Effects of Work Zone Infrastructure on Transitioning From Automated to Manual Driving for Work Zones With Lane Reductions

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FOREWORD

Advances in vehicle automation are changing the landscape of traffic and traffic management in work zones. Specifically, at lower levels of vehicle automation, successful transportation networks in the future may depend on the effective interaction between human drivers and vehicles equipped with cooperative automated driving systems (C-ADS) in a mixed fleet environment. C-ADS vehicles equipped with cooperative driving automation (CDA) offer the potential to communicate with work zones equipped with CDA devices. This technology is anticipated to improve safety by allowing automated driving systems to issue takeover requests that help transition automated vehicle control back to the human driver in advance of a work zone when needed.

Ongoing research into how drivers understand, trust, and use automated vehicles demonstrates the influence human factors will have on vehicle automation. This report investigates the ability of CDA work zone infrastructure to assist with the transition from automated to manual vehicle control in advance of a work zone. This report may be of interest to State and local transportation agencies that want to understand the behavior, attention, and perspectives of C-ADS vehicle drivers when they navigate through a C-ADS work zone.

Carl K. Andersen.
Acting Director, Office of Safety and Operations
Research and Development

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This study explored the impact of work zone infrastructure on driver response when transitioning vehicle control from SAE International (SAE) Level 2 automation to the human driver (SAE 2014). Study participants drove a test vehicle at about 50 mph on a four-lane, undivided, closed-track highway. The participants drove two passes through a work zone with a lane reduction. The participants received simulated cooperative driving automation (CDA) messages representing four types of work zones: a standard work zone, which uses work zone signing specified in the *Manual on Uniform Traffic Control Devices for Streets and Highways*; a machine-readable work zone, which uses signs to transmit work zone-specific information that can be used during a takeover request; a work zone equipped with a CDA device, which uses machine-to-machine (M2M) communication to relay basic information about the work zone, and a smart cooperative automated driving system work zone, which also uses M2M communication to convey work zone-specific information (FHWA 2012). Three types of CDA messages were provided to participants: basic, detailed, and no message (control condition). These messages were based on the amount of detail provided (basic versus detailed) and how far in advance of the work zone they were provided (short notification lead time versus long notification lead time). The results suggest that detailed CDA messages tend to have a greater impact (on some drivers and not others) when disengaging advanced driver assistance system (ADAS) features, merging into the open lane, and paying attention to the in-vehicle display. This study’s findings on the use of CDA messages to increase the safety of Level 2 ADAS vehicles supported transportation systems management and operations work zone safety strategies (SAE 2014). The study also showed the benefits of using CDA messages in Level 2 ADAS vehicles with partial automation when approaching a work zone (SAE 2014).</td></tr>
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or “metric ton”)	Mg (or “t”)
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or “t”)	megagrams (or “metric ton”)	1.103	short tons (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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LIST OF ABBREVIATIONS

ACC	adaptive cruise control
ADAS	advanced driver assistance system
ADS	automated driving system
C-ADS	cooperative ADS
CDA	cooperative driving automation
EDA	electrodermal activity
FHWA	Federal Highway Administration
M2M	machine-to-machine
MUTCD	*Manual on Uniform Traffic Control Devices for Streets and Highways*
NB	northbound
RT	response time
SB	southbound
TSMO	Transportation Systems Management and Operations
VMS	variable message sign

CHAPTER 1. INTRODUCTION

Ensuring the safety and reliability of a transportation network involves deploying crews to maintain, repair, and expand the roadway. This results in work zones. Work zones typically involve temporary changes to lane configurations that require vehicles to depart from normal traffic patterns (e.g., lane changes/merging and changes in vehicle speeds), which may be difficult for automated vehicles to navigate. The variable nature of work zones puts them outside the operational design domain of many driver assistance and automated driving systems (ADS). Drivers who approach a work zone in a vehicle with partial or conditional driving automation are responsible for taking manual control of the vehicle to navigate through the work zone. Drivers of vehicles with partial ADS are responsible for detecting the work zone and disengaging the vehicle's automation. For vehicles with conditional ADS, the automated system is responsible for issuing a takeover request. In both cases, safe work zone operation depends on the safe and smooth transition of the approaching vehicle control back to the driver.

AUTOMATION LEVELS

SAE International (SAE) Level 2 ADS are capable of both sustained lateral and longitudinal control (SAE 2014). All other aspects of the driving task remain the responsibility of the driver. When operating a vehicle with a Level 2 advanced driver assistance system (ADAS), the driver is responsible for monitoring the environment and disabling the driver assistance system if a situation beyond the capabilities of the system arises. Active monitoring of automation is known to pose challenges (e.g., maintaining vigilance over long periods of time or inadequate feedback to recognize and quickly perform corrective actions) (Bainbridge 1983). Drivers operating a vehicle in which an ADS is responsible for both lateral and longitudinal control have been found to delay their responses to unexpected emergencies relative to drivers operating a vehicle manually (De Winter et al. 2014; Yang, Ozbay, and Ban 2017). The impaired response of drivers using ADAS is typically attributed to reduced arousal and situational awareness. For example, Stanton and Young (2005) found that participants reported lower workload, lower levels of stress, and reduced situational awareness when driving with adaptive cruise control (ACC).

Although it is well known that high levels of stress can impair driving ability, the Yerkes-Dodson law suggests that extremely low levels of arousal can also reduce performance to below optimal levels (Yerkes and Dodson 1908). De Winter et al. (2014) argued that, while any level of automation has the potential to reduce driver workload, the reduced driver workload found in response to ACC is minimal compared to the reduction found for vehicles that automate both lateral and longitudinal control (De Winter and Dodou 2011). Thus, drivers operating a vehicle with Level 2 driving automation may be at risk when faced with unexpected, atypical driving environments (SAE 2014). Because work zones represent a departure from normal driving that is associated with an increased risk of collision, drivers operating a vehicle with Level 2 driving automation may benefit from in-vehicle alerts that notify the driver of an upcoming work zone, particularly if the work zone requires disengaging the driving automation features (Tudor, Meadows, and Plant 2003).

Unlike vehicles with Level 2 ADAS, drivers operating vehicles with Level 3 ADS are not responsible for monitoring the driving environment (SAE 2014). Drivers are free to engage in any nondriving tasks they choose as long as they can respond to a request to resume vehicle control in a timely manner. The propensity for users operating vehicles with ADSs to engage in nondriving tasks was demonstrated by Omozik et al. (2019). Omozik used a simulated automated vehicle to assess how comfortable drivers are after transferring control to an automated system within a real-world driving situation. While driving on a live public highway, participants switched vehicle control to what they believed was a fully automated system. During their first transfer of control, 78 percent of participants engaged in nondriving tasks. This figure rose to 93 percent during a second period of automated driving. Drivers who are given the opportunity to engage in nondriving tasks are highly likely to do so, particularly as they gain trust in the ADS. Once vehicle control has been ceded to an ADS, drivers engage in a wide range of activities and regularly switch between those activities (Hecht et al. 2020). Engaging in different types of activities before a takeover request results in different levels of driver workload immediately after resuming vehicle control, and nondriving activities are often found to slow the driver's ability to respond to takeover requests (Louw et al. 2015; Kim et al. 2019; Eriksson and Stanton 2017). Successfully transitioning vehicle control from ADS to the driver requires issuing a takeover request with sufficient lead time to allow drivers to disengage from nondriving activities and regain situational awareness before resuming vehicle control.

TAKEOVER REQUEST

Designing a takeover request that allows for the safe and smooth transition of control from the ADS to the driver is a human factors topic that has been considerably researched. Of particular concern is the amount of lead time that should be provided to a driver. SAE indicates that takeover requests should provide sufficient time to allow the driver to safely resume vehicle control (SAE 2014). Many studies have attempted to quantify the amount of time that may be considered sufficient. However, determining a sufficient lead time for all drivers and in all circumstances is challenging. For example, drivers who are older, drowsy, or who have been driving with ADS engaged for longer periods of time tend to take longer to respond to takeover requests than drivers who are younger, well-rested, and who have been engaged in the dynamic driving task more recently (Eriksson and Stanton 2017; Bourrelly et al. 2019).

LEAD TIME

Melcher et al. (2015) tested the viability of a 10-s takeover request lead time. Participants drove a simulated vehicle equipped with Level 3 ADS on a four-lane divided highway (SAE 2014). Participants were told they did not need to monitor the system but they must take control when prompted. While the system was engaged, participants played a quiz game on a provided cellular phone. After the takeover request, the ADS remained engaged for 10 s, at which point participants entered a work zone that required a lane change. All participants were able to disengage from the phone task and take control of the vehicle during the 10 s before the work zone. In a postdrive questionnaire, 68 percent of participants indicated that 10 s was an appropriate takeover time (30 percent indicated they would prefer more time, while only 1 percent indicated they would prefer less time). Video recordings of the takeovers revealed that participants did not make erratic movements when the request was issued, but instead finished the quiz question they had been working on and placed the phone in the passenger seat. Bourrelly et al. (2019) found similarly high satisfaction ratings for a 10-s lead time, even after participants had been using an ADS while watching a movie for 60 min before the takeover request being issued.

