Response to Emergency Vehicles When Driving in a Mixed Vehicle Fleet

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FOREWORD

Advances in vehicle automation show promise to improve transportation systems management and operations and traffic incident management. Ongoing research on how drivers understand, trust, and use automated vehicles highlights the influence that human factors will have on vehicle automation. Successful transportation networks in the future may depend on a symbiotic relationship between connected-automated vehicles (CAVs) and nonconnected vehicles. CAVs could potentially allow responders to arrive at traffic incidents more quickly. Little is known about how drivers will respond to emergency vehicles in a mixed fleet with different levels of CAV market penetration.

This report documents a driving simulator experiment that explores drivers' behavioral responses to emergency vehicles when traveling within a CAV mixed fleet. This report may be of interest to State and local transportation agencies and traffic incident management responders wanting to understand how CAVs can impact driver behavior in different levels of CAV market penetration.

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Research and Development

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16. Abstract
This study explored the impact of connected vehicle alert messages on drivers' responses to emergency vehicles. The participants drove a simulated vehicle either with or without SAE Level 2 automation (SAE International 2021). During the drive, an emergency vehicle approached the participant from behind. The participants' vehicle connectivity was manipulated so that half the participants received an in-vehicle alert that an emergency vehicle was approaching. Connected-automated vehicle (CAV) market penetration (MP) was also manipulated to create an environment where none, some, or all the surrounding traffic responded to a connected vehicle (CV) with a vehicle-to-vehicle (V2V) emergency vehicle alert. Vehicle kinematics and eye tracking were used to assess the impact of vehicle automation, V2V communication, and CAV MP on drivers' responses to emergency vehicles. The research team found CV alerts to be effective in getting the participants to yield to the approaching emergency vehicle. Drivers with CV alerts led to increased pullover rates and reduced speeds to pull over sooner than the participants without CV alerts. The participants driving Level 2 vehicles with CV alerts in low or full MP reduced speeds much sooner than the participants in no MP. These benefits were greatest in the full MP condition. However, in low or full MP, the participants in Level 2 vehicles who received CV alerts reduced speeds slightly later than the participants with manual vehicles who received CV alerts. Eye-tracking analyses found that the participants receiving CV alerts tended to spend more time gazing at the console and less time gazing at the roadway during the period when the emergency vehicle appeared to when the emergency vehicle passed. No crashes occurred at any time when the emergency vehicle appeared or when vehicles reentered the roadway. Overall, this study's findings support a promising future of V2V communication for emergency vehicle awareness and response and the potential for CAVs to help responders arrive at traffic incidents more quickly.

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SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or “metric ton”)	Mg (or “t”)
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or “t”)	megagrams (or “metric ton”)	1.103	short tons (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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

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LIST OF ABBREVIATIONS

CAV	connected-automated vehicle
CV	connected vehicle
FHWA	Federal Highway Administration
ITS	intelligent transportation system
MP	market penetration
TIM	traffic incident management
TSMO	transportation systems management and operations
V2I	vehicle-to-infrastructure
V2V	vehicle-to-vehicle

CHAPTER 1. INTRODUCTION

Transportation system management and operations (TSMO) refers to an integrated set of strategies designed to optimize the safety and reliability of a road network (Viriyasitavat and Tonguz 2012). Transportation agencies use TSMO to reduce congestion and manage the impact of nonrecurring events on the traffic network. One area of focus is traffic incident management (TIM). Unexpected incidents can reduce both the operational capacity and safety of a roadway. Incidents such as crashes, disabled vehicles, or spilled cargo can hamper the flow of traffic where the incident is occurring (Owens et al. 2010). Furthermore, travelers who reach the end of an unexpected queue or who are distracted by traffic incidents are at risk of being involved in secondary incidents. TSMO's goal is to minimize the impact of an incident. This goal can be facilitated by the rapid arrival of TIM responders. In addition to directly helping those who may be injured or at risk of injury, TIM responders help guide traffic around the incident and clear the roadway (Owens et al. 2010). The prompt arrival of responders can help ensure the safety of those directly involved in the incident, minimize the risk of secondary collisions, and reduce the negative impact the incident will have on the operation of the transportation system.

Connected-automated vehicles (CAVs) could potentially help responders arrive at traffic incidents more quickly. Multiple traffic simulation studies suggest that automated systems can use messages transmitted by connected emergency vehicles to create travel plans that speed the response of emergency vehicles while having a minimal effect on nonemergency vehicles traveling within the road network (See references Lu and Kim 2017; Jordan and Cetin 2014; El-Dalil, Sharkas, and Khedr 2017; Xie et al. 2017; Viriyasitavat and Tonguz 2012).

For example, Xie et al. (2017) studied the speed of emergency vehicle responses within a traffic simulation model of an intelligent transportation system (ITS) in which all vehicles and infrastructure were connected. Emergency vehicles transmitted information about their intended route and current lane via vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication. The receiving infrastructure responded by turning stoplights in the path of the emergency vehicle green. Connected Vehicles (CVs) cleared a path for the emergency vehicle by changing lanes and yielding at intersections. Compared to a conventional transportation system in which V2V and V2I communication was not possible emergency, vehicles within this simulated ITS were able to reach their destinations more quickly. The benefit of CAVs was found across a variety of road configurations, travel path lengths, and traffic volumes.

Research on interactions among CAVs and emergency vehicles has focused on highly automated driving systems (i.e., SAE Level 4 or Level 5) (SAE International 2021). The goal has been to generate and test algorithms that optimize the response of automated systems to emergency vehicle communications. Communication among connected emergency vehicles and drivers operating vehicles with lower levels of automation (i.e., Level 2 or Level 3) may also benefit from a TIM response. For example, responding to emergency vehicles is likely to be outside the operational domain of many Level 3 systems. Receiving intended path information from an emergency vehicle could allow a Level 3 system to initiate a takeover request more quickly, giving drivers more time to respond to the emergency vehicle and, thus, improving efficiency and safety.

Messages transmitted by connected emergency vehicles could be even more beneficial to drivers operating a Level 2 system (SAE International 2021). When using a Level 2 automated system, the driver is responsible for recognizing when it is safe to use the system and when the system should not be used. Unlike drivers operating a vehicle with a Level 3 system, drivers operating a Level 2 system cannot rely on the automated system to identify or alert them when an emergency vehicle is present. Therefore, V2V communication has the potential to increase the distance at which a driver can detect an approaching emergency vehicle (Xie et al. 2017).

In most cases, emergency vehicles transmit information about their location via lights and sirens. The distance at which drivers detect these signals is impacted by many factors, including siren pitch, the direction from which the vehicle is approaching, the amount of background noise in the area, and the number of objects in the environment because trees and buildings can block sound (Maddern, Privopoulos, and Howard 2011). Detection distances are reduced by noise-cancelling vehicle insulation, radio use, and hearing loss (De Lorenzo and Eilers 1991). Increasing siren volume is not a viable means of increasing emergency vehicle detection. Sirens with high volumes become a nuisance to communities and can cause hearing loss in emergency vehicle drivers, and unnecessary stress for patients during transport (Kupas 2017). According to Skeiber, Mason, and Potter (1978), "sirens will never become an effective warning device without also becoming an intolerable community noise problem. Order of magnitude improvements in future warning effectiveness will have to be based upon non-auditory means." In-vehicle alerts issued by connected emergency vehicles have the potential to serve as a nonauditory means of notifying drivers of an emergency vehicle (Skeiber, Mason, and Potter 1978).

