Real-World Use of Automated Driving Systems and Their Consequences

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16. Abstract

Automated driving systems (ADS) have the potential to fundamentally change transportation, and a growing number of these systems have entered the market and are currently in use on public roadways. However, drivers may not use ADS as intended due to misunderstandings about system capabilities and limitations. Moreover, the real-world use and effects of this novel technology on transportation safety are largely unknown. To investigate driver interactions with ADS, we examined existing naturalistic driving data collected from 50 participants who drove personally owned vehicles with partial ADS for 12 months. We found that 47 out of 235 safety-critical events (SCEs) involved ADS use. An in-depth analysis of these 47 SCEs revealed that people misused ADS in 57% of SCEs (e.g., engaged in secondary tasks, used the systems not on highways, or with hands off the wheel). During 13% of SCEs, the ADS neither reacted to the situation nor warned the driver. A post-study survey showed that drivers found ADS useful and usable and felt more comfortable engaging in secondary tasks when ADS were in use. This study also captured some scenarios where the ADS did not meet driver expectations. The findings of this report may help inform the development of human-machine interfaces and training programs and provide awareness of the potential for unintended use of ADS and their associated safety consequences.

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Abstract

Automated driving systems (ADS) have the potential to fundamentally change transportation, and a growing number of these systems have entered the market and are currently in use on public roadways. However, drivers may not use ADS as intended due to misunderstandings about system capabilities and limitations. Moreover, the real-world use and effects of this novel technology on transportation safety are largely unknown. To investigate driver interactions with ADS, we examined existing naturalistic driving data collected from 50 participants who drove personally owned vehicles with partial ADS for 12 months. We found that 47 out of 235 safety-critical events (SCEs) involved ADS use. An in-depth analysis of these 47 SCEs revealed that people misused ADS in 57% of SCEs (e.g., engaged in secondary tasks, used the systems not on highways, or with hands off the wheel). During 13% of SCEs, the ADS neither reacted to the situation nor warned the driver. A post-study survey showed that drivers found ADS useful and usable and felt more comfortable engaging in secondary tasks when ADS were in use. This study also captured some scenarios where the ADS did not meet driver expectations. The findings of this report may help inform the development of human-machine interfaces and training programs and provide awareness of the potential for unintended use of ADS and their associated safety consequences.

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Table of Contents

List of Figures

List of Tables

Introduction

The Insurance Institute for Highway Safety (IIHS) recently reported the real-world safety benefits of active safety systems such as forward collision warning (FCW), automatic emergency braking (AEB), lane departure warning (LDW), blind-spot detection, and rear-view camera (IIHS, 2019a). For example, by comparing vehicles with and without FCW plus AEB, IIHS showed that vehicles with these technologies had 50% fewer police-reported front-to-rear crashes and 23% lower insurance claim rates for injuries to people in other vehicles.

Automated driving systems (ADS) extend active safety systems by continually assisting drivers with lateral and longitudinal control of dynamic driving tasks. According to SAE International's defined levels of driving automation (SAE International, 2016), Level 1 (L1) automation refers to when either a longitudinal (e.g., Adaptive Cruise Control; ACC) or lateral (e.g., reactive Lane Keep Assist; LKA, or proactive Lane Centering Assist; LCA) control system is engaged. Level 2 (L2) automation refers to when both are engaged and coupled with each other. In higher levels of automation (i.e., SAE Level 3 and above), the ADS may conduct all driving tasks even without driver engagement within an appropriate operational design domain and set of conditions. Given ADS's targeted sensing and control capabilities, there is a potential to fundamentally transform transportation by reducing crashes, congestion, and cost while improving traffic efficiency and access to mobility for the transportation-challenged population (US Department of Transportation, 2020). In fact, lower level (L2 and below) ADS are already available on a wide variety of vehicles, and a growing number will continue to enter the market in the coming years.

