Driver Adaptation to Vehicle Automation: The Effect of Driver Assistance Systems on Driving Performance and System Monitoring

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FOREWORD

Advanced driver assistance systems (ADAS) are becoming increasingly prevalent on today's roadways. The long-term effects of using these systems are still being explored. Some researchers have noted that drivers' trust in automation tends to increase with continued use and caution that they may become overly reliant. Such reliance may make everyday drivers less capable of responding to critical events, yet automation has the potential to increase the operational efficiency of the roadway. However, these potential benefits can only be achieved if drivers are able to accept and use an automated system in a way that consistently promotes road safety.

This report documents a longitudinal experiment aimed at understanding how continued use of automated systems influences drivers' behavior over time as they adapt to the technology. Participants in a driving simulator gained experience with two ADAS over the course of four driving sessions. The results suggest that some driver assistance systems may facilitate increased attention to the forward roadway rather than reduce awareness. This report highlights the potential for these systems to improve drivers' safety even after they adapt to the technology following repeated exposure.

This report should be of interest to ADAS developers, State and local transportation agencies considering how infrastructure may adapt to ADAS, and others interested in understanding how the widespread implementation of these systems is anticipated to affect roadway safety.

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16. Abstract

Little is known about how driving performance and attention change over time with increased automation. The current study assessed the effect of varying levels of vehicle automation on driver performance over time. Participants gained experience with advanced driver assistance systems (ADAS) across four sessions in the driving simulator. The specific driver assistance system was manipulated between subjects and included cooperative adaptive cruise control (CACC), lane-keeping assist (LKA), a combination of CACC and LKA (CACC + LKA), and a control condition with no driving assistance features. Adaptation was assessed by measuring drivers' response to uneventful roadway conditions and unexpected critical events during both earlier and later exposure to the technology. Overall, the results of the current study paint an optimistic view of driver assistance technology. Participants who used the technology were able to do so in a way that benefited their driving performance and allowed them to direct more of their attention to the road ahead. Further, driver adaptation was not associated with impaired responses to emergency events. The results suggest that Level 1 driver assistance systems have the potential to benefit driver safety even after drivers have adapted to the technology following repeated use.

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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

ACC	adaptive cruise control
ADAS	advanced driver assistance systems
CACC	cooperative adaptive cruise control
EDA	electrodermal activity
LKA	lane-keeping assist
M	mean
PPG	photoplethysmography
SAE	SAE International
SCR	skin conductance responses

CHAPTER 1. INTRODUCTION

This report is in support of a project titled "Driver Acceptance of Vehicle Automation—Function-Specific Automation (Level 1) Applications." The goals of the project are threefold, as follows:

1. Improve general understanding of human factors issues related to vehicle automation.
2. Perform experiments to support Level 1 vehicle automation research.
3. Publish information to support the development of standards and performance requirements for Level 1 automation.

SAE (SAE International) specifies six levels of vehicle automation based on the roles and responsibilities of the driver and the automated system.(1) Under Level 1 automation, the driver remains responsible for all driving functions but temporarily cedes either lateral or longitudinal control of a vehicle to the automated system. A lane-centering system, which maintains lateral control of a vehicle, or an adaptive cruise control (ACC) system, which maintains longitudinal control of a vehicle, are examples of advanced driver assistance systems (ADAS) that represent Level 1 automation.

Parasuraman and Riley provided an excellent review of human factor issues in the automation of systems.(2) They define automation as work previously performed by a human that has transitioned to being performed by a machine. When enough time elapses, the work previously performed by a human tends to be forgotten, and the work is no longer thought of as automation. An increase in the processing power of computers has led to an increase in the speed of automation. In allocating system functions to humans and machines, functions performed more accurately, efficiently, reliably, or at a lower cost by machines are frequently assigned to the machine. This process of assigning to machines tasks best done by them sometimes fails to consider the role of the human in determining overall system performance and may lead to what Bainbridge describes as the irony of automation.(3) The less frequently a human is required to do a set of tasks, the more difficult doing those tasks may become. Automation often changes a person's job from doing tasks to monitoring tasks and intervening in the event of automation errors. However, if automation prevents a person from practicing a task, the person may be less qualified to intervene and more likely to be out of the loop—thus making it more difficult for them to accurately identify when an error has occurred.

Several studies have reported reductions in driving safety that result from increased automation.(4) For example, Stanton and Young found that participants reported less situational awareness when ACC was engaged.(5) Similarly, Strand et al. found that drivers who drove a simulated Level 2 vehicle that combined an automatic steering system with ACC were more likely to collide with a braking vehicle when the automation failed than drivers who drove with the ACC system alone.(6) The results suggest that driver assistance and driver automation systems can lead to reduced driver safety in unexpected emergency situations.

Kovordányi, Ohlsson, and Alm proposed that reductions in driver performance following the introduction of automation may be a result of negative behavioral adaptation.(7) Negative behavioral adaptation is an unintentional deterioration in behavior that occurs in response to a change in technology.(8) During conventional driving, the utility of one's actions are processed by comparing the actual outcome of a response with the expected outcome to that response. If the actual outcome is worse than expected, then the behavior is adjusted to create a more acceptable outcome. If the actual outcome is better than expected, then the behavior can be adjusted to create less effort. This process is nonconscious and allows for automatic procedural learning. However, when an automated system compensates for faulty behavior, the actual outcome of the behavior will be better than expected. As a result, drivers may be more likely to either continue producing the faulty behavior or adjust behavior to become even more risky.(7) Thus, behavioral adaption may negate the benefits of ADAS and create a driver that is less able to produce correct behavior in situations when the system is not present.

Nevertheless, it is unclear whether the reductions in safety found in studies assessing drivers' responses to automation failure indicate negative behavioral adaptation or simply reflect the difficulty that drivers have in learning the boundary conditions of automated driving systems. Sullivan et al. note that when drivers use advanced driver automation systems they create and update mental models of the technology as they use it.(8) When drivers first begin interacting with the system, their mental models will be incomplete. The models will become more accurate as they gain experience using the system and encounter the boundary conditions of the technology. Studies reporting reduced ability to respond in emergencies (e.g., device failures) when using ADAS have typically used drivers that are unfamiliar with the technology.(4,5,6) As such, it may be that these reductions in performance are due to failure to fully understand automation rather than true behavioral adaptation.