Connected emergency vehicles offer the potential to increase the distance at which drivers can detect emergency vehicles. If drivers can use this information to successfully clear a path for an emergency vehicle, the time required for responders to reach a traffic incident could be reduced. One factor that may impact driver response is CAV market penetration (MP). Studies on speed and response to traveler information have demonstrated that drivers are influenced by the actions of vehicles around them (Xuan and Kanafani 2014). Since the introduction of CAVs is expected to be gradual, some drivers may receive connected messages while driving among vehicles that have not received the same information. In other instances, a driver may be traveling among CAVs that are receiving information unknown to the driver. Understanding the impacts of different levels of CAV MP on drivers' responses to emergency vehicles could help TIM responders prepare to operate in mixed fleets.

This study explored the potential for V2V communication to speed drivers' responses to emergency vehicles. The participants operating either a manual vehicle or a vehicle with Level 2 automation drove in a semiurban environment. After a period of driving, the participants became the third vehicle in a four-vehicle string. An emergency vehicle approached the string from behind. Participant vehicle connectivity was manipulated so that half of the participants received an in-vehicle message indicating that the emergency vehicle was approaching. CAV MP was also manipulated. In the "no MP" condition, none of the surrounding vehicles received an alert about the approaching emergency vehicle. In the "low MP" condition, the vehicle directly in front of the participant vehicle received an alert and responded by pulling onto the shoulder of the roadway. In the "full MP" condition, all three vehicles in the string received and responded to the alert. The participants' response time to the emergency vehicle were measured. Vehicle kinematics and eye tracking were also measured to judge the impact of vehicle automation, V2V communication, and CAV MP of drivers' responses to emergency vehicles. The goal of this research was to examine how the driver changes the vehicle's speed/position in response to the emergency vehicle, investigate where the driver is looking after the emergency vehicle alert, and observe other safety metrics related to getting back on the road.

CHAPTER 2. METHOD

PARTICIPANTS

Ninety-six drivers from the Washington, DC, metropolitan area participated in the study. Forty-eight males and 48 females participated, and an equal number of males and females under the age of 46 yr and 47 yr or older completed the study.

APPARATUS

Simulator

The study was conducted using the Federal Highway Association's (FHWA) highway driving simulator at Turner-Fairbank Highway Research Center. The highway driving simulator consists of a full automobile chassis surrounded by a semicircular projection screen (radius of 8.5 ft). Three high-definition projectors rendered a 200° view (motorists' field of view) of high-fidelity, computer-generated roadway scenes. Three liquid-crystal display panels simulated the vehicle's rearview mirror and side mirrors. The simulator had a 6-degree-of-freedom motion base that provided 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 provided engine, wind, tire noises, and other environmental sounds.

Simulator Scenario

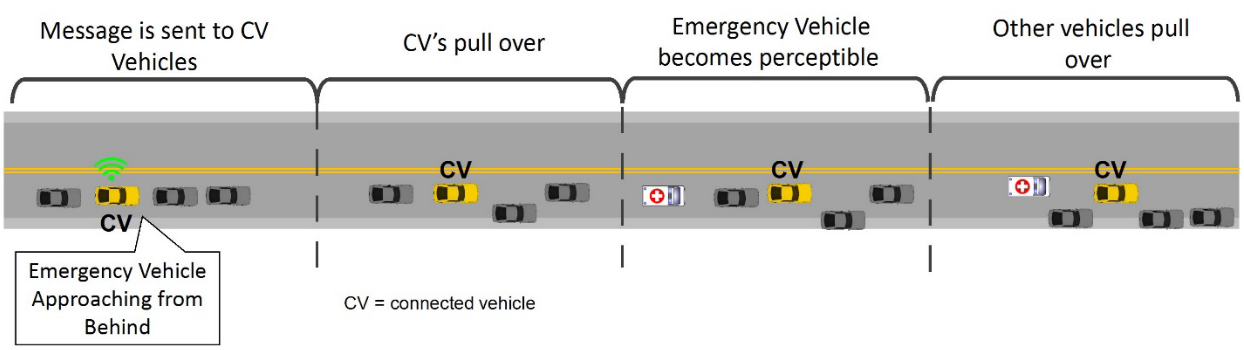
The participants drove on an 18-mi undivided two-lane road in a semiurban environment. The roadway was 12-ft wide and had a 3-ft shoulder. Light traffic in the opposing lane was included to deter the participants from crossing the lane boundary. The point at which the participants encountered the emergency vehicle was manipulated between subjects. Half the participants traveled for 11 mi before encountering drivers in their travel lane, and half the participants traveled for 2 mi. During this 11-mi drive, the participants passed additional elements of a semiurban road environment, including a marked bicycle lane with a single bicyclist, a transition to a shared bicycle lane, and a single bicyclist traveling on the side of the roadway in the shared bicycle lane.

During the drive, the participants passed through a signalized intersection where a vehicle was waiting on the cross street. When the participant's vehicle cleared the intersection, the waiting vehicle turned onto the roadway the participant was traveling on so that it followed the participant's vehicle. The trailing vehicle accelerated until there was a 1.1-s gap between the trailing vehicle and the participant's vehicle, and the trailing vehicle maintained that gap. Two miles after passing the first intersection, the participant approached another signalized intersection where two vehicles were waiting at a red light. When the gap distance between the participant's vehicle and the vehicle at the back of the queue reached 1.5 s, the light turned green, and the two vehicles accelerated to 35 mph such that the participant vehicle became the third vehicle within a four-vehicle string.

As depicted in figure 1, the vehicles traveled together for approximately 1 mi, at which point, a simulated emergency vehicle traveling at 45 mph appeared to approach 1,000 ft behind the participant vehicle. When the emergency vehicle was within 1/10 of a mile from the participant vehicle, an auditory siren was sounded and increased in volume as the emergency vehicle approached the participant vehicle. The participants in the CV condition received an alert on the center console indicating that an emergency vehicle was approaching from behind (the participants without vehicle connectivity did not receive an alert). The alert (shown in figure 2) included an audio component and a written message displayed in the center console of the vehicle. One second after the alert was issued (or would have been issued), any simulated CVs within the string began pulling over to the right shoulder of the road. The participants in the full and low MP conditions observed other vehicles in the string pulling over onto the shoulder of the roadway.

- In the full MP condition, all three vehicles in the string pulled over.
- In the low MP condition, only the vehicle directly in front of the participant vehicle pulled over, and the other two vehicles continued driving down the roadway.
- In the no MP condition, none of the vehicles pulled over.

Approximately 1 s after the simulated CVs pulled over, simulated vehicles within the string that were not connected (i.e., the simulated vehicles that had not already pulled over based on the in-vehicle alert), began pulling to the side of the roadway. Shortly afterward, the emergency vehicle appeared in the driver's rearview mirror. The participant was free to decide when to pull over or whether to pull over. The emergency vehicle maintained a 2-ft gap while passing the participant's vehicle and then exited the roadway at the nearest intersection approximately 1 mi downstream. After the emergency vehicle had passed, the remaining vehicles returned to the roadway and traveled to the next intersection where they also exited the roadway. The participant then continued to drive in the semiurban environment for one additional mile.



Source: FHWA.

Figure 1. Illustration. Simulated scenario.

Source: FHWA.

Figure 2. CV alert message.

Eye-Tracking System

A fixed eye-tracking system was used to collect participant glance data. The system was composed of three fixed cameras mounted on the vehicle's dashboard and focused on the participant's eyes. The fixed system required the participant to wear additional sensors. Prior to use, the system was calibrated to each participant's unique body dimensions.