However, a recent on-road test of five vehicles capable of L2 driving automation (i.e., equipped with FCW, ACC, LDW, and LKA) revealed that ADS may not work as expected in typical driving situations, such as approaching stopped vehicles and negotiating hills and curves (IIHS, 2018). Even worse, people may not use ADS as intended (i.e., disuse, misuse, and abuse) due to their misunderstanding of, over-trust, or distrust in such systems' capabilities and limitations. According to a recent survey, among more than 2,000 responders, many thought it would be safe to take their hands off the wheel (48%) or even watch a video (8%) while using Tesla's AutoPilot, an SAE L2 ADS (IIHS, 2019b). As L2 ADS have become commercially available, accounts of unintended uses of these systems and fatal consequences have emerged. For example, a recent news article reported a Tesla driver napping behind the wheel (The Guardian, 2019). An investigation of a Tesla Model S crash in Florida in 2016 found that the Autopilot was engaged at the time of crash, and that the driver's hands were not detected on the steering wheel, despite a design intent and owner's manual instructions that clearly indicate that the Autopilot's steering function is a hands-on feature intended to work under driver supervision (IIHS, 2019b).

Furthermore, unlike active safety systems, the real-world use and effects of ADS are largely unknown. Previous studies have investigated human interaction with automated longitudinal and lateral control features, either in test track settings (Blanco, 2015) or on public roadways (Russell et al., 2018). While these studies provide valuable insight into the potential benefits and drawbacks of ADS, they might not capture the real-world use of ADS and associated consequences, as participants were exposed to instrumented research vehicles either in controlled environments or for a short period of time on the road.

Given the growing availability of ADS on public roadways, as well as the risk of their unintended use and safety consequences, this work examined real-world driver interaction with commercially available ADS. For this purpose, the research team analyzed data collected from participants who drove personally owned vehicles with SAE L1 or L2 driving automation systems for 12 months. Specifically, we examined safety-critical events (SCEs; Guo & Fang, 2013) of different severity levels (e.g., crashes and near-crashes) captured in the data to address five research questions (RQs).

- RQ1: Of the SCEs identified, what proportion involved the use of ADS?
- RQ2: Of the SCEs identified with ADS engaged, how often did ADS neither react to the event nor warn the driver?
- RQ3: Of the SCEs identified with ADS engaged, what proportion involved the unintended use of ADS?
- RQ4: How did the participants rate the usefulness and usability of ADS features?
- RQ5: Were there any conditions where ADS did not work well or did not meet driver expectations?

Method

To better understand the real-world use of ADS, the research team investigated an existing naturalistic driving database collected from the Virginia Connected Corridor Level 2 Naturalistic Driving Study (VCC L2 NDS). The dataset contains data from 50 drivers with longitudinal control systems (e.g., ACC) at the minimum, although most also had lateral control systems of various capacity (e.g., LKA or LCA). The participants were adult drivers aged 24 to 76 who were recruited and primarily commuted in the Washington, DC metro area, which includes northern Virginia and sections of Maryland, for 12 months (estimated 684,931 miles driven across all participants). A recent analysis (Dunn, Dingus, & Soccolich, 2019) on a subset of the VCC L2 NDS data (from 30 out of 50 participants) captured 159 SCEs and showed that participants drove with ADS engaged about 24% of the time (6.98% with ACC, 5.03% with LKA, and 11.89% with both features) during 421 hours of driving. The current study expanded the scope of analysis to a larger subset of the data (from 44 participants) and considered not only objective measures but also participants' subjective impressions of ADS (i.e., survey responses).

Participants' personal vehicles were instrumented with advanced data acquisition systems (DASs) developed by the Virginia Tech Transportation Institute (VTTI). The DAS continuously recorded vehicular data such as GPS coordinates, headway, speed, six-axis acceleration, and videos of the forward roadway, the driver’s face, an over-the-shoulder view of the driver’s hands and lap area, a view of the footwell, and the instrument cluster. The available naturalistic driving study data support the simultaneous investigation of the driver, vehicle, and environmental factors pertaining to ADS operation across a wide range of drivers in various situations. Finally, the data allow for the identification of SCEs with and without ADS use. More information about the capabilities of the participating vehicles and DAS can be found in Dunn, Dingus, & Soccolich (2019).

Due to limited access to OEM variables on the vehicle controller area network (CAN) during data collection, the state of the ADS (e.g., ACC and LKA) and alerts (e.g., FCW, LDW, and Hands-on-Wheel) were captured post hoc using a machine learning algorithm based on the instrument panel camera view (Figure **1**). To achieve a high confidence level, the research team made an additional coding effort to validate these variables for all SCEs by reviewing associated videos and kinematic data.