Weaver et al. found that participants driving a field research vehicle on an actual roadway displayed increased alertness and somewhat reduced mind wandering when driving with automated technology compared to when driving the same route manually.(9) This result is in stark contrast to previous work that found delayed responses when driving with automation in a simulated scenario. When driving on a simulated roadway, participants with an incomplete mental model may attempt to test the limits of the automation in order to learn more about the system, whereas drivers in the real world may proceed with extra caution until more about the automation is learned. Thus, an incomplete mental model of vehicle automation may exaggerate the negative effects of vehicle automation on driving performance when testing occurs in a driving simulator.

Behavioral adaptation and a misunderstanding of the boundary conditions of vehicle automation can both result in reductions in driver performance during emergency situations that occur when drivers are still learning about the technology. However, different responses would be expected with increased use of the system. Behavioral adaptation is a largely automatic process that continues over time. Thus, reductions in performance that result from behavioral adaption would be expected to persist and even further degrade with increased experience using the system.

In contrast, an incomplete mental model would only be expected to influence behavior during early use of the technology. As drivers gain experience with the system, particularly with the boundary conditions of the technology, their mental model of the system should become more accurate, and their driving ability should improve. Thus, understanding whether a reduction in performance in the presence of vehicle automation stems from negative behavioral adaptation or from an incomplete mental model of the technology has important implications for the expected long-term effect of this technology on driver safety. Studying changes in performance as drivers gain experience with the technology, especially changes in responses to critical events, can help differentiate between the potential roles of behavioral adaptation and incomplete mental models on driving performance.

Within the current study, the effect of varying levels of vehicle automation on driver performance over time was assessed. Participants gained experience with driver assistance systems across four sessions in the driving simulator. The specific driver assistance systems were manipulated between subjects and included CACC, LKA, a combination of CACC and LKA (CACC + LKA), and a control condition with no driving assistance features. Driver performance metrics, eye tracking, and physiological data were collected to assess how driver behavior changes as one adapts to automation. Unexpected critical events during both early and later exposures to the technology were used to assess whether vehicle automation leads to reductions in driver responses during emergencies and whether such changes are indicative of behavioral adaptation. Thus, the goal of this research was to assess the effect of longer-term adaptation to vehicle automation on the driver's ability to monitor the driving system and drive the vehicle.

CHAPTER 2. METHOD

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

PARTICIPANTS

Forty-eight licensed drivers from the Washington, DC metro area participated in the study. All participants were over the age of 18 and had at least 20/40 visual acuity (with correction if needed). Each participant completed four drives.

EXPERIMENTAL DESIGN

The study employed a four (driver assistance system condition) by four (session number) research design. Driver assistance system type was manipulated between subjects. Participants drove either a conventional vehicle with no driver assistance system, a vehicle with LKA (a lateral control technology), a vehicle with CACC (a longitudinal control technology), or a vehicle with CACC + LKA (both lateral and longitudinal control technologies). Each participant drove in four driving sessions. Potential effects of participant gender and age (older or younger than 45) were also assessed. Changes in driving performance, eye-gaze patterns, and driver alertness were assessed as participants gained experience with the technology. Critical events occurred during the first and last experimental sessions. Participant responses to the critical events were thus assessed in a four (driver assistance system condition) by two (session number) design.

EQUIPMENT

The study took place in the Federal Highway Administration (FHWA) Highway Driving Simulator. The simulator consists of a compact sedan mounted on a six-degree-of-freedom motion base surrounded by a 200-degree portion of a cylinder with a radius of 8.7 ft. Directly in front of the driver, the design eye point of the simulator is 8.5 ft from the screen. Three projectors, each with a resolution of 4,096 by 2,400 pixels, project stimuli onto the screen.

Lane-Keeping Assist

Two of the four participant groups drove with LKA. The system assisted with lane keeping by using a seat vibration to alert participants when they got near the edge of their lane. If a participant's vehicle crossed the lane line, the LKA system gently steered the vehicle back toward the center of the lane. The participant could override the LKA by applying force to the steering wheel.

Cooperative Adaptive Cruise Control

Two of the four participant groups drove with CACC. This system assisted with longitudinal control by keeping the vehicle speed at 40 mph except when approaching a slower moving vehicle. When the participant's vehicle approached a slower moving vehicle, the CACC system ensured that the participant's vehicle maintained a 0.5-s following distance from the vehicle. Participants could override the system by either applying the brake or the accelerator.

Sensors To Detect Physiological Responses

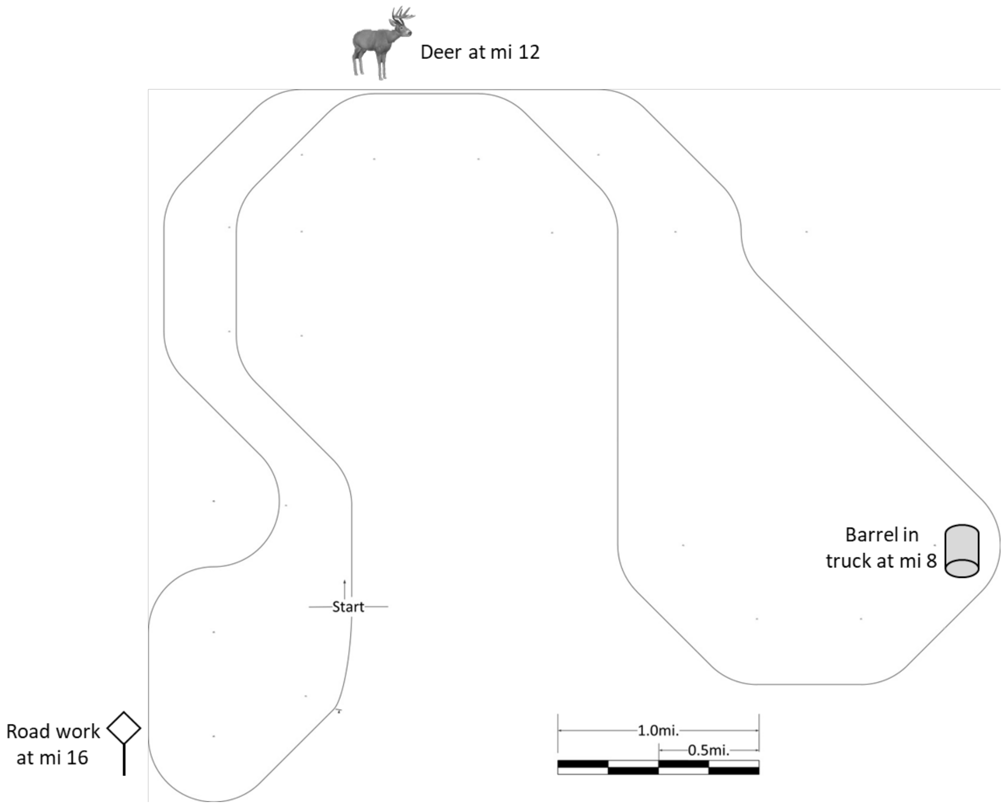
Disposable silver-silver chloride electrodes were used to collect electrodermal activity (EDA) data, and a photoplethysmography (PPG) sensor was used to collect heart rate data via pulse recordings. Both sensors connected to a small wireless transmitter that was worn on the wrist of the participant's nondominant hand. EDA and PPG signals were relayed to and processed by a commercially available physiological data acquisition system.

