Comparing Merging Behaviors of Drivers with Vehicles Equipped with Level 3 Automation and Connected Messaging when Merging in a Mixed Vehicle Fleet Environment of Various Traffic Densities

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FOREWORD

Advances in vehicle automation technology are anticipated to change the transportation landscape. While automated driving systems (ADSs), i.e., driving systems capable of performing the driving task, have received much public attention, cooperative driving automation (CDA) technology provides a means for ADS-equipped vehicles and roadway infrastructure to communicate safety messages, especially as it pertains to transportation safety management and operations. However, how occupants respond to driver alerts that are prompted by CDA messaging during basic travel maneuvers, such as merging, is currently unknown.

This report documents a driving simulator experiment that explores drivers' behaviors in response to merging in a mixed fleet environment of ADS equipped vehicles that include CDA messaging and non-CDA messaging. This report may be of interest to transportation engineers and researchers, in addition to personnel at State and local transportation agencies, who want to better understand the potential safety benefits of CDA technology.

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As the number of vehicles equipped with automated driving systems (ADS) that are using cooperative driving automation (CDA) technology to communicate safety messages are anticipated to increase in the future, maintaining the safety and efficient operation of roadways is important. ADS-equipped vehicles and CDA technology need to operate smoothly and safely with other vehicles under all typical driving scenarios, especially scenarios that are common but high risk, such as lane changes and merging. Merging onto highways from onramp locations is a safety-critical scenario that has the potential to create traffic bottlenecks. The current study used a driving simulator to assess the potential of ADS and CDA technology to increase the safety and efficiency of onramp merge scenarios. The research team manipulated automation levels and communication between vehicles, in addition to platoon size. The researchers measured driver gap acceptance, braking, and trust in the ADSs and CDA systems. The results of this study show some evidence that when merging, some driver safety behaviors may be influenced by the use of L3 automation and by communication between vehicles, especially when merging with increased platoon sizes. However, subjective measures indicated that participants may have been unclear about what features were active while in the simulation, and some incongruity occurred between the participants' expectations and how the vehicle behaved. The results of this research can be used to provide insights into how willing drivers may be to accept this kind of technology and what their level of comfort could be with using these new technologies.</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
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mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
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m^3	cubic meters	1.307	cubic yards	yd^3
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kg	kilograms	2.202	pounds	lb
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°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
FHWA	Federal Highway Administration
HDS	highway driving simulator
LL	lower limit
ODD	operational design domain
OR	odds ratio
SE	standard error
SSQ	simulator sickness questionnaire
UL	upper limit
V2I	vehicle-to-infrastructure
V2V	vehicle-to-vehicle

CHAPTER 1. INTRODUCTION

The concept of "basic travel" in transportation system management and operations refers to the recurring activities that transportation agencies, especially traffic management centers, routinely perform during normal operations when no incidents, events, or other anomalies occur (Nallamothu et al., 2019a). Lane changes and merges are some of the most demanding and dangerous driving tasks that occur during basic travel and are a source of traffic congestion (Zu & Tasic, 2021; Hu et al., 2020; Liu et al., 2019; Olia et al., 2018; Fitch et al., 2009). Crashes due to improper lane changes and merge maneuvers account for roughly 240,000 to 610,000 police-reported crashes annually (Fitch et al., 2009). Errors of human recognition and decisionmaking are typically the causal factors of these types of crashes (Stanton & Salmon, 2009; Treat et al., 1979). Identifying interventions to improve merging and lane changing is therefore an important part of improving safety and operations on highways.

AUTOMATION

The six SAE International Levels® for vehicle automation include Levels 0–2™ for driver assistance and Levels 3–5™ for automated driving features (SAE International, 2014). Vehicles with no automation capabilities are Level 0. Level 1 vehicles can maintain longitudinal or lateral control of the vehicle. Automated lane keeping is an example of lateral control, and adaptive cruise control is an example of longitudinal control. Level 2 vehicles are capable of maintaining lateral and longitudinal control simultaneously; however, the drivers of Level 2 vehicles still need to complete the majority of the driving tasks.

Merging and lane changing are actions that are outside of the capabilities of Level 1 and Level 2 automation. A minimum of Level 3 automation is needed for a vehicle to perform these complex driving maneuvers. Vehicles equipped with Level 3 automation can perform all vehicle operations within a predetermined set of conditions, geographical areas, and road parameters, also known as the system's operational design domain (ODD). One of the requirements for an automated driving system (ADS) to be considered as Level 3 automation is for the system to be able to evaluate whether a particular situation falls within its ODD. Whenever the system detects that a situation falls outside of its ODD, the vehicle alerts the driver to take over the control of the vehicle.

Little research has been done on the effects of ADS technology on the safety risk of merge locations, such as onramps, primarily due to the difficulty of automating lateral control (Bevly, 2016). According to Zhu and Tasic (2021), many studies have been conducted to evaluate the effect of ADS technology on safety at various types of traffic bottlenecks, including intersections, roundabouts, freeway corridors, etc., but minimal studies have examined freeway and highway onramp merging areas. Research on ADS technology and onramp merging areas has primarily focused on operational efficiency, not safety. Ahu and Tasic (2021) ran roughly 250,000 simulated merging scenarios and found that roughly 90 percent (1,385 out of 1,549) of near crashes that occurred during those scenarios were between normal vehicles. Only 163 were between at least one normal vehicle and an ADS-equipped vehicle, and only one near-crash occurred between two ADS-equipped vehicles. These scenarios were completed under the assumption that the ADS being used were capable of Level 4 automation. However, the primary difference between Level 3 and Level 4 automation is that Level 4 automation is capable of returning the vehicle to a safe stopped state if a takeover needs to occur and the operator is unable or unwilling to take over the control of the vehicle when requested. Therefore, Level 3 ADS-equipped vehicles would be expected to have a similar effect on the rate of near crashes at merge areas. Furthermore, studies show that ADSs have the potential to perform merging maneuvers without the need for intervehicle communication. Wang et al. (2015) developed a mathematical control framework to evaluate lane-change decisions and accelerations for ADSs. By predicting the response of human-driven conventional vehicles and using the information from onboard sensors, noncooperative ADS vehicles were able to perform merging maneuvers more efficiently and with less risk than human drivers operating conventional vehicles.

On the other hand, ADS-equipped vehicles are able to respond to a merge scenario when they are able to clearly sense the presence of other vehicles on the roadway. Therefore, if a Level 3 ADS-equipped vehicle is unable to sense the presence of other vehicles before it needs to execute a merge maneuver, then the ADS vehicle may need to brake unexpectedly or perform a maneuver the operator may not expect or be comfortable with executing. Such a scenario could occur for a number of reasons, including differing elevations just before the onramp or shorter onramps from which the main road is obscured. Additionally, as mixed fleets become more prevalent, ADS-equipped vehicles will have to adjust to ADS-equipped platoons. Navigating around these platoons may be difficult for vehicles that lack cooperative capabilities. To our knowledge, little research has been conducted specifically on the effect of ADS-equipped platoon length on a noncooperative ADS vehicle's ability to merge into a lane with such a platoon. Depending on platoon size and gap distance parameters set by the platoon, a merging ADS-equipped vehicle may need to drastically slow down to merge at the back of the platoon. Additionally, if the operator of the vehicle fails to trust the ADS, they may try to take control of the vehicle and merge into the platoon, negating any benefit from the ADS system. However, if ADS-equipped vehicles are able to communicate with other ADS-equipped vehicles and drivers across greater distances, the safety and efficiency of merging maneuvers would possibly increase and reduce conflicts with larger sized ADS platoons.

Cooperative Driving Automation

The connectivity provided by cooperative driving automation (CDA) allows the vehicle to transmit and receive safety and navigation information from other sources (Yang et al., 2017). ADSs with CDA capabilities are known as cooperative automated driving systems (C-ADSs). CDA and C-ADS vehicles include vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication types. The types of communication that can be shared between cooperative vehicles include basic safety messages such as current vehicle status (i.e., where the vehicle is located and the other objects the vehicle is able to detect are within its immediate vicinity) (Nallamothu et al., 2020b). Typically, human drivers are able to detect other vehicles when they can see or hear them. ADS-equipped vehicles have a similar limitation in that they use sensors to detect other objects on the roadway, and unless the object is detected by the sensors, the ADS cannot perceive its presence. CDA and C-ADS messaging, on the other hand, are capable of communicating around curves and over obstacles, and thus offer greater safety benefits and reduced traffic congestion. Additionally, at higher levels of cooperation, vehicles are able to plan joint maneuvers with other connected vehicles (Nallamothu et al., 2020b). One example of this high-level cooperation is a merge scenario.

Merging requires cooperation from all drivers and systems involved. Precoordinated movements between these entities offer the potential to increase both safety and operations of the road network. For example, when trying to merge under normal conditions without connected vehicles, the driver is responsible for identifying a gap between vehicles and safely maneuvering between oncoming traffic. Locating a gap can be difficult, especially when traffic is heavy, or the onramp is short. A merging vehicle may be forced to reduce speed or stop while waiting for a safe gap. This speed differential between the slow-moving merging vehicle and the faster moving vehicles on the highway could pose a safety risk and lead to a traffic shockwave that reduces highway throughput (Xu et al., 2002).

In comparison, a cooperative vehicle is able to communicate its intent to merge. Existing highway traffic can receive communication about the intent of the merging vehicle, and these vehicles can slow down slightly to create a gap. The merging vehicle can then continue accelerating to speed, preventing the shockwave that could have been present without the speed reduction of the oncoming traffic (Wolterink et al., 2011; Xu et al., 2002). Conversely, with the exchange of information, the merging vehicle could possibly adjust its speed on the ramp and merge into a fleet of vehicles at the optimal point without the fleet slowing down. This process could also prevent traffic shockwaves. In this case, the vehicle on the ramp would adjust its speed and acceleration to either merge in front of or behind the mainline vehicles. Eventually, the vehicle on the ramp would match the speed of the mainline ADS platoon and merge in front of or behind the platoon, as long as the space is sufficient.

CURRENT STUDY

The current study used a driving simulator to assess the effects of CDA alerts on the safety and efficiency of merging scenarios with a fleet of ADS-equipped vehicles. Participant vehicles were either driven manually or equipped with Level 3 automation. Vehicles with Level 3 automation merged automatically with ADS platoons of various sizes.

In addition to manipulating vehicle automation, the research team manipulated the presence of CDA alerts (i.e., half of the participants received communication with the ADS-equipped platoons). Compared with manual driving, the team expected an engaged Level 3 system to be associated with safer and more efficient merging behaviors as measured by driving metrics, such as slower driving speeds, lower speed variability, less acceleration variability, lower steering wheel angle variability, and eye-tracking metrics like greater fixation frequency on the platoon and proportionally more time spent fixated on the platoon. The researchers expected platoon size to moderate this relationship. Specifically, they anticipated that Level 3 systems and CDA alerts would both be more effective interventions on merging behavior as the platoon size increased.

In addition to the aforementioned hypotheses, this study sought to determine the patterns of Level 3 use in relation to trust in the system, demographics, and other factors. For instance, the team expected the group that experienced the Level 3 system and CDA alerts to report the highest general trust in automated driving. They also assessed patterns of automation disengagement. The research team expected that a participant would be more likely to take over the automated system and perform the merge maneuver manually as trust in automation decreased, platoon size increased, or participant age increased.

CHAPTER 2. METHODS

PARTICIPANTS

The research team recruited 96 participants who met the inclusion criteria of holding valid U.S. driver's licenses and having a visual acuity of at least 20/40, based on a Bailey-Lovie eye chart (Bailey & Lovie, 1976), from the Washington, DC, metropolitan area. The researchers recruited approximately equal numbers of males and females over and under the age of 46 yr. The team compensated the participants for their time at a rate of $40 per hour.

EXPERIMENTAL DESIGN

The study used a two (vehicle automation: conventional vehicle, Level 3 ADS vehicle) by two (platoon connectivity: no CDA alerts, CDA alerts present) by four (ADS vehicle platoon size: one, three, five, seven vehicles) mixed factors design. Table 1 shows the experimental matrix for the design.

Table 1. Experimental design.

Vehicle Automation	Platoon Connectivity	Autonomous Fleet Size
Conventional	No CDA alerts	One-, three-, five-, and seven-vehicle platoons
	CDA alerts	One-, three-, five-, and seven-vehicle platoons
Level 3	No CDA alerts	One-, three-, five-, and seven-vehicle platoons
	CDA alerts	One-, three-, five-, and seven-vehicle platoons

The research team manipulated the level of automation between subjects such that half of the participants drove a conventional vehicle and the other half drove a vehicle equipped with a Level 3 ADS. The Level 3 ADS was capable of lane centering, adaptive cruise control, and automated lane changes.

The researchers also manipulated the platoon connectivity between subjects. Half of the participants experienced C-ADS-equipped platoons while merging such that participants would receive a CDA alert while preparing to reenter the highway on the ramp. The message presented as part of the CDA alert included the number of vehicles in the platoon and advised the drivers to decelerate their vehicles to merge at the back of the platoon. The other half of the participants did not receive an alert from the platoons.

Finally, the team manipulated the platoon size within subjects whereby each participant experienced four merge events, one for each platoon size. The platoons included one, three, five, or seven vehicles along the main highway, with a gap distance of 0.7 s. The researchers counterbalanced the order in which participants were exposed to the different sized platoons between subjects based on a balanced Latin square (Wallis & George, 2011, p. 212) to control for ordering effects. See figure 1 for an example of a V2V CDA alert informing a driver about an approaching three-vehicle platoon.

Source: FHWA.

Figure 1. Photo. Text displayed on the instrument cluster by a V2V CDA alert indicating a three-vehicle platoon is approaching.

APPARATUS AND MATERIALS

Apparatus

The study was conducted in the Federal Highway Administration (FHWA) Highway Driving Simulator (HDS) at the Turner-Fairbank Highway Research Center. The HDS consists of a full automobile chassis surrounded by a semicircular projection screen (radius of 8.5 ft, or 2.6 m). Seven high-definition projectors render a seamless 220° field of view for the motorist that depicts high-fidelity, computer-generated roadway scenes. The researchers used three liquid-crystal display panels to simulate the vehicle's rearview and side-view 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, and tire noises, along with other environmental sounds.