Figure 1**. Example of FCW, Immediate Takeover, and Hands-on-Wheel alerts in the VCC L2 NDS (Dunn et al., 2019).**

Among the 50 participants recruited for this study, a subset of 44 participants was used due to the quality of the data collected. A total of 235 SCEs were captured from the VCC L2 NDS dataset. To accurately identify SCEs, established kinematic algorithms (e.g., hard decelerations, lane departures, high yaw rates) were first used to identify potential events. Trained data reductionists then inspected all video channels (30-second epoch) to verify the occurrence of an SCE, as well as to manually code confirmed events based on the established coding protocols and data dictionaries (VTTI, 2015; Russel et al., 2018).

To answer the RQs, the research team analyzed the coded data for all SCEs captured in the dataset and investigated the proportion of ADS use (RQ1), silent failure (RQ2), and unintended use of ADS (RQ3) during the SCEs. The number of SCEs in each category was compared to the total 235 SCEs to calculate proportions. As previously mentioned, the ADS and alert states were identified by machine-vision algorithm and validated by data reductionists. Unintended uses of ADS captured instances when the driver misused the system relative to the instructions provided within the vehicle's owner's manuals and included hands off the wheel, adverse weather conditions, not on highway or limited-access roads, and secondary task engagement, as coded by trained data reductionists by inspecting all video channels of each SCE epoch. Coding protocols and data dictionaries also covered other factors, such as driver behavior, passenger, environment, and traffic, as well as a description of the SCE.

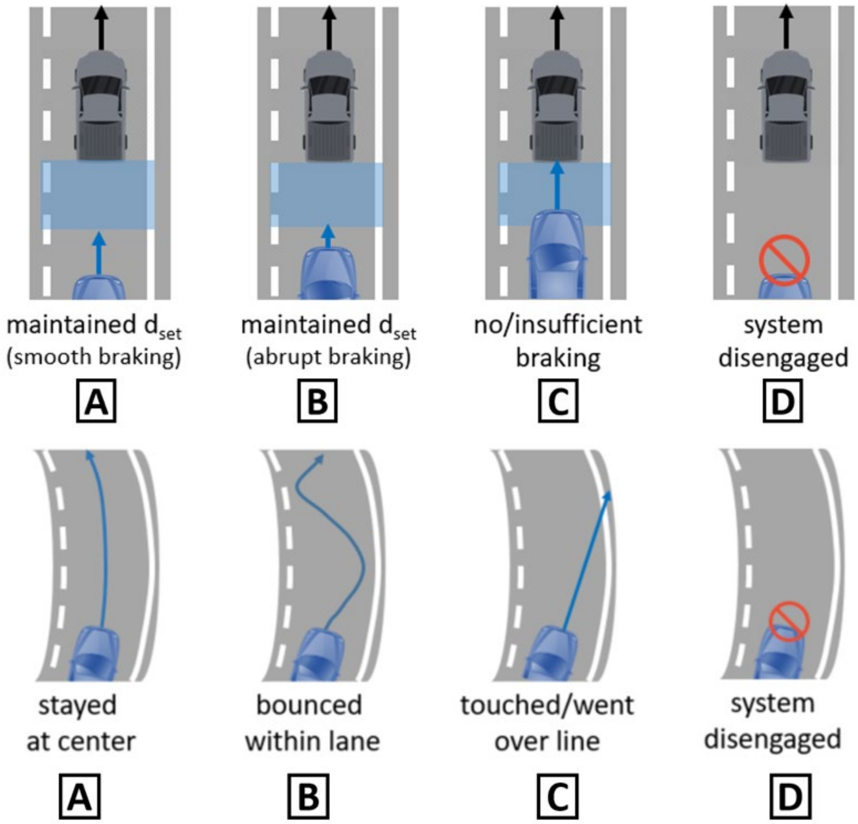


Figure 2. Example codes for the automated longitudinal control features' responses to a slow lead (top) and the lateral control features' responses on curves (bottom) used for classifying participants' qualitative comments.