PROCEDURE

Upon arrival to their first session, participants were asked to read and sign an informed consent. An eye chart was then used to verify better than 20/40 vision, the minimum requirements for licensure in most States. Participants then received study instructions. For those who were driving with a driver assistance system, these instructions provided the participants information on how the system they would drive with functioned. After learning about the driver assistance system(s) they would drive with, participants in the LKA, CACC, and CACC + LKA conditions completed the Van Der Laan questionnaire. This nine-item questionnaire provides separate measures for usefulness and satisfaction with new in-vehicle technologies.(10) When administered before and after technology use, the measure provides an assessment of how perceptions of technology change with use.

PPG and EDA sensors were attached to the participants, and the sensor functions were verified. Next, the eye tracker was calibrated to each participant. Finally, a practice drive was completed to allow the participant to become familiar with the simulated vehicle and the driver assistance system(s) they would use during the experiment.

Participants then completed an experimental drive on the simulated route shown in figure 1. The simulated highway was a four-lane, undivided loop of 18.5 mi with a speed limit of 40 mph. Drivers in the CACC and CACC + LKA conditions were asked to keep the CACC engaged whenever they felt it was safe to do so. Participants started each drive in the right lane of the roadway. They were free to change lanes as desired throughout the drive. Light traffic was present on the roadway traveling at speeds between 35–45 mph. The traffic was relatively evenly dispersed along the length of the roadway. The traffic volume was programmed to be high enough to help invoke realism but not so high as to limit participant driving behavior. To provide some variety, participants traveled in one direction during their first and third sessions and the opposite direction during their second and fourth sessions. The direction of travel during the first session was counterbalanced.



Source: FHWA

Figure 1. Illustration. Experimental route.

At three points during the drive, moving figures were visible from the roadway. These figures included deer by the side of the road, construction workers, and men loading a barrel into the back of a truck. The figures were present at the side of the road during all four sessions. During the first and last drive, one of these moving figures became a critical event that required driver reaction. During the deer event, one of the deer positioned at the side of the road would dart across the road. During the barrel event, the barrel would roll down from the truck and across the roadway. Critical events occurred during the first and the fourth session, and each participant encountered each event only once. That is, those who encountered the deer during session 1 would encounter the barrel in session 4 (or vice versa). The timing of the events was manipulated so that drivers who did not change their speed or direction of travel would be involved in a collision.

Participants completed four sessions. No more than two sessions were completed in a single week, and each session was completed within 7 d of the previous session. Following their last experimental drive, participants completed the Van der Laan questionnaire a second time.

DATA ANALYSIS

For vehicle dynamics, eye tracking, critical event, and questionnaire data, a linear mixed-effects model and a generalized linear mixed model with logit link or log link were used accordingly, depending on the characteristics of response variables in the analysis. For nonbinary response variables, outlier detection was implemented by examining whether an observation in a cell of the design was below the first quartile minus three times interquartile range, above the third quartile plus three times interquartile range, or resulted in large estimated deviation between subject average and the overall model average. Any detected outlier was excluded from the analysis. A significance level of 0.05 was adopted throughout the analysis. Each model started with day, condition, age, and gender factors, including the interaction between day and condition. Factors that did not contribute to the model were further excluded. Post-hoc analysis was conducted with Tukey correction as applicable.

PHYSIOLOGICAL ANALYSIS

Analysis of EDA data included the following steps. First, high-frequency noise was removed from EDA data using a 1-Hertz (Hz), low-pass filter. Then, each participant's data file was inspected for motion artifacts, which were removed manually. Next, skin conductance responses (SCRs) for each participant were identified as instances in which the phasic signal rose to a threshold of at least 0.02 microsiemens and the amplitude of the rise was at least 10 percent of the maximum amplitude of all SCRs detected within that ACC condition during the same direction of travel for each participant. SCR frequency rates were then calculated as the number of SCRs that occurred over the period during which artifact-free EDA data were being collected. A Poisson distribution with a log-link function was specified when analyzing SCR frequency to account for differences in recording duration between participants.

To assess PPG data, a high-pass filter of 9 Hz and a low-pass filter of 0.5 Hz were applied to PPG data offline to improve signal strength and reduce noise.(11) For each participant, peaks reflecting the maximum amplitude of blood volume during each pulse were identified and used to calculate average beats per minute within each session.

CHAPTER 3. RESULTS

Data analysis included an examination of how driving performance and gaze distribution changed over time as a function of condition and session. Driver response to the critical events that occurred during session 1 and session 4 was also evaluated. Finally, responses to the pre- and post-drive questionnaire were compared to assess whether participants' attitudes about driver assistance systems changed after repeated exposure to the systems.

DRIVING PERFORMANCE

Driver performance metrics were used to assess how longitudinal and lateral control of the vehicle changed in each condition across the four sessions.

Longitudinal Control

Participants were instructed to follow the speed limit, which was 45 mph, and drive as they normally would. Speed was assessed as a function of session, condition, gender, and age. A main effect of gender was found, F-value or $F(1,39) = 7.038$, p-value (p) = 0.011. However, this effect was qualified by a significant gender-by-condition interaction, $F(3,39) = 7.485$, $p < 0.001$. In the control condition, males (*mean* [M] = 47.4 mph) drove significantly faster than females (M = 43.4 mph). This difference in speed was not found in any of the conditions in which a driver assistance system was present (LKA: males = 45.6 mph, females = 46 mph, CACC: males = 45 mph, females = 44.6 mph, CACC + LKA: males = 44.8 mph, females 44.7 mph). No other effects of speed were found.

An assessment of speed variability revealed a main effect of session, $F(3,132) = 9.115$, $p < 0.001$, as well as a session by condition interaction, $F(9,132) = 2.116$, $p = 0.032$. Figure 2 shows mean variances in speed as a function of session and condition. Whereas speed variability remained relatively stable across sessions for those in the control and LKA conditions, variability seemed to be reduced for those participants in the CACC and CACC + LKA conditions during sessions 2 and 3, when no critical events occurred. This observation was confirmed by post-hoc tests. The greater speed variability in the control condition relative to the CACC + LKA was significant for session 2 ($p < 0.05$) and marginally significant for session 3 ($p = 0.05$). Likewise, the greater speed variability for the LKA condition relative to the CACC condition was marginally significant during session 2 ($p = 0.08$) and significant during session 3 ($p < 0.05$). No other significant effects were found.