Training Materials

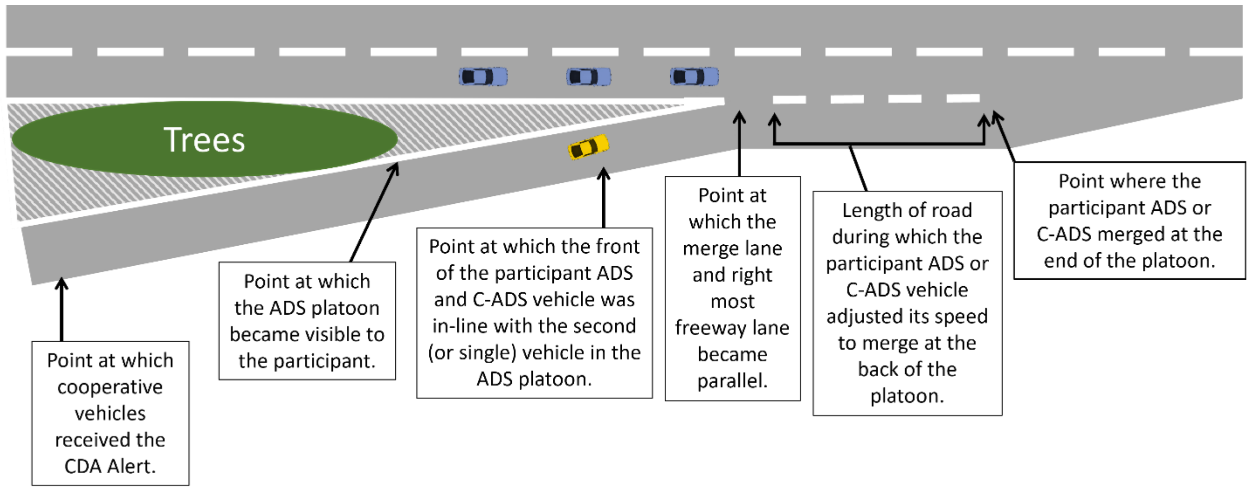
The research team prepared four separate training presentation deck slides for this study. The team used the slides to explain the vehicle technologies and features associated with Level 3 automation and CDA alerts. Specifically, they used the four sets of slides to familiarize the participants with vehicles equipped with Level 3 combined with CDA alerts, Level 3 without CDA alerts, no automation combined with CDA alerts, and no automation without CDA alerts. Each set also reminded participants to observe all posted signage, obey the speed limit, interact with other vehicles as they normally would, and take all exits on the right-hand side of the road. In addition, the two sets of slides that had information about Level 3 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 experimental drive consisted of a simulated four-lane divided highway (two lanes in either direction) with a posted speed limit of 55 mi/h (88.5 Km/h). The drive was approximately 20 mi (32.2 km) long and included several locations where the participant would exit and reenter the highway. The section of interest for the current study included a segment of highway that was roughly 16 mi (25.7 km) long and had four locations where the participant would exit and reenter the highway. The participants would drive on the highway for 2 mi (3.2 km) in moderate ambient traffic conditions and then take an exit ramp on the right-hand side of the highway with 40 mi/h (64.3 km/h) reduced speed limit signs. The first merge event started when participants merged back onto the highway via an onramp, where they merged with the presence of an autonomous platoon made up of either one, three, five, or seven vehicles. The participants then drove an additional 2 mi (3.2 km) after the merge event. The participants repeated this process a total of four times to experience each of the platoon sizes. figure 2 shows the process of the merge event, along with the specific behaviors of the participant ADS vehicle and C-ADS platoons.

The research team designed the V2V CDA alert to be delivered while the participants were on the onramp, roughly 328 ft (100 m) prior to the participants being able to see the C-ADS platoon. The message included the platoon size and a suggestion to merge behind the platoon (figure 1). The team designed the merge event so that the participants were able to see the ADS platoon roughly 500 ft (152.4 m) before the point at which the onramp merge lane and right lane of the freeway paralleled.

The researchers designed the Level 3 subject vehicle to follow the posted speed limit of 55 mi/h (88.5 km/h). The blinker was engaged for 2 s before the Level 3 subject vehicle changed lanes. When taking the offramp for each exit, the vehicle gradually reduced its speed to reach 40 mi/h (64.3 km/h) at the end of the exit. Once the vehicle began taking the onramp to reenter the highway, it gradually accelerated to reach 55 mi/h (88.5 km/h), at the point at which the onramp lane and highway became parallel. In the condition of Level 3 without the CDA alert, the vehicle would then slow down until it was able to merge on the highway at the end of the dotted white lines separating the right-most lane of the highway and the onramp lane. In the Level 3 with CDA alert condition, the subject vehicle would begin to adjust its speed after receiving the message to successfully merge after the passing of the platoon at the end of the dotted white line before the merge lane taper. The change in speed for this condition would vary depending on the platoon size, and the participant's Level 3 vehicle with CDA alert would only reach 55 mi/h (88.5 km/h) at the designated merge point, thus creating a more gradual adjustment of speed compared with the Level 3 without CDA alert scenario.



Source: FHWA.

Figure 2. Illustration. Roadway diagram showing merge onramp and points at which Level 3 automated vehicle speed changes and the merge point of the Level 3 vehicle.

Prior to the experimental drive, 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, and 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 the 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; sex; years of driving experience; vehicle type (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. Additionally, the team used a questionnaire to determine the participants' level of trust in automation (Appendix A). The researchers asked the participants to rate their agreement on statements related to ADSs on a scale of 1 to 5, where 1 meant "not at all true" and 5 meant "extremely true." The team gave 10 statements to the participants, and four of the statements had negative coding. The researchers reversed the scaling of these four items during the analysis.

In the third part of the postdrive questionnaire, the research team asked about the participants' experience driving through the scenarios in the simulator. The researchers asked the participants to answer "yes" or "no" questions and to further explain their answer if they answered "no." These questions are in Appendix B.

PROCEDURES

The research team asked the participants to review and sign an informed consent document when they arrived at the research center. Next, the experimenters asked the participants to verify their age and licensure by showing their driver's licenses. The experimenters also 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.

The researchers provided the participants with study instructions as well as information about ADS and C-ADS-equipped vehicles. The participants who were assigned to each condition reviewed a presentation that contained information needed for the particular condition. Once they understood the instructions, the participants responded to the simulator sickness questionnaire (SSQ) to provide a symptoms baseline (Kennedy et al., 1993).

Following this step, the experimenters provided an orientation to the simulation system (e.g., the turn signals, hard brake, how to engage or disengage the ADS). The experimenter asked the participants to complete a brief practice drive to become familiar with the simulator. During the practice drive, the researchers asked the participants to accelerate, brake, and change lanes. The participants who were assigned to the Level 3 conditions would also practice engaging, monitoring, and disengaging the ADS. After completing the practice drive, the participants would exit the simulator and complete the SSQ a second time to screen for any simulator sickness symptoms before beginning the experimental drive.

Once the participants sat back in the simulator, the research team provided further instructions about the upcoming driving task. The team told the backstory about going to a doctor's appointment. During the experimental drive, the participants would drive on a simulated four-lane divided (two lanes in either direction) highway with a posted speed limit of 55 mi/h (88.5 km/h). The researchers instructed the participants to drive as they normally would and to take each right exit before merging back onto the highway.

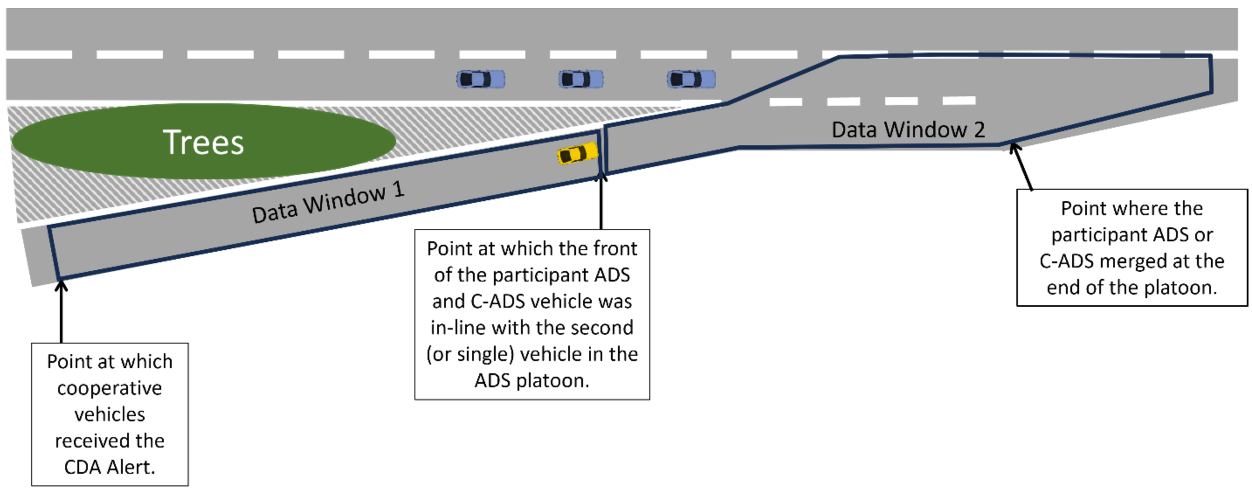
The research team told the participants in the CDA alert conditions that the C-ADS-equipped platoons were outfitted with V2V technology, and as such, the platoons would communicate with each participant's vehicle. The team explained that these communications would be relayed to the participant via an in-vehicle messaging system. The message alerted the participants about the size of the platoon and suggested that the drivers maintain a speed that would allow them to merge at the end of the platoon.

The experimenters told the participants in the Level 3 ADS-equipped vehicle to use the automated functionality of the vehicle. The team asked the participants to monitor the ADS and told them that they could take over control of the vehicle at any time. The team asked the participants in the conventional vehicle conditions to control the vehicle manually and exit and merge onto highways safely. After finishing the experimental drive, the participants completed the SSQ a final time to monitor for symptoms of simulator sickness. The participants later completed a postdrive questionnaire, and the experimenters thanked them and compensated them for their time.

ANALYTIC PLANS

Data Windows

The present study focused on two specific segments of the roadway. The first data window is defined as the point at which a CDA alert was received (or would have been received), to the point at which the vehicle would be in line with the second vehicle in the platoon (or only vehicle in the one vehicle platoon condition). The first data window captured driver behavior on the onramp. The second data window is defined as the point after window 1 ended and when the driver's vehicle merged onto the highway. Figure 3 shows the data windows.



Source: FHWA.

Figure 3. Illustration. Roadway diagram showing data collection windows.

Simulator Data

The research team analyzed several dependent variables from the simulator with logistic regression models or linear mixed-effects models.

Eye-Tracking Data

The researchers analyzed the total eye fixation duration and frequency for three different regions of interest. The regions of interest included the automated platoons that the participants merged into or behind; the instrument cluster; and the left mirror; which was potentially used to observe the platoon, depending on the platoon's size.

Questionnaire Data

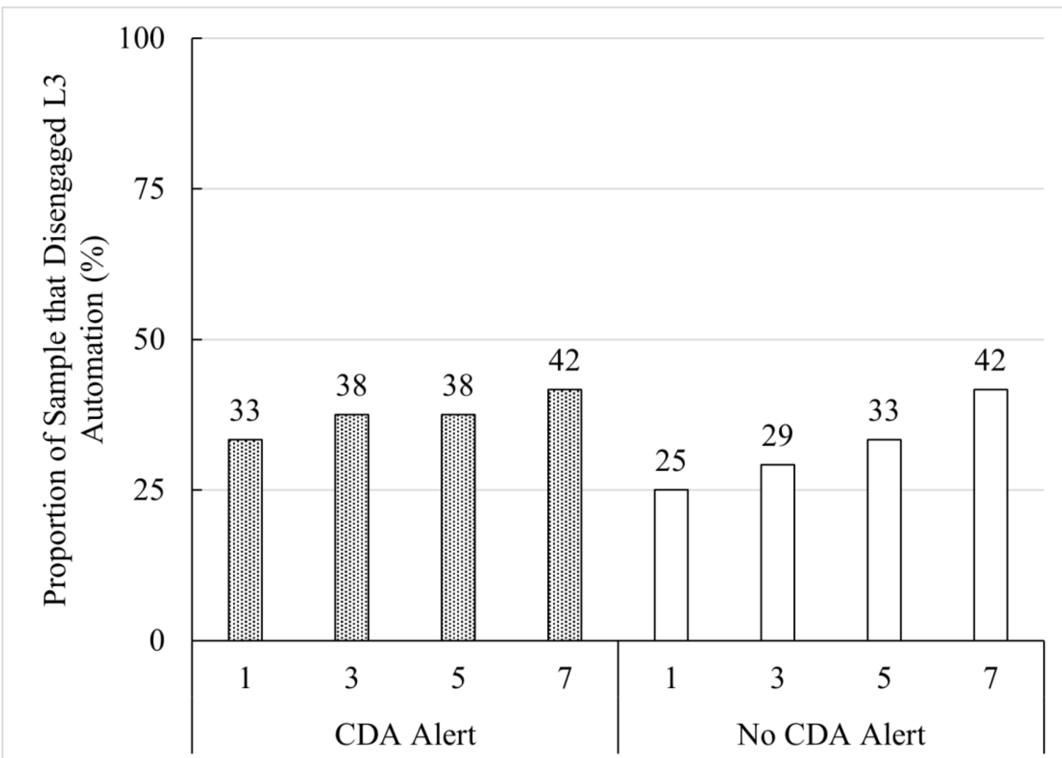
The team used a two-sample *t*-test to analyze the trust scores generated after the scenario. Additionally, the research team asked the participants to provide subjective feedback based on the condition they experienced. The researchers reviewed these subjective responses and used them to provide context to the participants' state of mind after driving through the scenario.

CHAPTER 3. RESULTS

DRIVING DATA

Patterns of Automation Use

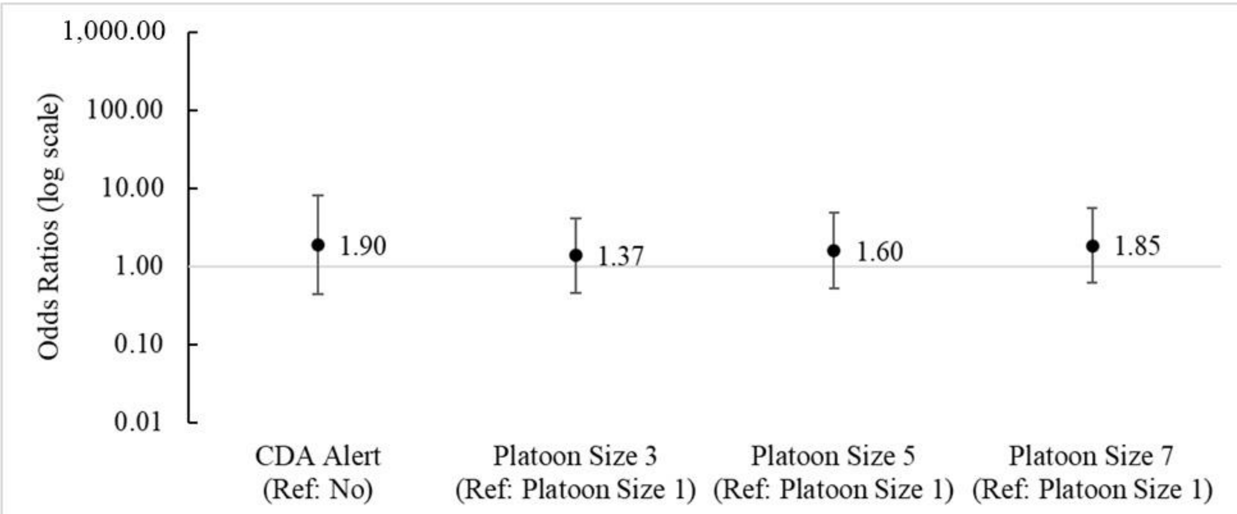
Forty-eight participants drove a simulated vehicle equipped with Level 3 functionality. Each participant experienced four merging events with different platoon-size configurations. In total, 192 merging events occurred where a manual takeover could have taken place. Overall, the research team only observed 65 manual takeovers during data windows 1 and 2 (33.85 percent of the 192 merge events). When the team broke down the events by platoon size and by whether each participant received the CDA alert, the drivers without the CDA alert and those participants who experienced a one-vehicle platoon had the lowest proportion of manual takeovers ($n = 6$; 25.00 percent). In comparison, the drivers who had CDA alert demonstrated the largest number of manual takeovers when experiencing a seven-vehicle platoon (figure 4).