The research team also examined drivers' responses to a post-study questionnaire that captured drivers' subjective ratings on the usefulness and usability of the ADS (RQ4). (See Appendix for example questions administered at the end of each driver's participation in the study.) The post-study questionnaire also captured drivers' comments on some open-ended questions about specific instances where the ADS did not the meet drivers' expectations (RQ5). The research team developed and applied a coding scheme to classify participants' comments. We identified six representative scenarios within which ACC may operate (e.g., driving without a lead vehicle, with a slow lead, stopped lead, cutting-in lead vehicles, on hills, or on curves) and possible outcomes of ACC responses. For example, Figure 2 (top) shows codes that were used to classify the automated longitudinal control features' responses to a slow lead vehicle: 'A' indicates the ADS maintained appropriate headway, 'B' means the ADS showed abrupt braking, 'C' means the ADS showed insufficient braking, 'D' means the ADS automatically disengaged, and 'E' encompasses other responses that were not in any pre-defined categories. Two researchers individually classified participants' responses based on the coding scheme and discussed until consensus was reached to adjust the outcomes for any disagreement.

Results

Real-world Use of ADS Found in SCEs

Comparable to the 24% probability of ADS activation in all driving conditions reported by Dunn, Dingus, & Soccolich, (2019), we found that 47 out of 235 SCEs (20%) involved ADS use (Figure **3**). Compared to the automated lateral control features (e.g., LKA or LCA), the longitudinal control features (e.g., ACC) were more often in use during SCEs—among the 47 events, the longitudinal control features were used in almost twice as many events (40 vs. 24). The lateral control features were less likely to be used alone and were only observed in seven events. In some of the research vehicles, such as the Tesla, the engagement of LCA requires ACC to be activated first, meaning the driver can have ACC active or both systems active, but not LCA alone. Other vehicles allow ACC, LKA/LCA, or both to be activated.

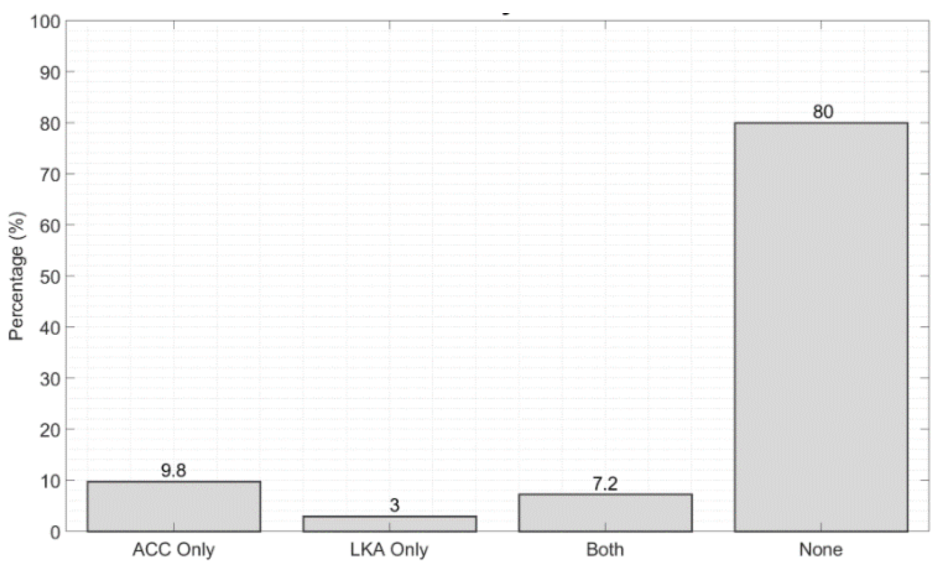


Figure 3**. Proportion (%) of SCEs by ADS feature (ACC or LKA/LCA) use.**

Error! Reference source not found. summarizes ADS's responses during SCEs. Of the 47 SCEs with ADS features in use, in 14 (29.8%) the ADS issued an alert and/or controlled the vehicle. On the other hand, no alert of any kind was identified in over 70% of events. However, in seven of these events (14.9%), ADS were not intended to address the direction of the threat (e.g., rear-end with the lead with only LKA activated, or crossed the line with only ACC); there was no alert in 20 events due to manual system deactivation. It is worth noting that one particular scenario was observed in all 20 of these events; specifically, ACC was manually disengaged by drivers due to other vehicles (mostly slower) attempting to cut in. In this scenario, it appears ACC was not designed to, or was not capable of, detecting vehicles that were changing lanes from an adjacent lane and about to cut in ahead, leading to a lack of reaction to the potential rear-end collision. Only six of the events were considered as silent failures, where the activated ADS was expected to prevent the SCE but failed to do so and did not warn the driver.

