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Conventional Vehicle Driver and Automated Driving System-Equipped Vehicle Interactions

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16. Abstract

This research explores interactions between conventional vehicle drivers and vehicles controlled by Automated Driving Systems (ADS). NHTSA is interested because an ADS-equipped vehicle could be so labeled, and effects of identifying a vehicle as self-driving are unknown. The behavior of other drivers with respect to a nearby ADS vehicle with explicit labeling and driving style is known to have an effect on safety.

This report describes findings of an on-road experiment that investigated drivers' behaviors around a vehicle identified as a "self-driving" vehicle. Researchers collected data on public highways using a research vehicle, which on different drives had the outward appearance of either a conventional vehicle or an ADS mockup vehicle. During data collection trips on a fixed freeway route, the behavior of nearby drivers and their vehicles were observed and recorded. Observers noted that nearby drivers exhibited longer glances, more surprised expressions, and occasional gestures or even camera use when approaching or passing the mockup research vehicle, and drivers generally took longer to pass it. However, objective measures of potentially unsafe actions (e.g., cut-ins, tailgating) showed no statistically significant differences between the mockup research vehicle and conventional vehicle.

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Executive Summary

This report documents an approach for observing and collecting data on interactions between the drivers of conventional vehicles and vehicles controlled by Automated Driving Systems (ADS).[1] According to SAE International (2021), ADS-equipped vehicles have driving automation capabilities and features ranging from Level 3 (conditional automation) to Level 5 (full automation). Unlike lower levels of driving automation, ADS technology does not require an attentive driver while the automation is engaged, and some implementations may not require driver presence. When an ADS system is engaged, it performs the dynamic driving task.[2]

While substantial research addresses human interaction with automated systems that they are supervising or interacting with, comparatively few studies have examined how drivers of conventional vehicles interact with ADS-equipped vehicles. The nature of interactions between ADS-equipped vehicles and human-driven vehicles is expected to differ from that among the drivers of conventional vehicles, potentially resulting in impacts on safety that may either be beneficial or detrimental.

To explore the behavior of drivers of conventional vehicles operating near vehicles controlled by ADS, this project mocked up a 2018 Cadillac CT6 with Super Cruise in an attempt to make it appear to other drivers on the road as if it were a vehicle with ADS. The Super Cruise system in the research vehicle is a driver support feature that provides lateral and longitudinal control with the driver's hands off the steering wheel, under certain conditions. Although the driver had to remain attentive to the driving task at all times, having their hands off the wheel contributed to providing outside observers the impression that the vehicle was potentially operating at higher levels of automation. This research vehicle was driven in various conditions to observe and record the other drivers' behaviors and reactions, both when it appeared like an ADS-equipped vehicle and as a conventional vehicle, allowing for comparison between the two scenarios.

Specific research questions examined in this study include the following.

1. *What is the effect of identifying a vehicle as "self-driving?"* Does the behavior of drivers with respect to a nearby vehicle differ if the nearby vehicle is clearly labeled as "self-driving" as compared to being unlabeled (i.e., having a conventional appearance)?
2. *What is the effect of identifying whether automation is engaged or not engaged?* For a vehicle labeled with "self-driving" signage, does the behavior of nearby drivers differ if the labeled vehicle is identified with additional signage as operating with "automation on" as compared to "automation off?"
3. *What is the effect of driving/operating style?* Does the behavior of nearby drivers differ if the research vehicle appears to be using driving automation with strict adherence to traffic laws, precise lane positioning, and speed control, as compared to being entirely in manual mode where lane positioning and speed typically vary?

[1] The term "conventional vehicles," as used in this report, describes vehicles operated manually by a driver rather than by an ADS.

[2] Dynamic driving task is the real-time operational and tactical functions required to operate a vehicle safely in on-road traffic.

4. *Does the driver behavior with respect to a nearby vehicle depend on an interaction between explicit labeling and driving style of the research vehicle?*

The study used a 3 x 2 factorial design with six treatment conditions that systematically varied the appearance and research vehicle's driving style. The three vehicle appearance conditions were (1) conventional vehicle appearance with no signage, (2) "self-driving" appearance with Automation ON signage, and (3) "self-driving" appearance with Automation OFF signage. The two driving style conditions included manual operation and what the study called "automated operation," which was driving with the aid of a commercially available driver support feature.

During repeated data collection trips on a fixed limited-access highway route in Maryland (I-270, MD 200, I-95, I-495) in 2019, the behavior of nearby drivers and their vehicles were observed and recorded using video cameras, a front-facing Mobileye 630 Collision Avoidance System, and rear-facing radar (SmartMicro Universal Medium Range Radar, Type 30).[3] [4] A researcher sitting in the research vehicle's back seat also recorded observations of passing drivers on a laptop computer with custom software. These observations included instances of a passing driver with a surprised facial expression, making a long glance (greater than 2 seconds) toward the research vehicle, and gesturing or waving at the research vehicle. Apparent instances of a passing driver (or passenger) using a cell phone to take a photograph of the research vehicle were also noted. Other data was collected about the time required for other drivers to complete passing maneuvers and the number of vehicles that made lane changes into or out of the lane next to the research vehicle.

Overall, the results show that nearby drivers behaved differently around the research vehicle when it appeared to be an ADS-equipped vehicle as compared to when it was not mocked up (i.e., appeared to be a conventional vehicle). While mocked up it elicited more long glances, surprised facial expressions, and gesturing from passing drivers, and instances of camera use by passing drivers and passengers. Drivers also generally took longer to pass the mocked-up research vehicle than when it was not mocked up, and drivers passing the research vehicle were more likely to make a lane change away from the vehicle when it was mocked up as compared to when it was not mocked up. Other objective measures of potentially unsafe behaviors, including cut-ins and tailgating did not reveal any statistically significant differences between the two vehicle appearances.

When the research vehicle appeared as a conventional vehicle, the driving style (fully manual versus with the aid of driver assistance/support systems) revealed some relationships with safety-relevant behaviors of nearby drivers. Drivers took a significantly longer time to pass the research vehicle when it was operating with the manual driving style at similar speeds, and there were more lane changes into and out of the lane adjacent to the research vehicle when it was operating with the driver support feature that maintained more consistent speeds and lane position, but there were no other significant differences in long glances, surprised expressions, gestures, camera use, tailgating, or cut-ins by nearby drivers among the two cases.

The research vehicle's appearance was likely novel for drivers on Maryland roadways when and where the study took place. It is possible that differences noted in nearby drivers' behavior were

[3] Mobileye Global Inc., Jerusalem, Israel.

[4] Smartmicro, Braunschweig, Germany.

due to the presence of signage rather than a reaction to what they might have thought was an ADS-equipped vehicle. However, there is some evidence that drivers were responding differentially to the signage's meaning rather than the vehicle's novel appearance. For some of the dependent variables examined, there were differences between the Automation ON and Automation OFF conditions. For those two conditions, the research vehicle's appearance was otherwise nearly identical. Drivers passing the research vehicle when the Automation ON sign was illuminated were more likely to have surprised facial expressions than were drivers passing when the Automation OFF sign was illuminated. Also, drivers following the research vehicle with the sign Automation ON were less likely to tailgate than were drivers following the research vehicle with the sign Automation OFF. The observed outcomes show that the independent variables could have exerted distinct influences on proximate drivers that cannot be attributed solely to novelty. In other words, nearby drivers' responses varied by the informational content of the signage rather than merely the vehicles' unfamiliar appearance. These findings could be specific to the time and place where the data was collected. Once ADS-equipped vehicles become more common and familiar, drivers may respond with other safety relevant behaviors not observed in this study such as illegal passing or active avoidance.