Source: FHWA.

Figure 4. Graph. Proportion of participants who disengaged the Level 3 system during the merge window by the platoon size and presence of CDA alert.

The research team conducted a logistic regression to determine whether CDA alerts, platoon size, age, or sex influenced the likelihood of a manual takeover occurring. However, none of these factors were statistically significant predictors of manual takeover events (figure 5).



Source: FHWA.
Ref = reference.

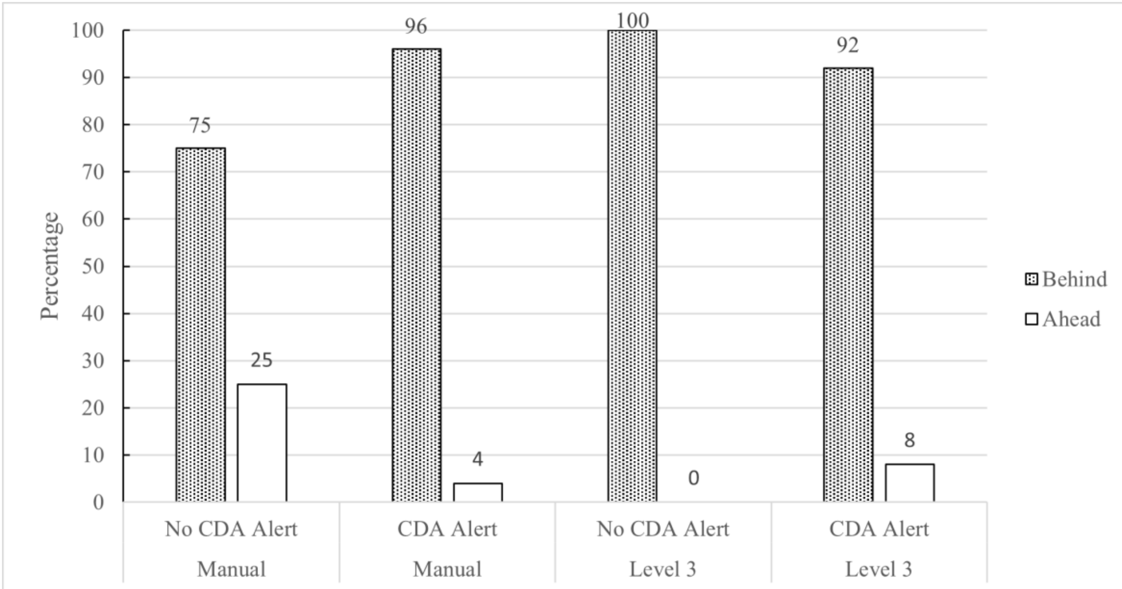
Figure 5. Graph. Odds ratios (ORs) with 95-percent confidence interval (CI) (adjusted for age and sex) from the logistic regression predicting whether a manual takeover event occurred.

Merge Location in Relation to the Platoon

The researchers investigated where the merge occurred in relation to the vehicle platoon. The areas of interest were behind the platoon, in between platoon vehicles, and ahead of the platoon. The team separated the analyses for the platoon size of one because in this condition, being between platoon vehicles would be impossible.

Platoon Size of One

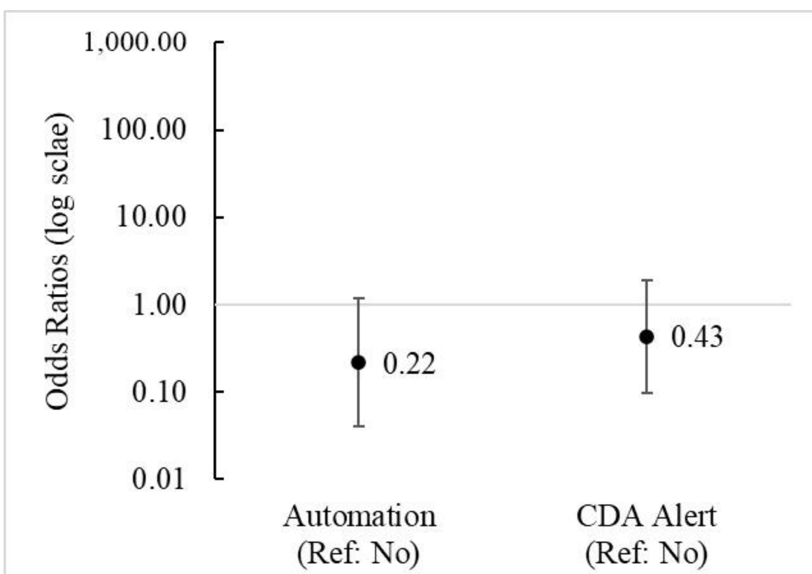
The participants predominantly merged behind the single platoon vehicle compared with merging ahead of the platoon vehicle, 90.7 percent versus 9.3 percent, respectively. Figure 6 shows the percentage of participants in each condition who merged behind or ahead of a single ADS-equipped vehicle.



Source: FHWA.

Figure 6. Graph. Percentage of sample who merged behind or ahead of the single vehicle platoon.

The logistic regression results indicated that neither the presence of Level 3 automation (OR = 0.22, 95-percent CI [0.04, 1.18]) or the presence of CDA alerts (OR = 0.43, 95-percent CI [0.10, 1.91]) were predicative of a participant merging behind the single-vehicle platoon (figure 7).

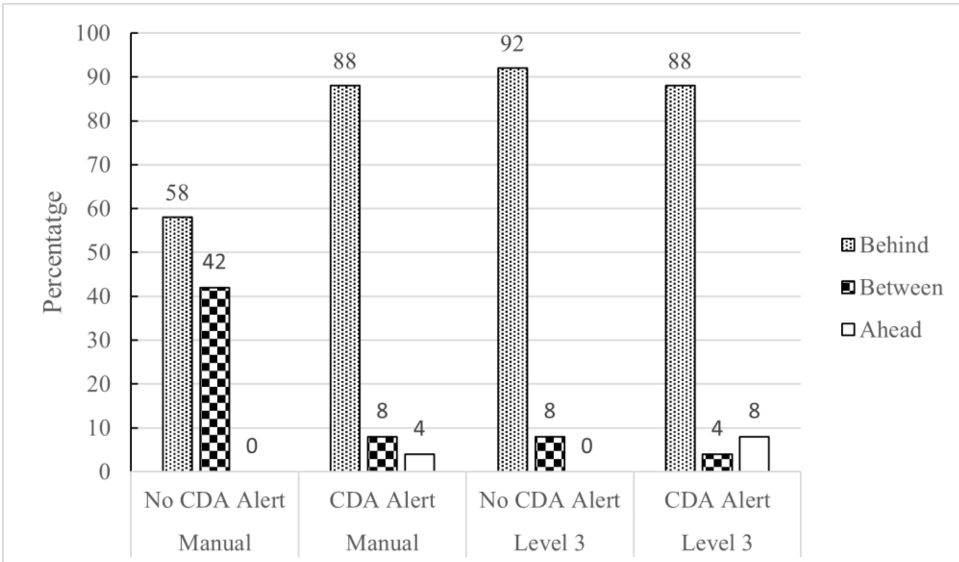


Source: FHWA.

Figure 7. Graph. ORs with 95-percent CI (adjusted for age and sex) from the logistic regression predicting the likelihood a merge occurred ahead of the single-vehicle platoon compared with behind the platoon vehicle.

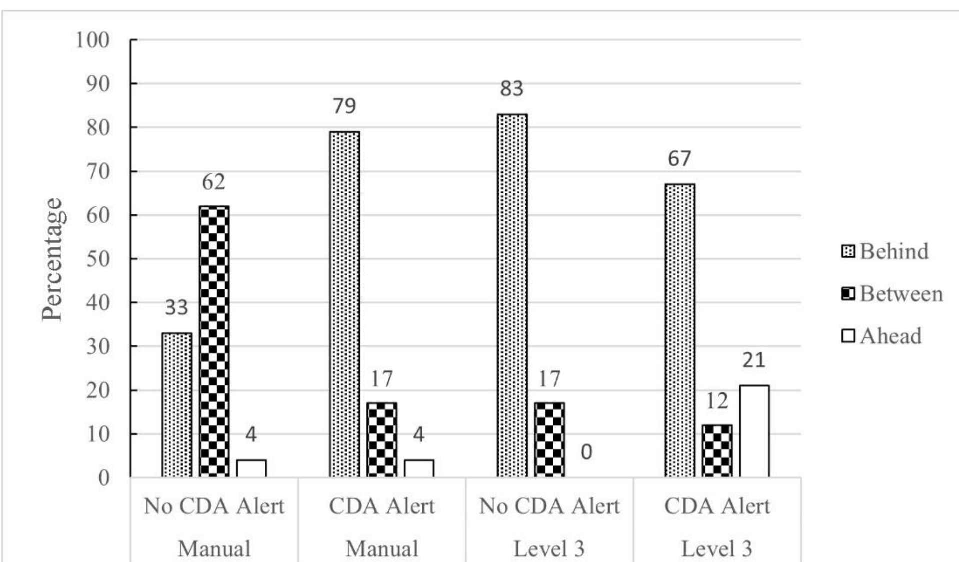
Platoon Size of Three, Five, and Seven Vehicles

The participants predominantly merged behind the multivehicle platoons (59.3 percent), followed by merging in the middle of the platoon (32.3 percent) and, lastly, merging ahead of the platoon (8.3 percent). Figure 8, figure 9, and figure 10 show the percentages of participants in each condition who merged behind, between, or ahead of the three-, five-, or seven-vehicle platoons, respectively.



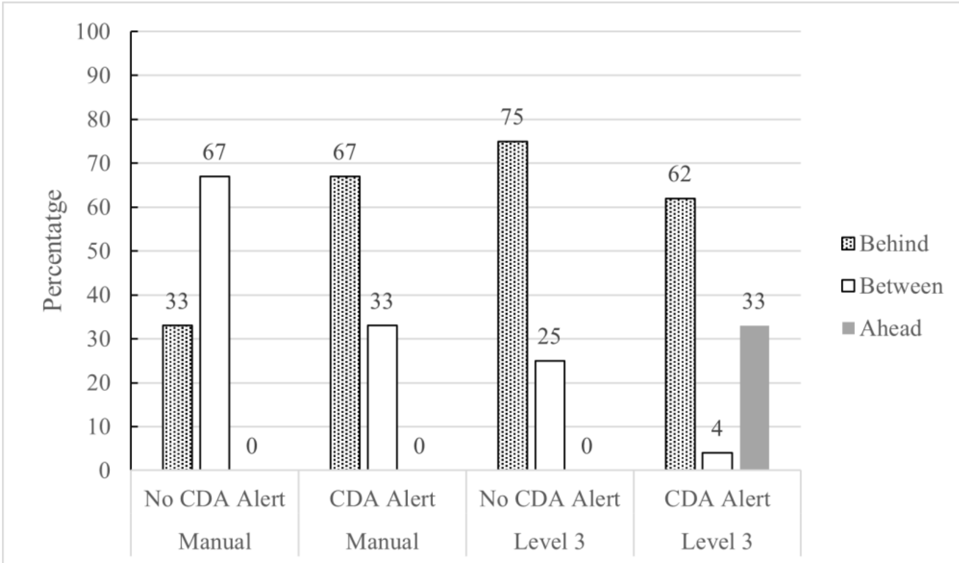
Source: FHWA.

Figure 8. Graph. Percentage of sample who merged behind, between, or ahead of the three-vehicle platoon.



Source: FHWA.

Figure 9. Graph. Percentage of sample who merged behind, between, or ahead of the five-vehicle platoon.



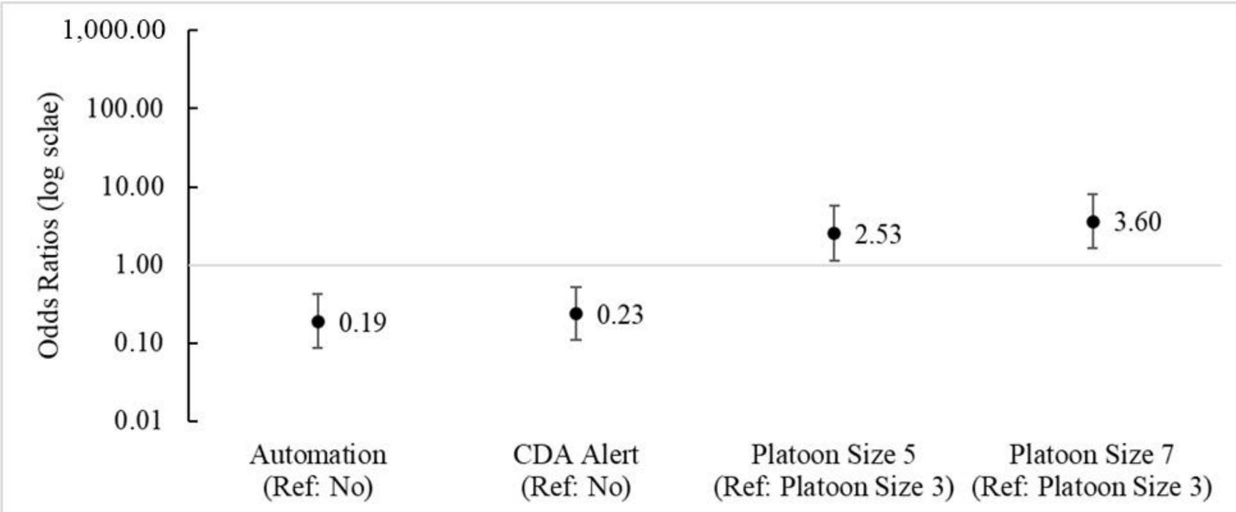
Source: FHWA.

Figure 10. Graph. Percentage of sample who merged behind, between, or ahead of the seven-vehicle platoon.

The research team conducted a multinomial logistic regression to determine the likelihood of merging in behind the platoon compared with the middle of the platoon and the likelihood of merging behind the platoon compared with ahead of the platoon.