While it is possible that the failure of ADS to warn drivers could contribute to missed opportunities to enhance safety, unintended active use of ADS could actively contribute to SCEs. Hands off the wheel, ADS activation in adverse weather conditions (e.g., rain or fog), unintended roadway or traffic (e.g., business or residential), and engagement in secondary tasks are common ADS risk examples. Out of 47 SCEs with ADS use, drivers had their hands completely off the wheel in 10.6% of cases; 2.1% of events were in adverse weather conditions; about 12.8% were not on highways; and slightly over half took place while drivers engaged in a secondary task (see **Error! Reference source not found.**). For secondary task engagement, any form of non-driving-related tasks that took place during the 5 seconds prior to the start of the SCE were recorded. These tasks did not necessarily contribute to the event sequence and severity. Additionally, some events involved multiple types of unintended use and thus may be reflected in more than one category in Table 1.

Table 1. Number (%) of SCEs by ADS Use and Alert/control Activation

ADS Use	Yes Alert or Control	No Sys. Manually Deactivated	No Sys. Not Designed For	No Sys. Did Not Respond	Subtotal
Intended Use	**5 (10.6%)**	**7 (14.9%)**	**5 (10.6%)**	**3 (6.4%)**	20 (42.6%)
Unintended Use	**9 (19.1%)**	**13 (27.7%)**	**2 (4.3%)**	**3 (6.4%)**	27 (57.4%)
Hands-off-wheel	2	2	0	1	5
Weather	1	0	0	0	1
Roadway	3	1	1	1	6
Secondary Tasks	7	12	1	3	24
Subtotal	**14 (29.8%)**	**20 (42.6%)**	**7 (14.9%)**	**6 (12.8%)**	**47 (100%**

As a comparison, out of 188 SCEs when ADS were not available or activated (i.e., manual driving), the driver's hands were off the wheel in 3.2% of the SCEs and drivers engaged in some sort of secondary task in 43.6% of the SCEs. This trend may be expected, as ADS afford the driver a reduction in the required vehicle control input frequency, thus allowing them to attend to secondary tasks and remove their hands from the steering wheel more readily.

Subjective Ratings on Usability and Usefulness of ADS

Overall, participants responded favorably to the usefulness and usability of ADS but were more positive about the longitudinal control features than the lateral control features (see Figure 4). For example, participants agreed that ADS were effective at preventing crashes (86% of participants responded positively to ACC and 42% responded positively to LKA), performed as they expected (93% for ACC and 65% for LKA), and were easy to use (95% for ACC and 81% for LKA). However, some participants reported that they often manually shut off the ADS (28% for ACC and 23% for LKA). While many participants found ADS useful and usable, people felt more comfortable engaging in secondary tasks (e.g., dialing cell phone) when ADS were active compared to when they were not active (49% for ACC and 35% for LKA).

