Disengagement from driving when using automation during a 4-week field trial

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Contents

Abstract

Introduction: A small body of research on the real-world use of commercially available partial driving automation suggests that drivers may struggle with or otherwise lapse in adequately monitoring the system and highway environment, and little is known about key issues such as how behavior associated with system use changes over time. The current study assessed how driver disengagement, defined as visual-manual interaction with electronics or removal of hands from the wheel, differed as drivers became more accustomed to partial automation over a 4-week trial.

Methods: Twenty volunteers drove a Land Rover Range Rover Evoque with adaptive cruise control (ACC), which automates speed and headway, or a Volvo S90 with ACC and Pilot Assist, which combines ACC and continuous lane centering. Instrumentation captured automation use, secondary task activity, hands-on-wheel status, vehicle speed, and GPS location during all trips.

Results: The longer drivers used partial automation, the more likely they were to become disengaged by taking their hands off the wheel, using a cellphone, or interacting with in-vehicle electronics. Results associated with use of the two ACC systems diverged, with drivers in the S90 exhibiting less disengagement with use of ACC compared with manual driving, and those in the Evoque exhibiting more.

Discussion: This study raises further concern about vehicle control and the degree to which drivers remain actively in the loop when using automation. Calls for implementing more robust driver monitoring with partial automation appear warranted—particularly those that track head or eye position.

Keywords: Driving automation, trust, complacency, disengagement, hands-off-wheel, secondary activity

1 Introduction

Reasons to automate include reducing operator workload and stress and eliminating human error (Sarter, Woods, & Billings, 1997), but it became clear decades ago in aviation (Wiener & Curry, 1980) and process control (Malone et al., 1980) that automation often has unintended safety risks. Wiener and Curry reviewed cases where cockpit automation contributed to errors that often led to catastrophe due to the operators' failure to adequately monitor imperfect systems. The current study adds to a small body of research on the open-road use of driving automation by assessing how in-vehicle behavior associated with the drivers' ability to monitor the environment and respond to events differs as a function of automation use over time. Recent National Transportation Safety Board (NTSB) investigations of fatal crashes implicating poor monitoring of automation underscore the value of this work (NTSB, 2017, 2019, 2020).

1.1 Automation and attentional demand

Workload and attentional demand are useful constructs for understanding how behavior with automation may differ from that observed during manual control. Very low and high levels of demand are linked with poor performance relative to intermediate demand in a manner that loosely parallels the "inverted U" relationship between arousal and performance known as the Yerkes-Dodson law (Matthews, Davies, Westerman, & Stammers, 2000). Differences in driver-related (e.g., experience, distraction, physiological state), vehicle-related (e.g., engine size, automation), and environmental (e.g., weather, lighting, road class and geometry, traffic density) variables have effects on attention and workload consistent with an inverted U-shape (Engström, Johansson, & Östlund, 2005; Matthews & Desmond, 2002; McCartt & Hu, 2017; Patten, Kircher, Östlund, Nilsson, & Svenson, 2006; Reimer, Mehler, Coughlin, Godfrey, & Tan, 2009; Teh, Jamson, Carsten, & Jamson, 2014; Thiffault & Bergeron, 2003). Factors associated with changes in workload and performance are often linked to crash risk (Ferguson, Preusser, Lund, Zador, & Ulmer, 1995; Mayhew, Simpson, & Pak, 2003; McCartt, Mayhew, Braitman, Ferguson, & Simpson, 2009; Owens et al., 2017). It is important to consider any effects that automation might have on behavior within specific roadway contexts, given how driver attentional load varies across these conditions.

Performance degradation and stress due to attentional load can occur when drivers are faced with monotony (e.g., Matthews & Desmond, 2002; Thiffault & Bergeron, 2003). Drivers operating in low-complexity situations (e.g., daylight, no intersections, free-flowing traffic) must maintain attention for threats that may never emerge, which can lead to ”underload” or “passive fatigue” (Desmond & Hancock, 2001). Passive fatigue during sustained attention tasks can result in a vigilance decrement within 15 minutes, which is typified by the delayed or failed detection of targets (Mackworth, 1948; Teichner, 1974) and increased mind wandering (Körber, Cingel, Zimmermann, & Bengler, 2015). The degree to which drivers are susceptible to passive fatigue or develop countermeasures to passive fatigue such as engaging in nondriving-related activities, with other attentional risks, is not well established.

The current study focuses on partial driving automation (henceforth “partial automation”) and one of its subcomponents, adaptive cruise control (ACC). Partial automation combines ACC and lane-centering functions to automate vehicle speed, time headway, and lateral position. Despite the separate or combined control provided by ACC or lane centering, the driver is fully responsible for the driving task when using the automation (Society of Automotive Engineers, 2018). These systems are designed for convenience rather than hazard avoidance, and they cannot successfully navigate all road features (e.g., difficulty negotiating lane splits); consequently, the driver must be prepared to assume manual control at any moment. Thus, when using automation, the driver has an added responsibility of monitoring it. This added task results in what Bainbridge (1983) describes as a basic irony of automation: while it removes the operator from the control loop, because of system limitations, the operator must monitor the automation; monitoring, however, is a task that humans fail at often (e.g., Mackworth, 1948, Warm, Dember, & Hancock, 2009; Weiner & Curry, 1980).

To compound this irony, ACC and partial automation function more reliably, and drivers’ level of comfort using the technology is greater in, free-flowing traffic on limited-access freeways than more complex scenarios such as heavy stop-and-go traffic or winding, curvy roads (Kidd & Reagan, 2019;

Reagan, Cicchino, & Kidd, 2020). Researchers frequently use interstate roads with light traffic as a low-complexity condition when studying sustained attention and fatigue, which supports the notion that driver workload on limited-access roads is relatively low (Faure, Lobjois, & Benguigui, 2016; Patten et al., 2006). Taken alone, findings of lower levels of perceived workload (de Winter, Happee, Martens, & Stanton, 2014) and improved situation awareness (Beller, Heesen, & Vollrath, 2013; Endsley, 2017) during ACC or partial automation use suggests that drivers may benefit from spare attentional resources. However, recent work shows that use of partial automation on freeways with moderate traffic can also be associated with slowed response to targets in the periphery, reduced levels of arousal (Biondi et al., 2018), and longer glance durations to in-vehicle displays (Gaspar & Carney, 2019).