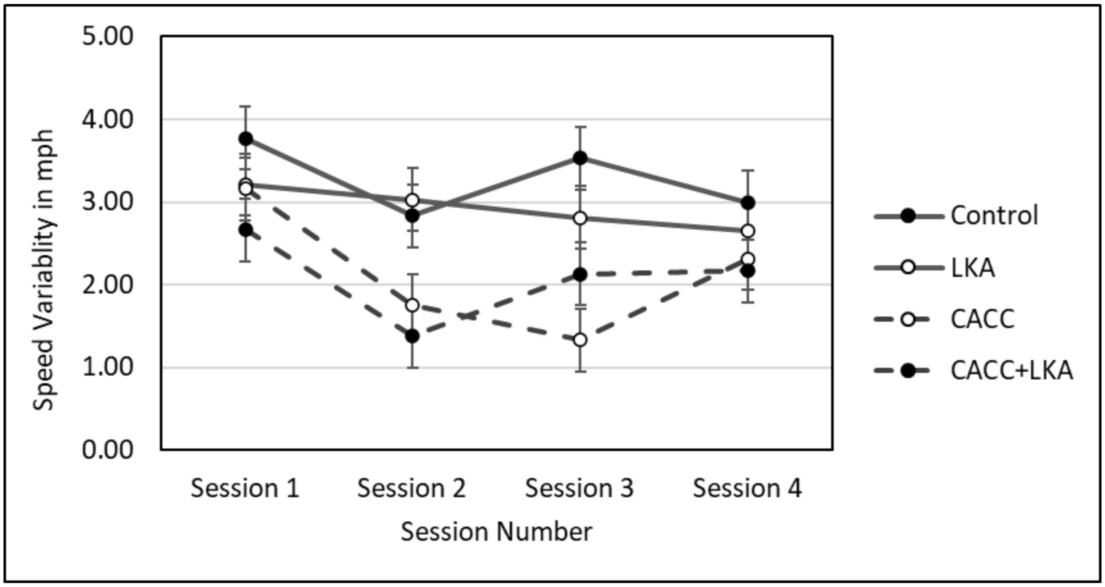


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Figure 2. Chart. Speed variability as a function of condition and session. Error bars represent standard errors.

Lateral Control

Lane deviation was assessed as a function of condition, session, age, and gender. Gender had a marginally significant effect on lane deviation, $F(1,38) = 3.210$, $p = 0.082$. The driving path of male participants ($M = 1.75$ ft) deviated from the center of the lane more than that of female participants ($M = 1.51$ ft). Condition also had a marginally significant effect on lane deviation, $F(3,38) = 2.400$, $p = 0.081$. As illustrated in figure 3, participants in conditions that included LKA tended to deviate from the center of the lane less than those who did not drive with a lateral driver assistance system.

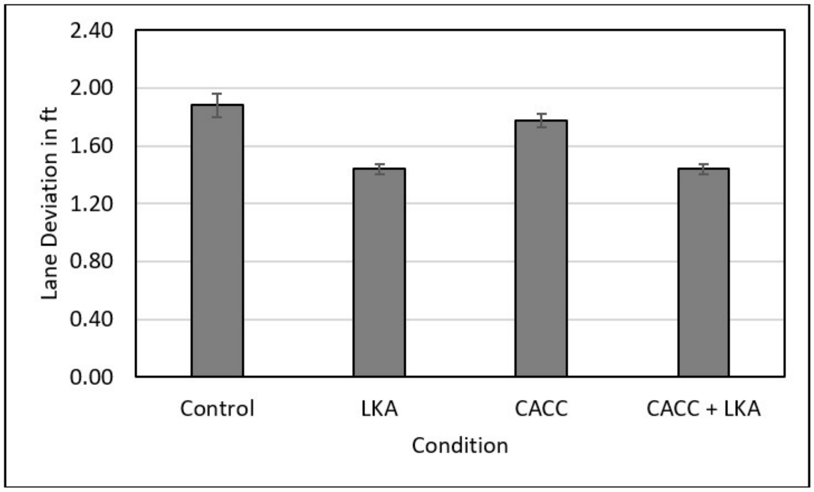

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Figure 3. Chart. Lane deviation as a function of condition. Error bars represent standard errors.

EYE GAZE

Eye gaze was classified broadly as being directed either out the front windshield, at locations inside the vehicle, at the mirrors, or out the left or right windows. Participants spent the majority of their drives (87.8 percent) looking out the front windshield of the vehicle. The second most common gaze location (8.7 percent) was inside the vehicle. The remaining 3.5 percent of the drive was fairly evenly distributed between the mirrors and left and right windows.

The specific portion of the drive spent looking out the windshield and mirror varied as a function of both condition and session. For gazes at the windshield, a main effect of session, chi squared or $\chi^2(3) = 15912.289$, $p < 0.001$; a main effect of condition, $\chi^2(3) = 8.133$, $p = 0.043$; and an interaction between session and conditions, $\chi^2(9) = 26763.258$, $p < 0.001$, were found. As illustrated in figure 4, all participants spent roughly equal amounts of time directing their gaze toward the front windshield during session 1. However, over time, the participants using CACC tended to direct more gazes toward the windshield than participants who did not have access to this technology. Post-hoc tests confirmed that no differences in gaze location were found during session 1. During session 2, participants in the CACC + LKA condition directed more gazes toward the windshield than participants in the control condition ($p = 0.06$). During session 3, participants in the CACC condition directed more gazes toward the windshield than participants in the control ($p < 0.01$) or LKA ($p = 0.08$) conditions, and participants in the CACC + LKA condition directed more gazes toward the windshield than participants in the control ($p < 0.01$) or LKA ($p = 0.05$) conditions. During session 4, only the differences between the CACC and the control condition ($p < 0.05$) and the CACC + LKA and the control condition ($p < 0.01$) remained significant.