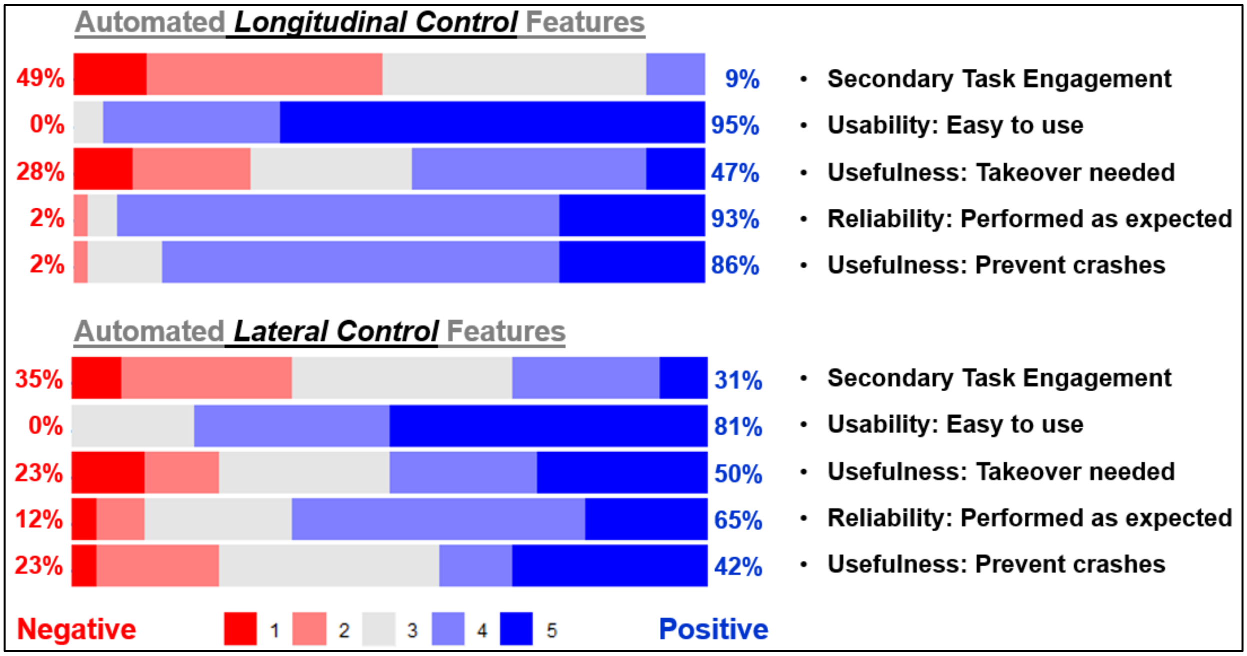
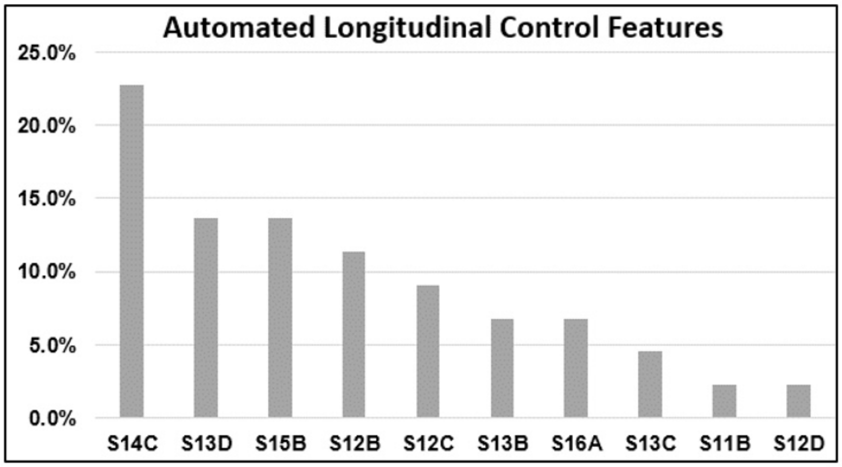


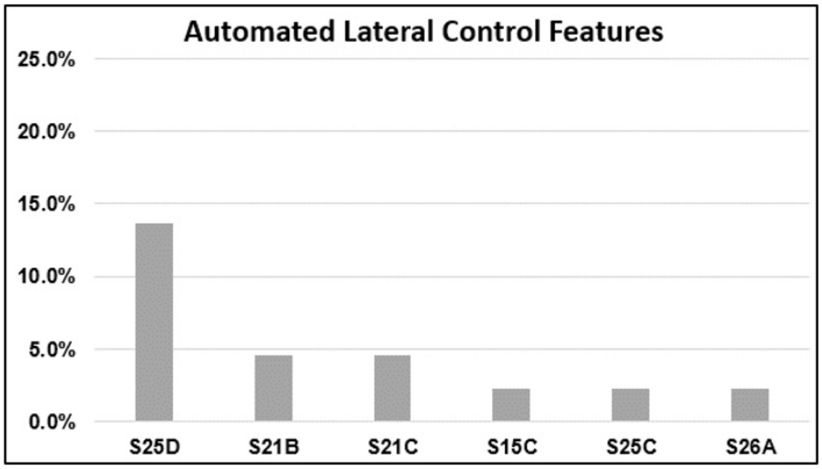
Figure 4. Participants' subjective ratings on the longitudinal (top; e.g., ACC) and lateral control features (bottom; e.g., LKA/LCA) after 12 months of the study.

Participants reported some instances where ADS did not work well or worked below their expectations. Figure 5 summarizes participants' comments on automated longitudinal control features. The most frequently reported instance (23% of participants) was insufficient braking of ADS for a cutting-in lead vehicle. Fourteen percent of participants experienced the ADS automatically disengaging when encountering an already stopped lead vehicle in traffic. Some participants (14%) complained about insufficient acceleration of the car when the traffic in front was clearing. Participants also reported unnecessary ADS braking without any lead vehicle (false positive, 2.5%) and failure to detect lead vehicles (false negative, 7%). Figure **6** summarizes participants' comments on the automated lateral control features. The most common comment was regarding the system automatically disengaging when encountering blurred lane markings.