In a 6-month case study of driving with Tesla's Autopilot, Endsley (2017) noted that as drive time on highways increased, periods of increased awareness of other traffic and roadway conditions when automation was engaged developed into moments associated with increased texting and mind wandering. In sum, research indicates the potential for overreliance on automation on limited-access roads, due to increased system reliability and to the relatively low-level environmental demand. The degree to which different automation systems (e.g., human-machine interface, automation performance, operational design domain) lead to more or less susceptibility for out-of-the-loop behavior has not been well established. What is known is that some systems have been openly critiqued to a greater degree, and that the specifics of the link between drivers' attention and automation performance needs to be better quantified. Improved understanding of this link will enable system designers to improve design standards and inform education, driver monitoring, and driver attention management.

1.2 Trust in automation over time

Trust is a major determinant of automation use that develops and transforms over time (Ghazizadeh, Lee, & Boyle, 2012; Lee & See, 2004). As reviewed by Lee and See, continued use of and trust in a system is shaped by judgments of whether its initial use met expectations. Drivers who develop little trust or have it eroded due to a system failure are likely to disuse it (Dikmen & Burns, 2017; Lee &

Moray, 1992; McDonald et al., 2016; Reagan, Cicchino, Kerfoot, & Weast, 2018). In contrast, those who place too much trust in an imperfect system are more likely to misuse it (Parasuraman & Riley, 1997), for example, by overestimating the system's reliability, becoming complacent, and then failing to monitor the technology appropriately (Sarter et al., 1997).

Existing research conducted on open roads or regarding production vehicles provide conflicting results about the use of vehicle technology over time, and how driver behavior changes over a time course of weeks or longer when using driver assistance or crash avoidance relative to unassisted driving. Regarding crash avoidance, Flannagan et al. (2016) and Reagan et al. (2018) identified a trend toward disuse of lane departure warning systems by showing that increased total mileage driven was associated with significant increases in the likelihood of system deactivation. Jermakian, Bao, Buonarosa, Sayer, and Farmer (2017) showed a greater increase in unsafe following distances among teens who drove test vehicles when forward collision warning became active for 8 weeks after an initial 3-week baseline period. However, secondary task activity of teen and adult drivers did not change significantly as a function of whether or not crash avoidance technology was active (Jermakian et al., 2017; Kidd & Buonarosa, 2017).

Regarding ACC and partial automation, Kessler et al. (2012) reported a 30% increase in ACC use during the final weeks of a 6-month field test compared with the first weeks when the system was available. Although there was no insight provided about driver engagement in nondriving-related activities, the researchers found that ACC use was associated with increased headway and decreased harsh braking. A recent report summarizes two naturalistic driving studies that examined automation use over extended periods of time (Dunn, Dingus, & Soccolich, 2019). In a study of owners of vehicles with partial automation who drove their vehicles for a year, Dunn et al. found increased odds of nondriving-related activity when automation was active relative to when it was available but inactive, which is consistent with the results reported by Biondi et al. (2018) and Rudin-Brown and Parker (2004). In a second study, Dunn et al. assessed the behavior of volunteers assigned to drive researcher-owned vehicles for one month and found the odds of secondary task activity was greater during manual driving than during assisted driving. The divergence in findings between the two studies may reflect differences in trust over time, but direct comparison of the two studies is problematic due to methodological differences in participation length, vehicle and system types, and level of training provided on assistance technologies.

1.3 Hypothesis

Our primary hypothesis is that driver disengagement, when using ACC or partial automation on open roads, is greater relative to manual driving but will only be evident after drivers experience the system for a period of time. We defined disengagement from driving as removing both hands from the steering wheel or conducting visual-manual activity with cellphones or in-vehicle systems. We included hands-off-wheel behavior as a component of disengagement because the partial automation system investigated in this study is a "hands-on-wheel" system that provides lateral support. Each NTSB fatal crash investigation involving overreliance on partial automation indicated that drivers' hands were on the steering wheel for only small fractions of time in the minutes leading up to a crash or were not detected on wheel in the moments prior to the crash (NTSB, 2017, 2019, 2020). Hand placement and steering wheel behavior has received little attention in manual driving research but has been shown to vary by level of objective risk and workload, with more secure placement associated with increased number of lanes and faster speed limits and less secure placement after merging into traffic on a limited-access road (de Waard, Van Den Bold, & Lewis-Evans, 2010; Walton & Thomas, 2005). At a minimum, having hands off the steering wheel affects drivers' motor readiness to control the vehicle (Zeeb, Buchner, & Schrauf, 2016). Nondriving activity that involves removing hands from the wheel or visual behavior associated with reduced scanning of the roadway and mirrors increases crash risk (Cunningham, Regan, & Imberger, 2017; Dingus et al., 2016).

To test our hypothesis, 20 volunteer adult drivers were assigned to drive a study-owned production vehicle for 4 weeks. Two vehicle models from different automakers were used.

Both models were equipped with ACC, but only one also had a partial automation system (ACC augmented with a lane-centering system). To incorporate time into the analysis, the 4-week deployment period was divided into period 1 (weeks 1 and 2) and period 2 (weeks 3 and 4).

2 Methods

2.1 Participants

This study is based on 10 participants (5 females) with an average age of 44.0 years old (SE = 4.8) who drove a 2016 Land Rover Range Rover Evoque and 10 participants (4 females) with an average age of 46.7 years old (SE = 5.0) who drove a 2017 Volvo S90 between November 2016 and September 2017, with the initial dealer-delivered partially automated driving features (Note: Dealer-deliverable software upgrades were not installed during this period, so that system functionality remained constant for this sample). All participants were licensed adult drivers who resided in the Boston, Massachusetts, metro area; reported commuting at least 30 miles a day, 4 days a week using a consistent route; and did not own an S90 or Evoque.