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Introduction

This report summarizes research conducted to explore interactions between drivers of conventional vehicles and vehicles controlled by ADS. According to SAE International (2021), ADS-equipped vehicles have driving automation capabilities and features ranging from Level 3 (conditional automation) to Level 5 (full automation). In contrast, conventional vehicles include those with advanced driver assistance systems that include SAE driving automation Level 0 to Level 2. Conventional vehicles, including those with advanced driver assistance systems, always require the drivers to be driving (the drivers must remain attentive and ready to retake control at all times) even when using support features that can control both speed and lane position without direct driver input. For an ADS-equipped vehicle, the driver is not driving when the vehicle is in an automated mode, even though some ADS-equipped vehicles may request driver takeover with adequate notice to the drivers if the vehicles exceeds their operational design domain (i.e., the set of conditions within which it is designed or allowed to operate).

While there is a substantial and rapidly expanding body of literature on driver interaction with ADS-equipped vehicles and features, there has been relatively little research on interactions between conventional vehicle drivers and ADS-equipped vehicles. These interactions could be critical to understand and facilitate as ADS-equipped vehicles transition from development and testing to wider-scale deployments and use by the general public.

Of particular concern is how interactions between ADS-equipped vehicles and drivers of conventional vehicles may differ from the existing interactions among the drivers of conventional vehicles, which could be critical for assessing potential safety outcomes. ADS-equipped vehicles may influence safety outcomes positively or negatively depending on various factors, including system design, operational behaviors, and the expectations and responses of drivers of conventional vehicles.

For example, some ADS-equipped vehicles often closely obey traffic laws, even in situations where human drivers might not. Examples include consistently obeying speed limits, yielding properly to pedestrians at crosswalks, coming to full stops at stop signs, and slowing at yellow traffic signals. While these behaviors conform to legal requirements, they might deviate from the expectations of other road users in some instances, potentially increasing or changing the risk of conflicts. For example, some reports have noted early indications that ADS-equipped vehicles may be more likely to be rear-ended. This may be partly attributed to their conservative, law-abiding design, which can lead to an expectation mismatch with human drivers (Goodall, 2021).

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On-Road Study of Drivers' Interactions With a Nearby ADS Mocked-up Research Vehicle

Purpose

The goal of this on-road study was to explore the behavior of drivers of conventional vehicles when operating near ADS-equipped vehicles, and to compare these interactions with interactions among drivers of conventional vehicles. The objective was to observe natural traffic interactions with a research vehicle, a 2018 Cadillac CT6 with Super Cruise, that was mocked up to appear to the other drivers on the road as if it were a vehicle with full automation, and then to drive in various conditions while observing and recording the other drivers' behaviors and reactions to what they might have thought was an ADS-equipped vehicle. The findings and methods of this study may be helpful for ADS development testing. Specific research questions for this study include the following.

1. *What is the effect of identifying a vehicle as "self-driving?"* Does the behavior of drivers with respect to a nearby vehicle differ if the nearby vehicle is clearly labeled as "self-driving" as compared to being unlabeled (i.e., having a conventional appearance)?
2. *What is the effect of identifying whether automation is engaged or not engaged?* For a vehicle labeled as "self-driving," does the behavior of nearby drivers differ if the labeled vehicle is identified as operating with Automation ON as compared to "Automation Off?"
3. *What is the effect of driving/operating style?* Does the behavior of drivers with respect to a nearby vehicle differ if the nearby vehicle is operated using automation with strict adherence to traffic laws, precise lane positioning, and speed control, as compared to being operated entirely in manual mode where lane positioning and speed typically vary?
4. *Does the behavior of drivers with respect to a nearby vehicle depend on an interaction between explicit labeling and driving style of the research vehicle?*

The goal of this study was to differentiate effects of a vehicle's driving style from the impacts of explicit identification of the vehicle as having automated capabilities or operating in ADS mode. The study's findings aim to inform the design of ADS-equipped vehicle by addressing key questions such as: Would it enhance safety for ADS-equipped vehicles to have a distinctive appearance that makes them readily identifiable to other drivers, thereby fostering accurate expectations regarding their behavior? Additionally, does strict adherence by ADS-equipped vehicles to posted speed limits pose safety challenges when interacting with traditional drivers who follow prevailing traffic flow dynamics?

Study Design

The study used a 3 x 2 factorial design using six treatment conditions that systematically varied the research vehicle's appearance and driving style, as shown in Table 1. The three vehicle appearance conditions included (1) conventional vehicle appearance with no signage, (2) "self-driving" appearance with Automation ON signage, and (3) "self-driving" appearance with

Automation OFF signage. The two driving style conditions included manual operation and what the study called "automated operation," which was driving with the aid of a commercially available driver support system.

Table 1. Driving data collected in six treatment conditions

		Conventional Vehicle No Signage	Research Vehicle Labeled "Self-driving" and ADS Mode Signage	
ADS Mode Indicator		**None**	**Automation ON**	**Automation OFF**
Driving Style	**Manual**	8 trips	8 trips	8 trips
	Automated	8 trips	8 trips	8 trips

Dependent variables included:

- Speed differential with vehicles passing in adjacent lane, measured by the time taken for vehicles to pass the research vehicle on the left.
- Number of close following events (tailgating) by other vehicles behind the research vehicle.
- Number of close lane change events (cut-ins) in front of the research vehicle detected by the Mobileye 630 Collision Avoidance System.
- Number of passing drivers who appeared to have their attention focused on the research vehicle (long glances at the research vehicle, surprised facial expressions, and waving or gesturing at the research vehicle).

Equipment

Research Vehicle

The research vehicle was a 2018 Cadillac CT6 with the Super Cruise driver support feature, which provides continuous longitudinal and lateral control on certain limited access highways, if other criteria for system use are met. The Super Cruise feature does not require the driver's hands or feet to be on the vehicle controls, however, it does monitor the driver and requires that the driver's head is positioned so that the driver remains looking forward at the roadway with only brief periods (a few seconds) looking elsewhere.

In some data collection sessions, the research vehicle had a conventional appearance (Figure 1), but for other sessions the vehicle had been professionally wrapped with external signage on the sides and rear that read, "self-driving" and "automated vehicle" (Figure 2). Dark tinted window films were applied to the rear window and rear side windows to help obscure the researcher seated behind the driver. The window tint was present in both conventional and self-driving conditions. An equipment pod was added to the roof for the "self-driving" condition to further distinguish it from a conventional vehicle. An illuminated sign was installed on the roof pod's

rear. An electronic part of this sign was controllable by researchers so that it could read either, Automation ON or Automation OFF.