S14C	Cutting-in lead, no/insufficient braking
S13D	Stopped lead, system disengaged automatically
S15B	No lead, insufficient accelaration
S12B	Slow lead, stopped with abrupt braking
S12C	Slow lead, no/insufficient braking
S13B	Stopped lead, stopped with abrupt braking
S16A	Slow lead on curves, failed to detect the lead (false-negative)
S13C	Stopped lead, no/insufficient braking
S11B	No lead, unnecessary braking (false-positive)
S12D	Slow lead, abrupt braking

Figure 5. Proportion of participants who reported instances where the automated longitudinal control features worked below driver expectations.



S25D	Responding to blurred markings, system disengaged automatically
S21B	Negotiating curves, bounced within the lane
S21C	Negotiating curves, touched/went over the line
S15C	Moving-out lead, changed the lane following the lead
S25C	Lane markings, incorrectely detected lane position
S26A	Lane markings, missed lane markings (false-negative)

Figure 6. Proportion of participants who reported instances where the automated lateral control features worked below driver expectations.

Discussion

Recall that ADS in general were used in 24% of all driving conditions (Dunn, Dingus, & Soccolich, 2019). The analysis of the SCEs captured across the naturalistic driving data revealed that a comparable 20% of all SCEs involved ADS use (RQ1). During these SCEs with ADS in use, 12.8% of the time the systems did not react to the events and did not warn the driver. (RQ2). Drivers showed unintended ADS use 57.4% of the time (RQ3). Drivers found ADS useful and usable and felt more comfortable engaging in secondary tasks while the systems were in use (RQ4). After 12 months of participation, drivers reported some scenarios where the ADS did not work well or did not meet their expectations (RQ5). Following, we further discuss the implications of these observations and study limitations.

The majority of SCEs, including all seven crash events identified in the dataset, occurred during manual driving when neither lateral or longitudinal ADS control features were engaged. In 41 out of the 47 SCEs that occurred with at least one ADS feature activated, all of which were near-crashes, the ADS helped prevent collisions, or at least did not negatively impact the event. However, it is worth noting that in close to half of the SCEs, when the ADS features were activated, drivers had to manually take over ACC control due to other (mostly slower) vehicles that attempted to cut in ahead of them. This is also the most frequently reported instance where participants felt the system did not work well or did not meet their expectations. Although all drivers properly responded and successfully avoided crashes, the potential gap between drivers' expectations and the ADS' capacity (particularly ACC) in this type of scenario may contribute to event severity to some degree.

Drivers' responses to the survey revealed their subjective impressions of currently available ADS after 12 months of participation. In general, drivers found the longitudinal control features more usable, useful, and reliable than the lateral control features. This may be associated with more frequent use of longitudinal control features (6.95% of the time with ACC) than lateral control features (5.03% of the time with LKA) according to Dunn, Dingus, & Soccolich (2019). However, the more positive participants were about ADS features, the more they felt comfortable engaging in secondary tasks while the features were activated. This is an unintended, and potentially dangerous, side effect of L1 or L2 ADS, as systems at these levels require the human driver's supervision. This finding has implications on the development of ADS. Designers of human-machine interfaces (HMIs) for such systems should always consider the possibility of drivers' overconfidence in the systems. Therefore, it might be better for vehicles to have multimodal HMIs (Large et al., 2019) that are adaptive to not only the urgency of situations but also to driver state via monitoring of driver behavior and engagement in the primary task of driving.

Participants' comments also captured some representative instances where ADS did not work well or worked below their expectations. Many drivers reported that the longitudinal control features did not respond well to cutting-in leads and stopped leads. Some participants experienced instances where the car failed to detect a lead vehicle (false negative) or braked without a lead (false positive). The lateral control features were often automatically disengaged when encountering blurred lane markings and had difficulties when negotiating curves. However, during many of these reported situations, the ADS worked as designed. For example, many ACCs are not designed to respond to an already stopped vehicle or are designed with some operational boundaries based on the vehicle speed (Schram, 2019). One important implication is that the ADS's response to some situations may be considered as inappropriate or not on par with drivers' expectations. Owner's manuals and HMIs could make the system capabilities and limitations clear and salient to the driver to avoid any unintended system use.