2.2 Vehicles and systems

Of primary interest for our analysis are the active vehicle control technologies Pilot Assist and ACC. In the S90, Pilot Assist is a partial automation technology that keeps the vehicle in its current lane by providing continuous steering assistance in addition to the ACC headway and speed control functionality. Wording in the S90 owner manual advises that “the driver is always responsible for steering the vehicle and maintaining a suitable speed and distance to the vehicle ahead and must intervene if necessary, even if Pilot Assist is being used.” In the Evoque, ACC is available to provide drivers speed- and headway-keeping assistance. The Evoque manual advises, “Adaptive cruise control system is not a substitute for driving safely, with due care and attention. It is the driver's responsibility to stay alert, drive safely and be in control of the vehicle at all times.”

The vehicles were instrumented with multiple video cameras, sensors, and data-logging equipment. System state was determined by a machine vision program that used video from the camera that captured the instrument panel view where automation status indicators are displayed. Secondary task activity was captured by video from a camera that recorded a top-down view of the driver cockpit area. GPS sensors recorded latitude, longitude, and vehicle speed.

2.3 Procedure

At vehicle delivery, participants received an overview of the on-board active safety technologies during a 1.5-hour training session, which consisted of a 30-minute in-vehicle instruction on basic functions and instrumentation while the vehicle was parked, followed by an hour-long training drive. As part of their training, in the S90, participants received an overview of ACC, Pilot Assist, City Safety, Lane Keeping Aid, Lane Departure Warning, Blind Spot Monitoring, and Park Assist. In the Evoque, participants received an overview of ACC, Lane Keep Assist, Lane Departure Warning, Blind Spot Monitor, and Forward Alert Function. During the training drive, participants actively went through the process of engaging and disengaging ACC and, in the S90, the Pilot Assist feature. Participants completed demographic and in-vehicle technology questionnaires at vehicle delivery and return sessions; these data are not included as part of this analysis.

Video data were reviewed manually at a rate of 30 Hz. Reviewers coded time spent performing 26 secondary tasks associated with in-vehicle displays and controls or cellphones (see Table 1) and time with both hands off the steering wheel. These behaviors needed to occur for a minimum of 500 milliseconds to be retained in the final data set used for the current analysis, which was downsampled at 1 Hz for storage and analytic efficiency. An additional category labeled “other tasks” was created to capture time participants spent conducting secondary behaviors that reviewers observed during the coding process other than the 26 specific behaviors listed in Table 1. The “other task” category was coded only if the activity duration was longer than 10 seconds; this threshold was set to enable coders to skip scoring of singular momentary actions such as single-world utterances or the brushing back of hair. Behaviors in the “other task” category included behaviors associated with personal hygiene and fidgeting; eating or drinking; talking/singing to oneself or a passenger; and any dancing, reading, or writing. Reviewers grouped all of these behaviors into a single bin, so further video review could be employed at a later date to separate individual activities.

Data on GPS location were sampled at 1 Hz and was used to identify interstates, freeways, and other expressways (henceforth termed "limited-access roads") using the Federal Highway Administration's functional classification system, and this data set was merged with the secondary task data set. Thus, each observation in the merged data set is equal to 1 second in time.

Table 1. Percentage of time a behavior was observed when participants were driving on limited-access roads at speeds over 25 mph

Behavior	Evoque	S90	Overall
Visual-manual	**3.00**	**7.38**	**4.39**
Cellphone-based	**1.22**	**3.72**	**2.01**
Holding phone	0.69	1.72	1.02
Manipulating phone	0.40	1.34	0.70
Talking on handheld phone	0.35	0.26	0.32
Reaching for handheld phone	0.08	0.14	0.10
Placing a handheld phone	0.08	0.40	0.18
Hands off steering wheel	**0.65**	**1.32**	**0.86**
Center stack interaction	**1.11**	**2.03**	**1.40**
Climate control	0.30	0.27	0.29
Stereo	0.56	1.24	0.78
Navigation	0.06	0.33	0.15
Accessing paired cellphone	0.03	0.03	0.03
Settings	0.14	0.00	0.09
Cameras	<0.01	0.00	<0.01
Other	0.02	0.15	0.06
Interacting with controls on steering wheel	**0.03**	**1.00**	**0.33**
Climate control	<0.01	0.00	<0.01
Stereo	0.00	0.92	0.29
Navigation	<0.01	0.08	0.03
Accessing paired cellphone	0.03	<0.01	0.02
Other	<0.01	0.00	<0.01
Voice-based system interaction	**3.39**	**2.51**	**3.11**
Hands-free voice conversation	3.14	2.33	2.89
Voice-command climate control	0.00	0.02	0.01
Voice-command stereo	0.02	0.04	0.03
Voice-command navigation	0.12	0.12	0.12
Voice-command accessing paired cellphone	0.10	0.00	0.07
Voice-command other	0.01	0.00	<0.01
Other tasks (e.g., eating, drinking, talking to self or passengers, personal hygiene)	30.59	38.87	33.22

Note: The sum of the percentage of times engaged in individual cellphone tasks may not equal aggregated totals, as drivers may have engaged in multiple behaviors simultaneously. Holding, reaching, or manipulating non-cellphone portable electronic devices were included as codable-specific behaviors but were not observed among Evoque participants, and observed less than 0.01% of the time among S90 drivers.

2.4 Analysis

In an earlier study investigating the roadway types where drivers use ACC and Pilot Assist while driving the S90 and Evoque, Reagan et al. (2019) reported that although some drivers used the automation on nonfreeways, use was primarily on limited-access roads. Additionally, there are many low-speed scenarios when the automation in the study vehicles would not have been available (e.g., minimum speed engagement requirements). For these reasons, the current analysis was limited to travel on limited-access roads when the vehicles were traveling above 25 mph.