A 10 s lead time may not be sufficient for all drivers. In a review of 25 studies on takeover request timing, Eriksson and Stanton (2017) found mean driver response time (RT) to takeover requests ranging from 1.14 to 15 s. Given the positive skew associated with RT distributions, Melcher cautioned against using mean scores to determine takeover request timing (Melcher et al. 2015). To illustrate this, Melcher had participants drive a simulated vehicle with Level 3 ADS while they were either engaging in a secondary task (e.g., reading a magazine) or sitting quietly in the driver's seat (SAE 2014). At random times during the drive, a takeover request was issued, and the time it took drivers to resume vehicle control was recorded. While mean RTs were similar to those seen in previous work (between 4 and 7 s) the maximum RTs for the undistracted and distracted drivers were 25 and 21 s, respectively. Participants in this study may have lacked incentive to retake control in a timely manner because the takeover requests did not appear to be triggered by any event in the driving environment. This study highlights the importance of providing takeover requests that not only cater to mean takeover RT, but also allow for safe transfer of vehicle control for at least 95 percent of drivers.

WORK ZONE DETECTION

Past research exploring the optimal lead time for takeover requests has focused on maximizing the opportunity for drivers to prepare to retake vehicle control. In a real-world setting, practical considerations are likely to limit available lead times (Melcher et al. 2015). In work zones, the lead time given to drivers before takeover will depend on how early the ADS learns that it is approaching a work zone. One possibility is that information from State and local transportation agencies could inform an ADS about the location of active work zones. Transportation agencies and traffic management centers use a variety of methods to make traveler information available to the public, including information about active work zones (Robinson et al. 2018). As market penetration of vehicles with ADS increases, that same traveler information likely will be available to download to ADS-equipped vehicles. This traveler information could then be used to determine when to issue takeover requests, or even to help systems plan alternative routes that avoid work zones. The variable nature of work zones—which often continuously move downstream as initial work is completed and new work begins—could make it challenging to distribute current and precise work zone location information to an ADS for takeover requests. For that reason, an ADS may likely require additional methods of obtaining information about and verifying the presence of a work zone.

The ADS may obtain information about an upcoming work zone by detecting work zone warning signs. ADASs currently on the market have already demonstrated the ability to successfully detect and interpret road signs using combinations of sensors including radar and computer vision. Future advances in these technologies are only expected to improve ADS sign-reading capabilities. These advances would make an ADS similar to a human driver in that both would read work zone signs to learn about the presence of a work zone. When approaching a work zone, drivers first reach the advance warning area. Signing within this area informs drivers about the upcoming road work. The *Manual on Uniform Traffic Control Devices for Streets and Highways* (MUTCD) specifies signing to use in the advance warning area (Federal Highway

Administration (FHWA) 2012). This standardized use of work zone signs can help ADS correctly recognize the presence of an upcoming work zone.

Many transportation agencies supplement standard work zone signs with additional signing to create a smart work zone (Datta et al. 2004). Sensors placed within a smart work zone are linked to variable signing to create customized messages based on current work zone queue length, traffic volume, and throughput (Bushman Berthelot, and Chan 2004; Tudor, Meadows, and Plant 2003; Meyer 2011). Smart work zones have been found to reduce collisions, decrease aggressive maneuvers among drivers, and reduce travel delays (Meyer 2011; Tudor, Meadows, and Plant 2003; McCoy and Pesti 2001; Datta et al. 2004). The custom messages within smart work zones are often presented on variable message signs (VMS) positioned upstream of the standard signs included in the MUTCD (Grillo, Datta, and Hartner 2008). If an ADS system relies on detecting standard work zone signs to issue a takeover request, then drivers who resume control after that takeover request are likely to miss the traveler information, particularly if they have been engaging in nondriving activities when their vehicle passed the VMS.

One way to ensure that drivers receive customized work zone information when resuming control from an ADS in advance of a work zone is to incorporate traveler information into the takeover request. For vehicles equipped with cooperative ADS (C-ADS) (or C-ADS driving support features), customized work zone information could be distributed by positioning cooperative driving automation (CDA) devices with machine-to-machine (M2M) capabilities within a work zone. C-ADS-equipped vehicles have ADS capable of transmitting and receiving safety and navigation information (Yang, Ozbay, and Ban 2017). C-ADS can communicate and cooperate with other C-ADS-equipped vehicles and CDA devices, including those positioned within a work zone.

A CDA device within a work zone would be capable of transmitting information about the upcoming work zone directly to the C-ADS. The technology can warn the system about the location of the upcoming work zone and also allow customized traveler information typically presented on a VMS to be communicated directly to the system and presented to the driver via in-vehicle alerts. The alerts could be used to complement existing roadway signs. Previous work suggests the beneficial effect that in-vehicle alerts containing information can have on driver behavior (Davis et al. 2018; Wu et al. 2019). The transmission range of CDA devices are longer than typical advanced warning areas. Thus, the information could be made available farther upstream than it would be reasonable for signing to be placed. As a result, use of C-ADS devices within a work zone could allow for longer lead times before a takeover request.

Work zones equipped with CDA devices offer the potential to improve safety by allowing ADS to issue takeover requests with greater lead times and customized traveler information. However, this information would not be available to ADS that are not capable of cooperative automation. In addition, some local transportation agencies may find the cost associated with implementing this technology to be prohibitively expensive.

Machine-readable signs may serve as a low-cost alternative to CDA devices. Recent research has shown proof of concept for signs that can transmit information directly to ADS using quick-response code technology. Using material that has high transparency in the visible light spectrum but low transparency in the near infrared spectrum, Snyder et al. (2018) was able to overlay machine-readable barcodes on existing traffic signs that were not visible to human drivers. A field test of these signs indicated the barcode messages could be read by vehicles traveling toward the sign at a distance of 312 ft in daylight and 282 ft at night. The results highlight the potential for conveying information, such as work zone information, to ADS via barcode overlays on existing work zone signs.

Machine-readable signs would be subject to the same detection ranges as standard work zones that rely on vehicle sensors for detection. The barcode messages can convey complex messages in a small amount of space. These machine-readable signs could provide ADS with work zone-specific information. Including information about the upcoming driving environment as part of a takeover request has been shown to help the driver gain situational awareness of the driving environment and understand what actions will be required when they retake control of the vehicle (Eriksson et al. 2019).

STUDY OVERVIEW

This study investigated the use of CDA messages in Level 2 ADAS vehicles to support work zone safety and that could be a useful part of other Transportation Systems Management and Operations (TSMO) work zone safety strategies. The study examined the ability of the work zone infrastructure to assist in the safe and prompt transition of vehicle control back to the human driver in advance of a work zone. The participants drove a test vehicle on a four-lane, undivided, closed-track highway that had a northbound (NB) and southbound (SB) work zone with a lane reduction. The participants drove two passes (NB and SB) through the work zones with a lane reduction. Each participant received one CDA message during one pass and no message during the other pass. The CDA message and no message order was balanced between participants. To simulate different types of work zone infrastructure, takeover requests contained either basic or detailed information and were delivered with either a short (312 ft) or long (1,640 ft) lead distance from the work zone.

The participants received simulated CDA messages for one of four work zone infrastructure types. A standard work zone, in which an ADS identifies a work zone by detecting standardized work zone signs, was simulated by issuing a basic takeover request with a short lead time. A machine-readable work zone, in which machine-readable signs convey work zone-specific information to the ADS, was simulated by issuing a detailed takeover request also with a short lead time. A C-ADS work zone, in which a CDA device uses M2M communication to relay the location of the work zone to the C-ADS, was simulated by issuing a basic takeover request with a longer lead time. Finally, a smart C-ADS work zone, in which a CDA device communicates work zone-specific information to the C-ADS, was simulated by issuing a detailed takeover request with a longer lead time.

The researchers were interested in driving performance measures, including the time to resume control in each condition relative to the lane reduction and the time that participants chose to merge into the open lane. Data from the vehicle controller area network were used to assess steering variability, speed, and the deceleration profile of the vehicle as it approached and entered the work zone. Driver attention was also assessed using eye-glance data recorded during the drive. Finally, postdrive questionnaires were used to assess driver trust in Level 2–3 automation and M2M communication (SAE 2014).

The objectives of this research were as follows: examine how the work zone infrastructure (i.e., CDA messages) influenced transitioning vehicle control to the driver, investigate driver behavior when drivers approach a work zone in a vehicle with partial automation, characterize driver attention when drivers approach a work zone, and assess driver stress and acceptance of vehicle automation when drivers navigate through the work zone.