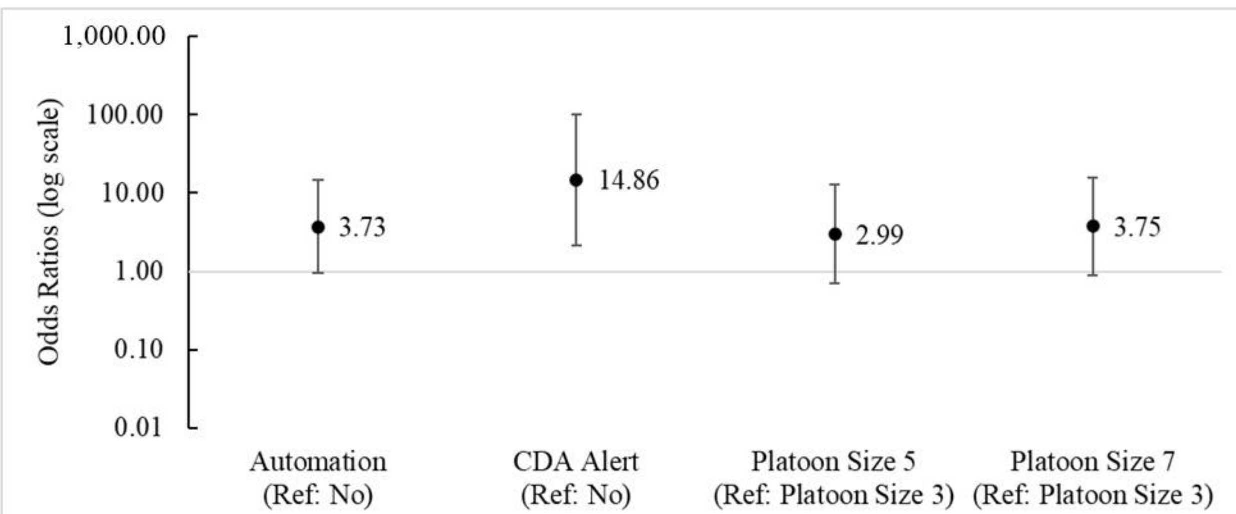
The findings shown in figure 11 indicate the likelihood a merge occurring in the middle of the multivehicle platoon decreases with the presence of both Level 3 automation (OR= 0.19, 95-percent CI [0.09, 0.42]) and CDA alerts (OR = 0.23, 95-percent CI [0.11, 0.51]) relative to merging behind the multivehicle platoons. However, the likelihood of merging in the middle of a multivehicle platoon increases with the platoon size. Compared with the three-vehicle platoon, the participants were more likely to merge into the middle of the fleet in the five-vehicle platoon (OR = 2.53, 95-percent CI [1.13, 5.69]) and the seven-vehicle platoon (OR = 3.60, 95-percent CI [1.61, 8.02]).

Figure 12 shows the researchers did not observe the same pattern when they compared the likelihood of merging ahead of the multivehicle platoon relative to merging behind the platoon. The presence of CDA alerts increased the likelihood of merging ahead of the multivehicle platoon relative to merging behind the platoon (OR = 14.86, 95-percent CI [2.17, 101.68]). Neither the presence of Level 3 automation (OR = 3.73, 95-percent CI [0.94, 14.84]); nor a platoon size of five (OR = 2.99, 95-percent CI [0.70, 12.80]); nor a platoon size of seven (OR = 3.75, 95-percent CI [0.89, 15.73]) were predicative of a participant merging ahead of the multivehicle platoon relative to merging behind the platoon.



Source: FHWA.

Figure 11. Graph. ORs with 95-percent CI (adjusted for age and sex) from the multinomial logistic regression predicting the likelihood of a merge in the middle of the platoon compared with behind the platoon.

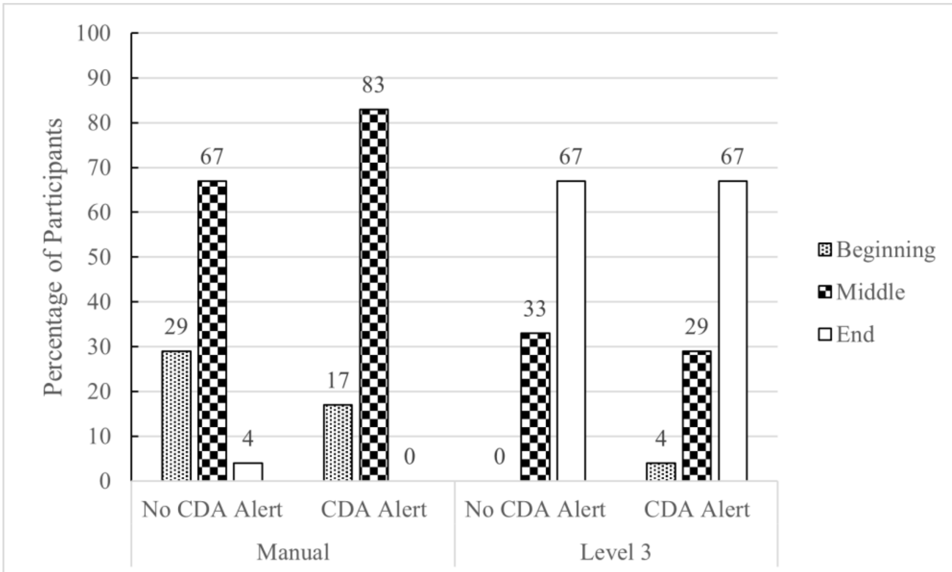


Source: FHWA.

Figure 12. Graph. ORs with 95-percent CI (adjusted for age and sex) from the multinomial logistic regression predicting the likelihood of a merge ahead of the platoon compared with behind the platoon.

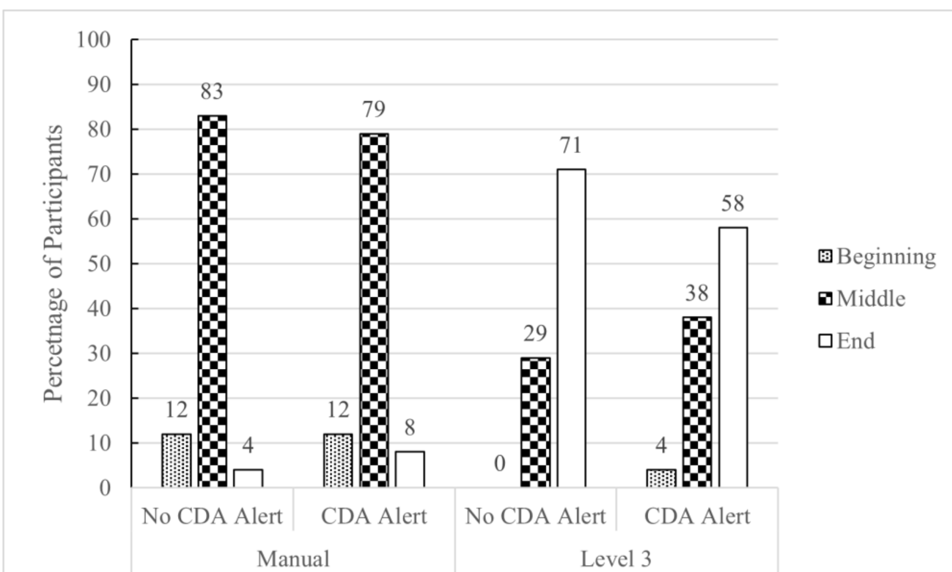
Merge Location in Relation to Roadway Location

The research team examined the merge location in relation to the location when the merging lane became parallel to the right-most highway lane, as shown in figure 2. The team segmented this roadway section in the following manner: start of the roadway to 262.5 ft (80 m) (beginning), between 262.5 ft and 524.9 ft (80 m and 160 m) (middle), and from 524.9 ft (160 m) onward (end). On average and across platoon size conditions, the participants tended to merge in the middle segment (53.63 percent) followed by the beginning segment (38.50 percent) and the end segment (7.69 percent). Figure 13, figure 14, figure 15, and figure 16 show the percentages of participants within each group who merged at the beginning, middle, or end of the merge lane for the one-, three-, five- or seven-vehicle platoons, respectively.



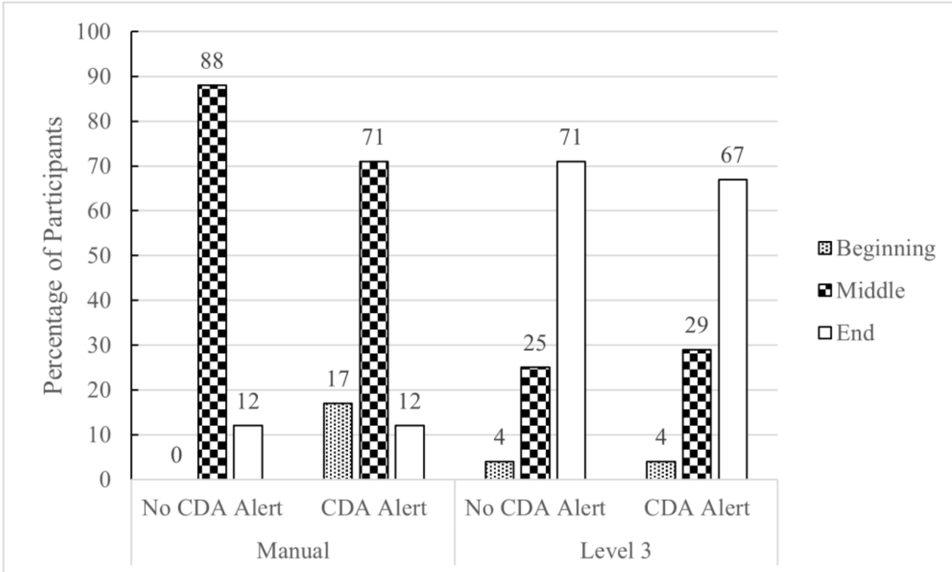
Source: FHWA.

Figure 13. Graph. Percentage of sample who merged at the beginning, middle, or end of the merge lane when merging with the one-vehicle platoon.



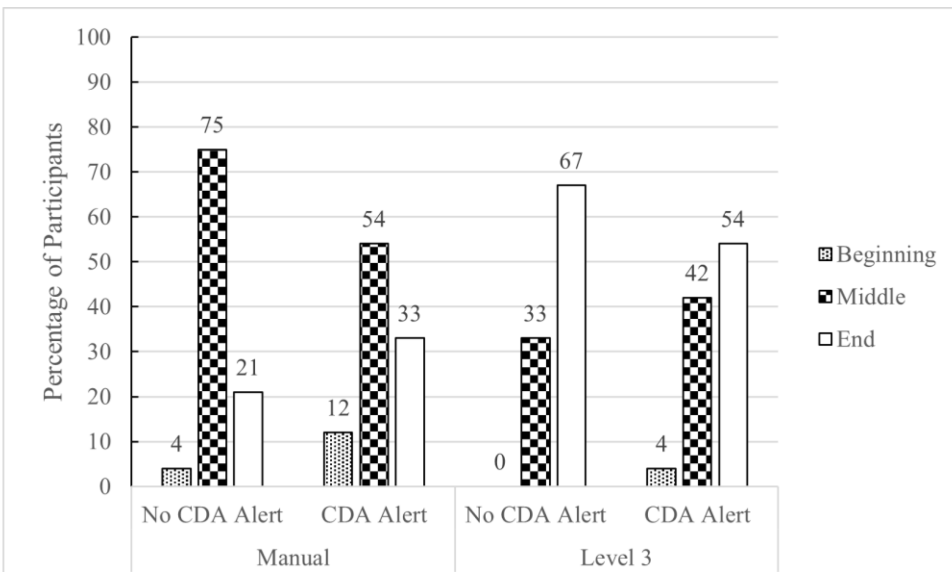
Source: FHWA.

Figure 14. Graph. Percentage of sample who merged at the beginning, middle, or end of the merge lane when merging with the three-vehicle platoon.



Source: FHWA.

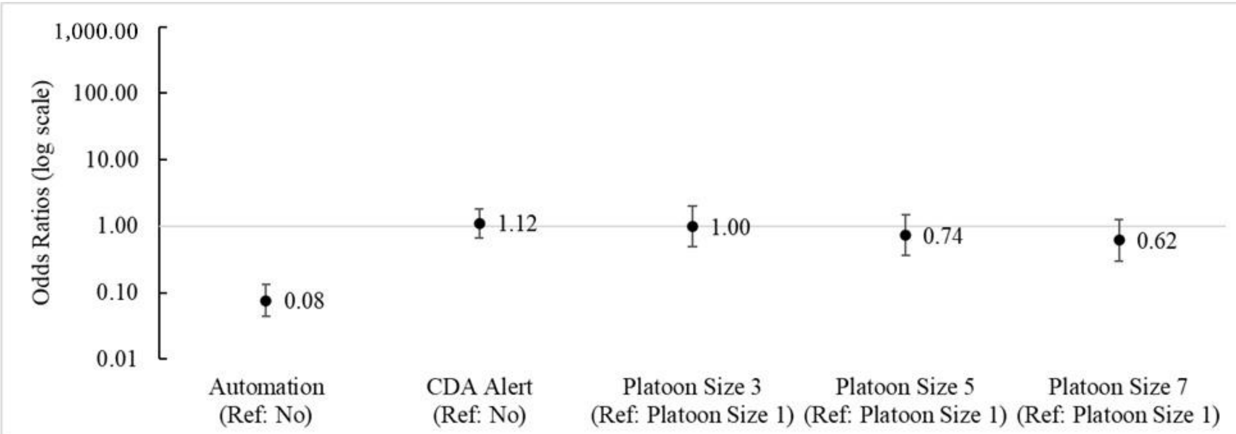
Figure 15. Graph. Percentage of sample who merged at the beginning, middle, or end of the merge lane when merging with the five-vehicle platoon.



Source: FHWA.

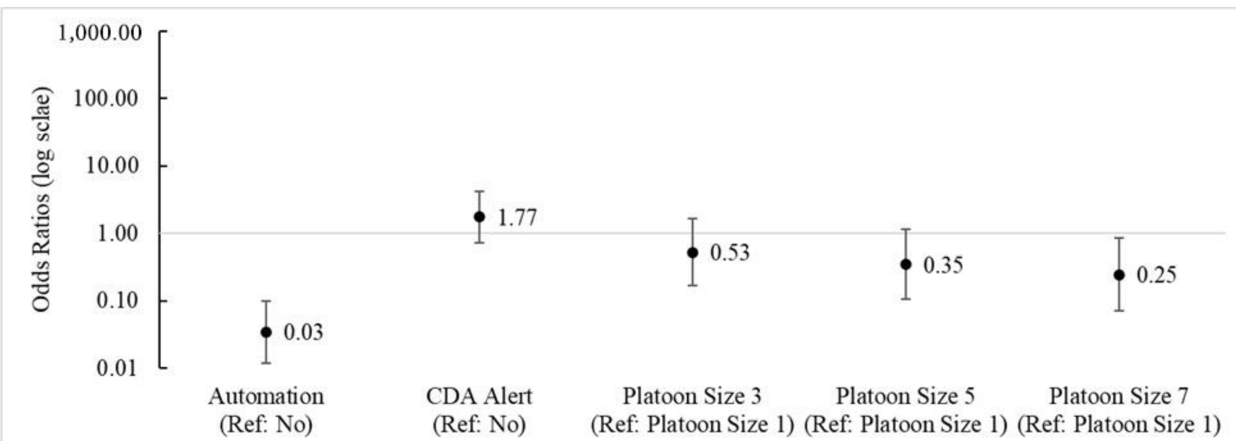
Figure 16. Graph. Percentage of sample who merged at the beginning, middle, or end of the merge lane when merging with the seven-vehicle platoon.