EXPERIMENTAL DESIGN

The 96 participants were divided equally across 3 independent variables. Table 1 displays the number of participants for the three independent variables included in this study, all of which were manipulated between subjects. First, the level of vehicle automation was manipulated so that half the participants drove a manual vehicle and half drove a vehicle with Level 2 automation (SAE International 2021). Second, vehicle connectivity was also manipulated. Half the participants drove a CV that received an in-vehicle alert, and the other half received no alert. Third, the level of CAV MP of the surrounding traffic was manipulated. In the no MP condition, none of the other three vehicles the participant was traveling with on the roadway received an advanced alert about the emergency vehicle. In the low MP condition, one of the three other vehicles received an advanced alert that the emergency vehicle was approaching and pulled over to the side of the road in response to the alert. In the full MP condition, all three vehicles received alerts about the approaching emergency vehicle and pulled over in response to the message. In the low MP condition and the full MP condition, the vehicles received the alerts before the emergency vehicle was visible to the driver.

Table 1. Experimental design table.

Level of CAV MP	Manual Vehicle: CV Alerts	Manual Vehicle: No CV Alerts	Level 2 Vehicle: CV Alerts	Level 2 Vehicle: No CV Alerts	Total
None	8	8	8	8	32
Low	8	8	8	8	32
Full	8	8	8	8	32
Total	24	24	24	24	96

PROCEDURE

The research team asked the participants to review and sign an informed consent. The participants had to show a valid driver's license. The team used a Bailey-Lovie eye chart to verify a minimum of 6/12 (20/40) visual acuity, with correction if necessary (Bailey and Lovie 2013). The participants provided a symptoms baseline by completing a simulator sickness questionnaire.

Next, the participants received study instructions. All participants received a brief introduction to the concept of connected and automated vehicles. The participants assigned to a Level 2 automation condition viewed a brief presentation describing the functions of the lateral and longitudinal systems present in their vehicles (SAE International 2021).

The participants then completed a practice drive to become familiar with the simulator. Each practice drive lasted 3–5 min, with the exact time determined by how long it took an individual participant to become familiar and comfortable with the controls of the simulated vehicle. During the practice drive, the research team asked the participants to accelerate, brake, and change lanes. The participants assigned to the Level 2 condition performed these tasks with the Level 2 system engaged (SAE International 2021). The participants in the CV condition received an alert during the practice drive. After completing the practice drive, the participants exited the vehicle and completed the simulator sickness questionnaire a second time. The participants then completed the simulated scenario and were paid before leaving.

ANALYSIS

The goal of the analysis was to investigate the participants' responses to an emergency vehicle and any effects on driving safety. The study team assessed the participant's responses with driving performance measures such as distance, speed, steering wheel variability, lane position, acceleration/deceleration, and following distance. The researchers used eye tracking to assess in-vehicle alerts as a source of distraction while driving. The researchers used appropriate statistical analysis to test the associations between variables for each dependent variable. These analyses were used to assess the impact of vehicle automation, V2V communication, and CAV MP on drivers' responses to emergency vehicles. A significance level of 0.05 was adopted.

CHAPTER 3. RESULTS

The analysis investigated the participants' responses to the emergency vehicle and any effects on driving safety. The study team assessed the participants' behavior by examining what proportion of the participants responded to the emergency vehicle by pulling over, the participants' response latency, and the participants' eye gaze on center stack, mirrors, and roadway. The team examined the effects on driving safety of the participants' distance to other vehicles at the time the emergency vehicle passed, the participants' blinker usage, the number of vehicle incidents when the participant reentered the roadway, the participants' driving speed, speed variability, following distance, and lane variability.

RESPONSE TO EMERGENCY VEHICLE

Driver performance metrics were used to assess participant response to the emergency vehicle. The metrics investigated were as follows: Pullover behavior, response latency, and eye gaze.

Pullover Behavior

The researchers examined the proportion of the participants responding to the emergency vehicle by pulling over as a function of vehicle automation level, CV condition, MP, age, and gender. Seventy-six of the 96 study participants pulled over and 20 participants did not. Table 2 shows the number of participants who pulled over by vehicle automation type, CV type, and MP conditions. Examining pullover rates by vehicle automation showed that for manual vehicle participants, 41 out of 48 (85 percent) pulled over versus 35 out of 48 (73 percent) of Level 2 vehicle participants (SAE International 2021). Pullover rates by CV type showed that more participants with alerts pulled over (43 out of 48 (89 percent) compared to the participants without alerts (33 out of 48 (69 percent)). Pullover rates by MP revealed roughly equal proportions across full, low, and no MP.

Table 2. Pullover behavior by vehicle automation type, CV type, and MP.

Pulled Over?	Manual Vehicle	Level 2 Vehicle	CV Alert	No CV Alert	Full MP	Low MP	No MP
Yes	41	35	43	33	26	26	24
No	7	13	5	15	6	6	8
Total	48	48	48	48	32	32	32

An exact logistic regression that examined the association between the pullover decision and the independent variables showed that the participants who received an alert about an approaching emergency vehicle were 3.5 times (p = .013) more likely to pull over than the participants who did not receive an alert. No significant evidence showed that vehicle automation and CAV MP could affect the participants' decisions to pull over. No statistical evidence of gender or age influence was found.

The research team investigated how far the participants moved their vehicles toward the right edge to yield to the passing emergency vehicle. The team examined the distance between the center of the participant vehicle and the left edge of the right line marking the right lane. As shown in table 3. Level 2 and manual vehicle participants who pulled over positioned their vehicles on average 3.5 and 3.1 ft from the right line (SAE International 2021). For manual vehicle participants who did not pull over, they positioned their vehicle an average of 3.1 ft from the right line at the time the emergency vehicle passed. The Level 2 automation participants who did not pull over were found to move over less and farther from the right line (4.9 ft) compared to the other participants.

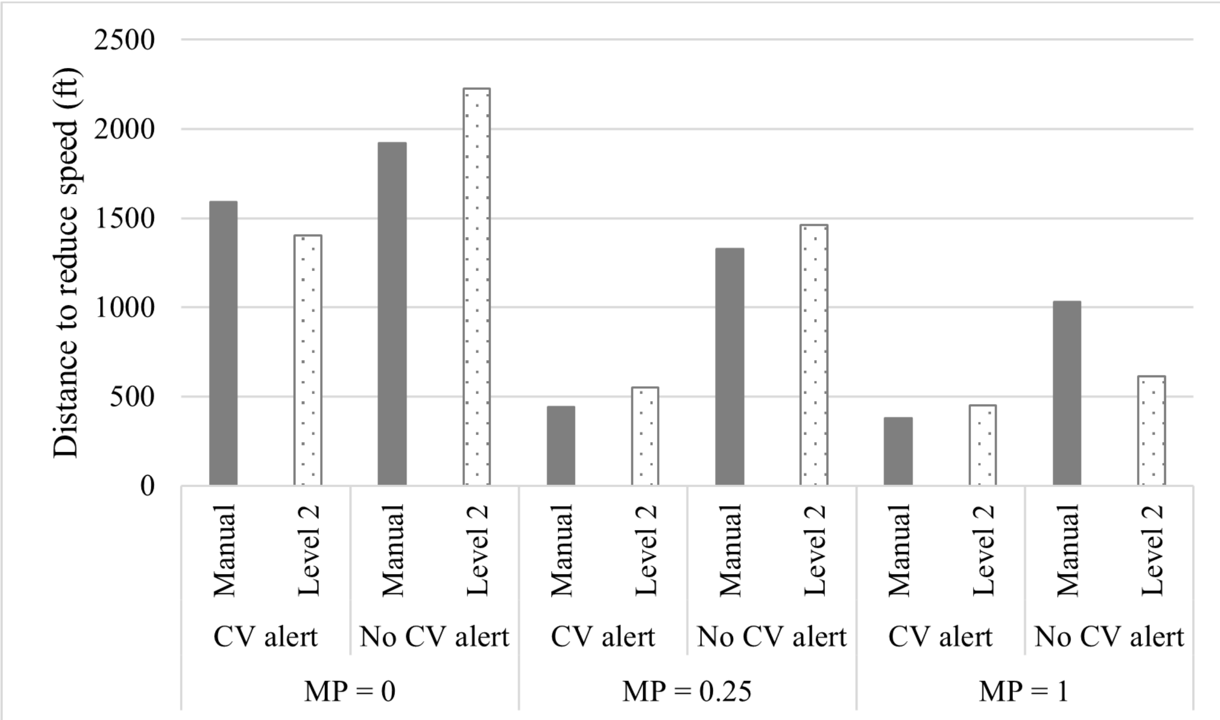
Table 3. Average pullover distance at time emergency vehicle passes.