Figure 1. Research vehicle with conventional appearance (no signage)

Figure 2. Research vehicle with self-driving appearance as seen from side (top photo) and rear (bottom photo)

Research Vehicle Instrumentation

During data collection trips, the behaviors of nearby drivers and their vehicles were observed and recorded using video cameras, the Mobileye 630 Collision Avoidance System, and radar (SmartMicro Universal Medium Range Radar, Type 30). A researcher sitting in the research vehicle's back seat also recorded observations of passing drivers on a laptop computer with custom software. Three GoPro cameras recorded views of the forward roadway, roadway directly behind the research vehicle, and adjacent travel lane to the left of the vehicle.[5] The Mobileye, mounted inside the top of the windshield, recorded the relative position and speed of vehicles traveling ahead of the research vehicle and the rear radar system, mounted on a hitch receiver, and centered approximately 37 cm above the road, recorded the relative position and speed of vehicles traveling behind the research vehicle. The data from the Mobileye and radar systems were logged for analysis.

Procedures

The study procedures were reviewed and approved by a federally certified institutional review board to protect the human subjects' rights and welfare. Before collecting study data, extensive pilot testing was performed (with the vehicle in its "conventional" appearance) to make sure that all sensor data was valid and reliable, and that all data collection procedures were well practiced.

[5] GoPro, Inc., San Mateo, CA.

The study was in 2019 in Maryland. At that time there were no ADS-equipped vehicles available for purchase in the United States, although there were some vehicles with driver support features available for sale (e.g., Cadillac, Tesla, Volvo). Various types of automated test vehicles were being driven extensively on public roads in cities such as San Francisco, Pittsburgh, and Phoenix, but no such testing was being conducted in Maryland, or the broader Washington, DC, metropolitan area, where the study took place.

Data Collection Route

Data was collected on limited-access highways in Maryland, including I-270, I-370, MD-200, I-95, and I-495. Figure 3 shows the route loop, which was followed in the clockwise direction. To create opportunities to interact with as many different vehicles and drivers as possible, the research vehicle exited and then re-entered the highway at prescribed locations shown by lettered points in Figure 3. This created eight independent data collection segments per loop from point "A" clockwise to point "I" on the map.

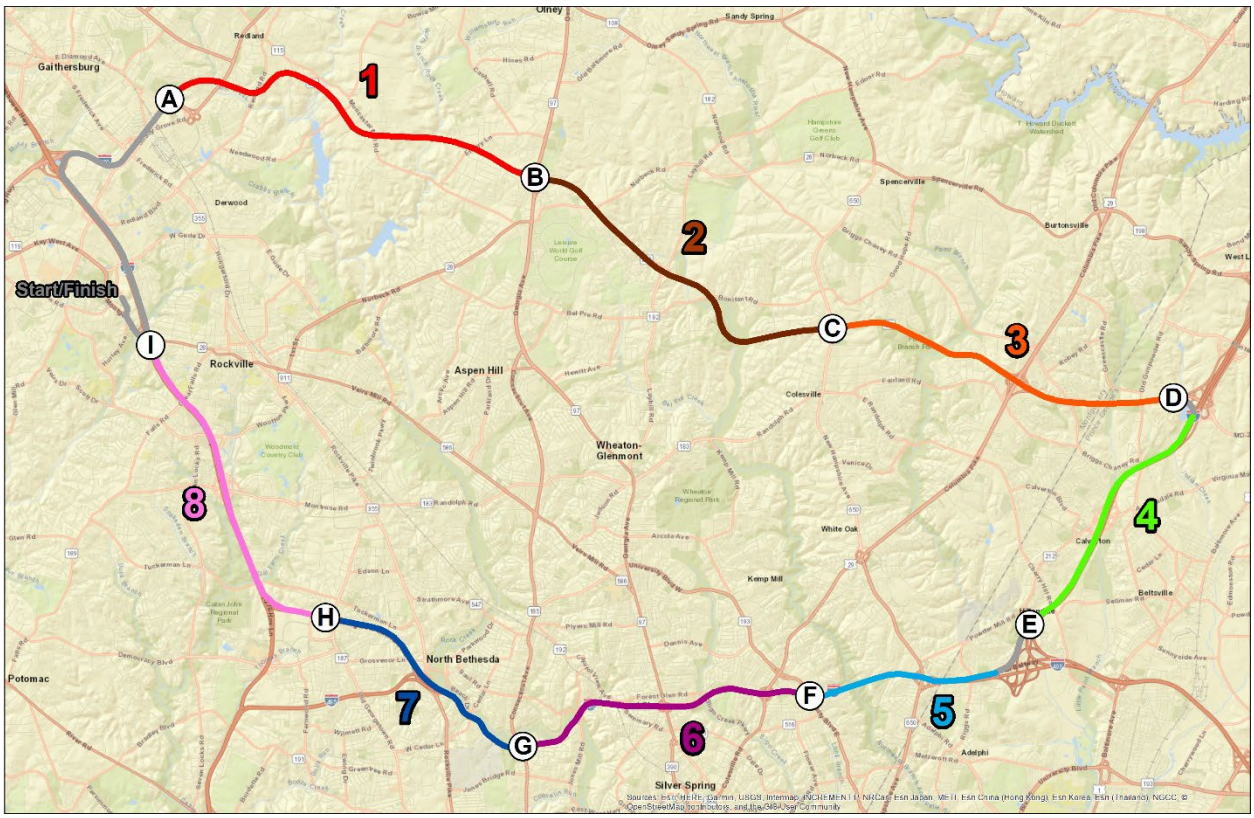

Figure 3. Data collection route

Data collection trips were balanced across treatment conditions for time-of-day and day-of-week to help balance traffic conditions encountered by the research vehicle. Trips were taken between 9:30 a.m. and 3:30 p.m. to avoid severe traffic congestion that occurs during morning and evening rush hours in the area. All data collection was conducted in daylight and fair weather to ensure good visibility of the research vehicle and its signage. No more than two sessions occurred on the same day.

It was not feasible to apply and remove the vehicle signage randomly between data collection trips. Therefore, data collection for the conventional and self-driving appearances was done in blocks of trips. To help control for possible order effects, half the data with the research vehicle in conventional appearance was collected, then the vehicle signage was applied, and all the ADS mockup driving sessions were conducted. Finally, after the vehicle signage had been removed, the second half of the data for the conventional appearance was collected. Driving style (manual or automated) was randomly assigned to each trip with the constraint that an equal number of trips would be conducted with each treatment condition.

Driving Styles and Researchers' Roles

During all data collection trips, the research vehicle was driven by the same researcher, who was trained to operate it in a standardized way. The researcher wore sunglasses and was instructed to avoid eye contact with other drivers in all six treatment conditions. The research vehicle generally travelled in the rightmost lane except when it was necessary to pass a slow-moving vehicle.

In the treatment conditions with automated driving style, the driver/researcher kept their hands out of sight below the bottom of the steering wheel and strictly obeyed the posted speed limit with Super Cruise engaged. When operating in manual driving style, the driver/researcher kept hands high on the steering wheel so that they would be visible to passing drivers. The driver manually controlled speed and lane position and matched the speed of the traffic flow up to 5 mph above the speed limit and introduced small variations in speed (approximately 5 mph) to differentiate manual driving style from automated driving style.