CHAPTER 2. METHOD

PARTICIPANTS

Eighty-eight licensed U.S. drivers who were at least 18 years old and had a visual acuity of 20/40 (as is required for licensure in most States), were recruited from the College Station, TX, area. The researchers recruited approximately equal numbers of males and females. Table 1 provides the distribution of the participants by age.

Table 1. Approximate participant count.

Age	Number of Participants	Percent of Total	Male	Female
19 and under	1	1.1	0	1
20–24	7	8.0	5	2
25–29	12	13.6	7	5
30–34	10	11.4	6	4
35–39	9	10.2	3	6
40–44	6	6.8	3	3
45–49	7	8.0	2	5
50–54	9	10.2	4	5
55–59	10	11.4	2	8
60–64	8	9.1	4	4
65–69	8	9.1	5	3
70–74	1	1.1	0	1
75 and older	0	0.0	0	0
Total	**88**	**100**	**41**	**47**

EXPERIMENTAL DESIGN

The 88 participants drove the experimental route and traversed work zones while traveling NB and SB. Each participant only made one pass in each direction, and the order was counterbalanced between participants. Each participant received one takeover request message during one pass and received no message during the pass in the other direction. Half of the participants received no messages on their first pass, but the other half received one of the four takeover messages. The four types of messages were: short lead time with basic message, short lead time with detailed message, long lead time with basic message, and long lead time with detailed message. The four types of messages were split among the 88 participants.

The primary variables of interest in the study were the type of takeover message (basic or detailed) and message lead time (short or long) and were represented by four work zone types: standard, machine-readable, C-ADS equipped, and smart C-ADS equipped. The following list describes the four types of work zones:

- **Standard work zone.** When approaching a standard work zone, the ADS identifies a work zone by detecting standardized work zone signs. Both the distance at which the takeover request could be issued, and the information contained in the takeover request is minimal. A standard work zone is simulated by issuing a basic takeover request with a short lead time (e.g., "WORK ZONE AHEAD/RESUME VEHICLE CONTROL" at 312 ft).

- **Machine-readable work zone.** A machine-readable work zone uses automated vehicle-friendly signs to transfer work zone-specific information to the ADS. In this condition, the distance at which the ADS can issue a takeover request is similar to that of a standard work zone; however, the takeover request could include more detailed information about the work zone because of the work zone-specific information contained in the machine-readable sign. A machine-readable work zone is simulated by issuing a detailed takeover request with a short lead time (e.g., "WORK ZONE/NEXT 3-MILES/MERGE LEFT" at 312 ft).

- **C-ADS-equipped work zone.** A C-ADS-equipped work zone uses M2M communication to transmit work zone information directly to the ADS. The distance at which the ADS could issue a takeover request is increased relative to work zones identified by sign detection. A C-ADS work zone is simulated by issuing a basic takeover request with a long lead time e.g., "WORK ZONE AHEAD/RESUME VEHICLE CONTROL" at 1,640 ft).

- **Smart C-ADS-equipped work zone.** A smart C-ADS-equipped work zone uses sensors within the work zone to gather work zone-specific information and uses a CDA device to transmit that information to the ADS. Both the distance at which the ADS issues a takeover request and the amount of detail provided within that takeover request is increased relative to a standard work zone. A smart C-ADS work zone is simulated by issuing a detailed takeover request with a long lead time (e.g., "WORK ZONE/NEXT 3-MILES/MERGE LEFT" at 1,640 ft).

Table 2 displays the number of participants for the CDA message conditions by pass. The study consisted of two independent variables that were tested between groups of participants: lead time and message type (each with two levels) and a control condition (no takeover request message) that was tested for all participants. All participants completed two passes through the work zone. One pass with a CDA message and one with the control condition (no takeover request message).

Table 2. Number of participants by CDA message condition and pass.

Work Zone Type	Standard Work Zone	Machine-Readable Work Zone	C-ADS Work Zone	Smart C-ADS Work Zone
Lead time: message type	Short lead time: basic message	Short lead time: detailed message	Long lead time: basic message	Long lead time: detailed message
Pass 1	12	13	9	10
Pass 2	10	8	13	13
Total	**22**	**21**	**22**	**23**

APPARATUS

Vehicle System

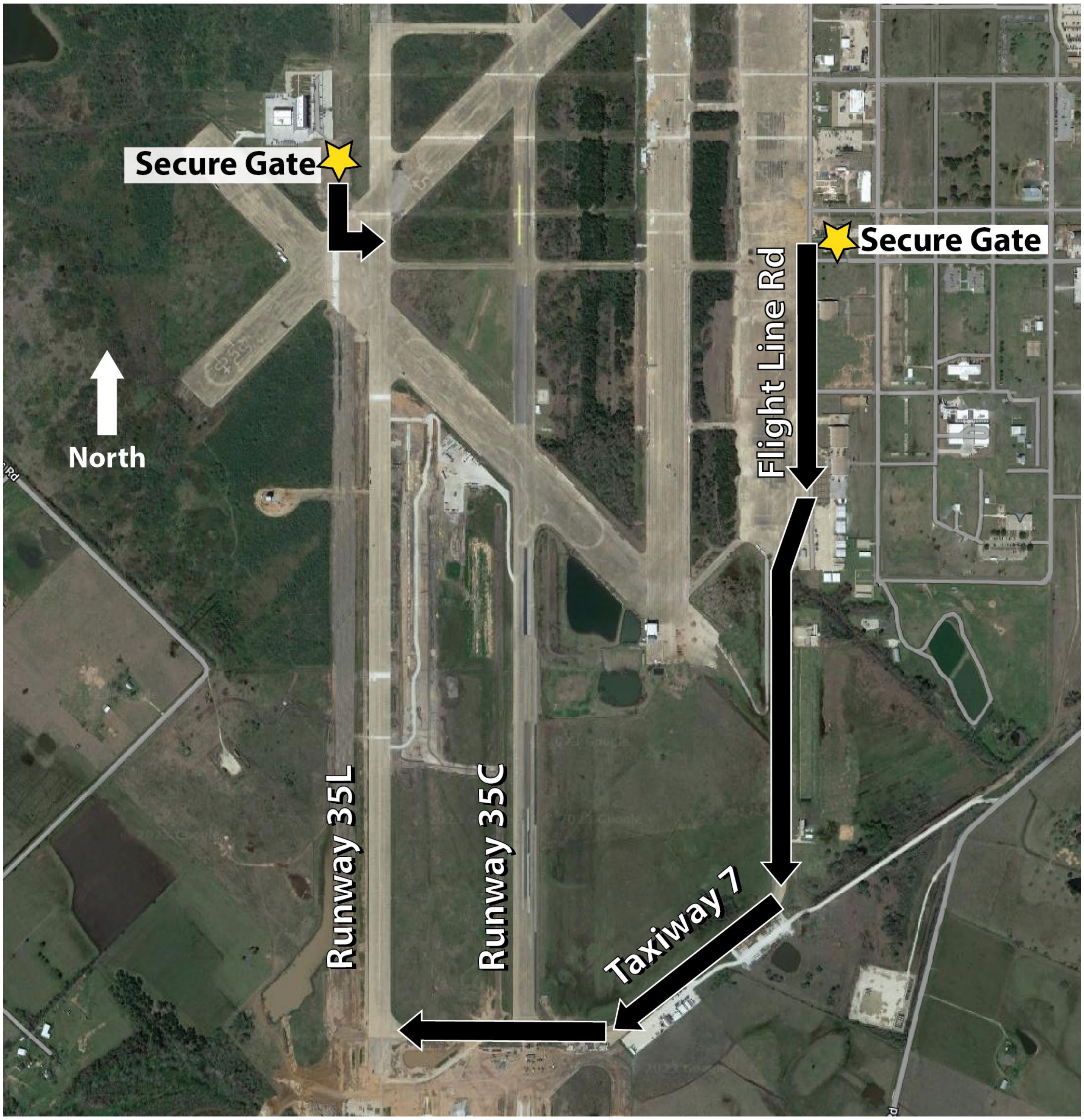
The test vehicle was an instrumented 2022 ADAS vehicle with ACC, lane centering, and evasive steering assist. Figure 1 shows the steering wheel-mounted controls. The vehicle monitored speed, location, steering input, accelerator input, brake input, and driver eye tracking. The vehicle location tracking was used to establish lane position and vehicle wander (i.e., a change in the vehicle's center alignment within the lane). Video cameras recorded the forward scene, including the participant's manipulation of the ADAS controls.

Source: FHWA.

Figure 1. Photo. Steering wheel controls for ACC and lane centering.

