Effects of Vehicle Automation and Cooperative Driving Messaging on Driver Behavior When Passing a Bicyclist on a Shared Roadway

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FOREWORD

Advances in vehicle automation have the potential to change the landscape of traffic and traffic management in the near future. Ongoing research on how drivers understand, trust, and use automated vehicles (AVs) highlights the influence that human factors will have on vehicle automation. Specifically, at lower levels of automation, safe interactions among drivers, automated vehicle systems and road users will depend on a symbiotic relationship among drivers, automated vehicles systems, and road users. Cooperative vehicle automation technology offers the potential to scaffold some of the gaps occurring in such mixed user environments. Little is known about how drivers in AVs will respond to passing a bicyclist in a shared-lane roadway with different levels of cooperative connectivity with infrastructure.

This report documents a driving simulator experiment that explores drivers' behavioral responses to bicyclists when traveling within a mixed user environment. This report may interest personnel at State and local transportation agencies and AV manufacturers.

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Director, Office of Safety and Operations,
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16. Abstract
Automated vehicle (AV) functionality depends on perceiving and understanding the surrounding roadway environment and infrastructure elements. SAE International® Level 2™ driving automation systems use sensors to perceive the environment and maintain a set headway with lead vehicles while remaining centered in the lane (SAE International, 2020). Although drivers of vehicles at low levels of automation are required to remain engaged in the driving task, a mismatch in comprehension of the roadway environment between the AV and driver may introduce safety risks for drivers and other road users. Vehicle-to-infrastructure communication using cooperative driving automation (CDA) technology may mitigate some of these risks by aligning driver expectation and the future behavior of the driving automation system. This study explores how Level 2 driving automation influences the passing behaviors of drivers when approaching a bicyclist after a dedicated bicycle lane ends, and whether CDA communication supports safer passing behavior. In a simulated driving experiment, the infrastructure transmitted a message about a roadway configuration change from dedicated lanes to shared-use lanes. Level 2 vehicle drivers approached and passed a bicyclist in the shared-use lanes with lane centering and adaptive cruise control engaged. The research team manipulated the level of automation and connectivity of the participant's vehicle across groups. The team used driving performance and visual attention to assess the impact of vehicle automation and CDA messages. The study found that Level 2 vehicle drivers took over vehicle control more often on shared-lane roadways than on dedicated-lane roadways; CDA messages had a greater impact on conventional and Level 2 vehicle drivers' passing behaviors on shared-lane roadways compared with dedicated-lane roadways; Level 2 vehicle drivers receiving CDA messages had fewer moderate and abrupt rate lateral position changes than those not receiving CDA messages; and conventional and Level 2 vehicle drivers receiving CDA messages gazed longer on the bicycle when on shared-lane roadways.

17. Key Words
Automated vehicles, cooperative driving automation, CDA messages, adaptive cruise control

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

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

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LIST OF ABBREVIATIONS

AV	automated vehicle
CDA	cooperative driving automation
FHWA	Federal Highway Administration
SAE	SAE International
SSQ	simulator sickness questionnaire
TFHRC	Turner-Fairbank Highway Research Center
V2I	vehicle-to-infrastructure

CHAPTER 1. INTRODUCTION

Automated vehicle (AV) technology presents new opportunities for improving highway safety, increasing environmental benefits, expanding mobility, and creating economic opportunities for jobs and investment. SAE International® (SAE) defines the vehicle classifications based on the level of automation, ranging from no automation (SAE Level 0™) to full automation (SAE Level 5™) (SAE International, 2020). The success of AV technology relies on safe, efficient AV operation as the vehicle navigates the roadway infrastructure. Until full driving automation (i.e., SAE Level 5) is achieved, drivers with partial AVs are expected to face challenges when navigating existing infrastructure safely and efficiently in the presence of other roadway users, such as bicycles.

Drivers with partial automation are responsible for detecting bicycles on the roadway and disengaging the vehicle's automation to safely pass around them. The lane-centering feature of partial driving automation systems uses small steering adjustments to help drivers keep vehicles centered between detected lane lines; however, lane centering typically does not accommodate steering adjustments for vehicles passing bicyclists in a shared-use lane. Drivers may need to override a driving automation system to maintain the minimum 3-ft passing distance or to avoid a collision when passing a bicyclist in a shared-use lane. Conversely, drivers may misunderstand the capabilities of partial driving automation technology. Drivers may not appropriately adjust their interactions with the system in response to changes in the roadway, potentially creating a vehicle–bicyclist conflict. Promptly detecting and navigating a safe lateral distance when passing the bicycle will minimize the risk of a collision and ensure the safety of the bicyclist.

As of June 2013, 22 States had regulations that prohibit bicyclists from riding on the sidewalk, requiring them to operate alongside other conventional vehicles and AVs (League of American Bicyclists®, 2013). The interactions between AVs and bicyclists have potential safety ramifications, as AVs without full automation may not reliably detect bicyclists or provide adequate lateral space when passing. The League of American Bicyclists (2015) recommends a minimum 3-ft lateral passing distance for motorists overtaking a bicyclist. As of April 2020, 33 States, along with the District of Columbia, have enacted laws that follow the minimum 3-ft passing distance recommendation (National Conference of State Legislatures, 2020). Dedicated bicycle lanes provide this separation between vehicles and bicyclists, but most roads do not have a dedicated bicycle lane and instead require shared use of the lane.

In January 2020, a research team at the Federal Highway Administration (FHWA) held a workshop with experts and stakeholders in the areas of infrastructure, automated and cooperative driving systems, and human factors to discuss key research areas related to the safety and success of automated driving systems operating on existing roadways (Roldan et al., 2020). The workshop participants identified and prioritized 13 research topics that have near-term relevance and the potential to impact roadway safety. The second most urgent topic participants identified for further exploration was understanding how AVs navigate interactions with bicyclists and pedestrians. These interactions include yielding, navigating right-turn conflicts with bicyclists, and providing appropriate buffer space while overtaking.

The cooperative driving automation (CDA) framework enables information to be shared between vehicles and infrastructure elements via vehicle-to-infrastructure (V2I) communication (SAE International, 2020). CDA messages that warn drivers of roadway configuration changes could be useful to improve safety. For example, drivers receiving CDA messages that inform them of shared-use lanes may be better prepared for the presence of bicycles in the roadway and may navigate their vehicles more safely when passing bicyclists. CDA communication between infrastructure and vehicles may help alert drivers to roadway changes that may challenge partial driving automation technology and may require increased awareness from drivers. The research team designed this experiment to explore these and other prioritized topics to support the safe integration of advanced vehicle technologies with existing infrastructure.

OBJECTIVES

The current study explores driver interactions and behaviors when passing a bicyclist in dedicated and shared-use lanes in a semiurban environment. Vehicle automation and CDA capabilities are manipulated to identify the effect on driving performance.

The objectives of this study are to evaluate the following parameters:

- Drivers' behaviors with different levels of vehicle automation when passing the bicyclist.
- CDA messages' effects on drivers' speeds and passing behaviors when drivers are in proximity to the bicyclist.
- Drivers' takeover decisions based on CDA messages on different bicycle lanes.
- Differences in drivers' visual attention based on CDA messages.