A second researcher (the observer) rode in the rear seat directly behind the driver. While traveling through data collection segments, the second researcher observed nearly every driver of a passenger vehicle who passed the research vehicle in the adjacent (left) lane. Using custom software and a laptop, the second researcher recorded time-referenced behavioral events including drivers who made long glances (greater than 2 seconds) toward the research vehicle, drivers who had surprised facial expressions, and drivers who waved or gestured toward the research vehicle. Each driver was counted only once per behavior. For example, a driver who made three long glances and two gestures was only counted once for long glances and once for gestures. No other passengers' behaviors were recorded except for camera use. Although this behavior was not anticipated in the research plan, the researcher counted all instances where a driver or passenger appeared to use a cell phone to take a photo or video of the research vehicle. No commercial vehicles or trucks were included in the set of observations because drivers of these vehicles were often not visible due to the height of those vehicles, and no observations were recorded for drivers in other travel lanes.

Data Reduction

Count data about passing drivers' observed behaviors was downloaded from the observer's laptop and combined to create analysis files. Descriptive and inferential statistics for all data types in this study were calculated using Microsoft Excel and IBM SPSS software.[6] [7] The criterion for identifying statistically significant differences was $\alpha = .05$.

Mobileye and radar data were reduced with custom software to identify principal lead vehicles and the principal following vehicles. These were defined as the closest vehicles in the same travel lane as the research vehicle. The data was smoothed by averaging within 1-second bins. The time gap between the research vehicle and the principal lead vehicle was defined as the distance from the research vehicle's front bumper to the lead vehicle's rear bumper divided by the research vehicle's speed. Similarly, the time gap for the following vehicle was defined as the distance between the research vehicle's rear bumper and the following vehicle's front end divided by the following vehicle's speed. Small time gaps between vehicles may not provide drivers with enough time to react to unexpected events and therefore increase the risk of crashes. Researchers examined the behavior of nearby vehicles to determine if the number of drivers whose maneuvers created small time gaps between their vehicles and the research vehicle varied with experimental conditions.

Vehicles entering the research vehicle's lane ahead with a time gap less than 0.6 second when the research vehicle was traveling at a speed of at least 25 mph were defined as "cut-ins." These two criteria were chosen so that less than 15 percent of vehicles entering the lane would be identified as cut-ins.[8] In total, 168 of 1,300 vehicles (12.9%) entering the research vehicle's lane were identified as such.

Following vehicles that had a time gap of less than 1.0 second for 20 seconds or more when the research vehicle was traveling at 25 mph or higher were defined as "tailgating" vehicles. Each tailgating vehicle was counted only once even if it met the tailgating criteria on more than one occasion. By these criteria, 252 of 2,123 following vehicles (11.9%) were identified as tailgating vehicles. Tailgating vehicle counts and cut-in vehicle counts were obtained for each experimental condition.

To determine whether there were any differences between experimental conditions in the differential speed of passing vehicles with respect to the research vehicle, researchers examined the amount of time it took vehicles in the left adjacent lane to pass the research vehicle. Vehicles that changed lanes by entering or exiting the travel lane adjacent to the research vehicle while passing were not included in the analysis of passing time. Trucks and commercial vehicles were also excluded from this analysis. Video recordings from the left side video camera were reviewed and manually coded using Morae Manager[9] software to determine the video frame (and time point) when each passing vehicle's front bumper first entered the video view (on the left side of the frame, approaching from behind the research vehicle) and to determine the first video

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[6] Microsoft Corporation, Redmond, WA.

[7] IMB Corporation, Armonk, NY.

[8] The 85th percentile is often chosen as a cutoff value by traffic engineers (e.g., for setting safe speed limits based on observed free flow travel speeds) and was used in this study because it provides a practical compromise that includes only short time gaps while still providing a sufficient number of cases for statistical analysis.

[9] TechSmith Corporation, East Lansing, MI.

frame (and time point) when the passing vehicle's front bumper exited the video view (on the right side of the frame). The difference between the two time points was calculated as the passing time for that vehicle. Vehicles in the lane next to the research vehicle's left side but then changed lanes away from the research vehicle while in view of the left side camera were counted for a separate analysis. Vehicles moving into the adjacent lane were also counted.

Results

Passing Times and Lane Changes

Passing times for 3,528 passenger vehicles passing in the adjacent lane to the research vehicle's left were obtained from video data based on the amount of time that the passing vehicle was within the left side video camera's view. Vehicles that entered or exited the adjacent lane in the view of the camera were excluded. The mean passing times for each experimental condition are shown in Figure 4. For both driving styles, the mean passing times for the no signage condition appear to be less than those for the conditions with signage. These results are discussed in a statistical manner below.

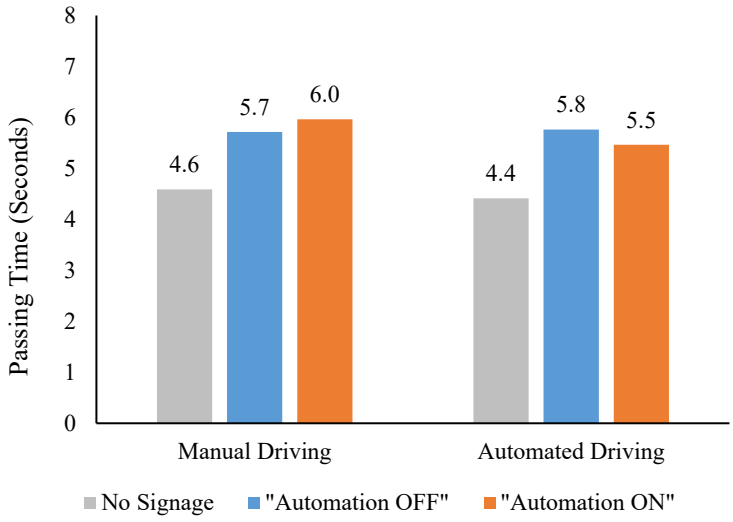

Figure 4. Mean passing times by experimental condition

As shown in Figure 5 (top graph), the distribution of passing times is positively skewed, deviating substantially from a normal distribution. Therefore, to compare passing times between experimental conditions using analysis of variance, passing times were first transformed by taking the common logarithm of each data point. As compared to the raw data, the transformed data more closely approximates a normal distribution. The transformed data distribution is shown in Figure 5 (bottom graph).

A two-way analysis of variance examined the effect of signage and driving style on passing times (log seconds). There was a significant main effect of signage, $F(2, 3{,}522) = 69.670$, $p < .001$, and a significant main effect of driving style, $F(1, 3{,}522) = 4.871$, $p = .027$. The interaction effect between signage and driving style was not statistically significant $F(2, 3{,}522) = 1.516$, $p = .220$. The interaction was explored using post-hoc Fisher's (1935) least significant difference test. Regarding signage, post-hoc least significant difference tests showed that the estimated marginal means differed significantly between a conventional vehicle with no signage and the

research vehicle with Automation ON conditions ($p < .001$) and differed significantly between a conventional vehicle with no signage and the research vehicle with Automation OFF conditions ($p < .001$). The difference between Automation ON and Automation OFF conditions was not significant ($p = .807$). Passing times were greater for each of the two signage conditions as compared to the conventional vehicle no signage condition. Regarding driving style, passing times were longer for the manual driving style as compared to the automated driving style.