Pulled Over?	Level 2 Vehicle (ft)	Manual Vehicle (ft)
Yes	3.5	3.1
No	4.9	3.1

Response Latency

The research team investigated how quickly the participants responded to an emergency vehicle. The team assessed the distance the participants traveled before reducing their vehicle speeds to 20 mph after the emergency vehicle had appeared. Figure 3 shows the mean distances traveled as a function of MP, CV condition, and vehicle automation. Across the three MP levels, higher levels of MP tended to result in less distance to reduce speeds. Within MP levels, the participants receiving CV alerts tended to reduce their speeds sooner (i.e., travel less distance) than the participants not receiving alerts.

Linear regression showed a significant interaction between MP, CV condition, and vehicle automation ($p = 0.022$). At full MP, the participants in Level 2 vehicles with CV alerts reduced speeds sooner (and traveled about 4132 ft less) than the participants in Level 2 vehicles without CV alerts (SAE International 2021). However, the participants in Level 2 vehicles with CV alerts reduced speeds later (and traveled about 61 ft farther) than those driving manual vehicles with CV alerts. When comparing the participants driving Level 2 vehicles with CV alerts, those who were in full MP reduced speeds much sooner (on average traveled about 678.5 ft less) than those in no MP. When comparing the participants driving Level 2 vehicles with CV alerts in full versus low MP, the participants who were in a full MP fleet reduced speeds sooner (on average about 95 ft less) in distance than those in low MP.



Source: FHWA.

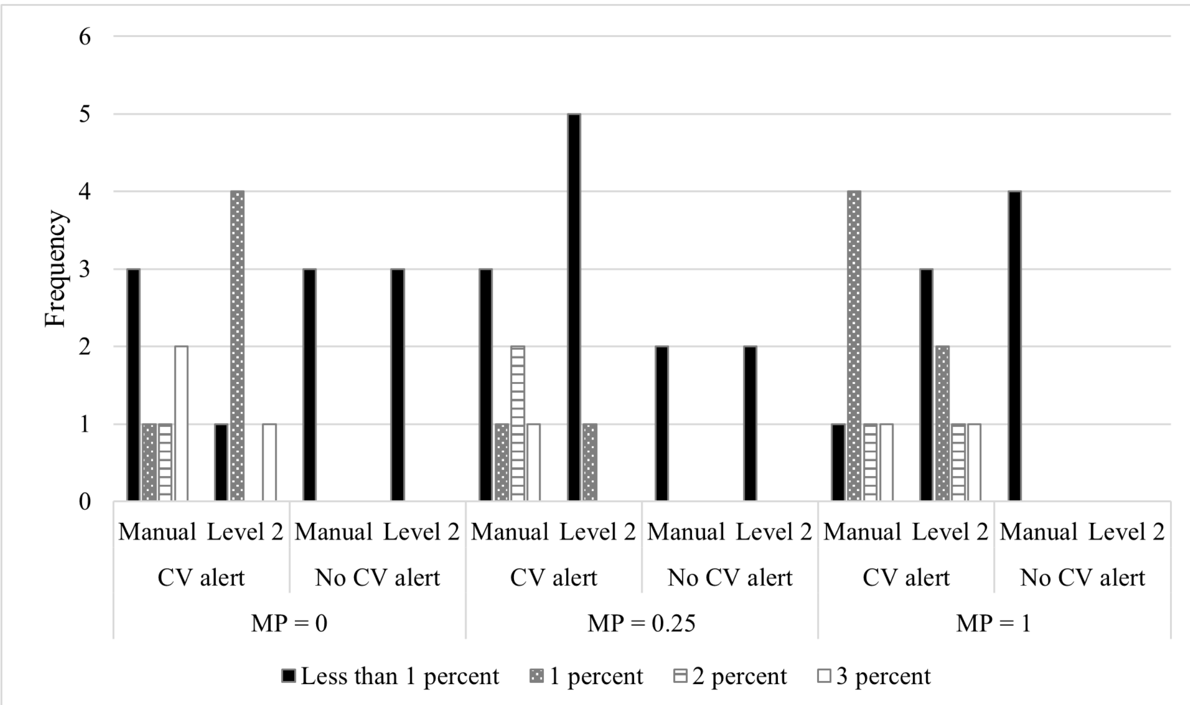
Figure 3. Graph. Mean distance to reduce speed by MP, connectivity, and vehicle automation.

Eye Gaze on the Console

The researchers classified the participants' eye gaze as either looking out the front windshield (i.e., center projection), side windows (i.e., left/right screen), at locations inside the vehicle (e.g., center stack console), or at the left/right mirrors. To assess a participant's behavior monitoring the emergency vehicle, the research team examined the proportion of time the participant spent on the center stack console. The proportion of time was during the period between when the emergency vehicle appeared and when the emergency vehicle passed the participant. During this period, 54 participants looked at the center stack console, and 42 participants did not look at it. Figure 4 displays the frequency of the participants by proportion of time as a function of MP, CV condition, and vehicle automation. In general, most of the participants (30 out of 54 (56 percent)) tended to have shorter gaze times (less than 1 percent) as depicted in the solid black bars. The frequency for longer gaze times tended to decrease with longer times.

Examination of gaze times in terms of MP, connectivity, and vehicle automation found the following:

- The frequency of the participants were relatively evenly divided between the 0, 0.25, and 1 MP levels (19, 17, and 18, respectively).
- Most of the participants who gazed at the center console also had CV alerts (40 out of 54).
- The frequency was slightly higher for the participants with manual versus Level 2 vehicles (30 versus 24 participants).