HYPOTHESES

Based on the objectives, the research team formulated the following three hypotheses:

- Participants driving vehicles with SAE Level 2™ automation (SAE International, 2020) will not override the system when passing bicyclists in shared-use lanes, resulting in unsafe passing distances.
- Vehicles with CDA messages will be more likely to pass bicyclists in shared-use lanes with greater lateral separation due to additional roadway information provided to the vehicles.
- Participants who receive CDA messages will give greater visual attention to bicyclists than participants who do not receive CDA messages.

CHAPTER 2. METHOD

This section describes the participants, experimental design, equipment, and procedures the research team used during data collection.

PARTICIPANTS

The researchers recruited 96 licensed drivers from the Turner-Fairbank Highway Research Center (TFHRC) participants database. Equal numbers of males (48) and females (48) completed the study. Within each gender, half (24 drivers) were aged 46 yr or younger, and half were aged 46 yr or older. The participants had a valid driver's license and a minimum of 6/12 (20/40) visual acuity, based on the Bailey-Lovie eye chart, with or without vision correction (Bailey & Lovie, 2013).

EXPERIMENTAL DESIGN

Table 1 displays the two independent variables—vehicle connectivity and automation level—included in this study. The research team manipulated both independent variables between subjects. The team manipulated the level of automation such that half the participants drove a conventional vehicle without driving automation (i.e., SAE Level 0) and half the participants drove a vehicle with a Level 2 driving automation system. The researchers also manipulated the vehicle connectivity whereby half the participants drove a CDA vehicle that received an alert from the infrastructure about an approaching change in roadway configuration, and the other half of participants did not receive these alerts.

Table 1. Experimental design and participants assigned to each condition.

Vehicle Connectivity	Automation Level	
	Conventional Vehicle	**SAE Level 2 Vehicle**
Without CDA messages	24	24
With CDA messages	24	24

The team defined each condition as follows:

- **Conventional vehicle without CDA:** Participants drove a conventional vehicle without Level 2 driving automation features (SAE Level 0) and without CDA messages.
- **Conventional vehicle with CDA:** Participants drove a conventional vehicle without Level 2 driving automation features (SAE Level 0). The vehicle provided a V2I CDA message that notified the participant of an approaching change in roadway configuration.
- **Level 2 vehicle without CDA:** Participants drove an SAE Level 2 vehicle with adaptive cruise control and lane centering engaged. The vehicle did not alert the participant to the approaching change in roadway configuration.

- **Level 2 vehicle with CDA:** Participants drove an SAE Level 2 vehicle with adaptive cruise control and lane centering engaged. The vehicle provided a V2I message that alerted the participants to an approaching change in roadway configuration.

The research team also counterbalanced segment group order, age, and gender, but those parameters were not of primary interest in this study, so the team only manipulated them to identify unforeseen effects on the data.

APPARATUS

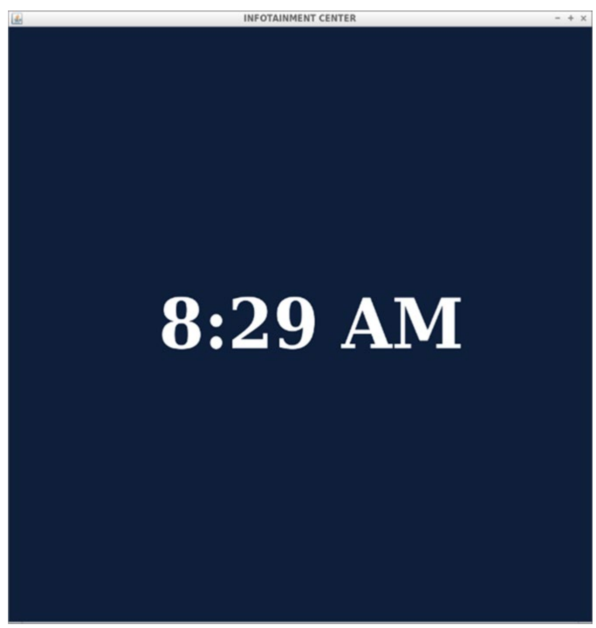
This section describes the CDA message, driving simulator, and eye-tracking device the research team used during data collection.

CDA Message

In this experiment, the roadway configuration changed from a travel lane and dedicated bicycle lane to a shared-use lane. Figure 1-A shows the center console display with a V2I CDA message notifying participants of the approaching change in roadway configuration and the intended use of the shared lane. The CDA message was always preceded by a short-duration audio signal to draw participants' attention to the change in the screen. The CDA message was displayed in the center console and remained on for 5 s before approaching the shared-use roadway segment. Figure 1-B shows the center console display without the CDA message.

Source: FHWA.

A. Center console display with CDA message.



Source: FHWA.

B. Center console display without CDA message.

Figure 1. Illustrations. Center console displays with and without CDA messages.

Driving Simulator

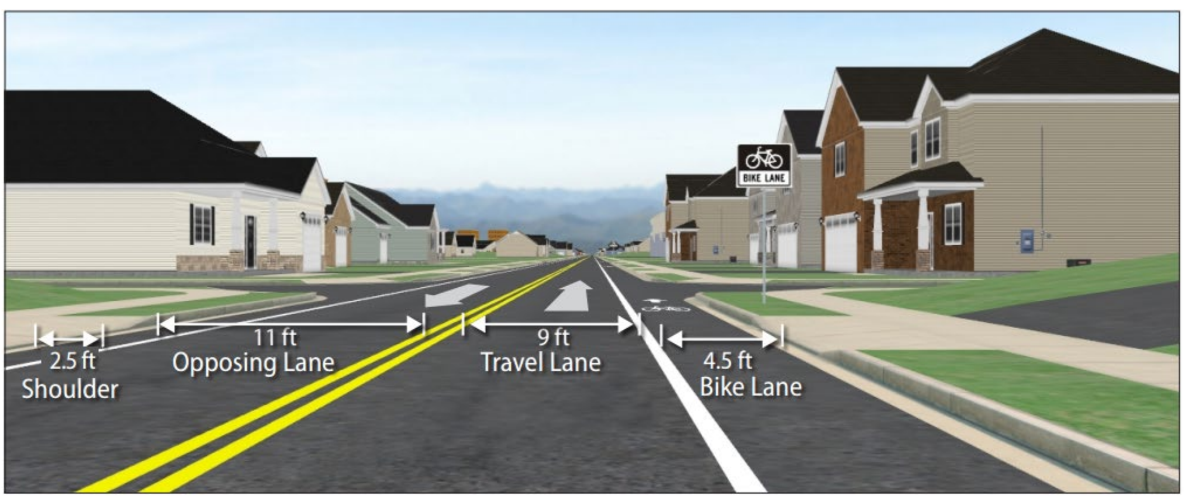
The research team conducted the study using the FHWA Highway Driving Simulator at TFHRC. The Highway Driving Simulator consists of a full automobile chassis surrounded by a semicircular projection screen with a radius of 8.5 ft. Three high-definition projectors rendered a seamless 200° view (i.e., motorists' field of view) of high-fidelity, computer-generated roadway scenes. The team used three liquid-crystal display panels to simulate the vehicle's rearview mirror and side mirrors. The six-degree-of-freedom motion base 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.