Test Route Configuration

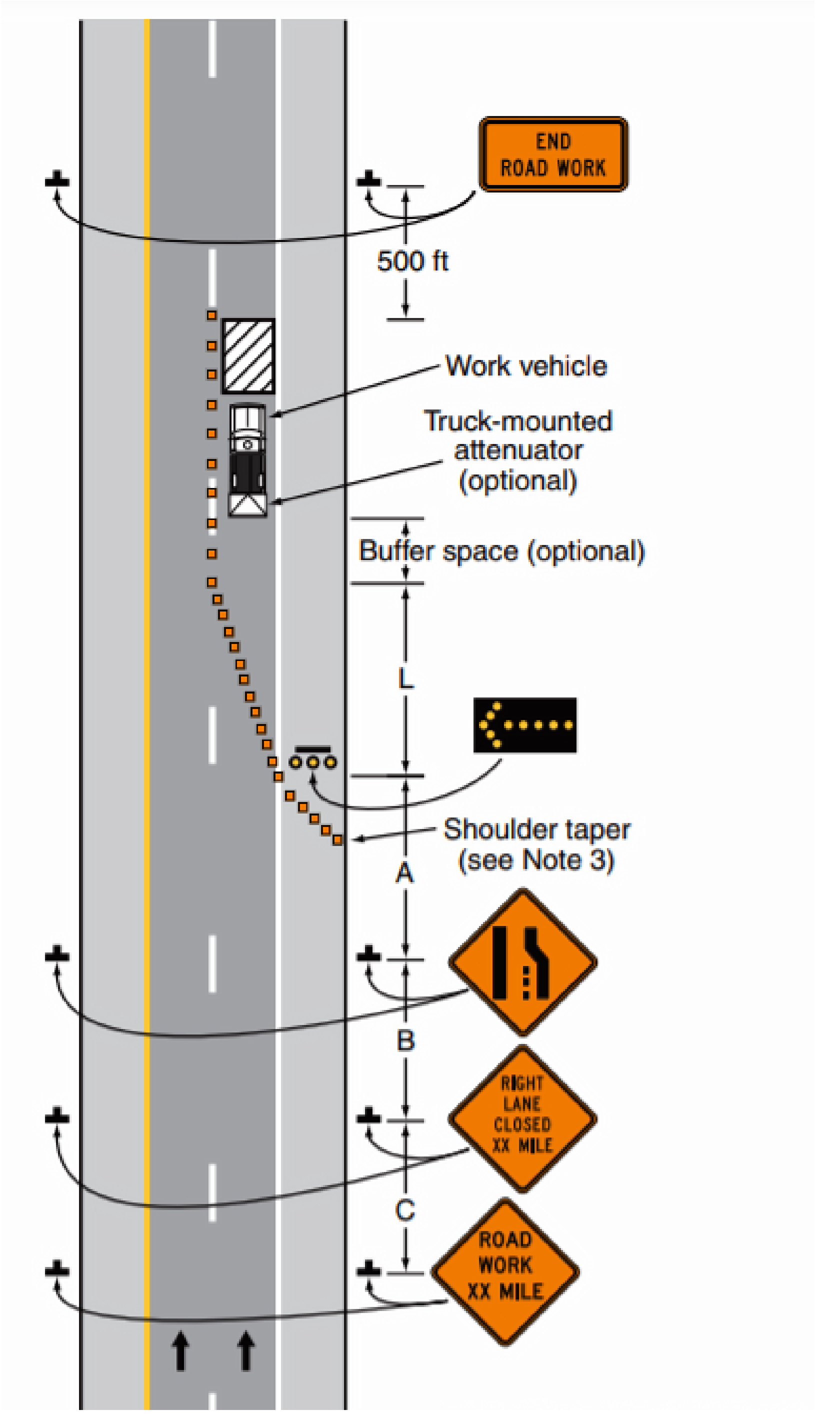
The entire experimental route was located within a secured runway system area on runway 35L. Figure 2 shows runway 35L and access points to the test area. Two work zones were set up on 35L, with one in the NB direction and the other in the SB direction. All participants entered the runway system through one of the secured entrance gates. Half of the participants saw the NB work zone first, so they began at the south end of 35L. Their proposed access route followed SB Flight Line Road to Taxiway 7, then westbound to the south end of 35L. The other half of the participants saw the SB work zone first, so they began at the north end of 35L. The north end secured gate was near the north starting point of the test area.



Original Map © 2023 Google® Earth™. Modified by FHWA (see acknowledgments section).

Figure 2. Map. Proposed access paths to the test area (Google 2023).

Each work zone was configured, as shown in Figure 3. The lane closure design is based on the MUTCD (FHWA 2012). Based on this design, no signs are placed on the left side, and three advance warning signs are used on the right side. Dimensions A, B, and C represent the spacing between the advance warning signs and the arrow panel, while dimension L represents the length of the merging taper.



Source: FHWA.

Figure 3. Illustration. Stationary lane closure on a divided highway (TA-33) (FHWA 2012).

Because the area of runway system was much like a rural roadway environment (with little visual clutter for participants), the distances between signs for A, B, and C were 500 ft, as shown in table 3. However, the arrow board was not used in the study, as most arrow boards can be visible for more than 1 mi and would have likely deterred participants from relying on in-vehicle notifications for information.

Assuming an operating speed of 50 mph, the distance for L (in ft) is calculated using the MUTCD formula $L=W\times S$, where W is the width of the lane (12 ft), and S is the operating speed (50 mph) (FHWA 2012). As a result, L=600 ft. No buffer space was required, but the researchers used a 100-ft length for the work vehicle and the work area combined. The END ROAD WORK sign was not required for this testing. Thus, the overall length of the stationary lane closure was 2,200 ft (500+500+500+600+100=2,200).

Table 3. Meaning of letter codes in TA-33 from the MUTCD (FHWA 2012).

Road Type	Distance Between Signs**		
	A (ft)	B (ft)	C (ft)
Urban (low speed)*	100	100	100
Urban (high speed)*	350	350	350
Rural	500	500	500
Expressway/freeway	1,000	1,500	2,640

*Speed category to be determined by highway agency.

**The column headings A, B, and C are the dimensions shown in Figures 6H-1 through 6H-46. The A dimension is the distance from the transition or point of restriction to the first sign. The B dimension is the distance between the first and second signs. The C dimension is the distance between the second and third signs. (The first sign is the sign in a three-sign series that is closest to the work zone. The third sign is the sign that is furthest upstream from the work zone.)

The research team reviewed advance warning signs from various State departments of transportation and selected the signs shown in figure 4.

Source: FHWA.

Figure 4. Illustration. Advance warning signs from the MUTCD (FHWA 2012).

A detailed layout for the NB work zone on 35L is shown in figure 5. The SB layout is shown in figure 6. The work zone area was striped as a four-lane, undivided section of highway with white edge lines, white broken lane lines, and a double yellow center line. Lane closure advance warning signs were installed only on the right shoulder of the roadway. The work zone area was centered within the width of the runway taking up approximately the middle third of the runway. The distance from the start of the work zone for the long and short notification point was 312 and 1,640 ft, respectively.

Original Map © 2023 Google® Earth™. Modified by FHWA (see acknowledgments section).

Figure 5. Map. NB work zone layout (Google 2023).

Original Map © 2023 Google® Earth™. Modified by FHWA (see acknowledgments section).

Figure 6. Map. SB work zone layout (Google 2023).

Takeover Messages

The researchers used three types of takeover messages: basic, detailed, and no message (control condition). The test messages provided to the participants were based on the amount of detail provided (basic versus detailed) and how far in advance of the work zone that information was provided (short versus long notification lead time). Table 4 provides an overview of the message conditions. The short and long lead-time messages were provided 312 and 1,640 ft before the first work zone sign. All messages were orange text on a black background. The basic message was a single line of text, "WORK ZONE AHEAD." The detailed message was three lines of text, "WORK ZONE |0.3 MILES | MERGE LEFT." The distance was 0.3 mi (short lead time) or 0.5 mi (long lead time) from the work zone closure. The direction of the merge was appropriate for the lane closure ahead, either right or left.

The in-vehicle messages were displayed on a small tablet positioned near the top of the center stack vehicle controls. When the message was displayed, a chime sounded. The message stayed on the screen until the lane closure was reached. The message was based on researcher selection and was displayed when triggered based on Global Positioning System location.

Table 4. Takeover request message conditions.

Takeover Request Type	Short Lead Time	Long Lead Time
Basic	Standard work zone condition	C-ADS work zone condition
Detailed	Machine-readable work zone condition	Smart C-ADS work zone condition
None	Control condition	Control condition

The control condition in which no information was delivered to the driver was included in the study. This condition served as a baseline to assess the in-vehicle alerts that warned drivers about upcoming work zones.

PROCEDURE

When the participants arrived, the researchers asked them to review and sign an informed consent form. Participants were then asked to show a valid driver's license. Next, the research assistant verified that the participant had a minimum visual acuity of 6/12 (20/40), with correction if necessary. The participants then received study instructions. Participants watched a video explaining the ADAS features, including the capabilities and limitations of the technology.