The outcomes of interest involve the percentage of time participants conducted nondriving visual-manual activity with portable or embedded electronics or had both their hands off the steering wheel. Table 1 indicates that the overall percentage of time drivers performed individual behaviors with some visual-manual demand was below 1% for all but holding the phone. Thus, four of the six outcome variables involved aggregation of specific behaviors. At the highest level, specific behaviors that divert visual or manual resources from driving were aggregated into a single measure termed "visual-manual driver disengagement." The aggregated behaviors included visual-manual activity with cellphones or other portable electronics, visual-manual use of the center stack or steering wheel controls (e.g., stereo), and removal of both hands from the steering wheel. Because of the focus on visual-manual disengagement, the "other task" category and voice-based tasks were not analyzed further.

To investigate the relationship between automation use and study period on driver disengagement, logistic regression models were constructed separately for the S90 and Evoque. The models included vehicle control condition (i.e., manual control, ACC active, and Pilot Assist active), study period (period 1 included weeks 1 and 2, period 2 included weeks 3 and 4), and the interaction between vehicle control condition and study period, with subject included as a repeated measure to account for multiple observations from each driver. Linear combinations of parameter estimates from the logistic regression models were used to compute estimates and confidence intervals for comparisons of interest. For the S90, four comparisons estimated the odds of visual-manual disengagement when driving with automation relative to driving manually within each study period, and three comparisons estimated the odds of visual-manual disengagement when driving manually or with automation in period 2 relative to using the same level of vehicle control in period 1. These comparisons are:

1. When driving manually in period 2 versus period 1.
2. When driving with ACC engaged in period 2 versus period 1.
3. When driving with Pilot Assist engaged in period 2 versus period 1.
4. Between driving manually or with ACC engaged during period 1.
5. Between driving manually or with ACC engaged during period 2.
6. Between driving manually or with Pilot Assist engaged during period 1.
7. Between driving manually or with Pilot Assist engaged during period 2.

For the Evoque analyses, the first, second, fourth and fifth paired comparisons in the previous list (i.e., those not involving Pilot Assist) were conducted. Tests below $p < 0.05$ were considered statistically significant. Odds ratios with 95% confidence intervals (CI) are provided with each analysis. The percent change associated with odds ratios are presented in the text, and were calculated by subtracting 1 from the odds ratios and then multiplying by 100.

Six logistic regression models per vehicle estimated the role of automation use and time period on various measures of disengagement. The dependent variables included the aggregated driver disengagement variable, visual-manual disengagement excluding time spent with hands off wheel, percentage of time spent with both hands off wheel, all visual-manual cellphone activity (i.e., holding, reaching, placing, or manipulating a cellphone; having a handheld cellphone conversation), only active cellphone manipulation, and all visual-manual interaction with the center stack.

3 Results

3.1 Vehicle exposure

Participants spent a total of 324.9 hours (S90 for 133.5 hours and Evoque for 191.5 hours) traveling on any road at speeds over 25 mph during the 20 months of data collection. A total of 44.0 of these hours among the 10 drivers assigned to the S90, and 94.4 hours among the 10 Evoque participants, were on limited-access roads; data reported in the remainder of the Results section are restricted to these periods. Table 2 lists summary statistics for trips meeting these inclusion criteria.

Table 2. Total number of trips, median, and range of trips across vehicles

Vehicle	Total trips	Median (SD)	Range
Evoque (n=10)	325	34.0 (12.7)	9–54
S90 (n=10)	247	22.5 (7.3)	18–39

Note: SD = standard deviation

3.2 Use of ACC and Pilot Assist

System use varied across system type and among individual drivers over the two study periods (Table 3). Of the seven S90 participants who used ACC during the first study period, one showed increased use from 2.5% to 3.4% of the time; two with relatively high rates of use in the first period sustained their rates of use at 44.0% and 26.0%; and the remaining four eliminated or cut their use in half. The three participants who did not use ACC during the first period did not activate it in the second period either. Participants' use of Pilot Assist in the S90 ranged from 0 to 49.0% in the first half of the study and 0 to 60.6% in the second half. Seven drivers used Pilot Assist in the first period, with one increasing and six decreasing their use in the second period. The three who did not use Pilot Assist during the first period did not use it in the second.

Table 3. Percentage of system use and range of use across drivers overall and by study period

Vehicle system	Overall (weeks 1–4)	Period 1 (weeks 1 and 2)		Period 2 (weeks 3 and 4)	
	Total	Total	Range	Total	Range
S90 ACC	9.7%	12.0%	0.0–25.5%	6.8%	0.0–44.1%
S90 Pilot Assist	8.9%	9.8%	0.0–49.0%	7.6%	0.0–60.6%
Evoque ACC	31.4%	33.1%	0.0–70.3%	28.5%	0.0–88.3%

Among the drivers assigned to the Evoque, all but one driver used ACC during both study periods. The other subject never activated the system during the study periods. Four drivers increased use from the first to the second half of the study by 1.7, 5.5, 60.0, and 61.9 percentage points; five showed decreases in use ranging from 9.0 to 38.5 percentage points.

3.3 Prevalence of driver disengagement

All participants showed some level of disengagement while driving manually, as defined by hands-off-wheel behavior and visual-manual activity. The percentage of time that individual drivers were disengaged during manual driving ranged from 0.05% to 18.1%. Among those assigned to the Evoque, eight drivers exhibited disengagement when ACC was used, with the percentage ranging from 0.3% to 19.6% across individuals. Seven participants assigned to the S90 showed varying levels of disengagement when ACC was used (the range was 1.0% to 8.3%), and six contributed to observations made when Pilot Assist was used (the range was 2.3% to 40.1%).

3.4 Effects of automation and study period on the odds of visual-manual disengagement

3.4.1 Driver disengagement in the S90

Figures 1a–1f. Percentage of time S90 participants exhibited visual-manual disengagement from driving by vehicle control condition and study period. Note the different scales on the y-axes.