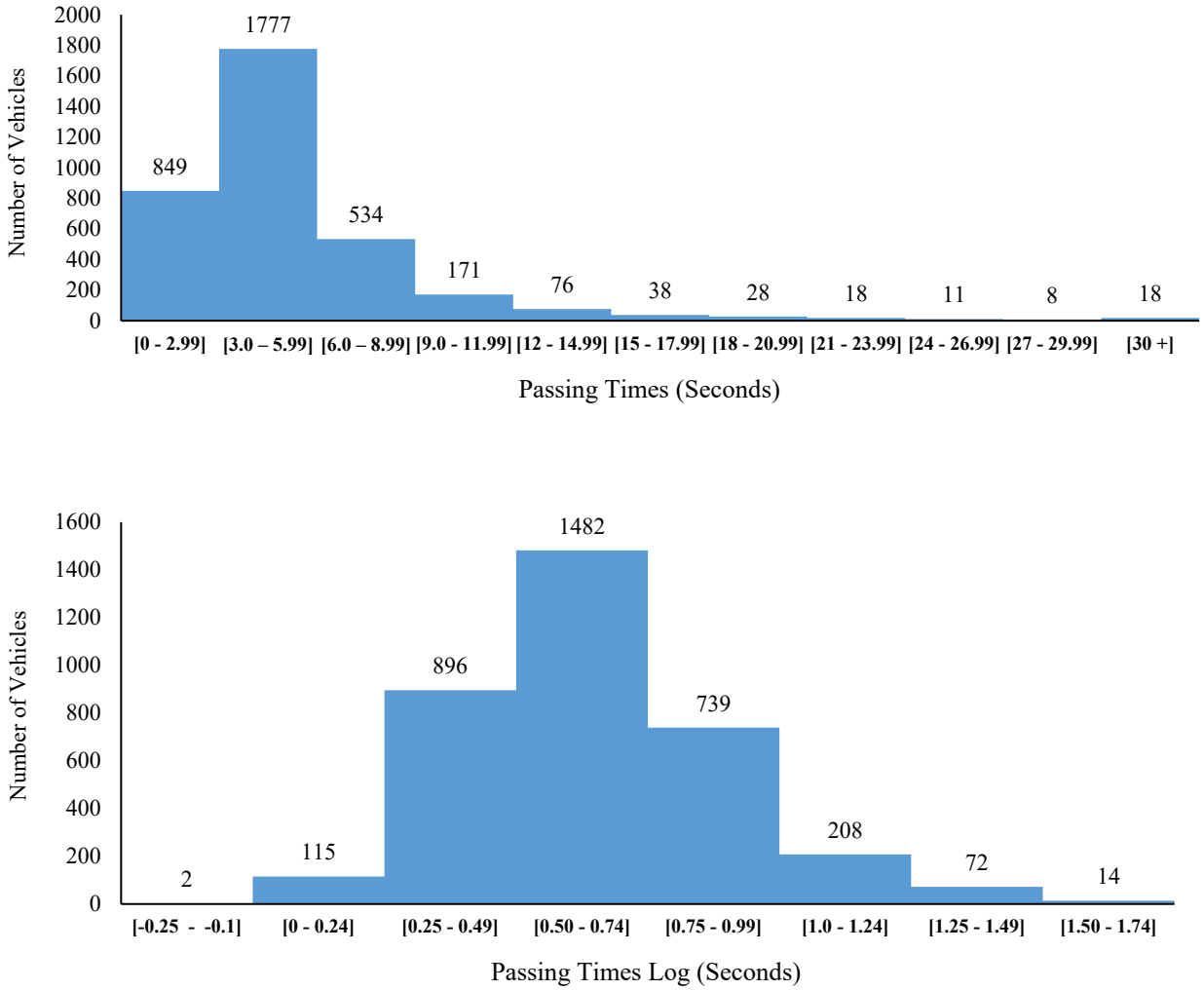

Figure 5. Distributions of passing times (top) and log transformed passing times (bottom)

Nearby Drivers' Behaviors

The observer-researcher made observations of 3,758 passenger vehicle drivers who passed the research vehicle on the left, in the adjacent lane. These vehicles were distributed across the six experimental conditions and the number of observed passing drivers for each condition is shown in Figure 6.

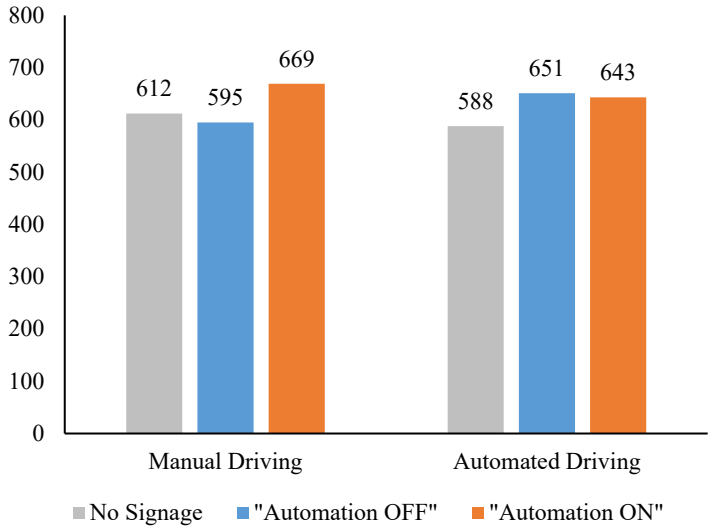

Figure 6. Observed passing drivers by experimental condition

Other drivers who did not complete their passing maneuver in the adjacent lane but made lane changes into or out of the adjacent lane while passing were counted separately. Figure 7 shows the number of nearby drivers making lane changes away from the research vehicle, from the left adjacent lane to a more distant lane further to the left, and Figure 8 shows the number of drivers who made lane changes from a more distant lane into the lane adjacent to the research vehicle. Table 2 compares the number of passing drivers who made lane changes out of the adjacent lane to the number of drivers who maintained their lane position while passing.

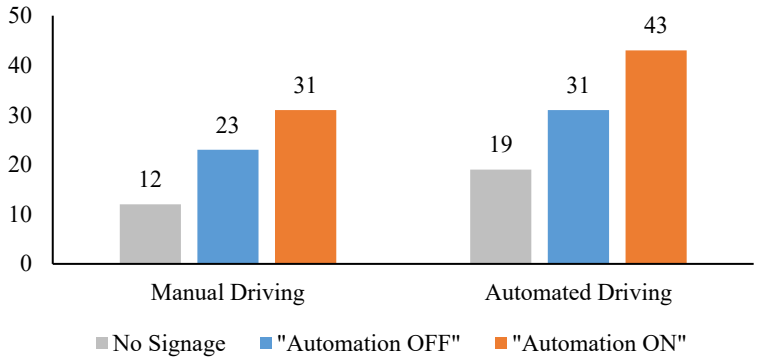

Figure 7. Drivers observed making lane changes out of lane adjacent to research vehicle

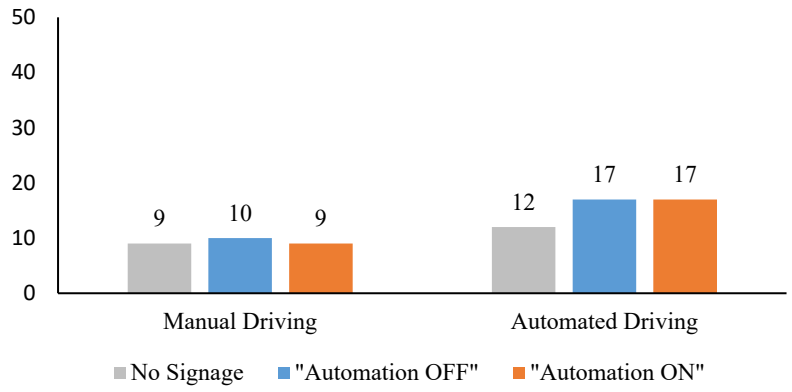

Figure 8. Drivers observed making lane changes into the lane adjacent to the research vehicle