Participants were escorted to the experimental vehicle and allowed to modify the vehicle seat position, wheel position, and mirrors as needed to get comfortable. As soon as the participants were comfortable, the researcher ensured they were able to correctly locate and operate the vehicle's ADAS functions—specifically, the buttons to control the adaptive cruise and lane-centering features. After the participants were in position and reviewed the vehicle controls, they were fitted with sensors and the eye tracker was calibrated. Participants were asked to use the ADAS functions as much as possible during the experimental drive.

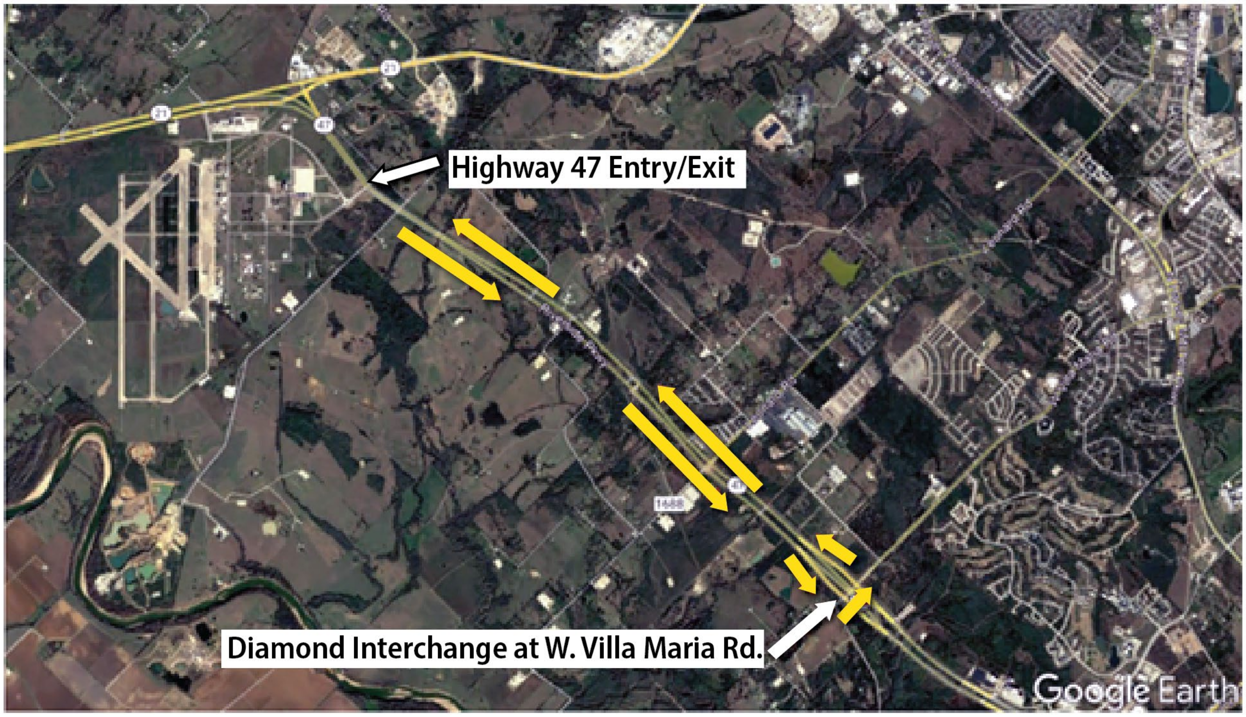
Participants drove a short practice route before data collection during which they practiced using the vehicle's ADAS system. During the practice drive, the research assistant instructed the driver to engage the ADAS system for a time with the system engaged, disengage the system by braking, and then reengage the system. The practice drive took approximately 5 min to ensure participants were able to successfully engage and disengage the ADAS system. Participants then drove the experimental route, which included the prescribed work zone.

Following the experimental route, participants completed a brief questionnaire that assessed their trust in the ADAS system and M2M communication. First, participants completed the Van der Laan questionnaire, a nine-item assessment that provides scores for total trust, perceived usefulness, and perceived satisfaction on in-vehicle systems (Van der Laan, Heino, and De Waard 1997). Participants also completed the safety gain and safety hazard subscales of the "evaluation of the acceptance of drivers assistance systems" (Gold et al. 2015). The researchers asked the participants to rate their level of comfort when approaching and entering the work zone and basic demographic information. Participants were then debriefed and paid.

Practice Drive

The participants drove the vehicle for approximately 20 min on Highway 47 to become familiar with the test vehicle and controls before starting the experimental drive. The route is shown in figure 7. Participants drove SB on Highway 47 and continued for another 3.1 mi until they reached the exit for West Villa Maria Road. After exiting, participants reentered Highway 47 and drove in the NB direction until reentering the main entrance to the experimental test track area.

During the practice drive, the participants engaged and disengaged the lane-centering and ACC ADAS features. In addition to becoming familiar with the ADAS features, at least two different practice messages were displayed to all participants as they drove the practice route. When entering the experimental test track area, the research team assessed the participants' comfort with operating the vehicle. If another lap around the practice route was needed, participants were instructed to do so. If another lap was not needed, participants were instructed to drive along 5th Street to the access gate for the closed course experimental area.



Original Map © 2023 Google® Earth™. Modified by FHWA (see acknowledgments section).

Figure 7. Map. Practice route (Google 2023).

Experimental Drive

The participants were instructed to follow the proper route to access the test area. The specific route each participant took was based on their participant number. Each individual participant number had a specific route that the participants followed to take their first pass through the test area in either the NB or SB direction (see table 4).

Before the start of each pass, the in-vehicle researcher started the data logging and ensured that the data were being recorded. After each pass, the data log was checked to make sure the data were captured. The in-vehicle researcher controlled the message (or no message) provided on each pass. The in-vehicle researcher also verified that the proper message was displayed.

Participants were instructed which lane to get in (right for NB and left for SB, switched halfway through the study) and accelerate the vehicle to 50 mph as quickly as possible when they reached runway 35L. The participants engaged the ACC and lane-centering features on the vehicle. After approximately 5 s of driving time with the ADAS features engaged and before the long-range notification being received, participants were instructed to obey the posted signs and to observe any in-vehicle messages received. Participants were asked to use the ADAS features and resume vehicle control when traversing the work zone. Participants were asked to maintain 50-mph speed until the researcher instructed them to slow down.

When the participants passed the work zone lane closure, they decelerated and prepared for the second pass. Participants were again instructed which lane to get in (right for NB and left for SB, switched halfway through the study) and again accelerated the vehicle to the 50-mph operating speed as quickly as possible. The second pass was similar to the first pass except for the change in the message condition. After completion of the second pass, the participants took the return path back to the parking area.

Postdrive Questionnaire

A postdrive Van der Laan questionnaire was administered in an office building near the test area (Van der Laan, Heino, and De Waard 1997). Each participant anonymously completed the survey, which took no longer than 10 min to complete. The Van der Laan questionnaire provided scores for perspectives of usefulness, satisfaction, and familiarity with the vehicle systems (Van der Laan, Heino, and De Waard 1997). Kruskal-Wallis Rank Sum tests were conducted to determine if there were any statistically significant differences in the ratings as a function of the message conditions (Kruskal and Wallis 1952).

CHAPTER 3. RESULTS

This study investigated participant response to the takeover request messages and the effects of automation in four areas: transitioning vehicle control to the driver, driving performance, driver attention, and driver stress and acceptance of automation. The transitioning vehicle control to the driver analyses examined when drivers disabled ADAS features and resumed vehicle control when approaching a work zone. Driving performance analyses investigated time to merge, speed deceleration profiles when approaching and driving through the work zone, steering variability, and following distance when approaching and entering the work zone. The driver attention analyses examined driver eye glances both in-vehicle and on work zone signs. Finally, driver stress and acceptance of vehicle automation was assessed using a postdrive questionnaire.