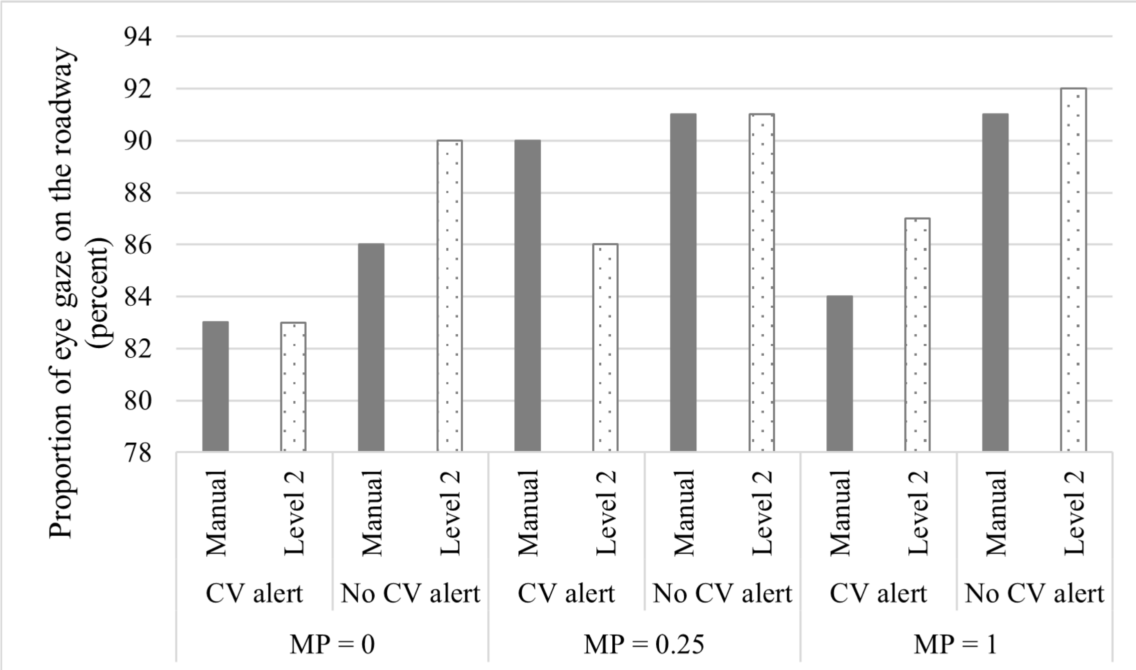


Source: FHWA.

Figure 4. Graph. Frequency and proportion of time of console eye gazes by MP, connectivity, and vehicle automation.

Eye Gaze on the Road

The research team also examined the proportion of time the participants spent looking at the roadway (left/right screen and center projection) during the period between when the emergency vehicle appeared and when the emergency vehicle passed the participant. Figure 5 displays the frequency of proportion of a participant's eye gaze on the roadway as a function of MP, CV condition, and vehicle automation. Regardless of MP level, the participants with CV alerts tended to spend slightly less time gazing at the roadway. A Poisson regression showed that the participants with CV alerts had about 7 percent ($p = 0.0001$) reduction in the time they spent looking at the roadway compared to the participants whose vehicles did not have CV alerts (Frost 2012). No other effects were found to be statistically significant.

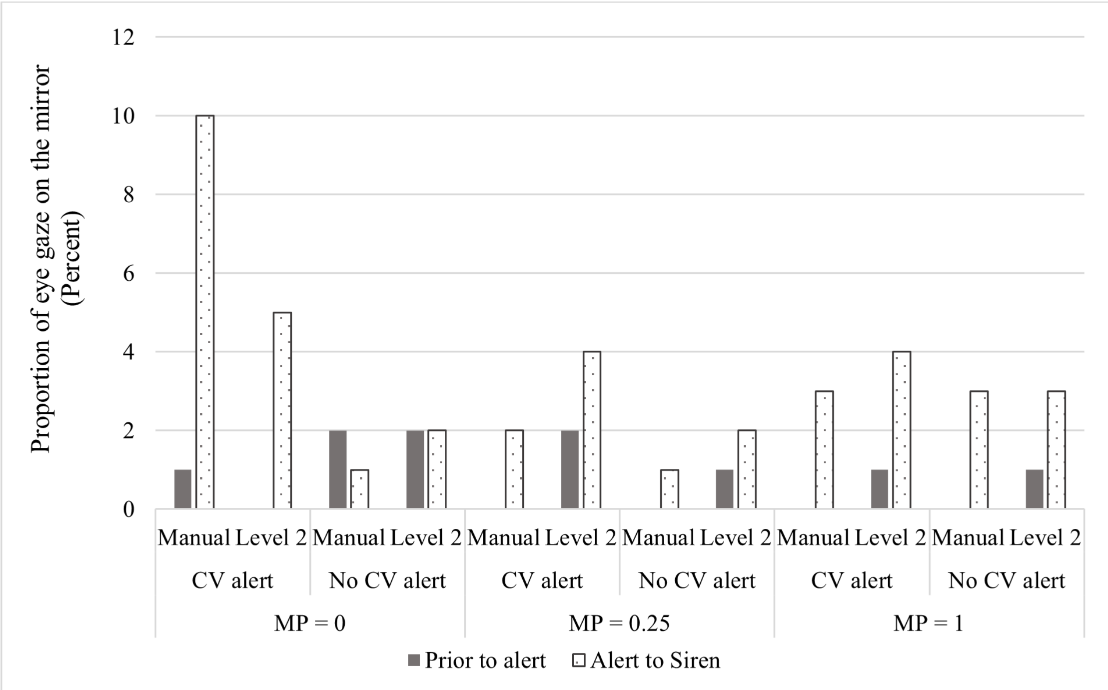


Source: FHWA.

Figure 5. Graph. Proportion of road eye gazes by MP, connectivity, and vehicle automation.

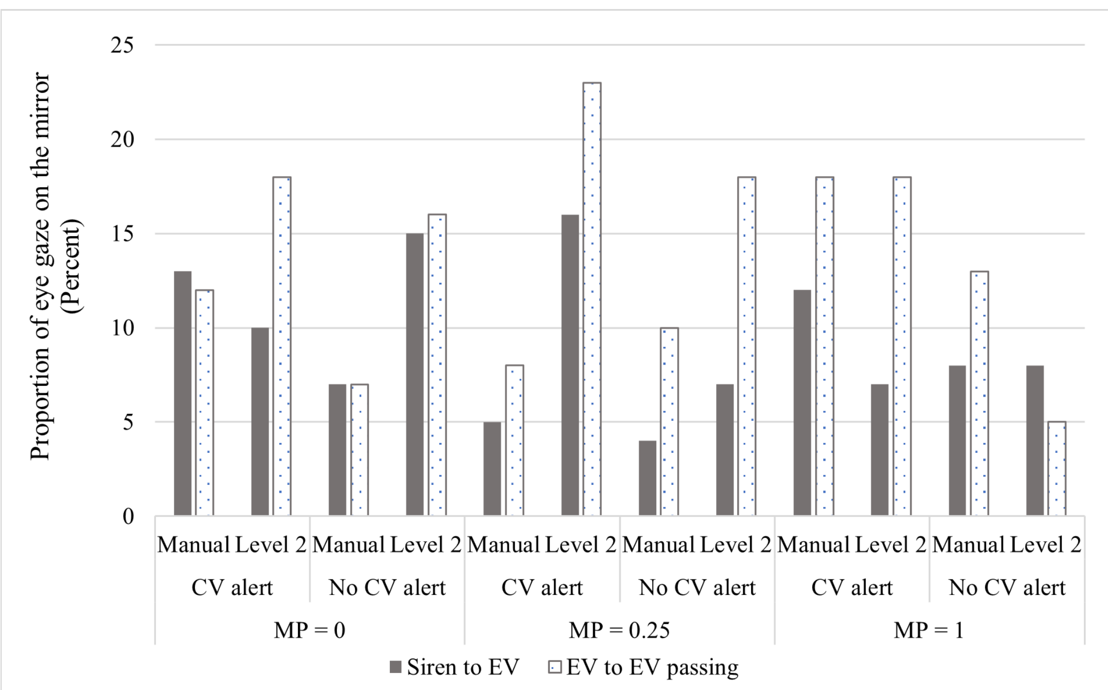
Eye Gaze on Rearview Mirror and Side Mirrors

The research team examined the proportion of time the participants spent looking at the rearview mirror and side mirrors during four intervals as a function of MP, connectivity, and vehicle type. The four intervals were: time from an emergency vehicle appearing (1,000 ft behind the participant's vehicle) to the alert; from alert to siren; from siren to the emergency vehicle in sight; and from the emergency vehicle in sight to the emergency vehicle passing. Figure 6 shows intervals before the alert and between the provided alert to when the siren sounded. Figure 7 shows intervals between the siren sounding to the emergency vehicle in sight and between the emergency vehicle in sight to the emergency vehicle passing. Figure 6 shows that prior to the alerts, the participants spent 2 percent or less time gazing at the mirrors regardless of MP, connectivity, or vehicle type. During the interval between alert to siren on, only the participants in the no MP condition that had CV alerts increased their eye gazes to more than 5 percent. Figure 7 shows that during the intervals after the siren was on, all participants tended to increase their gazes on the mirrors compared to before the siren was heard by the participants. During the interval between emergency vehicles in sight and until the emergency vehicle passed, Level 2 participants generally used the mirrors more than the manual participants in similar MP and connectivity conditions.