Table 2. Drivers making a lane change out of the lane adjacent to the research vehicle by experimental condition

	Manual Driving			**Automated Driving**		
Lane Change Out or Pass in Lane?	**No Signage**	**Automation OFF**	**Automation ON**	**No Signage**	**Automation OFF**	**Automation ON**
Lane Change Out	12	23	31	19	31	43
Pass in Adjacent Lane	612	595	669	588	651	643

A chi-square test of independence was used to determine if there was an association between the experimental conditions and nearby drivers making a lane change out of the lane adjacent to the research vehicle versus staying in the adjacent lane while passing. The test showed that the relation between these variables was significant, $\chi^2(5, N = 3{,}917) = 18.09$, $p = .003$. The same analysis was performed on the counts of drivers who made lane changes into the lane adjacent as compared to drivers who passed in the adjacent lane. The chi-square test showed that the relation between the experimental conditions and lane changes into the adjacent lane was not statistically significant, $\chi^2(5, N = 3{,}832) = 5.11$, $p = .403$.

More comparisons were performed to explore the association of research vehicle signage with lane changes by passing drivers. To determine whether overall vehicle signage was associated with lane changes away from the research vehicle, data were combined across conditions, as shown in Table 3. A chi-square test showed that the relation between these variables was

significant, $\chi^2(1, N = 3{,}917) = 10.94$, $p < .001$. Drivers passing the research vehicle with "self-driving" signage were more likely to make a lane change away from the vehicle.

Table 3. Effect of signage on lane changes out of adjacent lane

Lane Change Out?	No Signage	All Signage
Yes	31	128
No	1,200	2,558

Within the two signage conditions, data from the two driving styles was combined to examine whether differences in the automation mode sign (On versus Off) were associated with lane changes away from the research vehicle. The data is shown in Table 4. A chi-square test showed that the relation between these variables was not statistically significant, $\chi^2(1, N = 2{,}682) = 2.08$, $p = .150$. However, a similar analysis examining the association between driving style (manual versus automated) and lane changes out of the adjacent lane found a statistically significant relation, $\chi^2(1, N = 3{,}917) = 4.32$, $p = .038$.

Table 4. Comparing lane changes out of adjacent lane versus passing in adjacent lane for Automation ON and Automation OFF signage conditions

Lane Change Out?	Automation ON Sign	Automation OFF Sign
Yes	74	54
No	1,312	1,246

Drivers were more likely to move out of the left lane adjacent to the research vehicle when the driving style was automated (i.e., Super Cruise was engaged). Also, the research vehicle's driving style was significantly related to the number of passing drivers making lane changes into the adjacent lane, $\chi^2(1, N = 3{,}832) = 4.24$, $p = .040$. Drivers were more likely to enter the left lane adjacent to the research vehicle when the driving style was automated.

Long glances (greater than 2 seconds) away from the forward roadway have been associated with increased crash risk (Klauer et al., 2006). In the present study, the observer-researcher subjectively identified glances from passing drivers at the research vehicle that exceeded 2 seconds in duration. For each experimental condition, the number of drivers who made a long glance is shown in Figure 9. The data is also shown in Table 5.

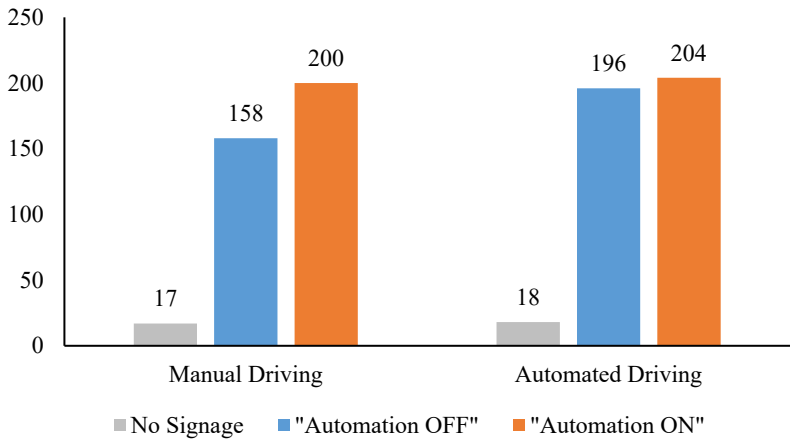

Figure 9. Observed passing drivers making a long glance by experimental condition

Table 5. Passing drivers making a long glance by experimental condition

	Manual Driving			Automated Driving		
Long Glance?	**No Signage**	**Automation OFF**	**Automation ON**	**No Signage**	**Automation OFF**	**Automation ON**
Yes	17	158	200	18	196	204
No	595	437	469	570	455	439

A chi-square test of independence was used to determine if there was an association between making a long glance (Yes or No) and the experimental conditions. The test showed that the relation between these variables was significant, $\chi^2(5, N = 3{,}758) = 355.4$, $p < .001$. More comparisons were performed to explore the influence of driving style and vehicle signage on long glances.

To determine whether overall vehicle signage was associated with long glances, data was combined across conditions, as shown in Table 6.

Table 6. Effect of signage on long glances

Long Glance?	**No Signage**	**All Signage**
Yes	35	758
No	1,165	1,800

A chi-square test showed that the relation between these variables was significant, $\chi^2(1, N = 3{,}758) = 350.2$, $p < .001$. Drivers passing the research vehicle with signage were more likely to make a long glance at the vehicle.

Within the signage conditions, data from the two driving styles was combined to examine whether differences in the automation mode sign (ON versus OFF) were associated with long glances. The data is shown in Table 7.

Table 7. Comparing long glances for Automation ON and Automation OFF signage

Long Glance?	Automation ON	Automation OFF
Yes	404	354
No	908	892

A chi-square test showed that the relation between these variables was not statistically significant, $\chi^2(1, N = 2{,}558) = 1.74$, $p = .187$.

Data was combined across experimental conditions to determine if the research vehicle's driving style was associated with long glances. The counts are shown in Table 8.

Table 8. Effect of driving style on long glances

Long Glance?	Manual Driving	Automated Driving
Yes	375	418
No	1,501	1,464

A chi-square test showed that the relation between these variables was not statistically significant, $\chi^2(1, N = 3{,}758) = 2.78$, $p = .095$.

For each experimental condition, the number of drivers who were observed to have a surprised facial expression (e.g. raised eyebrow, mouth open) while passing the research vehicle is shown in Figure 10. The data is also shown in Table 9.

