wheel angle during the lane change. The team found that these effects occurred in contrast to the drivers who received information only from the CMS. While such effects suggest smoother and possibly safer lane-change behaviors, drivers who received both sources of messaging also tended to merge ahead of the vehicle fleet, suggesting a potential increase in aggressive driving. This finding contrasts with some of the other findings suggesting CMS information may decrease aggressive maneuvers (Datta et al. 2004). However, the researchers did not observe a higher likelihood of crashes among the drivers who received messaging from both a CDA alert and the CMS in comparison to drivers who received information via a CMS only. Hence, this outcome supported the hypothesis that drivers who experienced both the CMS and CDA alerts will be more likely to modify their driving behavior in response to the messaging.

Approximately two-thirds of the participants who were equipped with L3 automation capabilities had disengaged the L3 automation system just before and during the lane-change maneuver. This large number of participants disengaging the L3 automation just before the lane-change maneuver is indicative of the participants preferring to take part in the planning stage of the lane-change maneuver. In the questionnaire, the majority of the participants who were equipped with L3 capabilities indicated feeling comfortable, feeling that they understood the system, and believed that the system behaved as expected. A common sentiment among those reporting feeling uncomfortable, misunderstanding, or incongruent in expectation was an uncertainty in how the L3 automation system would react in certain situations and a perception that how the system drove was incongruent with the driver's preferences. This outcome may, in part, explain the high number of participants who took over control just before and during the lane change. The system was designed to change lanes close to the road closure. Other comments suggested that participants may simply require more time with the L3 automation system to fully understand the system's capabilities. In the real world, a driver with an L3 automation-capable vehicle will have more time to become familiar with the system and, perhaps, over time, may be more willing to allow the vehicle's L3 automation system to complete the lane-change maneuver.

The research team observed differences in lane-change behavior between drivers equipped with the L3 automation system and those drivers without the system throughout the study. Compared with drivers without L3 automation capabilities, those drivers with L3 automation capabilities tended to merge behind the vehicle platoon and took longer to initiate the lane change. While more time was taken to initiate the lane change, drivers with L3 automation capabilities displayed faster and less "smooth" lane changes. Particularly, such drivers took less time to complete the lane change, traversed a shorter distance during the lane change, and displayed more variability in steering wheel angle during the lane change. Despite this seemingly less "smooth" lane change, drivers with L3 automation experienced fewer crashes during the lane change, which may be a factor of merging behind the vehicle platoon. Such differences may better reflect differences in conventional drivers' preferred driving style and the how the L3 automation system was programmed to drive.

The research team observed a few main effects regarding the message types. Drivers who received a message informing them of a lane closure ahead, as opposed to a message instructing the driver to slow down, tended to initiate a lane change soon after passing the CMS. Interestingly, the instructional message provided no effect over and above the informational message on average driving speed. As the L3 automation system was designed to slow down after receiving the instructional message, the researchers expected an interaction effect, but they did not observe one in the present study. Additionally, the main effects of the instructional message were not apparent. Rather, the effects of the instructional message tended to emerge with interactions of the other experimental factors.

The research team observed several noteworthy interactions throughout the study. The drivers with L3 automation capabilities, who received a CDA alert only and received an informational message, tended to disengage the L3 automation system less frequently than the other groups during the lane-change maneuver, displayed more driving speed variability within 800 ft (243.84 m) ahead of the CMS, and displayed less driving speed variability during the lane-change maneuver. The team also found this unique interaction to have a positive effect on the duration and frequency at which drivers viewed the left mirror just before and during the lane-change maneuver. This finding supports previous studies corroborating the benefits of in-vehicle alerts on driver behaviors (Craig et al. 2017; Davis et al. 2018).

Based on the eye-tracking software, very few participants took notice of the CMS, which is somewhat corroborated by the self-reported responses of participants as well. In contrast, the majority of participants took better notice of the instrument cluster, left mirror, and the emergency vehicle at the traffic incident. The drivers with L3 automation capabilities, who received information via a CDA alert and the CMS, and who received an informational message as well, tended to have longer fixations on the CMS and emergency vehicle, somewhat more fixations on the instrument cluster, but shorter fixations on the left mirror. While these eye-glance behaviors have merit, their general findings should be taken with caution due to the reduced sample sizes that resulted from the lack of observing the areas of interest among some participants.