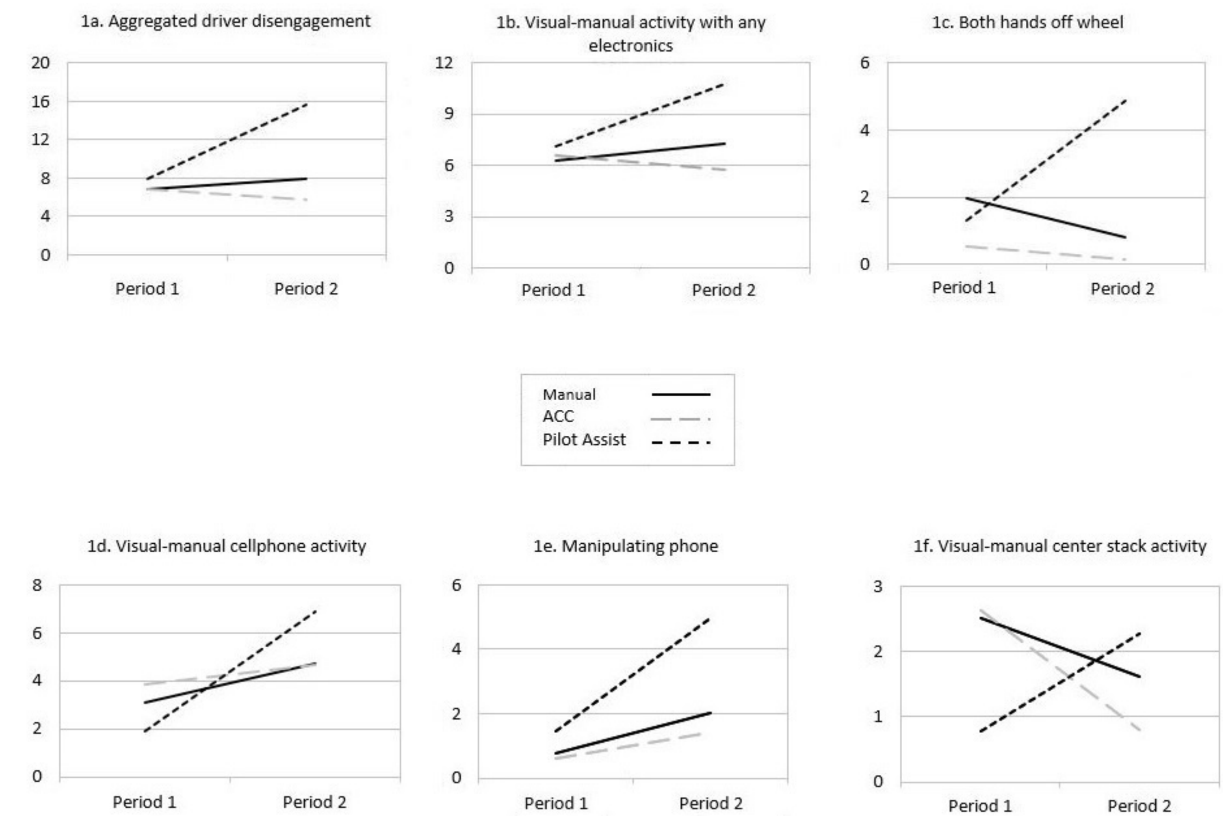

Table 4. Odds ratios (95% confidence intervals) for driver disengagement by vehicle control and study period

Comparison	Aggregated driver disengagement	Visual-manual use of any electronics	Both hands off wheel	Visual-manual cellphone use	Visual-manual use of center stack
Period 2 vs. 1, manual control	0.91 (0.40,2.07)	0.89 (0.41,1.92)	0.30 (0.02, 4.05)	1.13 (0.62, 2.04)	0.50 (0.13, 1.99)
Period 2 vs. 1, ACC use	0.80 (0.43, 1.49)	0.81 (0.47, 1.40)	1.20 (0.12, 11.84)	1.17 (0.56, 2.45)	0.36 (0.03, 5.01)
Period 2 vs. 1, Pilot Assist use	**2.44 (1.04, 5.72)**	1.77 (0.39, 7.95)	**2.73 (1.28, 5.82)**	3.98 (0.21, 74.92)	**2.94 (1.18, 7.29)**
ACC vs. manual, period 1	**0.39 (0.19, 0.81)**	**0.37 (0.19, 0.74)**	0.26 (0.02, 3.74)	0.46 (0.17, 1.22)	0.71 (0.17, 3.01)
ACC vs. manual, period 2	**0.34 (0.13, 0.90)**	**0.34 (0.13, 0.86)**	1.06 (0.15, 7.61)	**0.48 (0.29, 0.80)**	0.50 (0.05, 5.11)
Pilot Assist vs. manual, period 1	0.89 (0.34, 2.34)	0.78 (0.30, 2.02]	1.38 (0.25, 7.55)	0.43 (0.10, 1.9)	**0.28 (0.09, 0.85)**
Pilot Assist vs. manual, period 2	**2.39 (1.18, 4.83]**	1.55 (0.84, 2.83)	**12.65 (2.18, 73.50)**	1.52 (0.45, 5.05)	1.68 (0.71, 3.99)

Note: Statistically significant results are bolded.

Odds ratios with 95% confidence intervals produced from modeling the relationship of driver disengagement by vehicle control condition and study period are provided in Table 4. The model that examined cellphone manipulation failed to converge. Figures 1a–1f display the percentage of time that S90 participants displayed any visual-manual driver disengagement, visual-manual activity with any electronics, removal of both hands from the wheel, visual-manual cellphone activity, cellphone manipulation, and visual-manual center stack activity. As seen in Table 4, use of Pilot Assist during period 2 was associated with increases in the odds of driver disengagement compared with use of Pilot Assist during period 1, which was significant for aggregated driver disengagement behaviors (144%), having both hands off the wheel (173%), and visual-manual use of the center stack (194%). In contrast with Pilot Assist, the odds of driver disengagement when driving manually or with ACC during period 2 did not differ significantly from the same respective vehicle control condition during period 1 for any of the outcome measures.

Table 4 also shows the relationship of study period and vehicle control condition in comparisons that estimated the odds of driver disengagement associated with using Pilot Assist relative to manual driving. During period 1, the odds of most behaviors when using Pilot Assist did not differ significantly from manual driving, and the odds of visual-manual center stack activity when using Pilot Assist were significantly lower (−72%) than manual driving. Pilot Assist use during period 2 was associated with increases in the odds of all driver disengagement behaviors relative to manual driving during the same period, with significant changes in any visual-manual driver disengagement (139%) and removal of both hands from the wheel (1,165%).