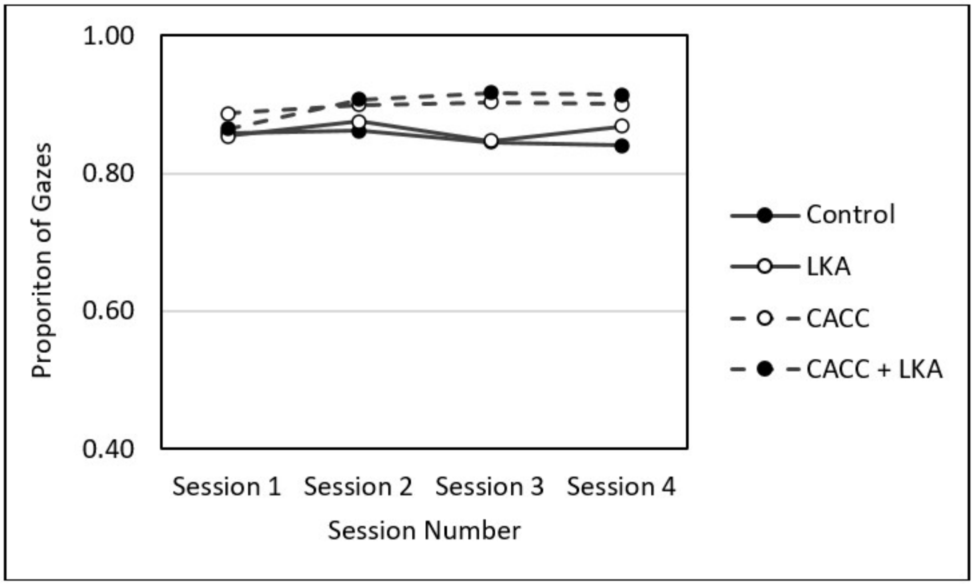

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Figure 4. Chart. Proportion of gazes directed at front windshield as a function of condition and session number.

Participants in the LKA and control conditions spent less time looking out the front windshield than participants in the CACC and CACC + LKA conditions; instead, these participants spent this difference in time directing their gazes inside the vehicle. The proportion of the gazes directed toward locations inside the vehicle as a function of condition and session number is shown in figure 5. Main effects of session, $\chi^2(3) = 19050.214$, $p < 0.001$; condition, $\chi^2(3) = 13.956$, $p < 0.01$; and the session-by-condition interaction, $\chi^2(9) = 36963.301$, $p < 0.001$, were all significant. The use of CACC appeared to have allowed participants to spend less time looking inside the vehicle to monitor their speed, and participants directed those extra gazes out the front windshield of the vehicle.

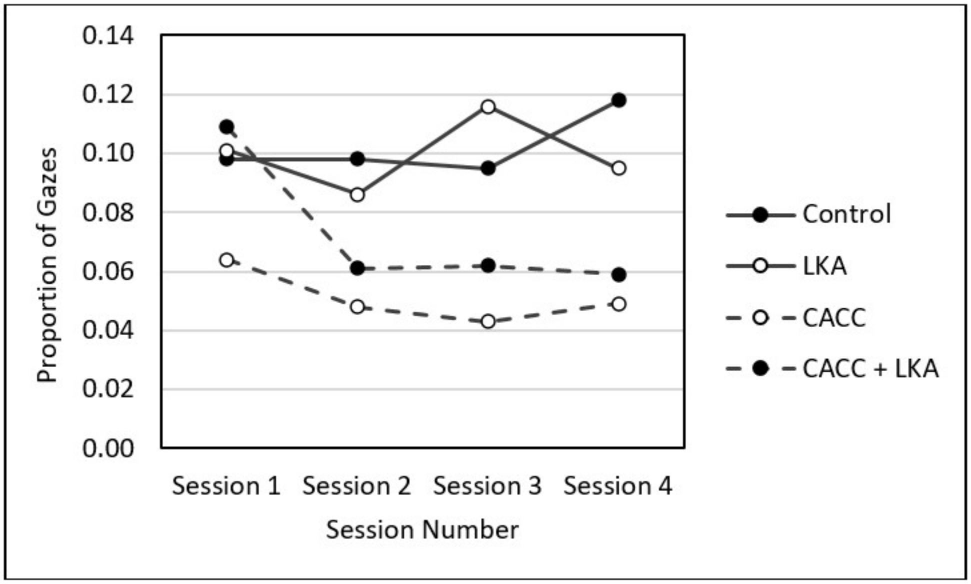

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Figure 5. Chart. Proportion of gazes directed toward the inside of the vehicle as a function of condition and session number.

Automation causing potential narrowing of attention was assessed by examining the standard deviation of X and Y gaze coordinates out the front windshield. However, no effects reached significance. The results suggest that use of CACC increased participants' opportunities to direct their gaze out the front windshield without narrowing their window of attention.

CRITICAL EVENTS

During both the first and last session, participants encountered a critical event that required a response to avoid a collision. During the deer event, a small group of deer stood near the right side of the road, approximately 12 mi into the drive. One of the deer bolted across the road when the participant's vehicle approached. The barrel event occurred after participants had driven for approximately 10.5 mi. Men at a gas station located on the right side of the road surrounded a barrel on the bed of a truck. As the participant's vehicle approached, the barrel rolled off the truck bed and across the road. In both events, participants had to respond to prevent a collision with the deer or barrel. The specific event that participants encountered was counterbalanced across sessions. Across both events, most participants were not able to avoid a collision—85.4

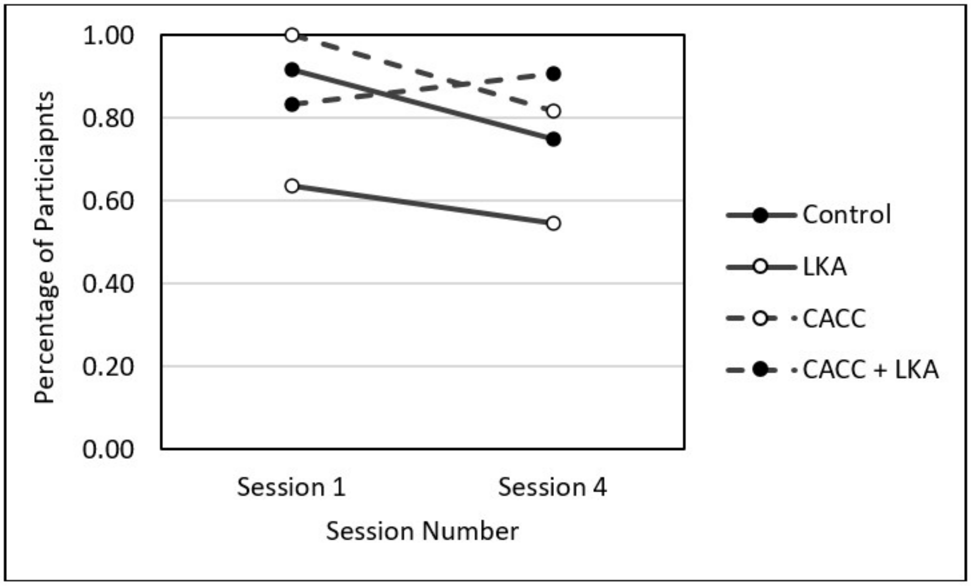
percent of participants collided with the barrel, and 81.2 percent struck the deer. A chi-squared test was used to confirm that event type did not impact crash rate, $\chi^2(1) = 0.299$, $p = 0.585$.