Eye Tracking

The research team used a fixed eye-tracking system to collect the participants' glance data. The system comprised three fixed cameras mounted on the vehicle's dashboard and focused on each participant's eyes. The fixed system did not require the participant to wear additional sensors. Before using the system, the team calibrated it to each participant's unique body dimensions.

SIMULATOR SCENARIO

The participants drove on a 9-mi undivided, two-lane road through a semiurban environment. The roadway consisted of two roadway configurations: a 9-ft vehicle travel lane with a 4.5-ft dedicated bicycle lane and a 14-ft shared-use lane. The research team split the participants into two groups so that the ordering of roadway configurations during the simulation was evenly counterbalanced between the two participant groups. Figure 2-A shows the dimensions of the dedicated lanes roadway, and figure 2-B shows the dimensions of the shared-use lane.



Source: FHWA.

A. Dimensions of the dedicated lanes.

Source: FHWA.

B. Dimensions of the shared-use lane.

Figure 2. Illustrations. Roadway configuration lane dimensions.

The researchers included light traffic in the opposing lane on dedicated lanes, but they did not include opposing traffic in the shared-use lanes. Pavement markings and signage used in the simulation complied with the *Manual on Uniform Traffic Control Devices for Streets and Highways* (FHWA, 2009). The transitions between the two roadway configurations only occurred at signalized intersections.

The research team instructed the conventional vehicle drivers to maintain a speed of 35 mph during the drive. Level 2 vehicle drivers traveled at a constant speed of 35 mph and remained centered 4.5 ft from the vehicle travel lane edges. After traveling for approximately 1 mi on the dedicated lanes roadway, the drivers passed a bicyclist traveling in the bicycle lane. The drivers then entered a signalized intersection 4 mi after passing the bicyclist, at which point the roadway transitioned to a 14-ft shared-use lane roadway, and oncoming traffic ceased. Drivers with CDA-enabled vehicles received a CDA message before entering the intersection, indicating an imminent change in roadway geometry. The CDA message included audible and visual characteristics, as shown in figure 1.

After traversing the intersection (i.e., roadway transition to shared-use lane), the Level 2 vehicle's automated lane-centering system gradually adjusted the lateral position to the center of the lane so the vehicle was centered 7 ft from the travel lane edges. Approximately 3 mi after transitioning to the shared-use lane, each participant approached a bicyclist traveling 2.5 ft from the right lane edge. The vehicle's width was 6 ft, so a 1.5-ft distance existed between the passenger side of the vehicle and the bicycle when lane centering was active. After passing the bicyclist, the participants drove for 1 mi to end the experiment.

PROCEDURES

The research team asked the participants to review and sign an informed consent document upon arrival. The team then asked the participants to show a valid driver's license. The researchers used a Bailey-Lovie eye chart to verify a minimum of 6/12 (20/40) visual acuity, with correction if necessary (Bailey & Lovie, 2013). The participants provided a symptoms baseline by completing a simulator sickness questionnaire (SSQ) (Kennedy et al., 1993).

The research team provided the participants with study instructions and a brief introduction to the concept of CDA messaging and AVs. The participants who were assigned to the Level 2 automation condition viewed a presentation that described the functions of the lateral and longitudinal systems present in their vehicles. The participants who were assigned to the CDA condition viewed a presentation that described V2I and vehicle-to-vehicle technology.

The participants then entered the Highway Driving Simulator vehicle cab so the research team could calibrate the eye-tracking system. After the team successfully calibrated the eye-tracking system, the participants completed a practice drive to become familiar with the simulator. Each practice drive lasted 3–5 mi. During the practice drive, the researchers 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. The participants in the CDA condition received an alert during the practice drive. The practice alert was different than the alert received during the experiment. After completing the practice drive, the participants exited the vehicle and completed the SSQ a second time. If the results of the second SSQ indicated participants were likely to experience simulator sickness, the researchers dismissed those participants from the data collection and compensated them for their time. If the SSQ indicated participants were okay to continue, the research team asked those participants to return to the vehicle and drive the experimental scenario, and the team paid those participants after they completed the route.

DATA ANALYSIS METHODOLOGY

The research team examined the participants' driving behaviors while passing bicyclists as a function of automation level, vehicle connectivity, and roadway configuration. The team assessed driver performance metrics, including the participants' takeover decisions, speed, maximum lateral distances from the bicyclist, and passing behaviors. The team used eye tracking to assess the effect of CDA messages and Level 2 automation on participants' visual attention to bicyclists. The analysis methodology used generalized estimating equation models to test the associations between independent and dependent variables. The team used a two-sample *t*-test to identify statistically significant differences in visual attention among different groups of participants. The team conducted all statistical analyses at a 95-percent confidence level.

CHAPTER 3. RESULTS

The analyses examined driver behaviors when approaching and passing a bicycle in dedicated and shared-use lanes. The research team assessed three driving behaviors: takeover decision, passing behavior, and visual attention to the bicyclist. Takeover decisions included brake pedal movement and steering wheel position metrics as indicators of drivers taking over control of the vehicle. Passing behavior involved examining vehicle lane positioning and vehicle speed data. Visual attention to the bicyclist involved using driver eye movements from the eye-tracking system.

TAKEOVER DECISION

The research team hypothesized that participants driving Level 2 vehicles would not override the system when passing bicyclists in shared-use lanes. To test this hypothesis, the researchers examined Level 2 vehicle driver behaviors to override and disengage the automated lane-centering system. Drivers could take over vehicle control by pressing the brake pedal or turning the steering wheel. Table 2 shows the percentage of Level 2 vehicle drivers who took over control of the vehicle by braking or turning the steering wheel as a function of roadway configuration and vehicle connectivity. The results showed that, overall, between 50 and 91 percent of Level 2 vehicle drivers took over vehicle control by braking or turning the steering wheel. Level 2 vehicle drivers on roadways with dedicated bike lanes took over control of the vehicle less often (between 50 and 58 percent) than Level 2 vehicle drivers in the shared-use lanes (between 88 and 91 percent). Generalized estimating equation models revealed that Level 2 vehicle drivers in the shared-use lane roadway were about two times more likely to take over vehicle control than those driving on the roadway with a dedicated bike lane ($p < 0.001$). The team found no other statistically significant differences.

Table 2. Percentage of Level 2 vehicle drivers taking over vehicle control.