A different relationship between vehicle control condition and study period on driver disengagement was found between ACC use and manual driving. During periods 1 and 2, ACC use was associated with significantly lower odds of any visual-manual disengagement (−61% and −66% during periods 1 and 2, respectively) and visual-manual activity with any electronics (−63% and −66% during periods 1 and 2, respectively) compared with manual driving. Use of ACC was also associated with a significant reduction in the odds of visual-manual cellphone activity (−52%) compared with driving manually but only during the second study period. The odds of hands-off-wheel time and visual-manual center stack activity did not vary significantly in association with ACC use relative to manual control during either study period.

3.4.2 Driver disengagement in the Evoque

Figures 2a–2f. Percentage of time Evoque participants exhibited visual-manual disengagement from driving by vehicle control condition and study period. Note the different scales on the y-axes.

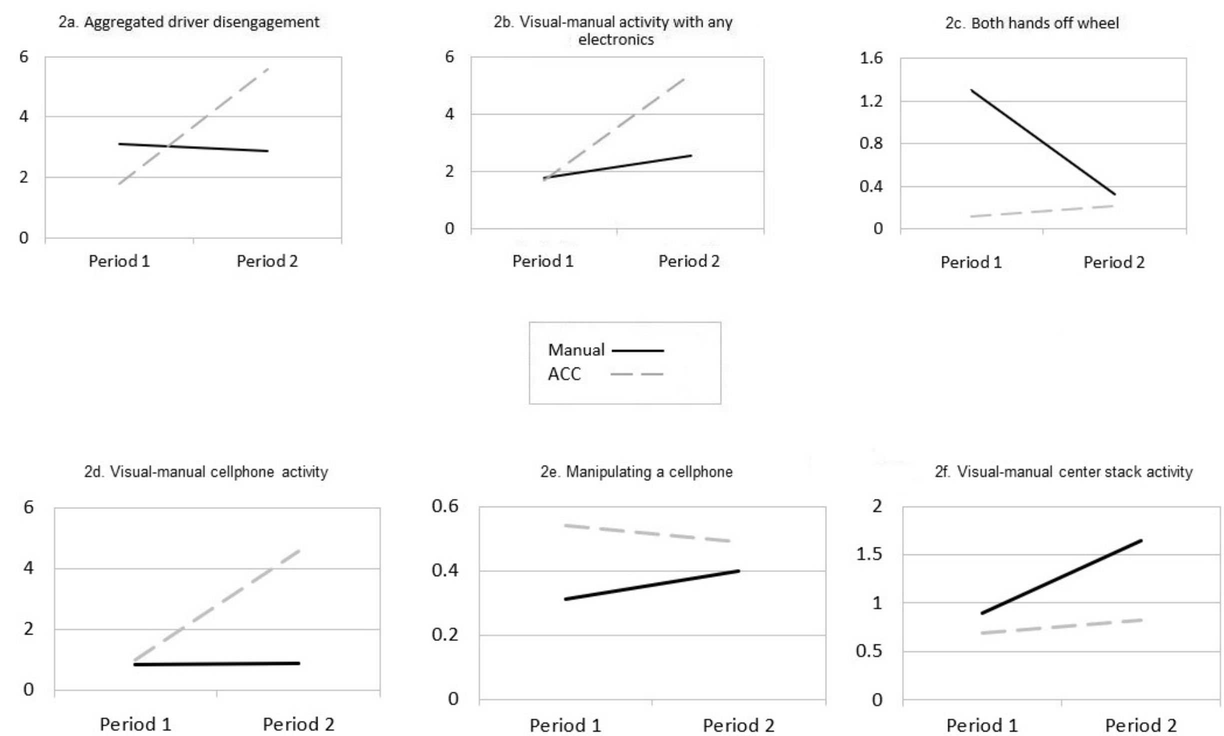

Table 5. Odds ratios (95% confidence intervals) of driver disengagement by vehicle control and study period

Comparison	Aggregated driver disengagement	Visual-manual use of any electronics	Both hands off wheel	Visual-manual cellphone use	Manipulating a handheld phone	Visual-manual use of center stack
ACC vs. manual, period 1	0.43 (0.18, 1.03)	0.69 (0.34, 1.40)	**0.06 (0.00, 0.71]**	0.87 (0.30, 2.55)	**1.79 (1.04, 3.07)**	0.51 (0.24, 1.09)
ACC vs. manual, period 2	1.54 (0.34, 6.92)	1.77 (0.43, 7.24)	0.27 (0.02, 4.29)	**3.34 (1.03, 10.79)**	0.62 (0.13, 3.06)	0.48 (0.16, 1.38)
Period 2 vs. 1, manual	1.11 (0.41, 2.99)	1.60 (0.69, 3.69)	0.30 (0.07, 1.29)	**1.87 (1.18, 2.98)**	**1.99 (1.13, 3.50)**	1.36 (0.43, 4.29)
Period 2 vs. 1, ACC use	3.96 (0.97, 16.11)	**4.12 (1.02, 16.69)**	1.40 (0.24, 8.09)	**7.16 (1.44, 35.66)**	0.69 (0.13, 3.55)	1.26 (0.57, 2.76)

Note: Statistically significant results are bolded.

Figures 2a–2f display the percentage of time participants exhibited the analyzed measures of visual-manual disengagement when driving manually or with ACC during each study period. The odds ratios in Table 5 reveal significant relationships between vehicle control condition and study period and driver disengagement among Evoque participants. The odds for aggregated driver disengagement when driving with ACC were nearly 3 times higher in period 2 compared with period 1, but the overlapping confidence bounds indicate the relationship was not significant ($p = 0.054$). Odds of these behaviors associated with ACC use were lower during period 1 relative to manual driving (−57%; $p = 0.06$), whereas the change in odds of aggregated driver disengagement when using ACC relative to manual driving in period 2 did not approach significance ($p = 0.57$). ACC use was associated with reductions in the odds of removing hands from the steering wheel compared with manual driving during both periods, which was significant during period 1 (−94%). The odds of hands-off-wheel behavior when driving manually or with ACC did not change significantly from period 1 to period 2.