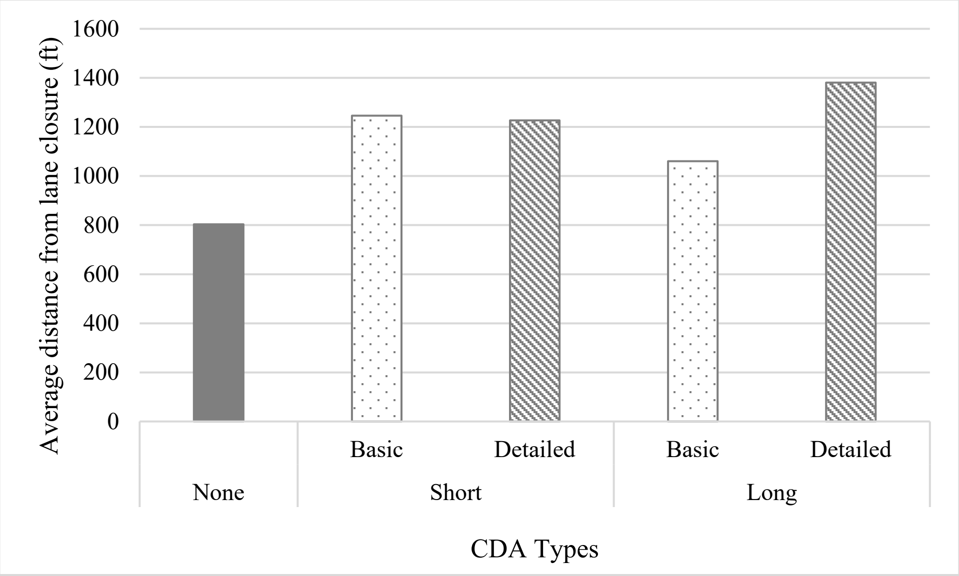
HOW DOES WORK ZONE INFRASTRUCTURE INFLUENCE TRANSITIONING VEHICLE CONTROL TO THE DRIVER?

To answer this question, the research team measured the distance from the lane closure when the ADAS was disengaged.

Distance From Lane Closure When Disabling ADAS Features

Participants disengaged the ADAS features and took back vehicle control sooner whenever CDA messages were provided. On average, the distance from lane closure when the system was disengaged by participants was significantly (p<001) farther away with CDA messages (1,230.3 ft) than without the CDA messages (803.4 ft) (p<0.001).

Figure 8 shows the average distance from the lane closure when the system was disengaged for the different CDA message conditions. The participants who did not receive a CDA message recorded the shortest average distance (803 ft). Among participants who received CDA messages, participants receiving the long lead time detailed messages had the longest average distance (1,380 ft) and, thus, took back vehicle control the farthest from the work zone.



Source: FHWA.

Figure 8. Bar graph. Average vehicle distance from lane closure by CDA type.

HOW DOES WORK ZONE INFRASTRUCTURE INFLUENCE DRIVING PERFORMANCE?

To answer this question, the research team measured the distance and speed where the vehicle merged into the open lane within the work zone.

Distance to Merge into the Open Lane (Relative to the Lane Closure)

Analysis of the distance from the lane closure when participants merged into the open lane found that participants changed to the open lane sooner when CDA messages were provided. On average, the estimated distance from the lane closure was 440 ft earlier when CDA messages were provided. Among the CDA types, participants who received detailed CDA messages tended to merge earlier than those participants who received basic CDA messages. Drivers who received long lead detailed CDA messages changed lanes earliest (1,840 ft from the lane closure, $p < 0.0001$), followed by those who received short lead detailed CDA messages (546 ft, $p < 0.0001$). No other significant effects were found.

Speed/Deceleration Profile When Approaching and Driving Through the Work Zone

The research team instructed the participants to obey the posted signs, observe any in-vehicle messages received, disengage the ADAS features and resume vehicle control when they felt they were in a work zone, and maintain the 50-mph speed until the researcher instructed them to slow down. The vehicle speeds were investigated to examine changes in speed at the location between long lead and short lead messages, the short lead message location, the location between the short lead message and the first work zone sign, and the location of the first work zone sign. The research team analyzed speed profiles for each participant using vehicle speeds extracted at the locations.

The Location Between Long-Lead and Short-Lead Messages

On average, the change in vehicle speed between the long-lead and short-lead message locations were small (<1 mph) for all participants. Only the participants who received long-lead detailed messages tended to reduce vehicle speeds more ($p<0.05$) than when they did not receive a CDA message. No other results were significant.

At the Short-Lead Message Location

On average, the vehicle speeds at the short-lead message location were similar (about 49 mph) for all participants. Only the participants who received long-lead detailed messages had lower vehicle speeds (48.9 mph versus 49.5 mph) compared to participants who did not receive a CDA message ($p<0.05$). No other results were significant.

The Location Between the Short-Lead Location and the First Work Zone Sign

On average, the change in vehicle speed between the short lead and first work zone sign locations were, again, small (from 0.31 to 1.36 mph). At this location, participants who received short-lead detailed messages tended to reduce vehicle speeds (about 1 mph) more ($p<0.01$) than participants who did not receive any CDA messages. No other results were significant.

At the First Work Zone Sign Location

On average, the vehicle speeds at the first work zone sign location were similar (48–49 mph) for all participants. Only the participants who received short-lead detailed messages had lower vehicle speeds (48.1 versus 49.1 mph) than participants who did not receive a CDA message ($p<0.001$). No other results were significant.

Overall, the speed profiles between the long-lead location and the first work zone sign location appeared to be similar among most participants regardless of CDA message type. Generally, the participants averaged about 49 mph when approaching the work zone. Although some differences were statistically significant, they tended to be minimal and likely were due to participant instructions to maintain vehicle speed.

Estimated Time From Lane Closure When Disabling ADAS Features

The estimated time from the lane closure was investigated using the speed profiles and average distances from the lane closure when the ADAS features were disabled. Using the average speed (about 49 mph), the participants who did not receive a CDA message were approximately 11 s (803 ft/71.86 ft per s) from the lane closure when disabling ADAS. In contrast, participants who received CDA messages disabled the ADAS features from 14 to 19 s (1,060 ft/71.86 ft per s and 1,380 ft/71.86 ft per s) from the lane closure. Consequently, participants who received CDA messages disabled ADAS features (took over vehicle control) an average of 3–8 s sooner.

The estimated time to disable the ADAS features was also examined using the location of the long and short notification points and the location of when participants disabled the ADAS features. The short and long lead time notification points were about 25 and 43 s before the lane closure, respectively. Both short and long lead times were found to provide sufficient time for participants to disable ADAS features before reaching the lane closure. Participants with short lead times showed that they took on average about 8 s after notification to disable ADAS, which is slightly faster but within the 10-s takeover request lead time found by Melcher, et al. (2015). Participants with long lead times (and greater distance before reaching the lane closure) waited on average about 27 s before disabling the ADAS.

HOW DOES WORK ZONE INFRASTRUCTURE INFLUENCE DRIVER ATTENTION?

The third research question assessed driver behavior when approaching a work zone in a vehicle with partial automation and the effect work zone infrastructure has on driver attention.

Proportion, Duration, and Location of In-Vehicle Glances

The duration of participant glances at the in-vehicle gauges were similar among the participants. On average, participants spent 0.72 more seconds glancing at the message display when CDA messages were available (1.049 s) than when no messages (0.328 s) were displayed (*p*<0.0001). Table 5 shows the average duration of message display glances by message type.

Table 5. Average duration of message display glances by message type.

Lead Time: Message Type	None	Short Lead: Basic Message	Short Lead: Detailed Message	Long Lead: Basic Message	Long Lead: Detailed Message
Time (s)	0.32	0.71	1.44	0.51	1.48

Significant interactions between the message type, age, and gender were found. Table 6, table 7, and table 8 display the significant post hoc contrast estimates that were found for younger males, younger females, and older females, respectively.

Younger Males

As shown in table 6, younger male participants tended to spend more time (attention) glancing at the detailed messages compared to when a basic message or no message was displayed. For example, younger males who received a short-lead detailed message gazed 1.65 s longer than when they received no message (*p*<0.0001). Similar results were found with younger males for the long-lead detailed messages (1.08 s longer) compared to when a CDA message was not available (p=0.001). Other significant glance times were also observed for younger males when comparing detailed versus basic CDA message conditions. As shown in table 6, younger males also tended to spend more time glancing at the detailed messages than the basic messages regardless of the (long or short) lead time from the work zone. No other significant effects were found for young males.

Table 6. Significant contrasts for younger males.

Type of Messages	Estimate	*p* Value
Short-lead detailed versus none	1.65 s longer	*p*<0.0001
Long-lead detailed versus none	1.08 s longer	*p*<0.0001
Short-lead detailed versus short basic	1.59 s longer	*p*<0.0001
Long-lead detailed versus short basic	1.02 s longer	*p*<0.05
Short-lead detailed versus long basic	1.41 s longer	*p*<0.0001
Long-lead detailed versus long basic	0.83 s longer	*p*<0.05

Younger Females

As shown in table 7, younger female participants tended to spend more time glancing at the detailed messages compared to when no message was displayed. For short-lead detailed messages, they gazed 2.19 s longer than when they received no message (*p*<0.0001). Similar results were found for the long-distance detailed messages (0.78 s longer) compared to when a CDA message was unavailable (*p*=0.05). Younger females also spent longer with the short-distance detailed messages compared to short-distance basic (1.77 s, *p*<0.0001), long-distance basic (1.88 s, *p*<0.0001), and long-distance detailed messages (1.41 s, *p*<0.001). No other significant effects were found.