Source: FHWA.

Figure 6. Graph. Proportion of mirror eye gaze before siren.



Source: FHWA.

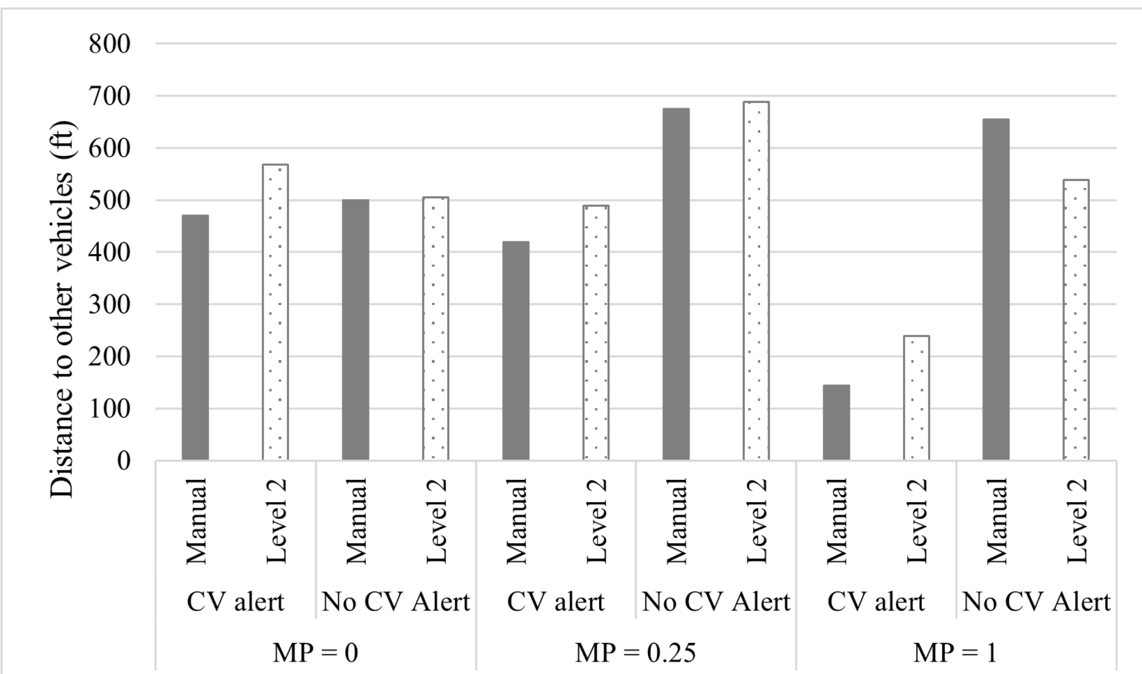
Figure 7. Graph. Proportion of mirror eye gaze after siren.

EFFECTS ON DRIVING SAFETY

Distance to Other Vehicles

The research team examined the mean distance between the participant vehicle and the other three vehicles at the time the emergency vehicle passed. Figure 8 displays the mean distances by MP, CV condition, and vehicle automation. In the no MP level condition, the average distance to other vehicles was relatively similar, and ranged from 469 to 568 ft regardless of connectivity and vehicle automation. In the low MP level condition, the average distance to other vehicles showed greater disparity between those vehicles with and without CV alerts. The participants with CV alerts ranged from 420 to 489 ft versus 673 to 686 ft for the participants without CV alerts. In the full MP level condition, the average distance to other vehicles showed the greatest disparity between those vehicles with and without CV alerts. The participants with CV alerts ranged from 141 to 240 ft versus 538 to 656 ft for the participants without CV alerts. A significant interaction between CV and MP ($p < 0.0001$) was found, indicating that the participants with CV alerts in low MP and full MP were significantly closer to the other vehicles at the time the emergency vehicle passed compared to those in no MP.

Linear regression showed that the participants driving Level 2 vehicles were significantly farther away (16 m, $p = 0.02$) from the other vehicles at the time of emergency vehicle passed compared to those driving manual vehicles.



Source: FHWA.

Figure 8. Graph. Mean distance between vehicles.

Blinker Use

The research team recorded the participants' use of right or left blinkers at the time the participants yielded to an emergency vehicle and when the participants returned to the roadway. As shown in table 4, male drivers used the blinkers more than female drivers (32 out of 48 male drivers used the right blinkers versus 21 out of 48 female drivers at the time the participant yielded to the emergency vehicle; 26 out of 48 male drivers used the left blinkers versus 14 out of 48 female drivers when returning to the roadway).

No significant association between the use of blinkers and the independent variables was found. Male drivers were found to be 2.5 times ($p = 0.04$) more likely to use the right blinker and 2.8 times ($p = 0.02$) more likely to use the left blinker than female drivers.

Table 4. Blinker use by gender when yielding to the emergency vehicle and returning to roadway.

Gender	Used Right Blinker to Yield	Did Not Use Right Blinker to Yield	Used Left Blinker to Return to Roadway	Did Not Use Left Blinker to Return to Roadway
Male	32	16	26	22
Female	21	27	14	34

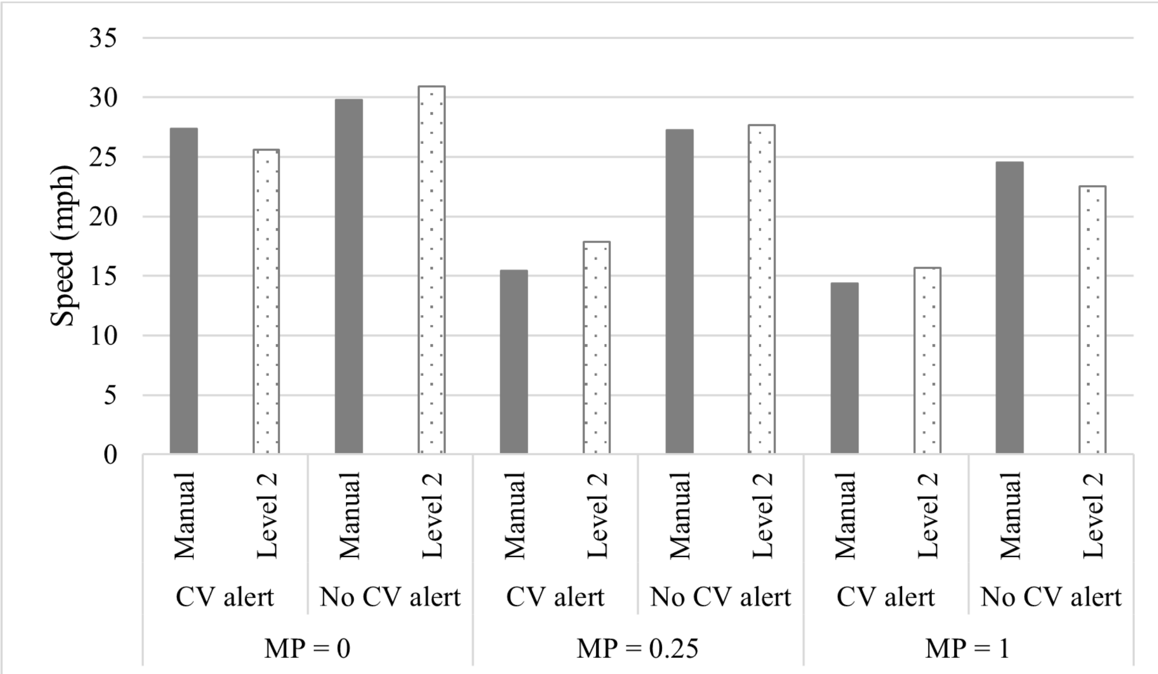
Vehicle Incidents

The research team observed no vehicle crashes when drivers reentered the roadway shortly after the emergency vehicle had passed.