Comparisons of disengagement when using ACC during period 2 relative to period 1 found significant increases in the odds of visual-manual use of any electronics (312%) and visual-manual use of cellphones (616%; Table 5). Manual driving during period 2 was associated with a smaller but still significant increase (87%) in the odds of visual-manual phone use relative to manual driving in period 1, but the increase in odds associated with visual-manual use of any electronics during manual driving in period 2 relative to period 1 was not significant. ACC-assisted driving was also associated with increased odds of visual-manual use of any electronics and visual-manual cellphone use relative to manual driving within period 2, although only the increase (234%) in odds of visual-manual cellphone use was significant. Visual-manual use of any electronics and visual-manual cellphone activity did not differ significantly during period 1 between ACC-assisted and manual driving.

Significant relationships between study period and vehicle control were found for the odds of cellphone manipulation when comparing ACC-assisted to manual driving within a study period. ACC use in period 1 was associated with a significant increase (79%) compared with manual driving during period 1. However, the decrease in odds associated with ACC use relative to manual driving during period 2 was not significant, which is related to the significant increase (99%) in odds of manipulating a cellphone when driving manually in period 2 relative to manual driving in period 1 (Table 5). Changes in the odds of cellphone manipulation for ACC and manual driving within period 2 and ACC-assisted driving in period 2 relative to period 1 were not significant. Finally, there were no significant differences between manual and ACC-assisted driving in the odds of visual-manual center stack activity when comparing the same control condition across study periods or when comparing the same level of control between study periods.

4 Discussion

In the current study, participant use of driving automation on limited-access roads at speeds over 25 mph was associated with increased disengagement from driving and a consequent reduction in monitoring of the technology and roadway environment. Use of ACC in the Evoque and Pilot Assist in the S90 was associated with increased odds of conducting visual-manual behaviors that naturalistic driving studies have consistently associated with significant increases in crash risk (Dingus et al., 2016; Guo et al., 2017), although ACC use in the S90 was associated with less disengagement relative to manual driving. The increases in disengagement were accompanied by an increase in the odds of removing both hands from the steering wheel when Pilot Assist was providing lateral support, which raises further concern about vehicle control and the degree to which drivers remain actively in the loop when using partial automation in free-flowing traffic on limited-access roads.

As supported by findings on the developmental nature of trust in technology (e.g., Ghazizadeh et al., 2012; Hoffman, Johnson, Bradshaw, & Underbink, 2013; Lee & See, 2004), the increased odds of disengagement were limited to period 2. Based on the primary role that experience with automation has on trust (i.e., Lee and See), participants likely had less trust when using the systems during period 1 relative to period 2. This effect may have been particularly prominent due to the majority of participants indicating by self-report never having driven vehicles with driver assistance or crash avoidance technology, and when considering that the training provided on assistance, while presumably substantively more than typical dealer-delivered technology training, was still relatively brief. This conclusion would be consistent with the increase in disengagement seen with a gradual build-up in trust with automation use that was limited to period 2.

Parasuraman and Riley (1997) emphasized that misuse often occurs with overtrust in automation, whereas disuse is a manifestation of distrust in automation. A number of participants who used automation in period 1 disused it in period 2. These participants would have contributed to the relatively low percentage of time that drivers were disengaged from driving when using automation in period 1 but did not have any exposure to automation use in period 2. Thus, automation use that occurred in period 2 was more likely limited to participants who had built trust in the systems. The increased disengagement associated with ACC use in the Evoque and Pilot Assist in the S90 in period 2 relative to period 1, and increased disengagement with either implementation relative to manual driving that was apparent in period 2 but not period 1, also support this conclusion. The results may also reflect a situation where an increase in inattention associated with use of automation over time relative to manual vehicle control is compounded by low-complexity, steady-state driving environments where degraded vigilance is a concern even for manual driving.

A recent report documents a 1-month field trial where participants drove study-owned vehicles equipped with ACC and partial driving automation and a separate naturalistic driving study that tracked owners of vehicles equipped with partial driving automation for a year (Dunn et al., 2019). The current results differ from Dunn et al.'s study of volunteers who drove study-owned vehicles for a month. Dunn and colleagues reported a significant increase in the odds of secondary activity with manual driving compared with driving with the automation. In contrast, their study of owners of vehicles with partial automation reported increased odds of secondary activity when the automation was active compared with when it was not, and the increase in the odds of visual-manual secondary activity was greater than the increase associated with all distractions. Differences among and between the current study and the two reported in Dunn are likely due in part to methodological differences. The current study was the only of the three that included time period as an experimental factor, thus providing a window into changes in behavior that might be associated with increased experience and trust as discussed above. Further, both studies in Dunn et al. were based on coding sampled epochs, whereas the current study used behavior coded across full trips, and the three studies varied their velocity thresholds applied for analysis (Dunn et al. used 20 and 40 mph, and the current study used 25 mph).

The version of Pilot Assist used in the current study had low functional reliability relative to a later version after a software update that improved its lane-centering performance (Reagan et al., 2019). Reagan and colleagues noted that Pilot Assist use doubled among a different set of participants who drove the vehicle model after the update. The increase in use reported by Reagan et al. begs the question of what the pattern of behavior might be among drivers who use more reliable partial automation. Secondary task activity was not coded for participants who drove with the improved system at the time of this study, however, and remains a compelling area of future research.