Table 7. Significant contrasts for younger females.

Type of Messages	Estimate	*p* Value
Short-lead detailed versus none	2.19 s longer	*p*<0.0001
Long-lead detailed versus none	0.78 s longer	*p*<0.05
Short-lead detailed versus short basic	1.77 s longer	*p*<0.0001
Short-lead detailed versus long basic	1.88 s longer	*p*<0.0001
Short-lead detailed versus long detailed	1.41 s longer	*p*<0.001

Older Females

Table 8 shows the only significant contrast for older female participants. Older female participants spent slightly longer (0.63 s) glancing at the long-distance detailed messages compared to the when they received no message (*p*<0.05). No other significant differences in glance times for older women participants were found.

Table 8. Significant contrasts for older females.

Type of Messages	Estimate	*P* Value
Long-lead detailed versus none	0.63 s longer	*p*<0.05

No significant differences were found in glance times for older males between any of the message conditions.

First Instance of Fixation on Work Zone Signs

On average, participants with and without CDA messages tended to look at the first work zone sign (“ROAD WORK AHEAD”) at about the same distance (380 ft versus 392 ft). However, the difference was not significant.

Duration and Quantity of Glances at Work Zone Signing

The analysis of duration of glances on the first work zone sign (“ROAD WORK AHEAD”) found that participants spent 0.28 fewer seconds on the first work zone sign when the CDA messages were available than when there was no CDA message ($p<0.05$). A significant interaction between message type and age was found. Younger participants who received the basic message at the short lead time location spent 0.45 more s on the first work zone sign than the time when there was no CDA message. Older participants who received the detailed message at the short lead time location also spent 0.43 more seconds on the first work zone sign than the time when there was no CDA message.

In terms of total duration of glances at all three work zone signs (“ROAD WORK AHEAD,” “LEFT LANE CLOSED AHEAD,” and the merge symbol), the analyses indicated that compared to the times when there was no CDA message, participants spent 0.66 fewer seconds on the work zone signs when the CDA messages were available ($p<0.01$), especially when the detailed message at the short-lead time location was presented (1.21 s less, $p<0.01$).

HOW DOES WORK ZONE INFRASTRUCTURE INFLUENCE DRIVER STRESS AND ACCEPTANCE OF VEHICLE AUTOMATION?

The last research question investigated driver stress and acceptance of vehicle automation when navigating through the various work zone infrastructure types.

Heart Rate When Approaching the Work Zone

Participant heart rate was used to assess participant stress when approaching the work zone. The analysis examined the number of heart beats per minute from short lead time message location to the location of the lane closure as a function of lead time and message type. No significant differences were found between participants with and without CDA messages. On average, participant heart rates ranged from 79.6 to 85.1 beats per minute.

Electrodermal Activity (EDA) When Approaching the Work Zone

Participant EDA was also used to assess participant stress when approaching the work zone. The analysis examined participant EDA from the short-lead time message location to lane closure as a function of lead time and message type. No significant differences were found between participants with and without CDA messages. On average, participant EDA ranged from 2.07 to 3.02 microsiemens.

Postdrive Questionnaire

Participants completed a postdrive Van der Laan questionnaire to rate their perspectives of usefulness, satisfaction, and familiarity of the vehicle automation when navigating through work zones with different types of work zone infrastructure (Van der Laan, Heino, and De Waard 1997). As shown in table 9–table 17, participants generally reported positive attitudes regardless of the types of messages they received. When asked to rate system usefulness on a five-point scale, where 1 represented useless and 5 represented useful, the median response for all message conditions was 5.0. Table 9 displays the percentage of participant ratings and shows that most participants viewed the system as useful, with about 72–82 percent of participants agreeing (rating of 5–useful). Using the Kruskal-Wallis Rank Sum test confirmed that most participants generally reported positive responses (i.e., the response patterns among the participants seeing different CDA messages were not statistically different) (Kruskal and Wallis 1952).

Table 9. Percentage of ratings for useless to useful.

The System Is Useless to Useful	Rating 1: Useless (percent)	Rating 2 (percent)	Rating 3 (percent)	Rating 4 (percent)	Rating 5: Useful (percent)
Short basic	0	0	4.5	13.6	81.8
Short detailed	0	0	9.5	14.3	76.2
Long basic	0	0	0	27.3	72.7
Long detailed	0	0	8.7	17.4	73.9

When asked to rate the system on a five-point scale, where 1 represented annoying and 5 represented nice, the median response was a 5 for all message conditions, except for the short lead basic messages, which was 4.5. Table 10 displays the percentage of participant ratings and shows that participants generally viewed the system as more nice than annoying, with a majority indicating a rating of 4 (somewhat nice) or 5 (nice). The Kruskal-Wallis Rank Sum test again confirmed that most participants generally reported positive responses, and the response patterns among the participants seeing different CDA messages were not statistically different (Kruskal and Wallis 1952).

Table 10. Percentage of ratings for annoying to nice.

The System Is Annoying to Nice	Rating 1: Annoying (percent)	Rating 2 (percent)	Rating 3 (percent)	Rating 4 (percent)	Rating 5: Nice (percent)
Short basic	0	0	14	36	50
Short detailed	5	5	5	24	62
Long basic	5	5	14	18	59
Long detailed	0	4	0	35	61

When asked to rate the system on a five-point scale, where 1 represented irritating and 5 represented likeable, the median response was 5 for all message conditions, except for the short-lead basic messages, which was 4. Table 11 displays the percentage of participant ratings and shows that participants generally viewed the system as more likeable than irritating, with a majority indicating a rating of 4 (somewhat likeable) or 5 (likeable). The Kruskal-Wallis Rank

Sum test confirmed that most participants generally reported positive responses, and the response patterns among the participants seeing different CDA messages were not statistically different (Kruskal and Wallis 1952).

Table 11. Percentage of ratings for irritating to likeable.

The System Is Irritating to Likeable	Rating 1: Irritating (percent)	Rating 2 (percent)	Rating 3 (percent)	Rating 4 (percent)	Rating 5: Likeable (percent)
Short basic	0	0	14	45	41
Short detailed	0	0	10	14	76
Long basic	5	5	9	23	59
Long detailed	0	0	4	43	52

When rating the system, where 1 represented sleep inducing and 5 represented raising awareness, the median response was 4 for all message conditions. Table 12 displays the percentage of participant ratings and shows that participants viewed the system as more raising awareness than sleep inducing. However, almost a quarter of the detailed message participants gave the system a neutral rating of 3. The Kruskal-Wallis Rank Sum test confirmed that most participants generally reported positive responses, and the response patterns among the participants seeing different CDA messages were not statistically different (Kruskal and Wallis 1952).

Table 12. Percentage of ratings for sleep inducing to raising awareness.

The System Is Sleep Inducing to Raising Awareness	Rating 1: Sleep Inducing (percent)	Rating 2 (percent)	Rating 3 (percent)	Rating 4 (percent)	Rating 5: Raising Awareness (percent)
Short basic	0	14	14	36	36
Short detailed	0	0	24	33	43
Long basic	0	0	9	55	36
Long detailed	0	13	22	22	43

When rating the system, where 1 represented superfluous and 5 represented effective, the median response was 5 for all message conditions. Table 13 displays the percentage of participant ratings and shows that most participants viewed the system as effective rather than superfluous. About three-quarters of the detailed message participants rated the system as effective (rating of 5). The Kruskal-Wallis Rank Sum test confirmed that most participants generally reported positive responses, and the response patterns among the participants seeing different CDA messages were not statistically different (Kruskal and Wallis 1952).

Table 13. Percentage of ratings for superfluous to effective.

The System Is Superfluous to Effective	Rating 1: Superfluous (percent)	Rating 2 (percent)	Rating 3 (percent)	Rating 4 (percent)	Rating 5: Effective (percent)
Short basic	0	9	9	27	55
Short detailed	0	0	14	10	76
Long basic	0	0	5	41	55
Long detailed	0	0	4	26	70

When rating the system, where 1 represented undesirable and 5 represented desirable, the median response was 5 for all message conditions. Table 14 displays the percentage of participant ratings and shows that most participants indicated the system as desirable rather than undesirable, with a majority indicating a rating of 4 (somewhat desirable) or 5 (desirable). The Kruskal-Wallis Rank Sum test confirmed that most participants generally reported positive responses, and the response patterns among the participants seeing different CDA messages were not statistically different (Kruskal and Wallis 1952).

Table 14. Percentage of ratings for undesirable to desirable.