Driving Speed and Variability

The participants traveled down an undivided two-lane road in a semiurban environment with a 35-mph speed limit. The participants were instructed to drive as they normally would on the roadway. The research team examined speeds to investigate if any of the independent variables affected driving speeds. Figure 9 shows the mean speeds during the interval from emergency vehicle appearance to emergency vehicle passing the participant as a function of MP, CV condition, and vehicle automation. Participant speeds in the no MP condition (25.7–30.8 mph) tended to be faster than participant speeds in the low MP condition (15.4–27.6 mph) and full MP condition (14.3–24.3 mph).

Linear regression showed significant interaction between CV and MP. The participants with CV alerts in low MP had, on average, a lower speed (6.9 mph slower, $p < 0.0001$) than those in a no MP fleet. The participants with CV alerts in full MP had a lower speed (4.6 mph slower, $p = 0.003$) than those in a no MP fleet. Evidence showed no significant effect of vehicle automation on driving speed. The significant effects of gender and age were not found.

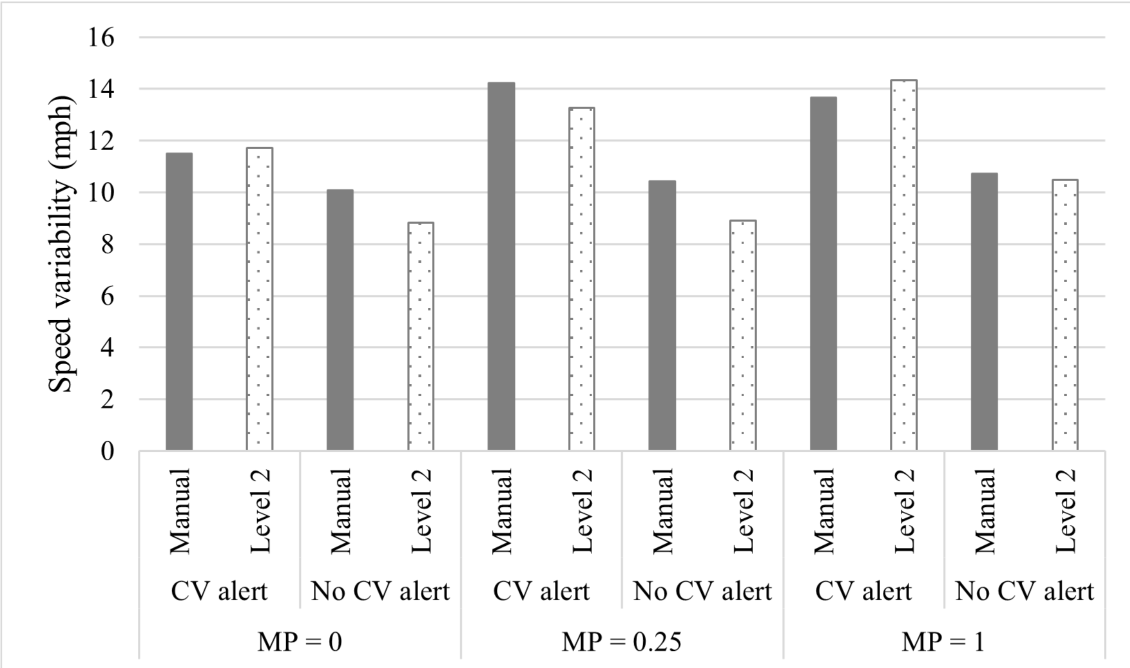


Source: FHWA.

Figure 9. Graph. Mean speeds by MP, connectivity, and vehicle automation.

The research team investigated speed variability to identify if MP, CV condition, and vehicle automation had any effect on speed variability. Figure 10 shows the speed variability as a function of MP, CV condition, and vehicle automation. Within each MP level, the participants with CV alerts tended to have greater speed variability than the participants without CV alerts.

A robust linear regression showed significant interaction between CV and MP. The participants with CV in low MP had, on average, a greater speed variability (3.3 mph greater, $p = 0.0003$) than those in a no MP fleet. The participants with CV alerts in full MP had a greater speed variability (2.7 mph greater, $p = 0.003$) than those in a no MP fleet. Evidence showed no significant effect of vehicle automation on variability of driving speed. The significant effects of gender and age were not found.



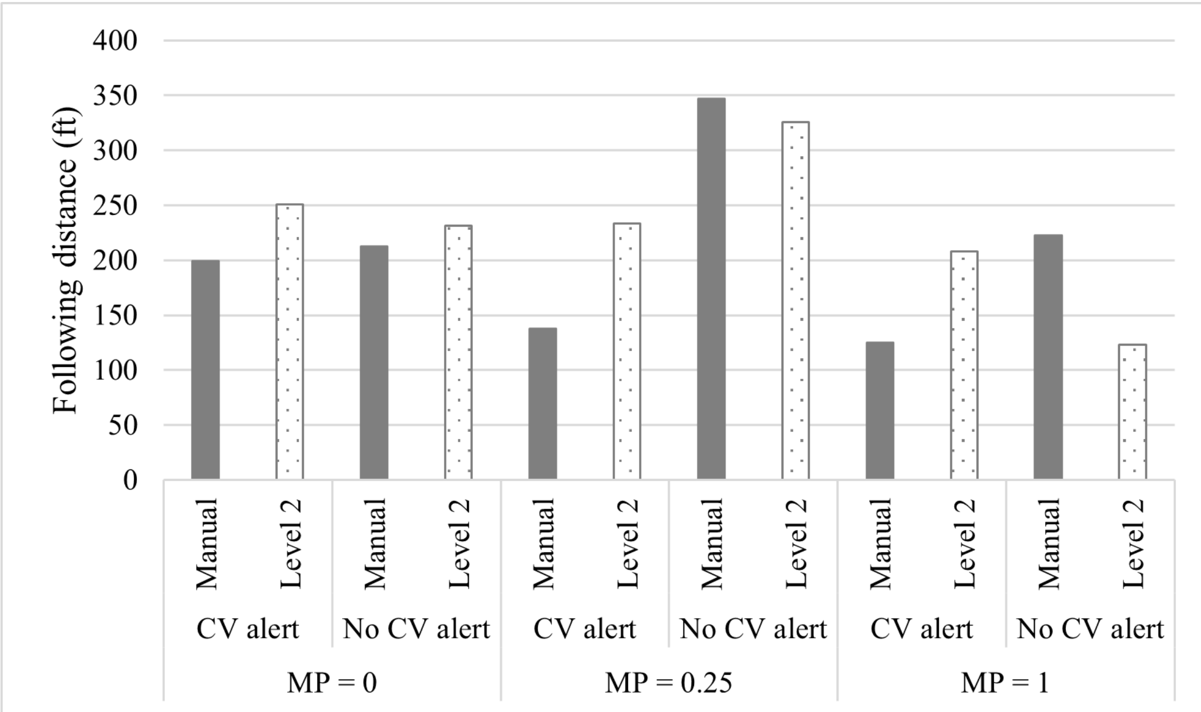
Source: FHWA.