Crash rates as a function of condition and session are displayed in table 1. Small reductions in crash rates were found in three of the four conditions in session 4 relative to session 1; however, this reduction was not statistically significant.

Table 1. Crash rate during each session as a function of condition.

Session	Control	LKA	CACC	CACC + LKA
Session 1	91.7 percent	75.0 percent	91.7 percent	100 percent
Session 4	75.0 percent	91.7 percent	75.0 percent	66.7 percent

Participants could attempt to avoid the collision by applying the brake. As displayed in figure 6, participants in the LKA condition were less likely to apply the brake than those in the other three conditions, *z*-score or $z = 2.173$, $p = 0.030$.



Source: FHWA

Figure 6. Chart. Percentage of participants in each condition who applied the brakes during the critical event.

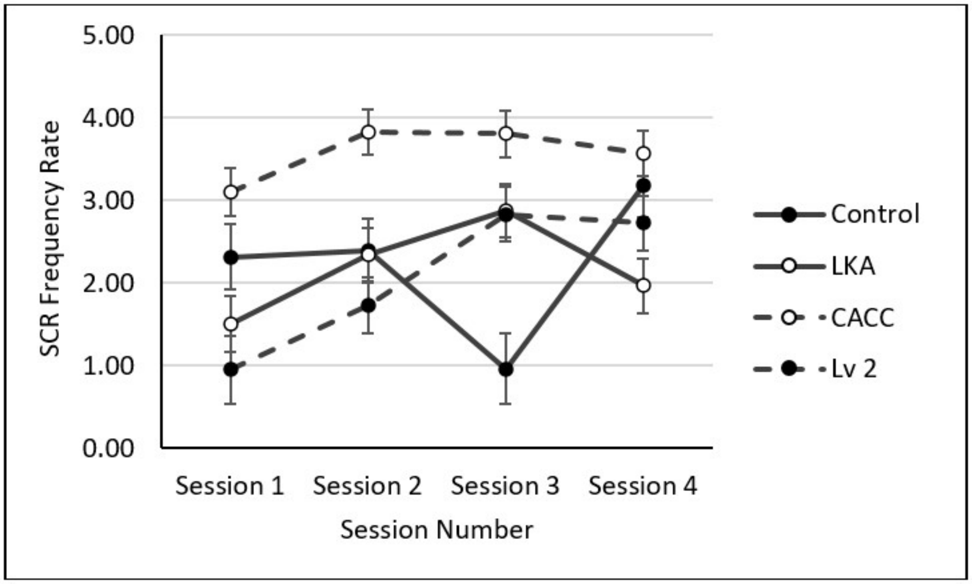
For those who crashed during the critical event, collision speed served as a metric of crash severity. Session had a marginally significant effect on collision speed, $\chi^2(1) = 3.00$, $p = 0.083$. Collision speeds were higher during session 1 (*M* = 39.21 mph) than in session 4 (*M* = 38.91 mph).

The speed at which participants applied the brake, relative to the critical event, was also assessed as a function of condition, session, gender, and age. Brake response times were marginally affected by participant age, $F(1,36) = 3.182$, $p = 0.083$. Older participants' braking responses tended to occur closer to the critical event (*M* = 0.570 s) than younger participants' braking responses (*M* = 0.677 s). No other effects reached significance.

PHYSIOLOGICAL RESPONSE

PPG data was collected for 43 participants. Heart rates were assessed as a function of condition, session, age, and gender; however, no significant differences in PPG rates were found.

EDA responses were available for 39 participants. For EDA data, SCR frequency rates, instead of counts, were modeled to account for the difference between the valid time durations during which recordings occurred and the EDA dropouts. This was done by adding an offset term to a Poisson mixed-effects model with a known coefficient of one. SCR frequency rates were assessed as a function of session, condition, gender, and age. A main effect of condition was found, $\chi^2(3) = 12.647$, $p = 0.005$. Response frequency was also influenced by session, $\chi^2(3) = 160.4770$, $p < 0.001$. The interaction between condition and session was also significant, $\chi^2(9) = 268.287$, $p < 0.001$. SCR frequency rates across sessions as a function of condition are shown in figure 7. Although the specific frequency rates varied by condition, the pattern across sessions for all conditions in which a driver assistance system was in use followed similar patterns. SCR frequency increased with each session from session 1 to session 3 and then decreased during session 4. In the control condition, SCR frequency had similar rates across sessions 1 and 2, decreased during session 3, and then increased to its highest rate during session 4.



Source: FHWA

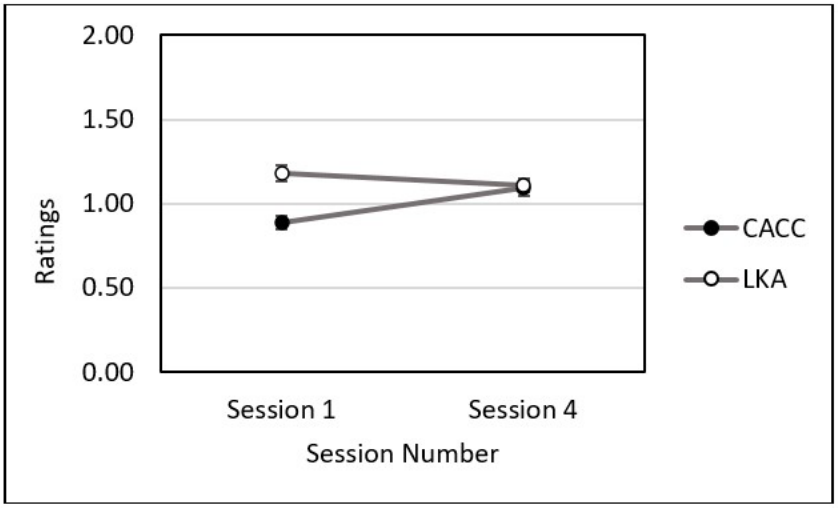
Figure 7. Chart. SCR frequency rate across sessions as a function of condition. Error bars represent standard errors.

Gender also had an influence on EDA response frequency, $\chi^2(1) = 10.519$, $p = 0.001$. Males (*M* = 1.668) experienced SCRs at a greater frequency than females (*M* = 1.127).