The research team conducted a multinomial logistic regression to assess the effects of automation, CDA alerts, platoon size, age, and sex on the roadway location of the merge event. Because the team designed the Level 3 automation system in the present study to merge toward the end of the roadway segment, they found that the Level 3 system reduced the likelihood of merging in the middle segment (OR = 0.08, 95-percent CI [0.03, 0.06]) and the beginning segment (OR = 0.03, 95-percent CI [0.02, 0.07]) relative to merging at the end (figure 17 and figure 18). The researchers did not observe any significant effects of the CDA alert on the chosen location of merging, although the drivers were less likely to merge in the beginning roadway segment relative to the end segment during the seven-vehicle platoon condition (OR = 0.25, 95-percent CI [0.18, 0.61]). Otherwise, the team observed no other effects.



Source: FHWA.

Figure 17. Graph. ORs with 95-percent CI (adjusted for age and sex) from the multinomial logistic regression predicting whether a merge occurred in the middle roadway segment compared with the end roadway segment.



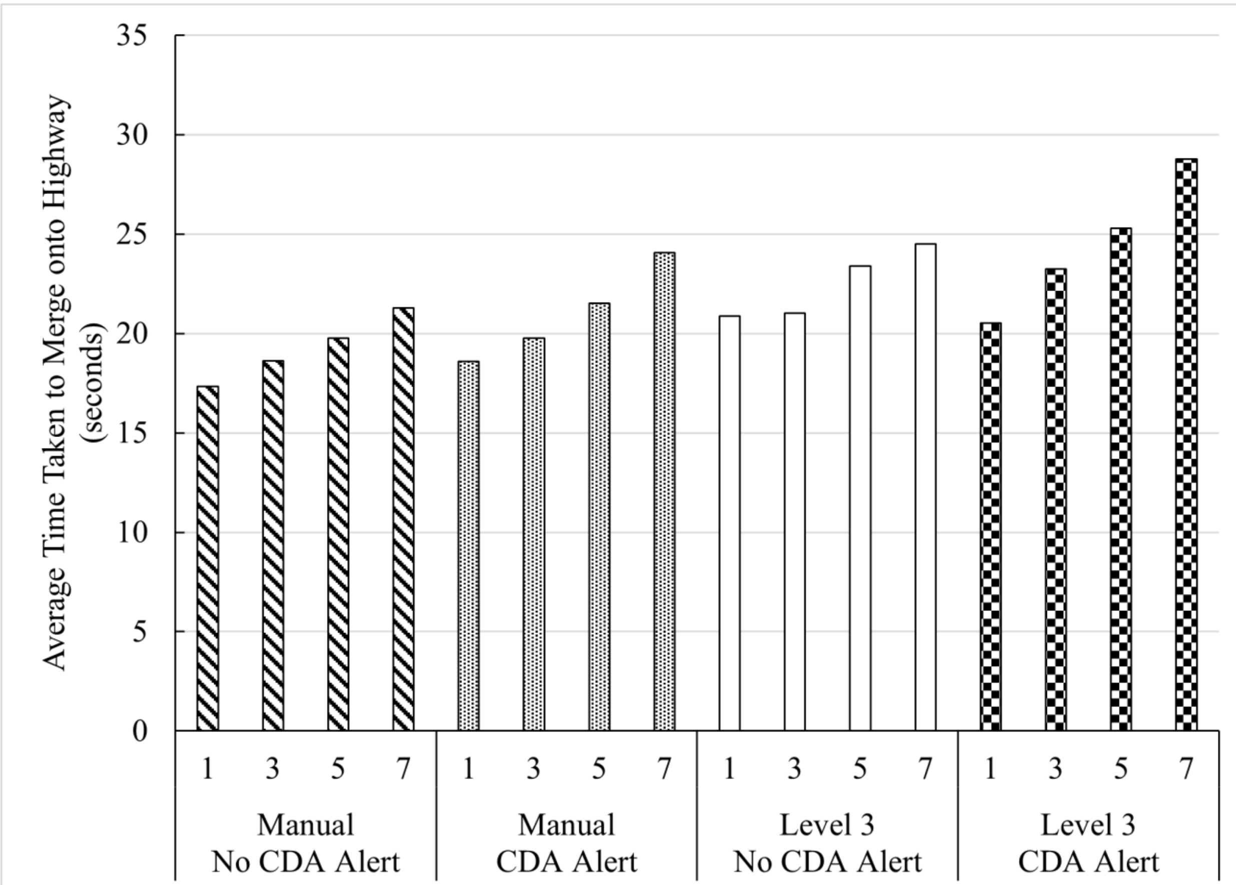
Source: FHWA.

Figure 18. Graph. ORs with 95-percent CI (adjusted for age and sex) from the multinomial logistic regression predicting whether a merge occurred in the beginning roadway segment compared with the end roadway segment.

Time Taken to Merge Onto the Highway

Overall, the participants' average time to merge onto the highway was approximately 21.8 s. When the research team broke these data down by platoon size, they noticed an upward trend (one-vehicle platoon: 19.3 s; three-vehicle platoon: 20.7 s; five-vehicle platoon: 22.5 s; seven-vehicle platoon: 24.7 s). That is, as the platoon size increased, the time taken to merge appears to have increased as well (figure 19).

The research team ran a linear mixed model to assess the effects of automation, CDA alerts, platoon size, age, and sex on the time taken to merge onto the highway (table 2). All the predictors were statistically significant in their relationship to merge time. Both the presence of Level 3 automation (b = 3.46, standard error (SE) = 0.44, p < .001) and CDA alerts (b = 1.88, SE = 0.44, p < .001) were associated with an increase in merge time. Corroborating the visual inspection of figure 19, the platoon size was associated with merge time. Compared with the one-vehicle platoon, the three-vehicle platoon, the five-vehicle platoon, and the seven-vehicle platoons each increased the merge time by 1.34 s (p = .002), 3.16 s (p < .001), and 5.33 s (p < .001), respectively. Additionally, younger drivers tended to have shorter merge times than older drivers (b = −0.88, SE = 0.44, p = .049). Male drivers merged approximately 1 s sooner than females did (b = −1.08, SE = 0.44, p = .018).



Source: FHWA.

Figure 19. Graph. Average time taken to merge onto the highway by group condition and vehicle platoon size.

Table 2. Linear mixed model predicting the time taken to merge onto the highway.

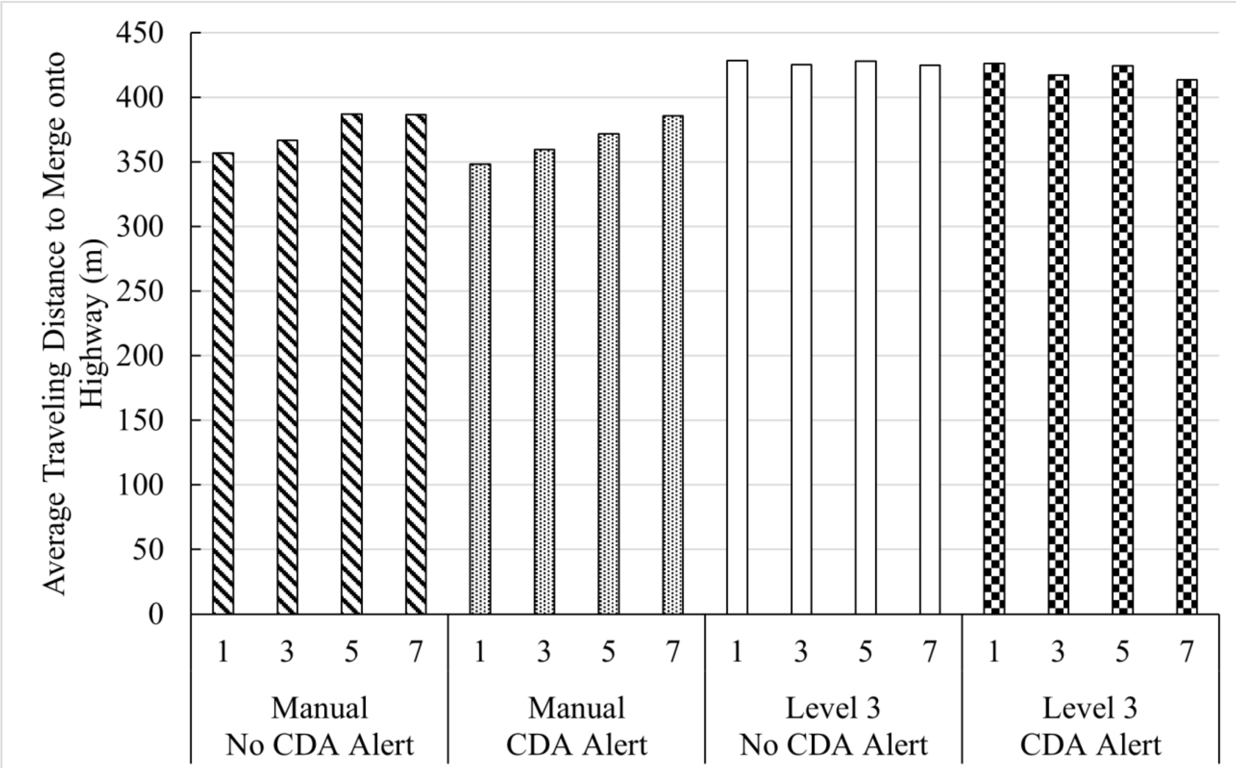
Predictor	Estimate	SE	*p*
Main Effects:			
Automation (ref: no)	3.46	0.44	<.001
CDA alert (ref: no)	1.88	0.44	<.001
Platoon size 3 (ref: platoon size 1)	1.34	0.42	.002
Platoon size 5 (ref: platoon size 1)	3.16	0.42	<.001
Platoon size 7 (ref: platoon size 1)	5.33	0.42	<.001
Age (ref: older)	−0.88	0.44	.049
Sex (ref: female)	−1.07	0.44	.018

p = *p*-value.

Distance Traveled To Merge Onto the Highway

Overall, the participants traveled an average distance of 1,301.8 ft (396.80 m) from when they received, or would have received, the CDA alert to when they were fully merged onto the highway. When the research team broke these data down by platoon size, they noticed an upward trend with 1,279.12 ft (389.88 m), 1,286.45 ft (392.11 m), 1,321.33 ft (402.74 m), and 1,320.77 ft (402.48 m) being the average distances traveled to merge onto the highway for the one-vehicle, three-vehicle, five-vehicle, and seven-vehicle platoon sizes, respectively. That is, as platoon size increased, the total distance the participants traveled before merging also increased (figure 20).

The research team ran a linear mixed-effects model to assess the effects of automation, CDA alert, platoon size, age, and sex on the distance participants traveled to merge onto the highway (table 3). The presence of automation, platoon size, and age were all significant predictors. The presence of Level 3 automation (b = 53.20, SE = 6.70, $p < .001$) was associated with longer travel distance to merge onto the highway. Younger drivers ($b = -15.43$, SE = 5.32, $p < .01$) were associated with shorter travel times compared with older drivers. Compared with the one-vehicle platoon, the five-vehicle platoon and the seven-vehicle platoon each increased the merge distance by 42.16 ft (12.85 m) (p = .02) and 41.34 ft (12.60 m) (p = .02), respectively.



Source: FHWA.

Figure 20. Graph. Average traveling distance, in meters, taken to merge onto the highway by group condition and vehicle platoon size.

Table 3. Linear mixed model predicting the time taken to merge onto the highway.

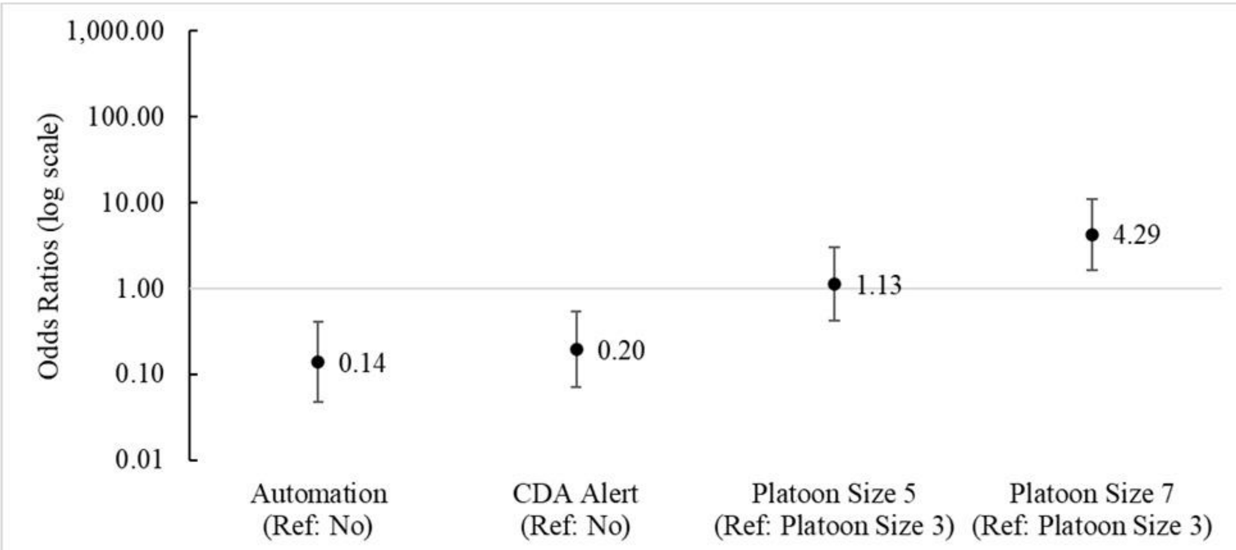
Predictor	Estimate	SE	*p*
Main Effects:			
Automation (ref: no)	53.20	5.39	<.001
Platoon size 5 (ref: platoon size 1)	12.85	5.41	<.05
Platoon size 7 (ref: platoon size 1)	12.60	5.41	<.05
Age (ref: older)	−15.43	5.32	<.01

Likelihood of Collision During the Merge

A total of 52 collisions occurred across all merging events during the study. All of these collisions occurred during merging with the three-, five-, or seven-vehicle platoons; i.e., crashes occurred in about 18 percent of all merges that occurred during a merge scenario that involved a three-, five-, or seven-vehicle platoon.