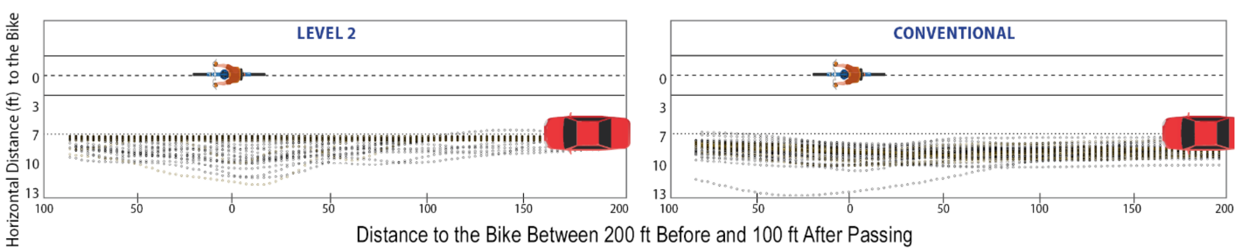
Roadway Configuration and Connectivity	Takeover by Braking or Steering (percent)
Dedicated bicycle lane without CDA message	58
Dedicated bicycle lane with CDA message	50
Shared-use lane without CDA message	88
Shared-use lane with CDA message	91

PASSING BEHAVIOR

The research team hypothesized that participants receiving CDA messages would be more likely to pass bicyclists in shared-use lanes with greater lateral separation due to additional roadway information provided to the vehicles. The researchers examined vehicle lane positioning in terms of lateral distance change from the bicycle, rate of lateral position change, and vehicle speed change when approaching the bicycle. Lateral distance is the maximum distance from the edge of the vehicle's right mirror to the edge of the bicycle position on the roadway as the vehicle approaches and passes the bicycle. The team compared lateral distance and speed from 200 ft upstream of the bicycle with the lateral distance and speed when the vehicle was about 20 ft behind the bicycle. The researchers examined the results as a function of level of automation, connectivity, roadway configuration, age, and gender.

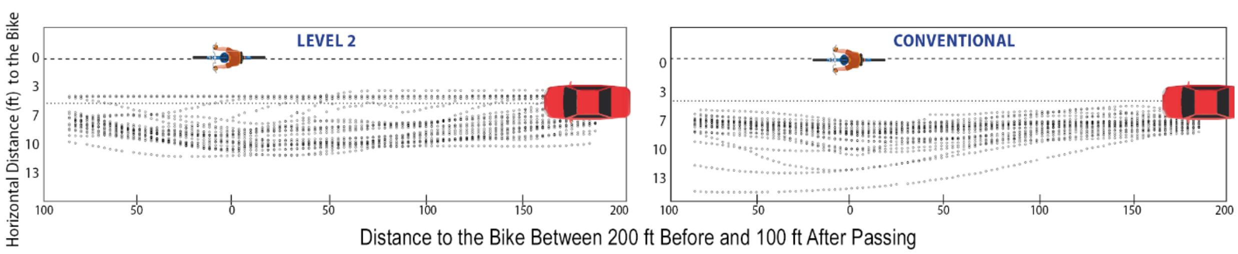
Lateral Distance Change

Figure 3 illustrates the vehicle trajectories for Level 2 and conventional vehicle drivers as a function of roadway configuration and vehicle connectivity. Within the figure, the trajectories of vehicles are depicted as small circles as the vehicle traveled from right (200 ft upstream of the bicycle) to left (100 ft past the bicycle). The solid lines represent the left and right boundary of the 4.5-ft dedicated bicycle lane. The dashed line (at the horizontal distance of 0 ft) represents the trajectory of the bicyclist. The dotted line (at the horizontal distance of about 6.5 ft) represents the lateral distance of the vehicle center from the right edge of the travel lane. For Level 2 vehicles, the lane-centering feature would automatically follow along the dotted line. Figure 3-A shows the vehicle trajectories of Level 2 and conventional vehicle drivers when driving on the dedicated lane roadway. Figure 3-B shows the vehicle trajectories of Level 2 and conventional vehicle drivers when driving on the shared lane roadway with CDA messages. Figure 3-C shows the vehicle trajectories of Level 2 and conventional vehicle drivers when driving on the shared lane roadway without CDA messages.



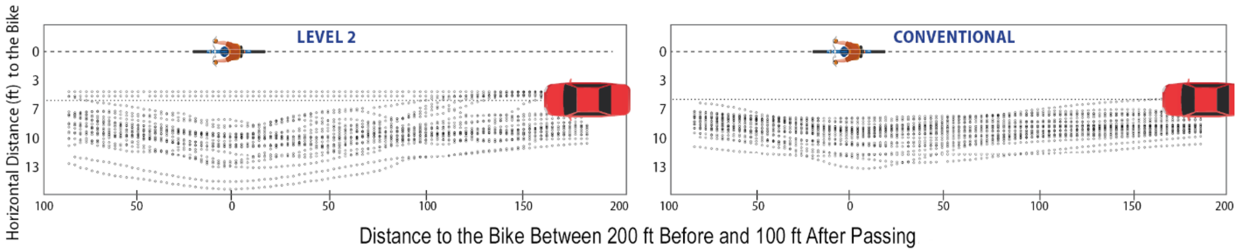
Source: FHWA.

A. Dedicated lane.*



Source: FHWA.

B. Shared lane with CDA messages.*

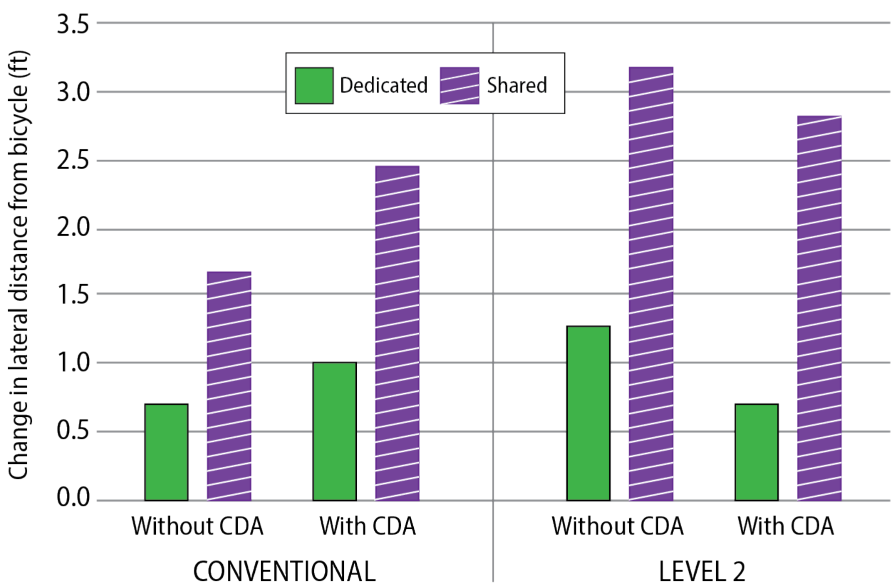


C. Shared lane without CDA messages.*

*Note: Small circles depict the trajectories of vehicles as the vehicles traveled from right to left. Solid lines represent the left and right boundary of the 4.5-ft dedicated bicycle lane. Dashed lines represent the trajectory of the bicyclist. Dotted lines represent the lateral distance of the vehicle center from the right edge of the travel lane.

Figure 3. Line graphs. Lateral distance from bicycle on dedicated-lane roadways.