Figure 10. Graph. Speed variability by MP, connectivity, and vehicle automation.

Following Distance

The participants drove as the third vehicle in a four-vehicle string when the emergency vehicle appeared. The research team examined the participants' average following distance to assess if any of the independent variables affected following distance. Figure 11 shows the average following distance as a function of MP, CV condition, and vehicle automation. Across all MP levels, the participants with CV alerts and manual vehicles tended to have shorter following distances compared to the participants with CV alerts and Level 2 vehicles.

A robust linear regression showed an interaction between CV and MP as well as vehicle automation and MP was found to be statistically significant (both $p < 0.05$). In low MP, the participants with CV alerts on average had 151 ft shorter following distance compared to those without CV alerts. In full MP, the participants driving Level 2 vehicles on average had 98.4 ft shorter following distance compared to those who driving manual vehicles. No effect of gender and age was found.



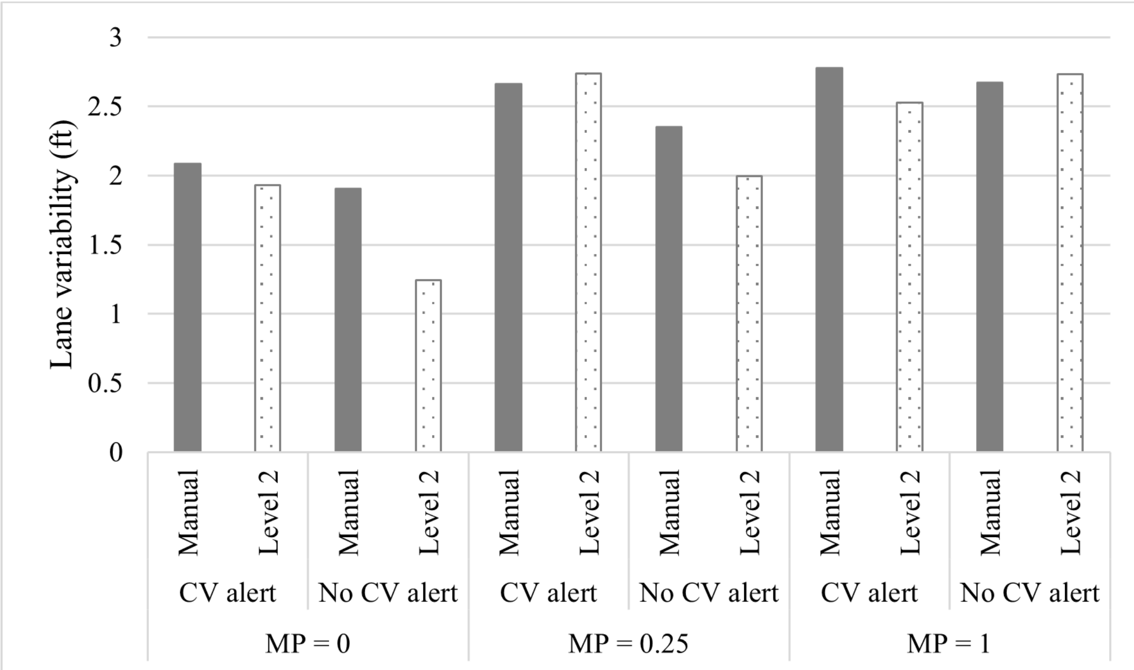
Source: FHWA.

Figure 11. Graph. Mean following distance by MP, connectivity, and vehicle automation.

Lane Variability

Figure 12 shows the average lane variability by MP, connectivity, and vehicle automation. The participants driving in no MP conditions had slightly less lane variability compared to participants driving in low or full MP conditions. In the no MP conditions, the participants' driving Level 2 vehicles had slightly less lane variability than those driving manual vehicles. This result was especially apparent for the participants without CV alerts (1.24 ft versus 1.90 ft). In the low MP conditions, the participants driving Level 2 vehicles again had slightly less lane variability than those driving manual vehicles but only when the participants did not have CV alerts. In the full MP condition, the lane variability for both connectivity and vehicle conditions were in the upper range (2.53–2.76 ft) compared to the no and low MP levels.

A robust linear regression showed that the participants driving Level 2 vehicles had slightly lower (0.23 ft, $p = 0.03$) lane variability compared to those driving manual vehicles. The participants in the low and full MP conditions had slightly more lane variability (0.43 ft, $p = 0.0006$ and 0.75 ft, $p < 0.0001$, respectively) compared to those in the no MP conditions. A significant interaction was not found between MP, connectivity, and vehicle automation. No significant interaction was found in age and gender effects.



Source: FHWA.

Figure 12. Graph. Mean lane variability as a function of MP, connectivity, and vehicle automation.

CHAPTER 4. DISCUSSION

Connected emergency vehicles communicating to CVs offer the potential to increase the distance at which drivers can detect emergency vehicles (Xie et al. 2017). This study found that CV alerts were effective in getting the participants to yield to an approaching emergency vehicle. Driving with CV alerts led to increased pullover rates and reduced speeds to pull over sooner than the participants without CV alerts. The participants driving Level 2 vehicles with CV alerts in low or full MP reduced speeds much sooner than those vehicles with no MP (SAE International 2021). These benefits were greatest in the full MP condition. However, in low or full MP, the participants in Level 2 vehicles with CV alerts reduced speeds slightly later than the participants with manual vehicles and CV alerts. Eye-tracking analyses found that the participants with CV alerts tended to spend more time gazing at the console and less time gazing at the roadway during the period from when the emergency vehicle appeared to when the emergency vehicle passed. No crashes occurred at any time from when the emergency vehicle appeared to when vehicles reentered the roadway. Eye gaze on the mirrors increased when the emergency vehicle was in sight until the emergency vehicle passed, with the Level 2 participants generally using the mirrors more than the manual participants in similar MP and connectivity conditions.

Traveler information studies have also demonstrated that drivers are influenced by the actions of vehicles around them (Xuan and Kanafani 2014). The research team had similar findings in this study, as the participants in the low and full MP reduced their speeds and pulled over sooner than the participants in no MP. Also, the level of MP affected the rate at which Level 2 drivers reduced speeds.

In terms of vehicle safety, the participants driving Level 2 vehicles had greater separation from other vehicles at the time the emergency vehicle passed compared to those driving manual vehicles. In general, the participants with CV alerts and low or full MP had lower speeds, greater speed variability, shorter following distances, and greater lane variability compared to those vehicles with no MP. Overall, the results and findings from this study support a promising future of V2V communication for emergency vehicle awareness and response and the potential of CAVs to help responders arrive at traffic incidents more quickly. The participants receiving the CV alerts were more likely to pull over, use the information to pull over sooner, and reduce their vehicle speeds sooner. The benefits of full MP CV communication for emergency vehicle warnings appear to exist even at lower MP levels. Future research opportunities could also examine driver safety metrics (e.g., vehicle separation) after the emergency vehicle has passed to investigate possible impacts of vehicle automation, connectivity, and MP as vehicles reenter the roadway.

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