Overall, the findings in this study support incorporating CDA alerts as a supportive system to work in tandem with CMSs. The study showed no apparent findings that CDA alerts in isolation provide a benefit over and above a CMS alone. Although how few noticed the CMS in the present study is surprising, this finding may highlight a need to increase the saliency of CMSs to better communicate roadway information to drivers. A CMS was present for all drivers, but that message was only presented on the CMS for specific experimental conditions (CMS and CMS+CDA). Although the present study supports the safety benefits of L3 automation technologies, the comments from participants highlight the need for these technologies to potentially accommodate some of the participants' driving styles (i.e., initiating a merge sooner) to increase driver comfort and adoption. The findings in the present study additionally support informational messages over instructional messages. Further investigation into potential benefits of informational messages in other contexts is merited.

LIMITATIONS

Use of a driving simulator offered several advantages for this study. Namely, the simulator allowed all the participants to have a safe, controlled, and consistent experience. As V2I CDA communications are not widely available in the public domain, the driving simulator provided a means for simulating this new technology for many participants in a short period. While driving simulators have many benefits, they also have disadvantages. This study attempted to replicate an L3 CDA system; however, differences may exist between the driving behavior of real-world L3 systems and the simulated L3 system in the present study. For example, a real-world commercial L3 CDA system may respond to an instructional message sooner or initiate a smooth lane change sooner in response to a lane closure than the simulated L3 system in the present study. Additionally, the findings from the eye-tracking data should be taken with caution due to the large number of participants who did not view particular areas of interest. Future studies may ameliorate this particular limitation with larger sample sizes.

APPENDIX A. TRUST QUESTIONNAIRE

No.	Questionnaire Statement
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 systems.
7	Automated driving systems are vulnerable for new hazards like hacker attack and issues with data safety.
8	To me, 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.
9	I implicitly trust all messages from the vehicle I am driving.
10	I would implicitly trust information I receive from surrounding vehicles about their location.

APPENDIX B. PARTICIPANT FEEDBACK QUESTIONNAIRE

No.	Questionnaire Statement
1	During your drive did you notice the black overhead sign prior to the lane closure?
2	Do you typically trust the information provided by overhead changeable message signs on the highway?
3	Was the vehicle you drove today equipped with Level 3 automation capabilities? If “yes,” four additional questions were asked:
3a	Did the Level 3 automation behave like you expected it to behave?
3b	Were you comfortable using the Level 3 automation?
3c	Did you feel like you fully understood how to operate the Level 3 automation?
3d	Did the Level 3 vehicle adjust its speed like you thought it would?
4	Did you drive a vehicle that received in-vehicle CDA messages at all during the drive? If “yes,” two additional questions were asked:
4a	Did you trust the connected in-vehicle messages from other vehicles on the road (such as merge alerts from the automated platoons)?
4b	Did you trust the connected in-vehicle messages from infrastructure on the roadway (such as the lane closure message)?
5	Did you receive both in-vehicle CDA alerts AND you drove a Level 3 vehicle? If “yes,” one additional question was asked:
5a	Did the Level 3 vehicle behave or responds as you expected after receiving an in-vehicle CDA message?

REFERENCES

Bailey, I. L., & Lovie, J. E. (1976). New design principles for visual acuity letter charts*. *Optometry and Vision Science*, *53*(11), 740–745.

Craig, C. M., Achtemeier, J., Morris, N. L., Tian, D., & Pratzer, B. (2017). *In-vehicle work zone messages* (Report No. MN/RC 2017-19). Minnesota Department of Transportation.

Datta, T., Schattler, K. L., Kar, P., & Guha, A. (2004). *Development and evaluation of an advanced dynamic lane merge traffic control system for 3 to 2 lane transition areas in work zones* (Report No. RC-1451). Michigan Department of Transportation.