The System Is Undesirable to Desirable	Rating 1: Undesirable (percent)	Rating 2 (percent)	Rating 3 (percent)	Rating 4 (percent)	Rating 5: Desirable (percent)
Short basic	0	5	0	32	64
Short detailed	0	5	5	19	71
Long basic	0	5	5	36	55
Long detailed	0	0	0	35	65

When rating the system, where 1 represented worthless and 5 represented assisting, the median response was 5 for all message conditions. Table 15 displays the percentage of participant ratings and shows that most participants viewed the system as assisting rather than worthless, with a majority indicating a rating of 4 (somewhat assisting) or 5 (assisting). The Kruskal-Wallis Rank Sum test confirmed that most participants generally reported positive responses, and the response patterns among participants seeing different CDA messages were not statistically different (Kruskal and Wallis 1952).

Table 15. Percentage of ratings for worthless to assisting.

The System Is Worthless to Assisting	Rating 1: Worthless (percent)	Rating 2 (percent)	Rating 3 (percent)	Rating 4 (percent)	Rating 5: Assisting (percent)
Short basic	0	0	5	23	73
Short detailed	5	0	14	0	81
Long basic	0	0	5	23	73
Long detailed	0	0	0	17	83

When rating the system, where 1 represented bad and 5 represented good, the median response was 5 for all message conditions. Table 16 displays the percentage of participant ratings and shows that most participants viewed the system as more good than bad, with a majority indicating a rating of 4 (somewhat good) or 5 (good). The Kruskal-Wallis Rank Sum test confirmed that most participants generally reported positive responses, and the response patterns among the participants seeing different CDA messages were not statistically different (Kruskal and Wallis 1952).

Table 16. Percentage of ratings for bad to good.

The System Is Bad to Good	Rating 1: Bad (percent)	Rating 2 (percent)	Rating 3 (percent)	Rating 4 (percent)	Rating 5: Good (percent)
Short basic	0	0	9	23	68
Short detailed	0	0	10	14	76
Long basic	5	0	5	23	68
Long detailed	0	0	4	26	70

When rating the system, where one represented unpleasant and 5 represented pleasant, the median response was 5.0. for all message conditions, except the short lead basic message condition, which was 4.5. Table 17 displays the percentage of participant ratings and shows that more participants viewed the system as pleasant instead of unpleasant, with a majority indicating a rating of 4 (somewhat pleasant) or 5 (pleasant). As previously found, the Kruskal-Wallis Rank Sum test confirmed that most participants generally reported positive responses, and the response patterns among the participants seeing different CDA messages were not statistically different (Kruskal and Wallis 1952).

Table 17. Percentage of ratings for unpleasant to pleasant.

The System Is Unpleasant to Pleasant	Rating 1: Unpleasant (percent)	Rating 2 (percent)	Rating 3 (percent)	Rating 4 (percent)	Rating 5: Pleasant (percent)
Short basic	0	0	14	36	50
Short detailed	5	0	10	10	76
Long basic	0	9	9	27	55
Long detailed	0	0	0	35	65

Ratings from the Van der Laan questionnaire were also used to investigate how familiar participants are with the system (Van der Laan, Heino, and De Waard 1997). When rating the system, where 1 represented very familiar and 5 represented very unfamiliar, the median response was 3, except for the long-lead detailed message condition, which was 2.

Table 18 shows the frequency of participant ratings by lead time and CDA message type. Although the ratings were scattered from very familiar to very unfamiliar, the distribution of ratings indicates that participants receiving the CDA message at the long lead time location generally reported they were familiar with the system. The responses from those who received the CDA message at short-lead time location were split on system familiarity.

Table 18. Frequency of participant ratings by lead time and message type.

Message Type	1:Very Familiar	2:Familiar	3:Neutral	4:Unfamiliar	5:Very Unfamiliar
Long basic	3	6	5	5	3
Long detailed	7	8	4	3	1
Short basic	6	4	4	7	1
Short detailed	5	5	2	4	5

CHAPTER 4. DISCUSSION

This study examined driver behavior when approaching a work zone in a Level 2 ADAS vehicle with partial automation, which could be a useful part of other TSMO safety strategies in work zones (SAE 2014). Participants drove two passes on a closed test track. During each pass, participants drove on a two-lane road at 50 mph while approaching a lane closure. The participants received one of four CDA message conditions or a control condition (no CDA message) during each pass. The study examined driver behavior in four areas: transitioning vehicle control to the driver, driver performance, driver attention, and driver stress. The study also examined participant perspectives of usefulness, satisfaction, and familiarity with the vehicle automation.

Level 2 ADS are capable of both sustained lateral and longitudinal control (SAE 2014). Drivers are responsible for continuously monitoring the environment and disabling the driver assistance system, if needed. The current study found that when approaching a work zone, participants with CDA messages disengaged the ADAS features and resumed vehicle control earlier (i.e., safely took back lateral and longitudinal vehicle control farther from the work zone) than participants without CDA messages. For participants receiving CDA messages, drivers with long lead times and detailed messages disengaged the earliest, and drivers with long lead time and basic messages disabled the ADAS the latest. Participants with short lead times took on average about 8 s after notification to disable ADAS. This is consistent with the findings of Melcher et al. (2015) and supports the viability of a 10-s minimum takeover request lead time.

In terms of driver performance, participants receiving CDA messages changed lanes earlier than drivers without CDA messages; thus, the participants safely moved out of the closing work zone lane sooner. Further, participants receiving the detailed CDA messages tended to merge earlier than those receiving the basic CDA messages. Participants receiving the long lead time and detailed messages merged into the open lane the earliest.

Participants were asked to try and maintain the posted vehicle speed through the work zone, and the results showed that the CDA message conditions had negligible impact on the participants' ability to maintain vehicle speeds after they disengaged the ADAS features.

Generally, CDA messages had minimal effects on driver attention with participants glancing at the in-vehicle message display slightly longer when CDA messages were displayed compared to when no message was presented. However, younger male and female participants tended to spend slightly more time (attention) on the detailed messages compared to when basic or no messages were displayed. Older female participants were also found to spend more time on the detailed messages when compared to when no message was displayed. For older male participants, no difference was found in glance times between any of the message conditions. Like other studies (e.g., Eriksson and Stanton 2017; Bourrelly et al. 2019), the differences between the various participant groups require additional research to better understand the nuances.

Although CDA messages appeared to result in participants having slightly different work zone sign viewing behavior, the messages most likely increased work zone safety for participants who received CDA messages. On average, participants with CDA messages tended to look at the first work zone sign about the same distance as participants without the messages but moved out of the closing work zone lane sooner. So, although participants with CDA messages tended to spend slightly less time gazing at the work zone signs, they seemed to have less of a need to glance at the signs because the vehicle was already in the open lane. However, in two instances, short lead time messages tended to increase the amount of time younger and older participants viewed the first work zone signs. Younger participants who received the basic message with a short lead time and older participants who received the detailed message with a short-lead time spent slightly more time on the first work zone sign compared to when there was no CDA message.

For driver stress, the findings from the heart rate and EDA analyses indicated no significant differences as a function of lead time or message type while approaching the work zone. In addition, a majority of participants had generally positive attitudes regardless of the types of messages they received. In terms of participant perspectives of usefulness, satisfaction, and familiarity with the vehicle automation, attitude ratings using the Van der Laan questionnaire showed that the majority of participants reported a positive attitude regardless of the CDA messages they received (Van der Laan, Heino, and De Waard 1997). Most participants viewed the system as useful, more nice than annoying, more likeable than irritating, mostly raising awareness than sleep inducing, mostly effective than superfluous, more desirable than undesirable, more assisting than worthless, more good than bad, and more pleasant than unpleasant.

Overall, this work zone infrastructure study supports TSMO work zone safety strategies through the use of CDA messages to increase the safety of Level 2 ADAS vehicles (SAE 2014). This study found that CDA messages expedited transition from automated vehicle control back to the human driver in advance of a work zone. Participants who received CDA messages disengaged the ADAS features and resumed vehicle control earlier (and farther from the work zone) than participants who did not receive CDA messages. The study also found that participants who received CDA messages tended to merge into the open lane sooner (i.e., moved out of the closing lane sooner) with minimal effect on driver attention in terms of glancing at the in-vehicle display. The findings also indicated that driver stress and the participants' positive attitudes were not negatively affected by the use of CDA messages. Nevertheless, the findings suggest that additional research may help further understand the reasons why detailed CDA messages tended to have a greater impact (on some drivers and not others) when disengaging ADAS features, merging into the open lane, and attention to the in-vehicle display.

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The original maps shown in figure 2, and figure 5–7 are the copyright property of Google® Earth and can be accessed from https://www.google.com/earth (Google 2023). Figure 2 was modified to include star icons and text representing the secure gate access points to the test area. Arrows and text were also added to show the direction of travel and paths leading to runway 35L and 35C. In figure 5 and figure 6, pin icons and text were added to indicate the approximate location of the entry point, notification points, sign locations, work zone merging taper, and U-turn point at the end. Figure 7 was modified to add arrows and text to identify the entry and exit points for the practice route.

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