Figure 4 shows the mean maximum lateral distance change between the vehicles and the bicycle as a function of vehicle automation, vehicle connectivity, and roadway configuration. In general, drivers on shared-lane roadways had a greater change in lateral separation distances (ranging from 1.7 to 3.2 ft) than drivers on dedicated-lane roadways (ranging from 0.7 to 1.3 ft). The generalized estimating equation models revealed that the estimated 1.6-ft change in the lateral separation difference was significant ($p < 0.001$). In addition, Level 2 vehicle drivers receiving CDA messages had an estimated 0.46-ft greater change in lateral distance than conventional vehicle drivers receiving CDA messages. Level 2 vehicle drivers not receiving CDA messages had an estimated 1.0-ft greater change in lateral distance than conventional vehicle drivers not receiving CDA messages.



Source: FHWA.

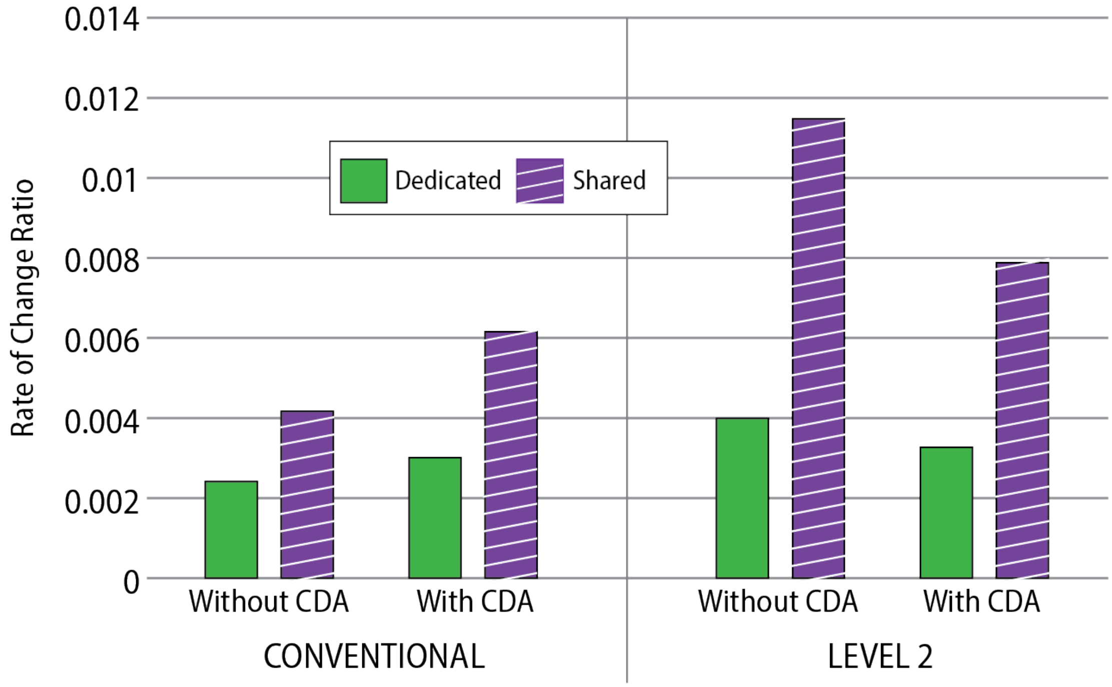
Figure 4. Bar chart. Change in lateral distance from vehicle mirror to the bicycle.

The research team also found a significant interaction between vehicle automation and connectivity ($p < 0.05$). The analyses showed that while conventional vehicle drivers receiving CDA messages on shared-lane roadways had about 0.79-ft greater lateral separation than conventional vehicle drivers not receiving CDA messages (2.44 − 1.65 = 0.79 ft), Level 2 vehicle drivers receiving CDA messages on shared-lane roadways had about 0.37-ft less lateral separation than Level 2 vehicle drivers not receiving CDA messages (2.81 − 3.18 = −0.37 ft). On dedicated-lane roadways, the analyses showed that conventional vehicle drivers receiving CDA messages tended to have 0.28-ft greater lateral separation than drivers not receiving CDA messages (0.97 − 0.69 = 0.28 ft). Level 2 vehicle drivers receiving CDA messages had 0.55-ft less lateral separation than those not receiving CDA messages (0.70 − 1.25 = −0.55 ft).

The differences between older and younger drivers were also statistically significant. Younger drivers (aged 46 yr or younger) had about 0.6-ft greater lateral distance ($p < 0.05$) than older drivers (aged 47 yr or older). The team found no other statistically significant differences.

Rate of Lateral Distance Change

The research team examined the rate of lateral distance change using the data points when the vehicle was 200 ft behind the bicycle and when the vehicle had a maximum lateral distance to the bicycle. The researchers calculated a rate of change ratio by using the difference in lateral position divided by the difference in longitudinal position, such that the higher the ratio, the greater the rate of lateral position change and the more abrupt the distance change. Figure 5 shows the rate of change ratio for lateral position as a function of vehicle automation, vehicle connectivity, and roadway configuration. In general, drivers on shared-lane roadways tended to have a greater rate of change ratios (i.e., more abrupt lateral distance change), ranging from 0.0042 to 0.0115, than drivers on dedicated-lane roadways (ranging from 0.0024 to 0.0041). The mixed-effects beta regression model revealed a significant interaction between vehicle automation level and connectivity ($p < 0.01$).



Source: FHWA.

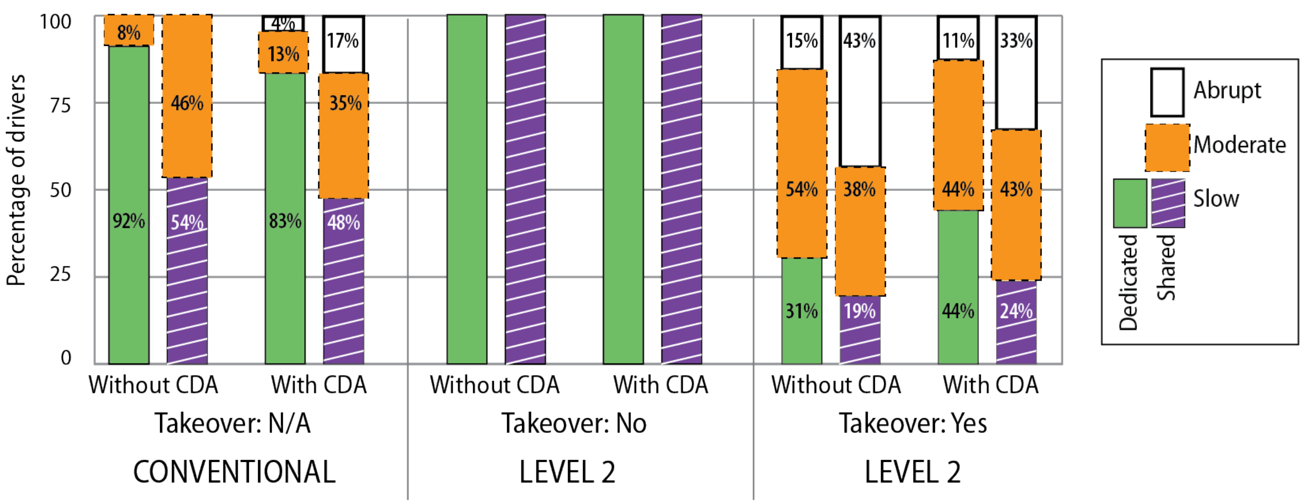
Figure 5. Bar chart. Rate of change ratio for lateral position.