Davis, B., Morris, N., Achtemeier, J., & Patzer, B. (2018). *In-vehicle dynamic curve-speed warnings at high-risk rural curves* –(Report No. MN/RC 2018-12). Minnesota Department of Transportation.

Dudek, C. L., & Ullman, G. L. (2006). *Dynamic message sign message design and display manual* (Report No. FHWA/TX-04/4023-P3). Texas Department of Transportation.

Kennedy, R. S., Lane, N. E., Berbaum, K. S., & Lilienthal, M. G. (1993). Simulator sickness questionnaire (SSQ) [Database record]. APA PsycTests. https://doi.org/10.1037/t04669-000

Lappin, J., & Bottom, J. (2001). *Understanding and predicting traveler response to information: A literature review* (Report No. FHWA-JPO-04-014). Federal Highway Administration.

Lerner, N., Singer, J., Robinson, E., Huey, R., & Jenness, J. (2009). *Driver use of en route real-time travel time information*. Federal Highway Administration.

Macuga, K. L., Beall, A. C., Kelly, J. W., Smith, R. S., & Loomis, J. M. (2007). Changing lanes: Inertial cues and explicit path information facilitate steering performance when visual feedback is removed. *Experimental Brain Research*, *178*, 141–150.

Federal Highway Administration. (2023). *Manual of uniform traffic control devices for streets and highways* (11th ed.) Federal Highway Administration.

McCoy, P., & Pesti, G. (2001). Dynamic late merge-control concept for work zones on rural interstate highways. *Transportation Research Record*, *1745*(1), 20–26.

Meyer, E. (2000, December 5). Midwest smart work zone deployment initiative: Kansas' results. *Mid-Continent Transportation Symposium Proceedings*, 57–61. Mid-Continent Transportation Symposium 2000, Ames, IA, United States.

Owens, N., Armstrong, A., Sullivan, P., Mitchell, C., Newton, D., Brewster, R., & Trego, T. (2010). *2010 traffic incident management handbook update* (Report No. FHWA-HOP-10-013). Federal Highway Administration. https://rosap.ntl.bts.gov/view/dot/41014

Robinson, E., Jacobs, T., Frankle, K., Serulle, N., & Pack, M. (2012). *Deployment, use, and effect of real-time traveler information systems*. National Academy of Sciences.

Roldan, S. M., Marchese, M., & Mero, L. (2020). *Investigating key automated-vehicle human factors safety issues related to infrastructure: Summary of stakeholder workshop* (Report No. FHWA-HRT-20-058). Federal Highway Administration.

SAE International. (2020). *Taxonomy and definitions for terms related to cooperative driving automation for on-road motor vehicles*, J3216-202005. SAE International.

SAE International. (2014). *Taxonomy and definitions for terms related to on-road motor vehicle automated driving systems*, J3016-201401. SAE International.

Schroeder, J. L., & Demetsky, M. J. (2010). *Evaluation of driver reactions for effective use of dynamic message signs in Richmond, Virginia* (Report Number : FHWA/VTRC 10-R16). Virginia Transportation Research Council.

Snyder, J., Dunn, D., Howard, J., Potts, T., & Hansen, K. (2018). *"Invisible" 2D bar code to enable machine readability of road signs – material and software solutions*. 3M Company®.

Tehran, D. S., Nahvi, A., Hajirasouli, M., Naseri, H., Lotfi, K., & Niknejad, M. (2016). Effects of stimulant and opiate drugs on driver behavior during lane change in a driving simulator. *Travel Behaviour and Society*, *4*, 69–78.

Tudor, L. H., Meadors, A., & Plant II, R. (2003). Deployment of smart work zone technology in Arkansas. *Transportation Research Record*, *1824*(1), 3–14. https://doi.org/10.3141/1824-01

van Winsum, W., De Waard, D., & Brookhuis, K. A. (1999). Lane change manoeuvres and safety margins. *Transportation Research Part F: Traffic Psychology and Behaviour*, *2*(3), 139–149.

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