The research team used a generalized linear mixed-effects model to analyze the effect of automation, CDA alerts, platoon size, age, and sex on the likelihood that a participant would engage in a driving maneuver that would result in a crash. The team did not include single-vehicle merge scenarios in this analysis because no collisions occurred across those merge events. Automation decreased the likelihood of a crash occurring (OR = 0.21, 95-percent CI

[0.1, 0.42]). Additionally, the presence of CDA alerts appeared to decrease the likelihood of crashes (OR = 0.3, 95-percent CI [0.15, 0.58]). Finally, platoon size had a significant influence on the likelihood of a crash occurring (OR = 2.54, 95-percent CI [1.24, 5.24]). Specifically, a crash was more likely to happen during trials that involved a participant merging with the seven-vehicle platoon (figure 21).



Source: FHWA.

Figure 21. Graph. ORs with 95-percent CI (adjusted for age and sex) from the multinomial logistic regression predicting whether the subject vehicle would collide with a platoon vehicle.

Average Driving Speed

The research team examined the average driving speed during two data windows (defined in the Analytic Plans section in chapter 2).

Data Window 1

The average driving speed during data window 1 was 42.75 mi/h (68.8 km/h). In assessing the association between speed and contributing factors, the team observed several interaction effects (table 4). Compared with those drivers without Level 3 automation and CDA alerts who experienced a one-vehicle platoon, drivers with Level 3 automation and CDA alerts displayed slower driving speeds while merging with the three-vehicle platoon ($b = -8.85$, SE = 2.02, $p < .001$); the five-vehicle platoon ($b = -8.29$, SE = 2.02, $p < .001$); and the seven-vehicle platoon ($b = -12.84$, SE = 2.02, $p < .001$).

Table 4. Linear mixed model predicting the average driving speed during data window 1.

Predictor	Estimate	SE	*p*
Main Effects:			
Automation (ref: no)	4.13	1.64	.013
CDA alert (ref: no)	−3.71	1.63	.024
Platoon size 3 (ref: platoon size 1)	−0.97	1.01	.340
Platoon size 5 (ref: platoon size 1)	−0.74	1.01	.463
Platoon size 7 (ref: platoon size 1)	−2.43	1.01	.017
Age (ref: older)	0.45	0.98	.647
Sex (ref: female)	1.12	0.99	.259
Interactions:			
Automation x CDA alert	−2.41	2.31	.298
Automation x platoon size 3	1.43	1.43	.320
Automation x platoon size 5	0.80	1.43	.576
Automation x platoon size 7	1.86	1.43	.194
CDA alert x platoon size 3	1.78	1.43	.215
CDA alert x platoon size 5	−0.93	1.43	.518
CDA alert x platoon size 7	−0.28	1.43	.844
Automation x connectivity x platoon size 3	−8.85	2.02	<.001
Automation x connectivity x platoon size 5	−8.29	2.02	<.001
Automation x connectivity x platoon size 7	−12.84	2.02	<.001

Note: The x indicates an interaction between the listed variables.

Data Window 2

The average driving speed during data window 2 was 43.09 mi/h (69.35 km/h). While assessing the association between speed and the contributing factors, the research team observed an interaction effect (table 5). Compared with drivers without Level 3 automation and CDA alerts, the drivers with both Level 3 automation and CDA alerts drove faster (b = 10.13, SE = 2.12, p < .001). The vehicle platoon size had an effect on the driving speed as well. Compared with the one-vehicle platoon, the team observed slower driving speeds for the three-vehicle platoon (b = −3.89, SE = 0.83, p < .001); the five-vehicle platoon (b = −6.59, SE = 0.83, p < .001); and the seven-vehicle platoon (b = −10.29, SE = 0.83, p < .001).

Table 5. Linear mixed model predicting the average driving speed during data window 2.

Predictor	Estimate	SE	*p*
Main Effects:			
Automation (ref: no)	−6.37	1.51	<.001
CDA Alert (ref: no)	−5.43	1.50	<.001
Platoon size 3 (ref: platoon size 1)	−3.89	0.83	<.001
Platoon size 5 (ref: platoon size 1)	−6.59	0.83	<.001
Platoon size 7 (ref: platoon size 1)	−10.29	0.83	<.001
Age (ref: older)	−0.84	1.06	.430
Sex (ref: female)	1.52	1.07	.161
Interaction:			
Automation x CDA alert	10.13	2.12	<.001

Driving Speed Variability

The research team examined speed variability during two data windows (defined in the Analytic Plans section in chapter 2).

Data Window 1

On average, driving speed varied by 3.29 mi/h (5.3 km/h) during data window 1. Due to convergence issues in the model, the team conducted regression analyses separately for each vehicle platoon size (table 6, table 7, table 8, and table 9). The researchers observed an interaction effect between Level 3 automation and the presence of a CDA alert during the one-, three-, and five-vehicle platoon conditions. Compared with drivers without Level 3 automation or CDA alerts, drivers with both Level 3 automation and CDA alerts displayed less variability in their driving speeds during the merge with the one-vehicle platoon ($b = -1.09$, SE = 0.23, $p < .001$); the three-vehicle platoon ($b = -0.77$, SE = 2.02, $p = .005$); and the five-vehicle platoon ($b = -0.71$, SE = 0.23, $p = .002$). The team found no interaction effect and excluded that parameter for the seven-vehicle platoon model. In the seven-vehicle platoon condition, the drivers with Level 3 automation displayed more variability in their driving speeds ($b = 0.36$, SE = 0.13, $p = .009$). Likewise, drivers with CDA alerts displayed more variability in driving speeds ($b = 0.59$, SE = 0.13, $p < .001$).

Table 6. General linear model predicting variability in driving speed for the one-vehicle platoon during data window 1.

Predictor	Estimate	SE	*p*
Main Effects:			
Automation (ref: no)	0.51	0.16	.003
CDA alert (ref: no)	0.17	0.16	.306
Age (ref: older)	0.04	0.12	.708
Sex (ref: female)	0.00	0.12	.996
Interaction:			
Automation x CDA alert	−1.09	0.23	<.001

Table 7. General linear model predicting variability in driving speed for the three-vehicle platoon during data window 1.

Predictor	Estimate	SE	*p*
Main Effects:			
Automation (ref: no)	0.78	0.19	<.001
CDA alert (ref: no)	0.21	0.19	.273
Age (ref: older)	0.05	0.13	.724
Sex (ref: female)	−0.09	0.13	.501
Interaction:			
Automation x CDA alert	−0.77	0.27	.005

Table 8. General linear model predicting variability in driving speed for the five-vehicle platoon during data window 1.

Predictor	Estimate	SE	*p*
Main Effects:			
Automation (ref: no)	0.57	0.16	.001
CDA alert (ref: no)	0.74	0.16	<.001
Age (ref: older)	−0.13	0.11	.262
Sex (Ref: female)	0.05	0.11	.655
Interaction:			
Automation x CDA alert	−0.71	0.23	.002

Table 9. General linear model predicting variability in driving speed for the seven-vehicle platoon during data window 1.

Predictor	Estimate	SE	*p*
Main Effects:			
Automation (ref: no)	0.36	0.13	.009
CDA alert (ref: no)	0.59	0.13	<.001
Age (ref: older)	0.12	0.13	.377
Sex (ref: female)	0.16	0.13	.228

Data Window 2

On average, driving speed varied by 5.86 mi/h (9.43 km/h) during data window 2. A linear mixed model revealed an interaction effect (table 10), whereby drivers with Level 3 automation and CDA alerts tended to display less variability in their driving speeds than drivers without automation and CDA alerts ($b = -0.69$, SE = 0.22, $p = .002$). Vehicle platoon size had an effect on driving speed variability as well. Compared with the one-vehicle platoon, the team observed increased driving speed variability for the three-vehicle platoon ($b = 0.25$, SE = 0.07, $p < .001$); the five-vehicle platoon ($b = 0.39$, SE = 0.07, $p < .001$); and the seven-vehicle platoon ($b = 0.61$, SE = 0.07, $p < .001$).

Table 10. Linear mixed model predicting variability in driving speed during data window 2.

Predictor	Estimate	SE	*p*
Main Effects:			
Automation (ref: no)	1.08	0.16	<.001
CDA alert (ref: no)	0.48	0.16	.002
Platoon size 3 (ref: platoon size 1)	0.25	0.07	<.001
Platoon size 5 (ref: platoon size 1)	0.39	0.07	<.001
Platoon size 7 (ref: platoon size 1)	0.61	0.07	<.001
Age (ref: older)	0.06	0.11	.618
Sex (ref: female)	−0.05	0.11	.652
Interaction:			
Automation x CDA alert	−0.69	0.22	.002

Driving Acceleration Variability

The research team examined acceleration variability during two data windows (defined in the Analytic Plans section in chapter 2).

Data Window 1

On average, the drivers' rate of acceleration varied by 3.29 mi/h (5.3 km/h) during data window 1. Due to convergence issues in the model, the research team conducted the regression analyses separately for each vehicle platoon size (table 11, table 12, table 13, and table 14). During the one-vehicle, three-vehicle, and five-vehicle platoon conditions, the team observed an interaction effect between Level 3 automation and CDA alert presence. Compared with drivers without Level 3 automation or CDA alerts, drivers with Level 3 automation and CDA alerts displayed less variability in their driving accelerations during the data window 1 period for the one-vehicle platoon ($b = -1.18$, SE = 0.39, $p = .003$); the three-vehicle platoon ($b = -1.27$, SE = 0.39, $p < .001$); and the five-vehicle platoon ($b = -1.02$, SE = 0.33, $p = .003$) scenarios. The researchers found no interaction effect and excluded that parameter for the seven-vehicle platoon model. During the seven-vehicle platoon condition, the drivers who received CDA alerts displayed greater variability in their driving acceleration ($b = 0.41$, SE = 0.18, $p = .021$). However, the team found the Level 3 automation presence had no effect on acceleration variability ($b = -.16$, SE = 0.18, $p = .364$).

Table 11. General linear model predicting variability in driving acceleration for the one-vehicle platoon during data window 1.

Predictor	Estimate	SE	*p*
Main Effects:			
Automation (ref: no)	0.41	0.28	.141
CDA alert (ref: no)	0.32	0.28	.256
Age (ref: older)	0.10	0.20	.620
Sex (ref: female)	−0.26	0.20	.186
Interaction:			
Automation x CDA alert	−1.18	0.39	.003

Table 12. General linear model predicting variability in driving acceleration for the three-vehicle platoon during data window 1.

Predictor	Estimate	SE	*p*
Main Effects:			
Automation (ref: no)	0.35	0.27	.209
CDA alert (ref: no)	0.19	0.27	.481
Age (ref: older)	−0.02	0.19	.929
Sex (ref: female)	−0.07	0.20	.736
Interaction:			
Automation x CDA alert	−1.27	0.39	<.001

Table 13. General linear model predicting variability in driving acceleration for the five-vehicle platoon during data window 1.

Predictor	Estimate	SE	*p*
Main Effects:			
Automation (ref: no)	0.18	0.24	.453
CDA alert (ref: no)	0.72	0.23	.003
Age (ref: older)	−0.12	0.17	.466
Sex (ref: female)	0.14	0.17	.411
Interaction:			
Automation x CDA alert	−1.02	0.33	.003

Table 14. General linear model predicting variability in driving acceleration for the seven-vehicle platoon during data window 1.

Predictor	Estimate	SE	*p*
Main Effects:			
Automation (ref: no)	−0.16	0.18	.364
CDA alert (ref: no)	0.41	0.18	.021
Age (ref: older)	0.05	0.18	.759
Sex (ref: female)	0.16	0.18	.377

Data Window 2

On average, the drivers' rate of acceleration varied by 1.08 mi/h (1.74 km/h) during data window 2. Due to convergence issues in the model, the research team conducted the regression analyses separately for each vehicle platoon size (table 15, table 16, table 17, and table 18). Across all vehicle platoon size conditions, the team observed an interaction effect between Level 3 automation and CDA alert presence. Compared with drivers without Level 3 automation or CDA alerts, drivers with Level 3 automation and CDA alerts displayed less variability in their driving accelerations during the one-vehicle platoon ($b = -0.97$, SE = 0.37, $p < .001$); the three-vehicle platoon ($b = -0.75$, SE = 0.30, $p = .013$); the five-vehicle platoon ($b = -1.37$, SE = 0.25, $p < .001$); and the seven-vehicle platoon ($b = -1.49$, SE = 0.30, $p < .001$).

Table 15. General linear model predicting variability in driving acceleration for the one-vehicle platoon during data window 2.

Predictor	Estimate	SE	*p*
Main Effects:			
Automation (ref: no)	1.26	0.26	<.001
CDA alert (ref: no)	0.10	0.26	.712
Age (ref: older)	0.10	0.18	.577
Sex (ref: female)	−0.06	0.19	.744
Interaction:			
Automation x CDA alert	−0.97	0.37	.010

Table 16. General linear model predicting variability in driving acceleration for the three-vehicle platoon during data window 2.

Predictor	Estimate	SE	*p*
Main Effects:			
Automation (ref: no)	0.81	0.21	<.001
CDA alert (ref: no)	−0.06	0.21	.762
Age (ref: older)	−0.10	0.15	.503
Sex (ref: female)	0.07	0.15	.645
Interaction:			
Automation x CDA alert	−0.75	0.30	.013

Table 17. General linear model predicting variability in driving acceleration for the five-vehicle platoon during data window 2.

Predictor	Estimate	SE	*p*
Main Effects:			
Automation (ref: no)	0.92	0.18	<.001
CDA alert (ref: no)	−0.15	0.18	.388
Age (ref: older)	0.16	0.13	.201
Sex (ref: female)	0.11	0.13	.401
Interaction:			
Automation x CDA alert	−1.37	0.25	<.001

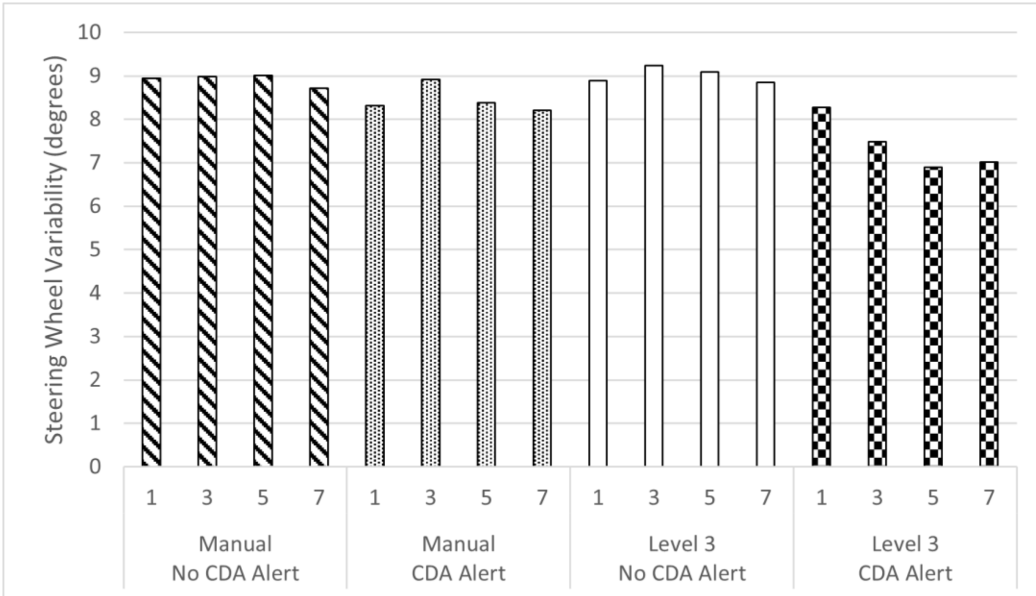
Table 18. General linear model predicting variability in driving acceleration for the seven-vehicle platoon during data window 2.