The model results indicated the following estimations:

- Level 2 vehicle drivers receiving CDA messages were about 0.77 times less likely to have a more abrupt rate of change than Level 2 vehicle drivers not receiving CDA messages.
- Level 2 vehicle drivers receiving CDA messages were about 1.4 times more likely to have a more abrupt rate of change than conventional vehicle drivers receiving CDA messages.
- Level 2 vehicle drivers not receiving CDA were about 2.5 times more likely to have a more abrupt rate of change than conventional vehicle drivers not receiving CDA messages.
- Conventional vehicle drivers receiving CDA messages were about 1.4 times more likely to have a more abrupt rate of change than conventional vehicle drivers not receiving CDA messages.

The differences between roadway configurations were statistically significant ($p < 0.001$). Drivers on shared-lane roadways were about 1.7 times more likely to have a more abrupt rate of change than when driving on dedicated-lane roadways. The team found no other statistically significant differences.

To probe deeper into the rate of change ratio, the research team grouped the rate of change ratios of individual drivers to examine the number of drivers making slow, moderate, and abrupt changes in a lateral position. The researchers grouped the rate of change ratios into three categories: slow (<0.005), moderate (>0.005 and <0.01), and abrupt (>0.01). Figure 6 shows the percentage of drivers in each category by vehicle automation, connectivity, and roadway configuration. The team also separated the percentages for the Level 2 vehicle drivers based on whether the drivers took over vehicle control by pressing the brake pedal or turning the steering wheel. The results and trends were consistent with the rate of lateral distance change results shown in figure 5. In general, drivers on shared-lane roadways tended to have fewer slow rate lateral position changes (and more moderate and abrupt changes) than drivers on dedicated-lane roadways. In addition, the conventional vehicle drivers tended to have about 48–92 percent slow rate lateral position change and 8–52 percent moderate and abrupt rate changes. This outcome contrasts with the Level 2 vehicle drivers who took over vehicle control and tended to have about 20–45 percent slow rate lateral position change and 55–80 percent moderate and abrupt rate changes. The results also showed that conventional vehicle drivers receiving CDA messages tended to have more moderate and abrupt rate lateral position changes than those not receiving CDA messages. However, Level 2 vehicle drivers receiving CDA messages tended to have fewer moderate and abrupt rate lateral position changes than those not receiving CDA messages. All the Level 2 vehicle drivers who did not take over vehicle control had slow lateral position rates of change due to the automated lane-centering feature controlling the vehicle's lateral position.



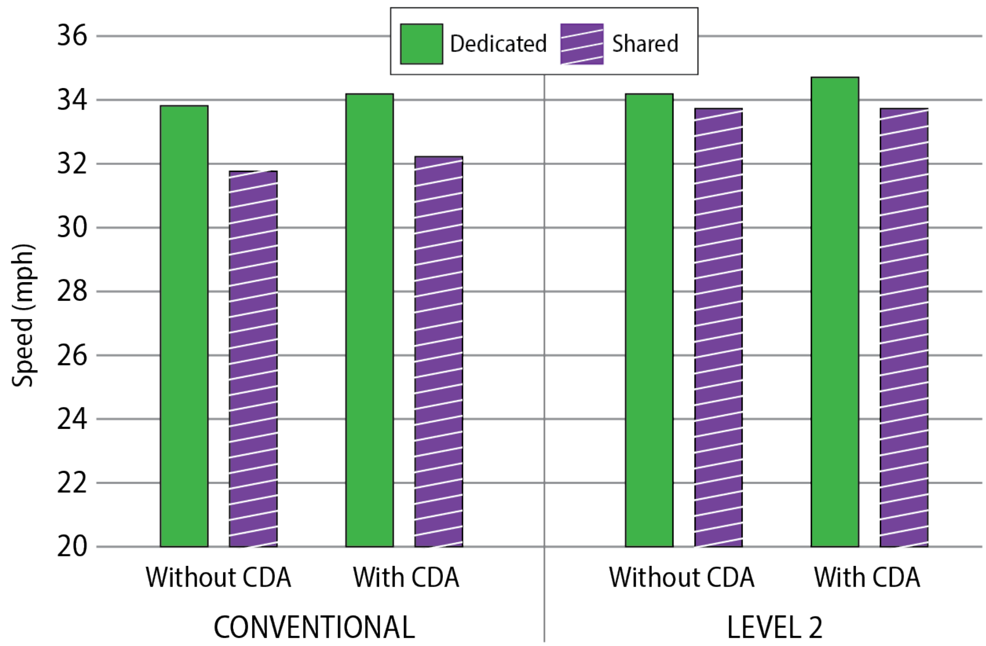
Source: FHWA.

Figure 6. Bar chart. Percentage of drivers making slow, moderate, and abrupt lateral changes.

Vehicle Speed

The research team examined the average vehicle speeds and vehicle speed changes to determine whether vehicle automation, connectivity, or roadway configuration had an effect when drivers approached the bicycle. The team calculated the average vehicle speeds and change in vehicle speeds by using the speeds when the vehicles were 300 ft upstream and when they were 100 ft past the bicycle. Figure 7 shows the average speeds across the different conditions. In general, the average speed for drivers on the dedicated-lane roadway ranged from 33.7 to 34.7 mph, while the average speed of drivers on the shared-lane roadway ranged from 31.7 to 33.8 mph. The difference in speed between drivers on dedicated-lane versus shared-lane roadways ranged from