TRUST IN TECHNOLOGY

Following their last session, participants were asked, “List any driver assistance systems within the vehicle that you drive most frequently.” Of the 48 participants that completed the questionnaire, 36 (75 percent) indicated that their vehicle was equipped with cruise control. Eight (16 percent) used a vehicle equipped with ACC, and seven (14 percent) had a lateral control assistance system.

Participants who used driver assistance systems during their drive completed the Van der Laan questionnaire both before their first session and after their last session. Scores were compared to assess changes in trust in technology that occurred as a result of experiences with the systems. Scores ranged from +2 to -2, with positive scores indicating a positive view of the system and negative scores indicating a negative view. As shown in figure 8, trust levels in both CACC and LKA were similar and did not change significantly over the course of the four sessions. Participants appeared to have a fairly neutral opinion of the technologies they used during the experiment, and repeated use of the technology did not impact their opinions of it.



Source: FHWA

Figure 8. Chart. Trust ratings as a function of session and driver assistance technology.

CHAPTER 4. DISCUSSION

The goal of this experiment was to assess the effects of adaptation to driver assistance systems on drivers' performance over time. Participants completed four experimental drives in a driving simulator over the course of approximately 2 w. During these drives, participants gained experience with different driver assistance systems. One group of participants gained experience with CACC, another with LKA, and another with both CACC and LKA; meanwhile, a final group that was not exposed to any driver assistance system served as a control group. Vehicle dynamic and eye-tracking data provided an assessment of how participants' attention and driving performance changed over time. A critical event during both the first and last session of the study was used to examine how adaptation to driver assistance systems impacted participants' ability to respond to unexpected emergencies. Physiological responses, along with pre- and post-drive questionnaires, were used to assess participant arousal levels and changes in trust in technology over time.

Driver assistance systems are marketed as convenience systems that are designed to make the driving task easier.(10) Nevertheless, there seems to be an expectation that this technology will also make driving safer, particularly as lower level driver assistance systems are replaced by higher level automated driving systems.(9,13) In the current study, the driver assistance systems were effective in aiding driving performance. Driving with CACC led to reduced speed variability for participants in both the CACC and CACC + LKA conditions during sessions in which the critical event did not occur. Similarly, driving with LKA, in both the LKA and CACC + LKA conditions, led to reduced lane deviation across all sessions relative to those found in the CACC and control conditions. In both cases, the driver assistance system effectively elicited less variable driving behavior, which tends to be associated with safer driving.(14,15)

Eye-tracking analysis was also suggestive of the potentially positive impact of driver assistance systems. Participants in the CACC and CACC + LKA condition spent more time looking out the front windshield and less time looking at the inside of the vehicle than participants in the LKA and control conditions. This change in gaze pattern only happened after the first session, when participants had become familiar with and adapted to the CACC technology. The results suggest that once drivers become comfortable with CACC controlling their speed, they are able to start relying on the technology and can spend less time monitoring speed and more time monitoring their environment.

The results are similar to those of Mars, Franch, and Navarro, who assessed the influence of automatic lane control on gaze position when negotiating curves.(16) They found that participants who drove with automation were able to devote some of the attention they might have previously used for negotiating their hand movements during a curve to look for potential obstacles further down the roadway. As a result, participants who used the technology were better prepared to deal with unexpected hazards. It seems that, as drivers come to rely on driver assistance systems, they can redirect attentional resources previously devoted to basic aspects of the driving task to paying more attention to the forward roadway.

In this study, when participants responded to critical events, collision speed, which serves as a metric for crash severity, tended to be lower in session 4 than in session 1, suggesting that participants' ability to respond to the critical event over time was not negatively affected by the use of driver assistance technology. Though not significant, crash frequency rates tended to display a similar pattern. Across the control, CACC, and CACC + LKA conditions, the percentage of participants who were involved in a collision during the critical event was lower during session 4 than session 1. The opposite numerical pattern was found for participants in the LKA condition. Further, participants in the LKA condition were less likely to apply the brake prior to the critical event than those in the other three conditions. The effect was found across both sessions. It is unclear why participants in this condition were less likely to brake and more likely to crash than those in the other three conditions.

One complaint about driver assistance technology is that it can lead to overreliance, rendering drivers less prepared to deal with an emergency situation, should one occur. Indeed, multiple studies have found reductions in the speed at which drivers could respond to an emergency event when using driver assistance or vehicle automation systems.(4,5,6) Some researchers have attributed this reduction in performance to negative behavioral adaptation—i.e., the deterioration of driving skills due to overreliance on technology.(4,7) However, other researchers have noted that these findings could also be explained by faulty or incomplete mental models of in-vehicle technology.(8) Since past research has tended to be completed with drivers who were unfamiliar with the driver assistance or automated driving system they were using, such research has not been able to differentiate between these competing hypotheses.

The current study introduced a critical event, both in the beginning of the study, when the driver was still gaining knowledge about the driver assistance systems, and again during session 4, when the driver had practiced using and had hopefully gained familiarity with the systems. If reductions in response to the critical event were due to negative behavioral adaptation, then crashes in response to the critical event should be more prevalent and severe in session 4 than in session 1. However, if reductions in response were due to an incomplete mental model, then crashes should be less frequent and severe during session 4 than in session 1. Unlike previous work on this topic, use of driver assistance technology in the current study did not result in a reduction in drivers' responses to critical events (at least for those in the CACC and CACC + LKA conditions). As a result, it is difficult to differentiate between these two hypotheses. However, the results tend to suggest that extended use of the technology (at least over the four sessions completed in this study) did not reduce participants' ability to respond during an emergency. Future work should continue to assess this research question using higher levels of vehicle automation and perhaps longer adaptation periods.

Physiological responses were used to assess changes in arousal over time. Both PPG and EDA data were collected. No differences in PPG data were found between conditions. However, varying patterns of EDA responses were found. The SCR frequencies of participants using driver assistance systems tended to increase with each session from session 1 to session 3 and then decrease during the final session. This pattern was not found in the control group. Instead, SCRs were reduced in session 3 and then increased in session 4. It is possible that participants in the driver assistance systems tested the boundaries of that condition during session 1 only to encounter a critical event and then became more cautious in the next two sessions. However, any interpretations of EDA data must be taken with caution as several difficulties prevented a clear examination of these arousal measures. First, data collection took place during the COVID-19 pandemic. Due to safety restrictions during that time, the research team was able to collect physiological data from only 39 of the 48 participants.