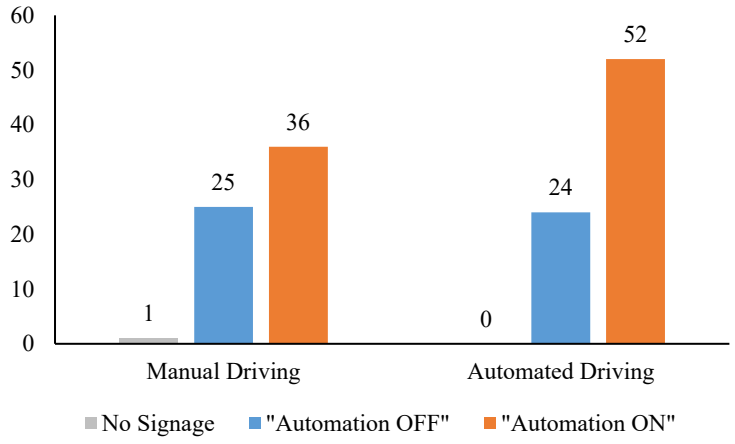

Figure 10. Passing drivers with a surprised facial expression

Table 9. Passing drivers with a surprised facial expression by experimental condition

	Manual Driving			Automated Driving		
Surprised Expression?	**No Signage**	**Automation OFF**	**Automation ON**	**No signage**	**Automation OFF**	**Automation ON**
Yes	1	25	36	0	24	52
No	611	570	633	588	627	591

A chi-square test was used to determine if there was an association between passing drivers making a surprised facial expression (Yes or No) and the experimental conditions. The test showed that the relation between these variables was significant, $\chi^2(5, N = 3{,}758) = 85.1$, $p < .001$. More comparisons were performed to explore relations between driving style and vehicle signage on surprised expressions.

To determine whether overall vehicle signage was associated with surprised facial expressions, data was combined across conditions, as shown in Table 10.

Table 10. Association between signage and surprised expressions

Surprised Expression?	**No Signage**	**All Signage**
Yes	1	137
No	1,199	2,421

A chi-square test showed that the relation between these variables was significant, $\chi^2(1, N = 3{,}758) = 64.2$, $p < .001$. Drivers passing the research vehicle with signage on it were more likely to make a surprised expression.

Within the signage conditions, data from the two driving styles was combined to examine whether differences in the automation mode sign (On versus Off) were associated with surprised facial expressions. The data is shown in Table 11.

Table 11. Comparing surprised expressions for Automation ON and Automation OFF signage

Surprised Expression?	**Automation ON**	**Automation OFF**
Yes	88	49
No	1,224	1,197

A chi-square test showed that the relation between these variables was statistically significant, $\chi^2(1, N = 2{,}558) = 9.71$, $p = .002$. Drivers passing the research vehicle when the Automation ON sign was illuminated were more likely to have surprised facial expressions than were drivers passing when the Automation OFF sign was illuminated.

Data was combined across experimental conditions to determine if the research vehicle's driving style was associated with making surprised facial expressions. Those counts are shown in Table 12.

Table 12. Association between driving styles and surprised expressions

Surprised Expression?	Manual Driving	Automated Driving
Yes	62	76
No	1,814	1,806

A chi-square test showed that the relation between these variables was not statistically significant, $\chi^2(1, N = 3{,}758) = 1.43$, $p = .23$.

The percentage of passing drivers who gestured or waved was very small (0.5%). However, these events occurred only in the two vehicle signage conditions, as shown in Figure 11.

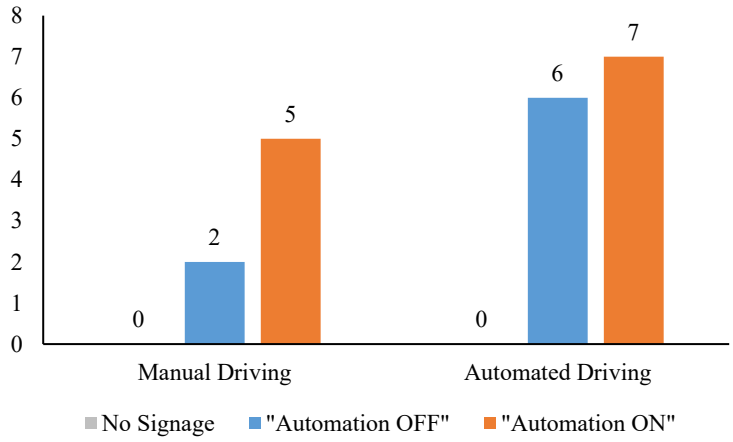

Figure 11. Drivers gesturing or waving at the research vehicle

The data was combined across conditions to examine the effect of vehicle signage, as shown in Table 13.

Table 13. Drivers gesturing or waving by signage condition

Gesture or Wave?	No Signage	All Signage
Yes	0	20
No	1,200	2,538

A chi-square test showed that the relation between these variables was statistically significant, $\chi^2(1, N = 3{,}758) = 9.43$, $p = .002$. This shows that the probability of a passing driver waving or making a gesture was higher when the research vehicle had signage. Another chi-square test comparing the subset of data collected with the research vehicle signs Automation ON and Automation OFF was not statistically significant, $\chi^2(1, N = 2{,}558) = .61$, $p = .43$. A similar chi-

square test comparing data by manual versus automated driving style also was not significant, $\chi^2(1, N = 3{,}758) = 1.79, p = .18$.

Another behavior that was observed from occupants of passing vehicles was using a cell phone to capture a photo or video of the research vehicle. It appeared to the observer-researcher that photos were captured by both passengers and drivers. This behavior was not observed in pilot testing, nor was it anticipated when programming the data collection interface for the observer-researcher. Therefore, the exact counts of photo taking by drivers versus passengers was not recorded. However, occupants of 28 passing vehicles were observed to be taking photos. This behavior was observed only when the research vehicle had signage, as shown in Figure 12. A chi-square test showed that the relation between signage (versus no signage) and camera use (or not) was statistically significant, $\chi^2(1, N = 3{,}758) = 13.23, p < .001$. This shows that the probability of a passing driver or passenger using a phone camera was higher when the research vehicle had signage. Another chi-square test comparing the subset of data collected with the research vehicle signs Automation ON and Automation OFF was not statistically significant, $\chi^2(1, N = 2{,}558) = .02, p = .891$. A similar chi-square test comparing data by manual versus automated driving style also was not significant, $\chi^2(1, N = 3{,}758) = 1.23, p = .259$.

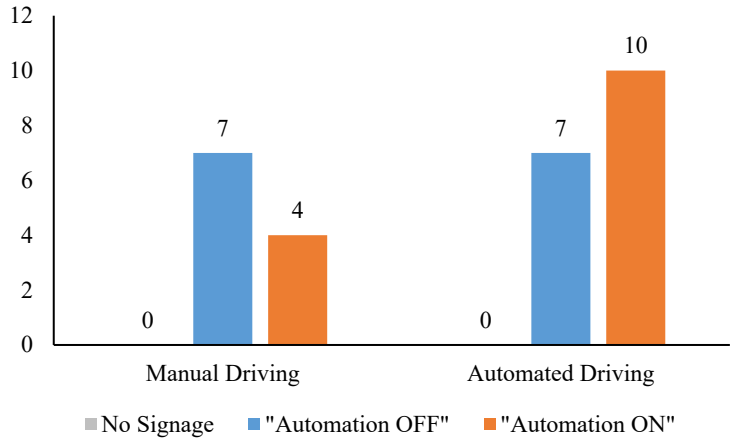

Figure 12. Apparent camera use by occupants of passing vehicles

Close Following and Close Lane Changes

As was described and defined in the Data Reduction section, data from the rear radar and Mobileye system on the research vehicle was examined to identify vehicles that were tailgating (following closely for at least 20 seconds) behind the research vehicle or made lane changes into the research vehicle's lane very close to the research vehicle's front (cut-ins). Table 14 shows the counts of drivers tailgating by experimental condition.