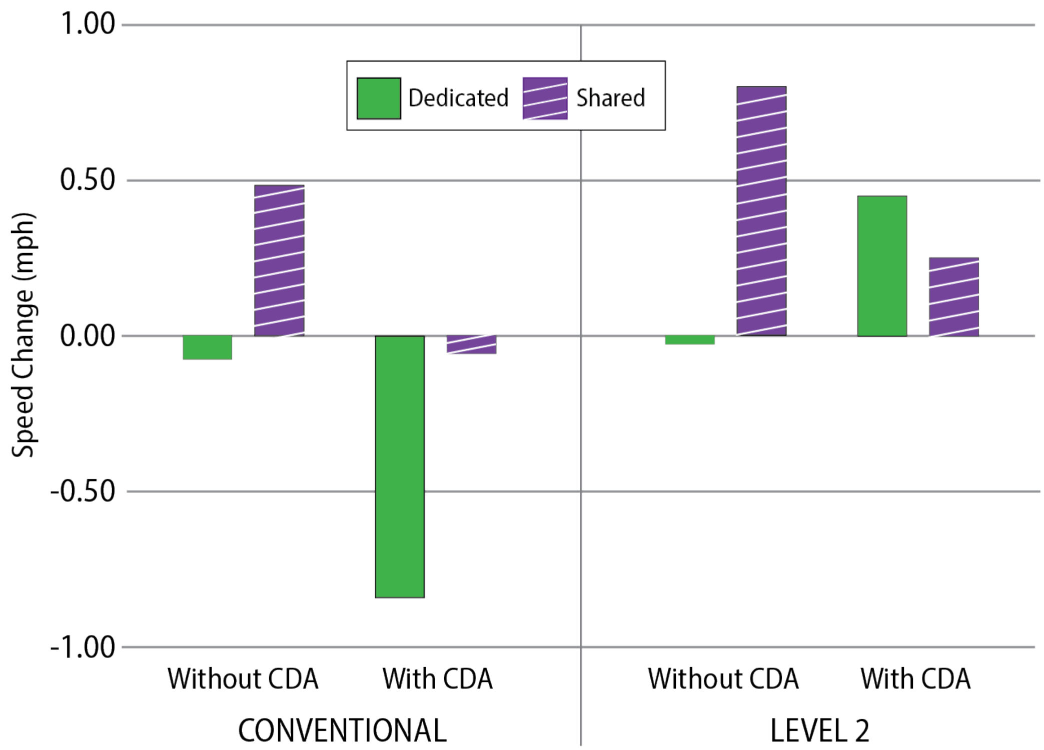
0.36 to 2.1 mph. The researchers assessed the impact of vehicle automation, connectivity, and roadway configuration using the generalized estimating equation models. The results showed that the difference in speed between roadway configurations was statistically significant ($p < 0.01$). Drivers on the shared-lane roadway had about 0.61-mph slower speeds than drivers on the dedicated-lane roadway. The differences in vehicle speeds for vehicle automation and connectivity were not statistically significant. The team found no other statistically significant differences.



Source: FHWA.

Figure 7. Bar chart. Average vehicle speeds.

Figure 8 shows the mean vehicle speed change as a function of vehicle automation, vehicle connectivity, and roadway configuration. In general, the average changes in speed from 200 ft upstream to the bicycle were small and less than 1 mph. Conventional vehicle drivers receiving CDA messages on the dedicated-lane roadway had the largest decrease in speed (−0.83 mph). Level 2 vehicle drivers not receiving CDA messages on the shared-lane roadway had the largest increase in speed (0.80 mph). The team assessed the impact of vehicle automation, connectivity, roadway configuration, age, and gender by using the generalized estimating equation models. The results showed that male drivers reduced their vehicle speeds about 1 mph more than female drivers ($p < 0.01$). The team found no other statistically significant differences.

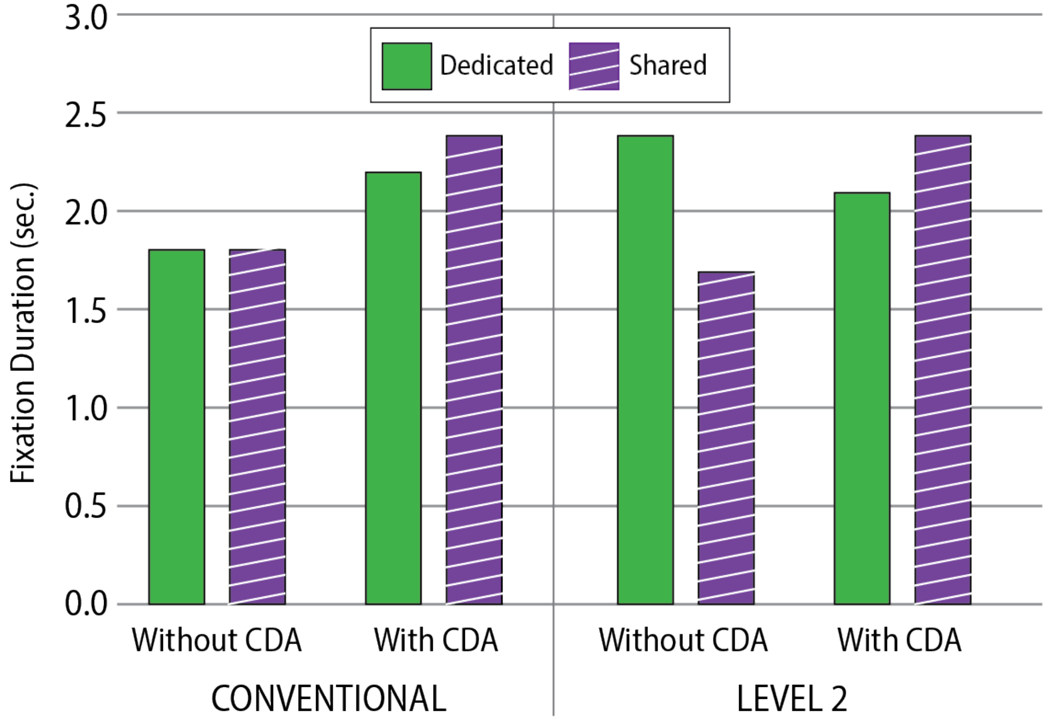


Source: FHWA.

Figure 8. Bar chart. Average change in vehicle speed.

VISUAL ATTENTION ON THE BICYCLIST

The researchers hypothesized that participants receiving CDA messages would have higher rates of giving visual attention to bicyclists than participants not receiving CDA messages. To test this hypothesis, the research team used the eye-tracking system to investigate the drivers' visual attention to the bicyclist and determine the total duration. The eye-tracking system software collected participants' eye movements during the period when the bicyclist was in the field of view. The software processed the eye movements and calculated fixation for specific areas of interest to measure participant visual attention to the bicyclist. Figure 9 shows the average of total fixation durations by vehicle automation, connectivity, and roadway configuration. The results showed that the fixation duration ranged from 1.7 to 2.4 s, depending on vehicle automation, connectivity, and roadway configuration. Conventional vehicle drivers receiving CDA messages tended to spend slightly more time gazing at the bicycle than conventional vehicle drivers not receiving CDA messages on dedicated-lane roadways (2.2 − 1.8 = 0.3 s) and on shared-lane roadways (2.4 − 1.8 = 0.6 s). Level 2 vehicle drivers receiving CDA messages tended to spend slightly more time gazing at the bicycle than conventional vehicle drivers not receiving CDA messages on the shared-lane roadway (2.4 − 1.7 = 0.7 s). However, Level 2 vehicle drivers receiving CDA messages tended to spend slightly less time gazing at the bicycle than Level 2 vehicle drivers not receiving CDA messages on dedicated-lane roadways (2.1 − 2.4 = −0.3 s). The team assessed the impact of vehicle automation, connectivity, and roadway configuration by using the generalized estimating equation models. The results showed that none of the fixation duration differences for vehicle automation, connectivity, roadway configuration, gender, or age were statistically significant.



Source: FHWA.
sec. = seconds.

Figure 9. Bar chart. Average bicycle fixation duration.