Further, data collection occurred via electrodes that were placed on each participant's fingers and connected to a data acquisition system on the participant's wrist. The device was worn on the participant's nondominant hand. However, driving tends to be a two-handed activity; as a result, data loss was prevalent during the drive. Specifically, when processing the EDA data, researchers noted relatively frequent drops in data during the period when the critical event occurred. It seems likely that participants responded to the critical event with swift movements of their hands (e.g., tightly grabbing the steering wheel), and these movements were sufficient to disrupt physiological data collection. As a result, data from sessions 1 and 4 may be less reliable than data collected during sessions 2 and 3. Future research should examine mechanisms for physiological data collection that are not reliant on collecting data from the hands.

Participants completed the Van der Laan questionnaire both before their first session and after their last session to assess changes in trust in technology that occurred as a result of experiences with each driver assistance system.(10) Participants' opinions about the technology they used during the experiment were neither positive nor negative. Further, their levels of trust did not change over time. These results stand in contrast to previous work that has tended to see trust of in-vehicle technology increase with use.(17,18) It is possible that any increase in trust participants gained in the technology during the course of the experiment was eliminated by the critical event that occurred during session 4. Previous work has found that increased trust tends to be associated with safe use of the system over time. However, this trust can be reduced temporarily by safety-critical automation errors. (18) Since the majority of participants were involved in a collision just prior to completing the post-drive questionnaire, participants might not have viewed their most recent interaction with the technology as safe and thus might have reported reduced trust in the system.

Overall, the results of the current study paint an optimistic view of driver assistance technology. Participants who used the technology did so in a way that benefited their driving performance and allowed them to direct more of their attention to the road ahead. Further, these benefits were not associated with the reductions in attention or impaired responses to emergency events that have sometimes been seen in previous research. Even after four driving sessions, participants in the current study remained fairly neutral in their opinions of the technology and tended to remain at higher levels of alertness during uneventful driving conditions. The results suggest that Level 1 driver assistance systems have the potential to benefit driver safety even after drivers have adapted to the technology following repeated use.

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REFERENCES

1. SAE On-Road Automated Vehicle Standards Committee. 2018. *Taxonomy and Definitions for Terms Related To On-Road Motor Vehicle Automated Driving Systems*. SAE J3016_201806. Warrendale, PA: SAE International.

2. Parasuraman, R., and V. Riley. 1997. "Humans and Automation: Use, Misuse, Disuse, Abuse." *Human Factors* 39, no. 2: 230–253.

3. Bainbridge, L. 1983. "Ironies of Automation." In *Analysis, Design and Evaluation of Man-Machine Systems*. Baden, Germany: Pergamon. 129–135.

4. De Winter, J. C. F., R. Happee, M. H. Martens, and N. A. Stanton. 2014. "Effects of Adaptive Cruise Control and Highly Automated Driving on Workload and Situation Awareness: A Review of the Empirical Evidence." *Transportation Research Part F: Traffic Psychology and Behaviour* 27: 196–217.

5. Stanton, N. A., and M. S. Young. "Driver Behaviour With Adaptive Cruise Control." *Ergonomics* 48, no. 10: 1294–1313.

6. Strand, N., J. Nilsson, I. C. M. A. Karlsson, and L. Nilsson. 2014. "Semi-Automated Versus Highly Automated Driving in Critical Situations Caused by Automation Failures." *Transportation Research Part F: Traffic Psychology and Behaviour* 27: 218–228.

7. Kovordányi, R., K. Ohlsson, and T. Alm. 2005. "Dynamically Deployed Support as a Potential Solution to Negative Behavioral Adaptation." *IEEE [Institute of Electrical and Electronics Engineers] Proceedings. Intelligent Vehicles Symposium*: 613–618. Las Vegas, NV: IEEE.

8. Sullivan, J. M., M. J. Flannagan, A. K. Pradhan, and S. Bao. 2016. *Literature Review of Behavioral Adaptations to Advanced Driver Assistance Systems (Technical Report).* Washington, DC: AAA Foundation for Traffic Safety.

9. Weaver, S. M., S. M. Roldan, T. B. Gonzalez, S. A. Balk, and B. H. Philips. 2020. "The Effects of Vehicle Automation on Driver Engagement: The Case of Adaptive Cruise Control and Mind Wandering." *Human Factors: The Journal of the Human Factors and Ergonomics Society*, December 9, 2020.

10. Van Der Laan, J. D., A. Heino, and D. De Waard. 1997. "A Simple Procedure for the Assessment of Acceptance of Advanced Transport Telematics." *Transportation Research Part C: Emerging Technologies* 5, no. 1: 1–10.

11. Mohanalakshmi, S., A. Sivasubramanian, and A. Swarnalatha. 2017. "Statistical Analysis of Pulse Rate Variability Quantified Through Second Derivative Photoplethysmogram (SDPPG) and Its Compatibility With Electrocardiographic (ECG) Heart Rate Variability." *Biomedical Research—India* 28, no. 2: 689–694.

12. Xiong, H., and L. N. Boyle. 2012. "Drivers' Adaptation to Adaptive Cruise Control: Examination of Automatic and Manual Braking." *IEEE Transactions on Intelligent Transportation Systems* 13, no. 3: 1468–1473.

13. Fagnant, D. J., and K. Kockelman. 2015. "Preparing a Nation for Autonomous Vehicles: Opportunities, Barriers and Policy Recommendations." *Transportation Research Part A: Policy and Practice* 77: 167–181.

14. Garber, N. J., and R. Gadirau. 1988. *Speed Variance and Its Influence on Accidents.* Washington, DC: AAA Foundation for Traffic Safety. https://files.eric.ed.gov/fulltext/ED312438.pdf, last accessed March 17, 2022.

15. Dijksterhuis, C., K. A. Brookhuis, and D. De Waard. 2011. "Effects of Steering Demand on Lane Keeping Behaviour, Self-Reports, and Physiology: A Simulator Study." *Accident Analysis & Prevention* 43, no. 3: 1074–1081.

16. Mars, F., and Navarro, J. 2012. "Where We Look When We Drive With or Without Active Steering Wheel Control." *PLOS ONE* 7, no. 8: e43858.

17. Gold, C., M. Körber, C. Hohenberger, D. Lechner, and K. Bengler. 2015. "Trust in Automation—Before and After the Experience of Take-Over Scenarios in a Highly Automated Vehicle." *Procedia Manufacturing* 3: 3025–3032.

18. Hergeth, S., L. Lorenz, J. F. Krems, and L. Toenert. 2017. "Effects of Take-Over Requests and Cultural Background on Automation Trust in Highly Automated Driving." *Driving Assessment* 1591: 331–337.

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