Conclusions and Recommendations

This small study contributes to a better understanding of the capabilities and limitations of early production SAE L2 vehicles, the prevalence of unintended ADS use, and drivers' perceptions of these new technologies. The findings from this study may inform the development of HMIs, training programs, and owner's manuals to reduce the unintended use of ADS and associated potential safety consequences. The identified characteristics of situations where the ADS failed to warn drivers during SCEs will further inform the development of testing scenarios to ensure ADS safety.

This article reports descriptive statistics of ADS use found in SCEs. Therefore, our findings are preliminary rather than conclusive. Future work will apply statistical analysis on the data to better understand the relationship between the unintended uses of ADS and their safety consequences. Finally, findings from this study can be further compared with those from previous studies conducted in driving simulators, on test tracks, and on public roadways over a short period of time to gain insight into drivers' behavioral adaptation to ADS over time.

Additional Products

The Education and Workforce Development (EWD) and Technology Transfer (T2) products created as part of this project are described below and are listed on the Safe-D website here. The final project dataset is located on the Safe-D Dataverse.

Education and Workforce Development Products

The proposed methods for the data collection, reduction, and analysis will be translated into a learning module entitled "Naturalistic Driving Studies for Automated Driving Systems". The research team develop this learning module. This module will showcase the opportunities and challenges of NDS to better understand the real-world use of driving automation. These learning materials will be designed as a one-week class module for a graduate-level course of Advanced Vehicle Safety Systems (BME 5984) which is a part of the Graduate Certificate in Human Factors of Transportation Safety program at Virginia Tech.

Technology Transfer Products

The research team composed a paper in March 2020 for submission for a presentation at the 2020 Human Factors and Ergonomics Society Annual Meeting. The paper is now under review.

Based on the findings from this study, the research team has developed a summary of the lessons learned related to driver interaction with L1 and L2 driving automation features. This will be shared with stakeholders such as members of the Automated Mobility Partnership (AMP). The research team is aware of the sensitivity involved in performing any analyses in which makes/models are compared. Therefore, valuable information on general types of ACC or LKA will be gained in a way that is model agnostic. The summary may inform OEMs' future development of HMIs, training programs, and owner's manuals to reduce unintended use of ADS and associated safety concerns.

Data Products

The data uploaded to the dataverse includes collected data from the Virginia Connected Corridor 50 Elite Vehicle Naturalistic Driving Study (VCC50 Elite NDS). The data acquisition systems continuously recorded vehicular data including GPS coordinates, speed, acceleration, and video streams of the forward roadway, the driver's face, an over-the-shoulder view of the driver's hands and lap area, a view of the footwell, and instrumented cluster. The dataset can be accessed at: (https://doi.org/10.15787/VTT1/98NBN7).

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Appendix: Post-Study Questionnaire

The post-study questionnaire captured drivers' subjective ratings on the usefulness and usability of the ADS. The post-study questionnaire also captured drivers' comments on some open-ended questions about specific instances where the ADS did not the meet drivers' expectations. Here are selected questions about the Adaptive Cruise Control features.

Q1. To what degree, if any, do you feel more comfortable engaging in secondary tasks (e.g., tuning radio, dialing cell phone) while *Adaptive Cruise Control* is active compared to when it is not active, on a scale from 1-5 (1 being extremely comfortable and 5 being extremely uncomfortable)?.

Q2. Generally, how easy is it to use the *Adaptive Cruise Control* on a scale of 1-5 (1 being extremely difficult and 5 being extremely easy)?

Q3. When the system is available and engaged how often do you manually shut off the *Adaptive Cruise Control* system on a scale from 1 to 5 (1 being every time and 1 being never)?

Q4. How often did the Adaptive Cruise Control system perform as you expected on a scale of 1 to 5 (1 being never and 5 being every time)?

Q5. In your opinion, how effective is the *Adaptive Cruise Control* at preventing crashes on a scale of 1-5 (1 being not effective at all and 5 being extremely effective)?

Q6. What were your most common reasons for manually deactivating the *Adaptive Cruise Control* system?

Q7. If you were talking to a design team, what concerns would you express regarding the *Adaptive Cruise Control* system in your vehicle?