CHAPTER 4. DISCUSSION

This study examined the effects of vehicle automation and CDA messages on drivers' behaviors when passing a bicycle on dedicated-lane and shared-lane roadways in a semiurban environment. Ninety-six participants drove the FHWA Highway Driving Simulator on a 9-mi undivided, two-lane road through a semiurban environment. The roadway consisted of two roadway configurations: a 9-ft vehicle travel lane with a 4.5-ft dedicated bicycle lane and a 14-ft shared-use lane. Half the participants drove a conventional vehicle without driving automation (SAE Level 0), and half the participants drove a vehicle with an SAE Level 2 driving automation system. Within each group, half the participants received a CDA message alerting them to an approaching change in roadway configuration and the intended use of the shared lanes. The other half of participants did not receive the alert message. The researchers examined the effects of vehicle automation (conventional vehicle versus Level 2 vehicle) and vehicle connectivity (CDA message versus no CDA message) and the potential of CDA messages to encourage drivers to safely pass bicyclists. Of particular interest were Level 2 vehicle drivers' recognition of whether to safely use the automation system or to override the system when passing bicyclists in shared-use lanes. The research team also examined lateral distance, vehicle speed, and visual attention to understand how drivers react when passing a bicyclist.

HYPOTHESES

The research team investigated three hypotheses in the study. The first hypothesis—participants driving vehicles with Level 2 automation will not override the system when passing bicyclists in shared-use lanes, resulting in unsafe passing distances—was not supported by the results of this experiment. On shared-use lane roadways, about 88–91 percent of Level 2 vehicle drivers took over control of the vehicle by braking or turning the steering wheel. Those drivers were about two times more likely to take over vehicle control than those participants who were driving on the dedicated-lane roadway. Given that on shared-use lanes, the bicycle was positioned 2.5 ft from the right edge of the roadway and the Level 2 vehicle's lane-centering system provided 1.5 ft of lateral separation from the bike, most Level 2 vehicle drivers apparently chose to override the system to increase the separation distance for safely passing the bicycle.

On dedicated-lane roadways, about half (50–58 percent) of the Level 2 vehicle drivers took over control from the automated settings to increase the lateral distance. Given that on the dedicated-lane roadway, the bicycle was positioned 2.5 ft from the right edge of the roadway and the Level 2 vehicle's lane-centering system provided 3 ft of lateral separation from the bike, it appears most Level 2 vehicle drivers felt comfortable and confident that the lateral distance provided by the Level 2 lane positioning was adequate for safely passing the bicycle. The 3-ft lateral separation was consistent with the League of American Bicyclists recommendation of a minimum of 3-ft lateral distance when passing a bicycle (League of American Bicyclists, 2013).

The statistical analyses did not support the second hypothesis—vehicles with CDA messages will be more likely to pass bicyclists in shared-use lanes with greater lateral separation due to additional roadway information provided to the vehicles. Although conventional vehicle drivers receiving CDA messages on shared-lane roadways tended to have 0.79-ft greater lateral separation than drivers not receiving CDA messages, Level 2 vehicle drivers receiving CDA messages on shared-lane roadways had 0.37-ft less lateral separation than those drivers who were not receiving CDA messages. A similar effect was found for drivers on dedicated-lane roadways. Conventional vehicle drivers receiving CDA messages on dedicated-lane roadways tended to have 0.28-ft greater lateral separation than drivers not receiving CDA messages. Level 2 vehicle drivers receiving CDA messages on shared-lane roadways had 0.55-ft less lateral separation than those drivers who were not receiving CDA messages.

Regarding the rate of lateral distance change, drivers on shared-lane roadways tended to be about 1.7 times more likely to have a more abrupt lateral distance change than drivers on dedicated-lane roadways. The results indicated that Level 2 vehicle drivers receiving CDA messages were about 1.4 times more likely to have a more abrupt rate of change than conventional vehicle drivers receiving CDA messages. However, Level 2 vehicle drivers not receiving CDA messages were also about 2.5 times more likely to have a more abrupt rate of change than conventional vehicle drivers not receiving CDA messages. Furthermore, Level 2 vehicle drivers receiving CDA messages were about 0.77 times less likely to have a more abrupt rate of change than Level 2 system vehicle drivers not receiving CDA messages.

The research team also investigated passing behaviors grouped by slow, moderate, and abrupt change rates and found the trends to be consistent with the rate of lateral distance change results. Conventional vehicle drivers tended to have more slow rate changes (about 48–92 percent) and fewer moderate and abrupt rate changes (about 8–52 percent) compared with the Level 2 vehicle drivers' 20–45 percent slow and 55–80 percent moderate and abrupt rate changes. The impact of CDA messages showed mixed results. Whereas conventional vehicle drivers receiving CDA messages tended to have more moderate and abrupt rate lateral position changes than those not receiving CDA messages, Level 2 vehicle drivers receiving CDA messages tended to have fewer moderate and abrupt rate lateral position changes than those not receiving CDA messages.

The research team also investigated vehicle speeds and speed changes to examine whether vehicle automation, connectivity, or roadway configuration had an effect when drivers approached the bicycle. The effects for vehicle automation and connectivity were not statistically robust. However, roadway configuration did affect vehicle speed, as drivers on shared-lane roadways drove about 0.61 mph slower than drivers on the dedicated-lane roadway. Regarding speed changes, the only significant effect was gender, as male drivers reduced their vehicle speeds about 1 mph more than female drivers.

The statistical analyses did not support the third hypothesis—participants receiving CDA messages will have higher visual attention to bicyclists than participants not receiving CDA messages. Although conventional and Level 2 vehicle drivers receiving CDA messages tended to spend slightly more time gazing at the bicycle than conventional and Level 2 vehicle drivers not receiving CDA messages (except for Level 2 vehicle drivers on dedicated-lane roadways), the differences were not statistically significant. These results indicate that receiving CDA messages had a small positive impact on conventional and Level 2 vehicle drivers paying more attention to the bicycle on shared-lane roadways. These results suggest that Level 2 vehicle drivers receiving CDA messages when driving on the dedicated-lane roadway may spend slightly less time (0.3 s) fixating on the bicycle due to the dedicated-lane roadway and the Level 2 lane-positioning feature.

The analysis of driving performance, when using different levels of vehicle automation and CDA messages on dedicated and shared-use lanes when passing a bicycle, revealed insight into the benefits and limitations. This study found that most participants would override Level 2 automation settings when they thought their vehicle was passing too close to a bicyclist. The reliance on CDA messages to ensure safe lateral distance when passing was not assured for all drivers. The use of the CDA message did not persuade Level 2 vehicle drivers to increase their lateral distance from the bicycle when on the shared-lane roadway. Although, Level 2 vehicle drivers receiving CDA messages were less likely to have a more abrupt lateral distance change than Level 2 system vehicle drivers not receiving CDA messages, they still tended to have more moderate and abrupt changes than conventional vehicle drivers. Nevertheless, the CDA messages did tend to result in higher rates of driver visual attention to the bicycle. The study provided insight into the differences between conventional and Level 2 vehicle drivers, but some limitations are acknowledged:

1. The research team derived the results and findings from this simulator study, and they may not be reflective of real-world driver behavior when passing a bicyclist.

2. The team only investigated one configuration of an in-vehicle message, and future research evaluating other configurations and modes of CDA messages may change (for better or worse) drivers' behaviors.

3. This study did not query the drivers to better understand their thoughts and attitudes. Future studies could provide a better understanding of drivers' behaviors when using vehicle automation and their CDA capabilities when approaching and passing bicycles on various roadway configurations.

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