Table 14. Drivers tailgating behind research vehicle by experimental condition

	Manual Driving			Automated Driving		
Following With Less Than 1 Second Time Gap for 20 Seconds?	**No Signage**	**Automation OFF**	**Automation ON**	**No Signage**	**Automation OFF**	**Automation ON**
Yes	35	54	32	40	51	40
No	295	295	280	305	343	353

A chi-square test showed that the relation between these variables was not statistically significant, $\chi^2(5, N = 2{,}123) = 7.15$, $p = .210$. Researchers pooled data across driving styles and signage conditions to compare no signage to all signage conditions (Table 15).

Table 15. Tailgating with and without research vehicle signage

Tailgating?	**No Signage**	**All Signage**
Yes	75	177
No	600	1,271

The chi-square test showed that the relation between these variables was not statistically significant, $\chi^2(1, N = 2{,}123) = .54$, $p = .460$. However, pooling data across driving styles to compare only the two conditions with vehicle signage resulted in the counts shown in Table 16.

Table 16. Comparing tailgating for Automation ON and Automation OFF signage

Tailgating?	**Automation ON**	**Automation OFF**
Yes	72	105
No	663	638

A chi-square test showed that the relation between these variables was significant, $\chi^2(1, N = 1{,}448) = 5.18$, $p = .022$. Drivers following the research vehicle with the sign Automation ON were less likely to tailgate than were drivers following the research vehicle with the sign Automation OFF. Researchers then pooled data across signage conditions to compare the effect of driving style (Table 17).

Table 17. Tailgating between driving style conditions

Tailgating?	Manual	Automated
Yes	121	131
No	870	1,001

A chi-square test showed that the relation between these variables was not statistically significant, $\chi^2(1, N = 2{,}123) = .21, p = .651$.

The number of vehicles that changed lanes into the research vehicle's travel lane with less than a 0.6 second time gap in front of the research vehicle are shown by experimental condition in Table 18.

Table 18. Drivers making cut-ins in front of research vehicle by experimental condition

	Manual Driving			Automated Driving		
Less Than 0.6 Second Time Gap?	**No Signage**	**Automation OFF**	**Automation ON**	**No Signage**	**Automation OFF**	**Automation ON**
Yes	20	27	26	31	31	33
No	189	177	176	191	220	179

The chi-square test showed that the relation between these variables was not statistically significant, $\chi^2(5, N = 1{,}300) = 4.94, p = .422$. In fact, none of the additional pooled data comparisons was statistically significant (i.e., no signage versus no signage, Automation ON versus Automation OFF signage, and manual versus automated driving style).

Discussion

The on-road study was conducted to determine how nearby drivers' behavior may differ when encountering an ADS-equipped prototype vehicle as compared to a conventional vehicle. ADS-equipped test vehicles operating on public roadways in various cities across the United States (e.g., Las Vegas, Pittsburgh, San Francisco) at the time this research was conducted sometimes had signage identifying the vehicle's automated capability and sometimes did not. It is not yet clear whether it would be in the interest of safety for production ADS-equipped vehicles to be easily identifiable as ADS-equipped to shared road users.

The signage used on the research vehicle in this study was intended specifically to influence other drivers' perception of the research vehicle to induce the beliefs that (1) the research vehicle was capable of automated, self-driving operation, and (2) the state of the vehicle's automation system was either on or off. Another manipulation used in the study was to vary the driving style of the research vehicle, either operating under automated control that included precise lane keeping and adaptive speed control that did not exceed the speed limit, or operating under manual control, where lane position and speed were more variable. The purpose of including this

manipulation in the research design was so that researchers would be able to differentiate between the effects of operating style on the behavior of other road users from the effects of explicit identification (e.g., signage and other visual cues).

The research vehicle's appearance was novel for the region where the study took place. It is possible that differences noted in nearby drivers' behavior for the signage conditions versus the no signage condition were due to drivers reacting to a vehicle with an unusual appearance, rather than to the fact that the research vehicle was shown to be self-driving. Further research into how unusual signage or appearance that is unrelated to automation could clarify this. However, there is some evidence in the data collected for this study that drivers were responding differentially to the signage's meaning rather than just to the vehicle's novel appearance. For some of the dependent variables examined, there were differences between the Automation ON and Automation OFF conditions. For those two conditions, the research vehicle's appearance was nearly identical and equally novel. Drivers passing the research vehicle when the Automation ON sign was illuminated were more likely to have surprised facial expressions than were drivers passing when the Automation OFF sign was illuminated. Also, drivers following the research vehicle with the sign Automation ON were less likely to tailgate than were drivers following the research vehicle with the sign Automation OFF. These results suggest that the experimental treatments had differential effects on nearby drivers that went beyond the possible effect of novelty.

Overall, the results show that nearby drivers behaved differently around the research vehicle as compared to the conventional vehicle based on both its appearance and driving style. The research vehicle (with signage) elicited more long glances, surprised facial expressions, and gesturing from passing drivers, and instances of camera use by passing drivers and passengers. Drivers also generally took longer to pass the research vehicle than the conventional vehicle. However, objective measures of potentially unsafe behaviors, including cut-ins and tailgating did not reveal any statistically significant differences between the research vehicle and the conventional vehicle. In fact, drivers were more likely to make lane changes away from the research vehicle when it was labeled as a self-driving vehicle as compared to having a conventional appearance.

The research vehicle's driving style was associated with two differences in the behavior of nearby drivers. Drivers took significantly longer to pass the research vehicle when it was operating with the manual driving style, and they were more likely to move into and out of the adjacent (left) lane next to the research vehicle while it operated using automation, but there were no other significant differences in long glances, surprised expressions, gestures, camera use, tailgating, or cut-ins by nearby drivers when the automated driving style was used as compared to the manual driving style. Longer passing times observed for the manual driving style condition could have been influenced by the research vehicle's speed, which varied up to a maximum of 5 mph above the posted speed limit. When the research vehicle was operated in automated driving style, its speed did not exceed the posted speed limit.

A possible limitation of the study is that some of the dependent variables were collected by a trained observer who was aware of the experimental condition being tested. The observer recorded counts about events in real time as they occurred. The original research plan called for video records of passing drivers' behaviors to be coded after data collection by researchers who were not aware of the experimental conditions to avoid any possible bias in subjective coding. However, pilot testing with several different video cameras, different lighting conditions, and

different passing vehicles did not produce data of sufficient quality to clearly see the passing drivers in their vehicles.

Another limitation of this study is that observations were made only on limited-access highways. It is possible that other differences in interactions between vehicles may be observed on other types of roadways, and since this research was conducted in 2019, the trend in ADS deployments has been particularly focused on urban environments.

Finally, it is likely that the vast majority of drivers observed in this study had never previously encountered an ADS-equipped vehicle. It is possible that as ADS-equipped vehicles become more common, drivers of conventional vehicles will adapt and they may exhibit other safety-relevant behaviors not observed in this study.

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