Predictor	Estimate	SE	*p*
Main Effects:			
Automation (ref: no)	0.91	0.21	<.001
CDA alert (ref: no)	0.17	0.21	.411
Age (ref: older)	0.02	0.15	.908
Sex (ref: female)	0.06	0.15	.691
Interaction:			
Automation x CDA alert	−1.49	0.30	<.001

Steering Wheel Turning Angle Variability

Data Window 1

The steering wheel turning variability averaged 8.45° during data window 1. Figure 22 shows the average steering wheel variability from each condition during data window 1.



Source: FHWA.

Figure 22. Graph. Average steering wheel variability, in degrees, by group condition and vehicle platoon size during data window 1.

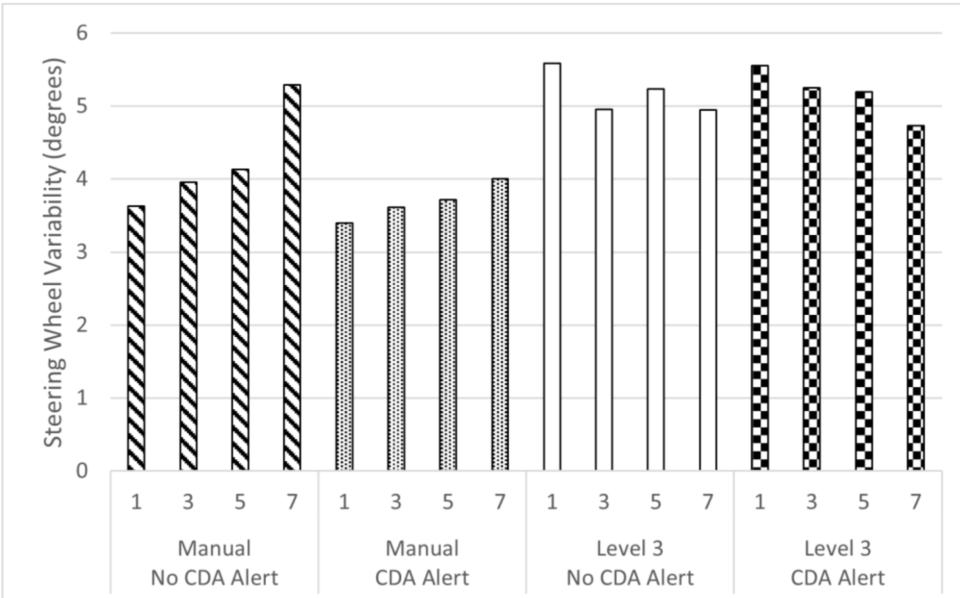
The research team ran a linear mixed model to assess the effects of automation, connectivity, platoon size, age, and sex on the variability of steering wheel turning angle (table 19). Although no main effects occurred across the predictors, a three-way interaction transpired between automation, connectivity, and platoon size. Specifically, steering wheel variability was significantly lower for the three-vehicle platoon ($b = -0.19$, SE = 0.06, $p < .001$); the five-vehicle platoon ($b = -0.21$, SE = 0.06, $p < .001$); and the seven-vehicle platoon ($b = -0.17$, SE = 0.06, $p < .001$) compared with the single-vehicle platoon conditions, but only when Level 3 automation and CDA alerts were engaged (figure 22).

Table 19. General linear model predicting steering wheel variability during data window 1.

Predictor	Estimate	SE	*p*
Main Effects:			
Automation (ref: no)	0.00	0.06	0.95
CDA alert (ref: no)	−0.07	0.06	0.25
Platoon size 3 (ref: platoon size 1)	0.00	0.03	0.98
Platoon size 5 (ref: platoon size 1)	0.00	0.03	0.97
Platoon size 7 (ref: platoon size 1)	−0.03	0.03	0.34
Age (ref: older)	−0.01	0.04	0.85
Sex (ref: female)	0.03	0.04	0.54
Interactions:			
Automation x connectivity x platoon size 3	−0.19	0.06	<.001
Automation x connectivity x platoon size 5	−0.21	0.06	<.001
Automation x connectivity x platoon size 7	−0.17	0.06	<.01

Data Window 2

On average, the variability in steering wheel turning averaged 4.57° during data window 2. Figure 23 shows the average steering wheel variability for each condition during data window 2.



Source: FHWA.

Figure 23. Graph. Average steering wheel variability, in degrees, by group condition and vehicle platoon size during data window 2.

The research team conducted a linear mixed model to assess the effects of automation, connectivity, platoon size, age, and sex on the variability of steering wheel turning angle (table 20). The main effect of automation was significant. When automation was engaged, steering wheel variability increased ($b = 0.25$, SE = 0.10, $p < .05$), as shown in figure 23. No other significant main effects or interactions occurred.

Table 20. General linear model predicting steering wheel variability during data window 1.

Predictor	Estimate	SE	*p*
Main Effects:			
Automation (ref: no)	0.25	0.10	<0.01
CDA alert (ref: no)	−0.05	0.10	0.63
Platoon size 3 (ref: platoon size 1)	0.04	0.05	0.41
Platoon size 5 (ref: platoon size 1)	0.07	0.05	0.20
Platoon size 7 (ref: platoon size 1)	0.08	0.05	0.11
Age (ref: older)	−0.10	0.10	0.31
Sex (ref: female)	−0.13	0.10	0.19

EYE-TRACKING DATA

The research team implemented outlier detection for the "fixation frequency" derived from the SE log files by examining whether an observation was above the third quartile plus 1.5 times interquartile range, or resulted in large, estimated deviation between subject average and the overall model average. The team excluded any detected outliers from the analysis.

Automated Vehicle Platoon at Merging Event

The researchers made a total of 248 observations of the automated platoon during the merge events from a total of 89 participants.

Total Fixation Duration

On average, the drivers fixated on the automated platoon for roughly 1.09 s during the merge window. The research team ran a gamma-generalized linear model with a log link to determine the effects of the experimental design factors on the total duration of fixation on the automated platoon during the merge (table 21). The team observed a three-way interaction effect between automation, CDA alerts, and platoon size. Specifically, the fixation duration was lower when automation was engaged, CDA alerts were available, and platoon size was either five vehicles (OR = 0.29, 95-percent CI [0.11, 0.79]) or seven vehicles (OR = 0.26, 95-percent CI [0.10, 0.67]).

Table 21. Estimates from a gamma-generalized linear model with a log link predicting the total duration of fixations on the automated platoon.

Predictor	OR	95% CI LL	95% CI UL
Main Effects:			
Automation (ref: no)	1.44	0.82	2.55
CDA alert (ref: no)	1.02	0.54	1.94
Platoon size 3 (ref: platoon size 1)	0.94	0.61	1.45
Platoon size 5 (ref: platoon size 1)	1.03	0.66	1.62
Platoon size 7 (ref: platoon size 1)	1.17	0.77	1.79
Age (ref: older)	0.88	0.64	1.20
Sex (ref: female)	0.85	0.62	1.17
Interactions:			
Automation x CDA alert	2.05	0.88	4.78
Automation x platoon size 3	1.22	0.66	2.24
Automation x platoon size 5	1.02	0.55	1.91
Automation x platoon size 7	1.73	0.94	3.20
CDA alert x platoon size 3	0.83	0.41	1.70
CDA alert x platoon size 5	1.24	0.59	2.62
CDA alert x platoon size 7	1.12	0.57	2.21

Predictor	OR	95% CI LL	95% CI UL
Automation x connectivity x platoon size 3	0.64	0.25	1.62
Automation x connectivity x platoon size 5	0.29	0.11	0.79
Automation x connectivity x platoon size 7	0.26	0.10	0.67

LL = lower limit; UL = upper limit.

Fixation Frequency

On average, the drivers fixated 0.12 times per second on the automated platoon during the merge event. The research team ran a Poisson-generalized linear model with a log link to determine the effects of the experimental design factors on the fixation frequency per second (table 22). The team observed a main effect of platoon size, but only for the seven-vehicle platoon condition (OR = 0.92, 95-percent CI [0.58, 1.46]). Additionally, the researchers observed an interaction effect. A three-way interaction was present when the automation was engaged, CDA alerts were available, and a participant was merging with a seven-vehicle platoon (OR = 0.31, 95-percent CI [0.13, 0.74]).

Table 22. Estimates from a Poisson-generalized linear model with a log link predicting the total fixations per second on the automated platoon during a merge event.

Predictor	OR	95% CI LL	95% CI UL
Main Effects:			
Automation (ref: no)	1.03	0.63	1.68
CDA alert (ref: no)	1.09	0.63	1.89
Platoon size 3 (ref: platoon size 1)	1.14	0.72	1.81
Platoon size 5 (ref: platoon size 1)	1.26	0.79	2.00
Platoon size 7 (ref: platoon size 1)	0.92	0.58	1.46
Age (ref: older)	0.99	0.82	1.20
Sex (ref: female)	0.99	0.82	1.20
Interactions:			
Automation x CDA alert	1.30	0.65	2.59
Automation x platoon size 3	1.03	0.56	1.90
Automation x platoon size 5	0.95	0.51	1.76
Automation x platoon size 7	1.91	1.05	3.45
CDA alert x platoon size 3	0.75	0.36	1.55
CDA alert x platoon size 5	1.17	0.59	2.33
CDA alert x platoon size 7	1.26	0.65	2.47
Automation x connectivity x platoon size 3	0.96	0.39	2.40
Automation x connectivity x platoon size 5	0.50	0.21	1.23
Automation x connectivity x platoon Size 7	0.31	0.13	0.74

Instrument Cluster

The research team made a total of 347 observations of the automated platoon during the merge events from a total of 93 participants.

Fixation Duration

On average, the participants fixated on the instrument cluster for approximately 0.85 s during the merge event. The 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 the merge events (see table 23). The automation level had a significant effect on the total fixation duration (OR = 1.70, 95-percent CI [1.01, 2.85]); specifically, Level 3 automation engagement led to increased time fixating on the instrument cluster. Furthermore, males fixated on the instrument cluster significantly more than females (OR = 2.22, 95-percent CI [1.32, 3.73]).

Table 23. Estimates from a gamma-generalized linear model with a log link predicting the total duration of fixations on the instrument cluster during a merge.

Predictor	OR	95% CI LL	95% CI UL
Main Effects:			
Automation (ref: no)	1.70	1.01	2.85
CDA alert (ref: no)	0.77	0.46	1.29
Platoon size 3 (ref: platoon size 1)	0.90	0.68	1.17
Platoon size 5 (ref: platoon size 1)	1.14	0.86	1.50
Platoon size 7 (ref: platoon size 1)	1.16	0.88	1.52
Age (ref: older)	1.07	0.64	1.77
Sex (ref: female)	2.22	1.32	3.73

Fixation Frequency

Throughout the merge event, the drivers fixated on the instrument cluster an average of 2.93 times per second. The research team conducted a Poisson-generalized linear model with a log link to determine the effects of the experimental design factors on the fixation frequency per second (table 24). The researchers observed a main effect of platoon size. Specifically, a higher frequency of fixations occurred for the three-vehicle platoon (OR = 1.36, 95-percent CI [1.24, 1.50]) and the five-vehicle platoon (OR = 1.42, 95-percent CI [1.30, 1.55]) compared with the one-vehicle platoon. Additionally, a greater frequency of fixations on the instrument cluster occurred among men compared with women (OR = 1.85, 95-percent CI [1.17, 2.93]). Several significant interactions also occurred, including a significant interaction between automation and platoon size and between connectivity and platoon size, as well as a three-way interaction between automation, connectivity, and platoon size. Specifically, a positive effect on the log likelihood of fixation frequency occurred as automation and connectivity were engaged and as the platoon size increased from a single-vehicle to a three-vehicle platoon (OR = 1.55, 95-percent CI [1.28, 1.87]). A slightly negative effect on the log likelihood of fixation frequency occurred as automation and connectivity were engaged and as the platoon size increased from a single-vehicle to a seven-vehicle platoon (OR = 0.78, 95-percent CI [0.65, 0.93]).

Table 24. Estimates from a Poisson-generalized linear model with a log link predicting the total fixations per second on the instrument cluster during a merge event.

Predictor	OR	95% CI LL	95% CI UL
Main Effects:			
Automation (ref: no)	1.43	0.75	2.73
CDA alert (ref: no)	0.68	0.36	1.30
Platoon size 3 (ref: platoon size 1)	1.36	1.24	1.50
Platoon size 5 (ref: platoon size 1)	1.42	1.30	1.55
Platoon size 7 (ref: platoon size 1)	0.94	0.85	1.04
Age (ref: older)	0.95	0.61	1.49
Sex (ref: female)	1.85	1.17	2.93
Interactions:			
Automation x CDA alert	1.28	0.52	3.18
Automation x platoon size 3	0.63	0.56	0.72
Automation x platoon size 5	0.66	0.59	0.75
Automation x platoon size 7	1.16	1.02	1.31
CDA alert x platoon size 3	0.59	0.50	0.68
CDA alert x platoon size 5	0.90	0.79	1.04
CDA alert x platoon size 7	1.31	1.14	1.51
Automation x connectivity x platoon size 3	1.55	1.28	1.87
Automation x connectivity x platoon size 5	1.13	0.95	1.35
Automation x connectivity x platoon size 7	0.78	0.65	0.93

Left Mirror

The research team made a total of 152 observations of the automated platoon during the merge events from a total of 69 participants.

Total Fixation Duration

On average, the drivers fixated on the automated platoon for roughly 0.6 s during the merge window. The researchers 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 automated platoon during the merge (table 25). The team observed a significant main effect of automation and connectivity on total fixation duration on the left mirror. Specifically, when automation was engaged, the participants were more likely to have increased fixation duration on the left mirror (OR = 2.43, 95-percent CI [1.03, 5.72]). When connectivity was enabled, an increase in fixation duration also occurred on the left mirror (OR = 2.46, 95-percent CI [1.07, 5.64]). No significant interactions occurred.

Table 25. Estimates from a gamma-generalized linear model with a log link predicting the total duration of fixations on the instrument cluster during a merge.

Predictor	OR	95% CI LL	95% CI UL
Main Effects:			
Automation (ref: no)	2.43	1.03	5.72
CDA alert (ref: no)	2.46	1.07	5.64
Platoon size 3 (ref: platoon size 1)	0.96	0.65	1.43
Platoon size 5 (ref: platoon size 1)	0.77	0.51	1.15
Platoon size 7 (ref: platoon size 1)	0.95	0.65	1.39
Age (ref: older)	1.66	0.72	3.78
Sex (ref: female)	1.06	0.45	2.48

Fixation Frequency

Throughout the merging event, the drivers fixated on the left-side (driver's side) mirror an average of 1.76 times per second. The research team ran a Poisson-generalized linear model with a log link to determine the effects of the experimental design factors on the fixation frequency per second (table 26). The researchers observed the main effects of automation and platoon size. The use of automation increased the likelihood of fixation frequency on the left mirror (OR = 3.15, 95-percent CI [1.06, 9.37]). Additionally, the frequency of fixations on the left mirror was more likely to increase for the five-vehicle platoon (OR = 1.99, 95-percent CI [1.25, 3.16]) and the seven-vehicle platoon (OR = 1.69, 95-percent CI [1.10, 2.62]) compared with the one-vehicle platoon. Younger drivers were more likely to have a higher frequency of fixations on the instrument cluster compared with older drivers (OR = 2.01, 95-percent CI [1.02, 3.98]). Several significant interactions also occurred, including a significant interaction between automation and platoon size and between connectivity and platoon size, as well as a three-way interaction between automation, connectivity, and platoon size. Specifically, a positive effect on the log likelihood of fixation frequency occurred as automation and connectivity were engaged and as the platoon size increased from a single-vehicle to a five-vehicle platoon (OR = 4.17, 95-percent CI [2.38, 7.33]). A positive effect on the log likelihood of fixation frequency also occurred as automation and connectivity were engaged and as the platoon size increased from a single vehicle to a seven-vehicle platoon (OR = 2.21, 95-percent CI [1.30, 3.76]).

Table 26. Estimates from a Poisson-generalized linear model with a log link predicting total fixations per second on the left-side mirror during a merge event.

Predictor	OR	95% CI LL	95% CI UL
Main Effects:			
Automation (ref: no)	3.15	1.06	9.37
CDA alert (ref: no)	2.04	0.70	5.97
Platoon size 3 (ref: platoon size 1)	1.19	0.74	1.89
Platoon size 5 (ref: platoon size 1)	1.99	1.25	3.16
Platoon size 7 (ref: platoon size 1)	1.69	1.10	2.62
Age (ref: older)	2.01	1.02	3.98

Predictor	OR	95% CI LL	95% CI UL
Sex (ref: female)	1.31	0.65	2.65
Interactions:			
Automation x CDA alert	1.19	0.28	5.05
Automation x platoon size 3	0.41	0.25	0.69
Automation x platoon size 5	0.15	0.09	0.24
Automation x platoon size 7	0.30	0.19	0.48
CDA alert x platoon size 3	0.83	0.51	1.37
CDA alert x platoon size 5	0.48	0.29	0.79
CDA alert x platoon size 7	0.56	0.35	0.89
Automation x connectivity x platoon size 3	1.72	0.99	3.00
Automation x connectivity x platoon size 5	4.17	2.38	7.33
Automation x connectivity x platoon size 7	2.21	1.30	3.76

QUESTIONNAIRE DATA

Trust in ADSs

The researchers ran an independent *t*-test to compare 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. This study found no significant differences between the participants' subjective trust in Level 3 automation after driving a Level 3 automation (32.90 ± 6.68) compared with their subjective trust in Level 3 automation after driving manual vehicles ((32.08 ± 5.64), $t(94) = -0.64$, $p > 0.05$).

Awareness and Attitudes Toward the Level 3 Automation System

The researchers asked the participants, "Was the vehicle you drove today equipped with Level 3 automation capabilities?" Of those participants who experienced the Level 3 automation, 46 (95.83 percent) were aware that they experienced the Level 3 automation. Of the manual drivers, 14 (29.17 percent) believed the vehicle they drove had Level 3 automation capabilities.

The research team assessed the following items for those 46 participants who both experienced and were aware of the Level 3 automation system.

Perceived Comfort

The researchers asked the participants, “Were you comfortable using the Level 3 automation?” The majority *(n* = 36; 78.26 percent) reported feeling comfortable with the Level 3 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 Level 3 automated system drives differently than how the participant drove).

Perceived Understanding

The researchers asked the participants, “Did you feel like you fully understood how to operate the Level 3 automation?” The majority (*n* = 37; 80.43 percent) reported feeling they understood the Level 3 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., interacting with hazards or exiting the highway).

System Expectations

The research team asked the participants, “Did the Level 3 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).

The researchers asked the participants, “Did the Level 3 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

The full simulated drive was 20 mi long and included two experimental segments of interest. In each experimental segment, exposure to a CDA alert was possible. Experiencing a CDA alert in either or both experimental conditions was possible, and 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 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 Level 3 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 Level 3 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 research team asked the participants who correctly answered “yes” to being aware they had Level 3 automation functionality and receiving a CDA alert (n = 36), “Did the Level 3 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: Being unsure how the vehicle would respond to certain situations (e.g., interacting with hazards or exiting the highway). Some participants expected the vehicle to, or desired it to, merge sooner.

CHAPTER 4. DISCUSSION

The study's goal was to examine the potential benefit of using Level 3 ADS and CDA alerting technology to assist drivers with onramp merging behavior. Specifically, the research team examined drivers' onramp merging behaviors amidst variations in fleet size of the oncoming traffic. The team used several metrics to assess the effect of CDA alerts on highway merging safety, including driving simulation data, questionnaire data, and eye-tracking data.

The researchers expected Level 3 automation and CDA alerts to be associated with safer and more efficient merging behaviors, as measured by driving metrics (e.g., slower driving speeds, lower speed variability, less steering wheel variability) and eye-tracking metrics (e.g., quicker to fixate on the platoon, proportionally more time spent fixated on the platoon). The team expected the platoon size to moderate this relationship. Specifically, they anticipated that automation and connectivity would be associated with even safer and more efficient merging behavior when merging with large platoons (five and seven vehicles) compared with the improvements when merging with smaller platoons (one and three vehicles).

Overall, Level 3 automation seemed to influence merging behaviors. Based on the statistical results, this influence is visible across several of the dependent variables. When merging, the participants were more likely to merge behind an existing platoon of vehicles than between those vehicles. Additionally, the participants were more likely to merge at the end of the merge lane when using Level 3 automation. While the likelihood of the subject vehicle merging between the platoon of vehicles was greater for larger platoon sizes, the use of Level 3 automation reduced that likelihood. The same was true for using CDA alerts, especially when merging with five- or seven-vehicle platoons when no automation was used.

Furthermore, Level 3 automation was associated with longer merge times and longer distances to complete merging, indicating that the merging behavior of the Level 3 automation was more gradual and less aggressive than the average manual driver's merging behavior. Before the merge event (data window 1), automation was associated with higher speeds and greater speed variability. However, during the actual merge event (data window 2), the Level 3 automation had lower overall speeds than manual drivers and slightly more speed variability. This outcome was most likely due to the differences in manual drivers' behaviors and the way the Level 3 automation was programmed to behave.

The CDA alerts also seemed to influence some merging behaviors. When the participants received the CDA alerts and merged with the three-, five-, or seven-vehicle platoons, they were less likely to merge in between the platoon vehicles compared to merging in front of, or behind the platoon vehicles. The platoon vehicles only had a gap distance of 0.7 s, so merging between them would be very difficult to do while also trying to accelerate up to the speed limit of the highway. Additionally, while participants were most likely to merge behind the three-, five-, and seven-platoons across all conditions, the likelihood that participants merged ahead of those platoons increased when CDA alerts were present compared to when they were not present. This outcome was most likely due to drivers wanting to increase their speed to drive ahead of the platoon rather than requiring a greater speed adjustment to merge behind the platoon or having to risk merging between the vehicles of the platoon. This choice could be safer than merging between the vehicles of the platoon. The CDA alerts were also associated with increased speed, but not speed variability before the merge.

The research team observed a surprisingly large number of collisions during this study. A total of 52 collisions (13 percent) occurred across all merging events. No collisions occurred during a one-vehicle platoon merging event. However, the presence of Level 3 automation and CDA alerts each significantly reduced the likelihood of collisions occurring. When observing the proportions of collisions for each experimental condition, conditions with CDA alerts showed a lower proportion of collisions, even in conditions where the participant was operating the vehicle manually. This outcome would indicate that the manual driver identified the risk and used the information provided by the system to perform significantly safer merging behavior.

Overall, the study results supported the theory that an engaged Level 3 system with CDA alerts could be associated with safer and more efficient merging behaviors. The interactions the team found between automation, CDA alerts, and platoon size suggest that these safety features would have the biggest impact during merge events with platoons of other CDA-equipped vehicles. Additionally, participants may not have completely understood or fully trusted the system, so they may not have opted into using the system in the real world. Therefore, driver education and training on Level 3 automation and CDA alerts are needed to facilitate their use and prepare drivers for what to expect when using these safety features.

LIMITATIONS

Using 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 replicating this new technology for many participants in a short period. While driving simulators have many benefits, they are not without their disadvantages. This study attempted to replicate a Level 3 CDA alerting system; however, the driving behaviors of real-world Level 3 systems may differ from the behaviors of the simulated Level 3 system in the present study. For example, a real-world commercial Level 3 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 Level 3 system in the present study.

The research team used a scenario for this study that facilitated two different studies. However, the team counterbalanced the order in which they exposed all the participants to the events of the two different studies. Additionally, the researchers kept the Level 3 automation feature consistent across the two studies for participants. The current study had two levels of connectivity, whereas the second study had three levels of connectivity. Therefore, some participants received CDA alerts in both studies, while other participants received them in the current study but not the second study and vice versa. The participants gave their responses to the questionnaires after both studies were complete. Therefore, some of the confusion on whether the participants' vehicles were equipped with CDA alerts may have come from the fact that they received alerts in one study but not the other. This result means that the participants' text-based responses could have been related to either the driving events that occurred during the current study or the second study. However, the participants' feedback was still useful for understanding their opinions on Level 3 automation and CDA safety systems.

FUTURE RESEARCH

The study team recommends additional research on the influence of Level 3 automation and CDA alerts on driver behavior during basic travel and mixed fleet merging events. Specifically, varying the behavior of the Level 3 automation with more controlled braking and acceleration could improve ratings of trust and reduce takeovers. Furthermore, the location at which the participant vehicle becomes parallel with the C-ADS-equipped platoon could be adjusted slightly to see whether being closer or further away from the end of the merge ramp changes the merging location (ahead, behind, or between the platoon). Differences in speeds of the participant vehicles and platoon vehicles may cause different results. Finally, the behavior of the C-ADS-equipped platoon could be modified, such as the platoon vehicles making room in the middle of the platoon for the participant vehicles in the CDA alert conditions. This modification could greatly influence driver behavior and provide additional insight into how trusting drivers are of other vehicles they believe are using C-ADS features.

APPENDIX A: POSTDRIVE 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 an automated driving system.
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 locations.

APPENDIX B: POSTDRIVE 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:
6	Did the Level 3 vehicle behave or respond 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.

Bevly, D., Cao, X., Gordon, M., Ozbilgin, G., Kari, D., Nelson, B., Woodruff, J., Barth, M., Murray, C., Kurt, A., Redmill, K., & Ozguner, U. (2016). Lane change and merge maneuvers for connected and automated vehicles: A survey. *IEEE Transactions On Intelligent Vehicles*, *1*, 105–120.

Fitch, G. M., Lee, S. E., Klauer, S., Hankey, J., Sudweeks, J., & Dingus, T. (2009). *Analysis of lane-change crashes and near-crashes*. (Publication No. DOT HS 811 147). National Highway Traffic Safety Administration.

Hu, J., He, L., & Wang, R. (2020). Safety evaluation of freeway interchange merging areas based on driver workload theory. *Science Progress*, *103*(3), 0036850420940878. https://doi.org/10.1177/0036850420940878

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

Liu, H., Kan, X. (David), Shladover, S. E., Lu, X.-Y., & Ferlis, R. E. (2018). Impact of cooperative adaptive cruise control on multilane freeway merge capacity. *Journal of Intelligent Transportation Systems*, *22*(3), 263–275. https://doi.org/10.1080/15472450.2018.1438275

Nallamothu, S., Stark, J., Birriel, E., Inamdar, I. Rosenbohm, N., Shah, A., Ticatch, J. L., Vadakpat, G., & Lochrane, T. (2020a). *Detailed concept of operations: Transportation systems management and operations/cooperative driving automation use cases and scenarios*. (Publication No. FHWA-HRT-20-064).

Nallamothu, S., Stark, J., Birriel, E., Inamdar, I. Rosenbohm, N., Ticatch, J. L., Vadakpat, G., & Lochrane, T. (2020b). *High-level concept of operations: Examination of the relationships between transportation systems management and operations strategies and cooperative driving automation*. (Publication No. FHWA-HRT-20-063).

Olia, A., Razavi, S., Abdulhai, B., & Abdelgawad, H. (2018). Traffic capacity implications of automated vehicles mixed with regular vehicles. *Journal of Intelligent Transportation Systems*, *22*(3), 244–262. https://doi.org/10.1080/15472450.2017.1404680

SAE International. (2014). *Taxonomy and definitions for terms related to on-road motor vehicle automated driving systems*, j3016-201401. SAE International.

Stanton, N. A., & Salmon, P. M. (2009). Human error taxonomies applied to driving: A generic driver error taxonomy and its implications for intelligent transport systems. *Safety Science, 47*(2), 227–237.

Treat, J. R., Tumbas, N. S., McDonald, S. T., Shinar, D., Hume, R. D., Mayer, R. E., Stansifer, R. L., & Castellan, N. J. (1979). *Tri-level study of the causes of traffic accidents: final report. Executive summary*. Indiana University, Institute for Research in Public Safety.

Wallis, W. D., & George, J. C. (2011). *Introduction to combinatorics*. CRC Press.

Wang, M., Hoogendoorn, S. P., Daamen, W., van Arem, B., & Happee, R. (2015). Game theoretic approach for predictive lane-changing and car-following control. *Transportation Research Part C: Emerging Technologies*, *58*(part A), 73–92.

Wolterink, W. K., Heijenk, G., & Karagiannis, G. (2011). Automated merging in a cooperative adaptive cruise control (CACC) system. *Computer Science, Engineering*. https://api.semanticscholar.org/CorpusID:15444229

Xu, Q., Hedrick, K., Sengupta, R., & VanderWerf, J. (2002). Effects of vehicle-vehicle/roadside-vehicle communication on adaptive cruise controlled highway systems. *Proceedings IEEE 56th Vehicular Technology Conference*, *2*, 1249–1253.

Yang, D., C. Y., Ozbay, K., & Ban, X. (2017). Developments in connected and automated vehicles. *Journal of Intelligent Transportation Systems, 21*(4), 251–254. https://doi.org/10.1080/15472450.2017.1337974

Zhu, J., & Tasic, I. (2021). Safety analysis of freeway on-ramp merging with the presence of autonomous vehicles. *Accident Analysis & Prevention*, *152*, 105966. https://doi.org/10.1016/j.aap.2020.105966

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