Increased levels of disengagement associated with use automation use were identified in the current study among participants assigned to either vehicle, but the specific behaviors differed between the two groups, largely as a function of hands-off-the-wheel behavior. Among those who drove the S90, the measure that included removing both hands from the steering wheel and visual-manual interactions with cellphones or in-vehicle systems was sensitive to changes in disengagement associated with different levels of vehicle control during the two study periods. Excluding points in time when drivers' hands were off the wheel for analyses of visual-manual interaction with cellphones or in-vehicle systems and visual-manual interaction only with cellphones produced effects that were in the same direction as models that included removing hands from the wheel, but the results were not statistically significant. The odds of visual-manual interaction with the center stack increased significantly during the second period of the study, but only when drivers were using Pilot Assist. Finally, some findings associated with use of ACC in the S90 were in a different direction than findings associated with the two other implementations of automation. Continued research would help clarify whether the divergence is due to sample size or other factors, as use of ACC in the S90 was very low, which could be partly attributable to the availability of

Pilot Assist. Only four of 10 participants used the S90's ACC during the second half of data collection, and two of those four drivers used it less than 10% of their travel time on limited-access roads.

Participants in the Evoque had a high level of ACC use and spent little time with their hands off the wheel. In fact, the odds of removing both hands from the wheel when using the Evoque's ACC were significantly lower than manual driving during period 1, with no significant increase in the odds of taking hands off the wheel when using ACC across the month. The analysis that combined hands-off-wheel time with visual-manual interactions with cellphones or in-vehicle systems produced a near 3-fold increase in the odds of disengagement when participants used the Evoque's ACC during the second half of the data relative to the first, but the result was not significant ($p = 0.054$).. Excluding hands-off-the-wheel time resulted in significant increases over time in the odds of visual-manual interaction with cellphones and in-vehicle interfaces and visual-manual interaction of cellphones alone when ACC was engaged. It is noteworthy that the increased odds of visual-manual interaction with cellphones associated with ACC use during period 2 was not due to cellphone manipulation, given the increased crash risk associated with manipulating a phone relative to other visual-manual secondary tasks (Dingus et al., 2016; Guo et al., 2017).

The availability of lane centering in addition to ACC likely explains the different between-vehicle effects associated with removing both hands from the steering wheel, as automated lateral control affords such behavior despite designation as a hands-on system. Compared with ACC use in the Evoque, there was a more consistent pattern of increased visual-manual disengagement with Pilot Assist relative to manual control during period 2 and Pilot Assist use in period 1. This difference is apparent in the percentage of time participants' hands were off the wheel (Figures 1c versus 2c) or manipulating a cellphone (Figures 1e versus 2e). This pattern supports previous research that indicates drivers' ability to maintain attention to the road is more challenging with lane centering than ACC. Young and Stanton (1997) and Carsten, Lai, Barnard, Jamson, and Merat (2012) conducted simulator studies that found secondary task activity and perceived workload when driving with lane centering alone was similar to that observed with a system that combined ACC and lane centering. In contrast, use of ACC alone was associated with an attentional load comparable with manual driving (Young and Stanton, 1997) or one that fell between manual and partially automated driving (Carsten et al., 2012).

As discussed by Carsten et al. (2012), manual lateral control requires constant updating of visual information to manually adjust the car's path, and this resource demand may be sufficient to keep drivers in the loop during highway driving. Emerging research shows haptic shared control of steering, which adapts lateral support based on driver input, improves lateral control compared with manual steering while maintaining driver vigilance (Mulder, Abbink, & Boer, 2012). Design features such as haptic shared control may be key to maintaining driver vigilance for driving automation that provides continuous lateral support that also includes a manual mode of operation.

The disengagement associated with automation use during the second period of data collection was consistent with other research showing decreased attention to the road relative to manual driving (Biondi et al., 2018; Endsley, 2017; Gaspar & Carney, 2019) and is consistent with overreliance (Parasuraman & Riley, 1997). However, the behavior could also be a manifestation of testing a systems' operational limits, for example intentionally taking hands off the wheel to experience the automated steering. Testing functional performance is a common practice associated with the trial-and-error learning frequently used by vehicle owners (Sullivan, Flannagan, Pradhan, & Bao, 2016). Observations suggest some proportion of the visual-manual interaction with in-vehicle interfaces may reflect demand associated with monitoring the automation. Safety implications may differ somewhat for drivers who are over-relying on the technology, cautiously testing lane-centering functionality, or monitoring an automation display. Analysis of eye glance behavior similar to that conducted by Gaspar and Carney (2019) could help identify underlying reasons for the behavior change and more precisely estimate risk associated with the visual-manual activity. Eye glance analysis could be particularly helpful with understanding the risks associated with the increase in hands-off-wheel behavior associated with partial automation.

If the increased interaction with visual-manual interfaces or hands-off-wheel time identified in this study indicates that drivers have degraded focus on driving, then there should be serious concern about the reliability of current implementations of driver-monitoring systems in detecting and preventing driver inattention. The matter is particularly troubling, considering that few existing systems monitor behaviors associated with visual demand. Calls for more robust driver monitoring to be implemented with partial automation appear warranted—particularly those that track head or eye position (Coughlin, Reimer, & Mehler, 2011; Mueller, Reagan, & Cicchino, 2020; Reimer, 2020). The implications for driver monitoring regarding the increased odds of disengagement associated with using ACC over time in the current study are less clear, given research that indicates safer following behavior (Kessler at al., 2012) and lower levels of inattention associated with ACC relative to lane centering and partial automation (Young and Stanton, 1997; Carsten at al., 2012).

4.1 Conclusion

One of the most challenging research needs is to determine the net effect of existing implementations of automation on crash risk. These systems are designed to provide continuous support for normal driving conditions, and they exist in tandem with crash avoidance systems that have been proven to reduce the types of crashes for which they were designed (Cicchino, 2017, 2018a, 2018b, 2019a, 2019b). There is support from field operational tests that the automated speed and headway provided by ACC may confer safety benefits beyond those provided by existing front crash prevention (e.g., Kessler et al., 2012), and this work exists alongside findings that suggest drivers remain more engaged when using ACC (Young & Stanton, 1997) relative to lane centering. In contrast, the current field test data and recent analyses of insurance claims are unclear about the safety benefits of continuous lane-centering systems extending beyond that identified for existing crash avoidance technologies (Highway Loss Data Institute [HLDI], 2017, 2019a, 2019b). Investigations of fatal crashes of vehicles with partial driving automation all indicate the role of inattention and suggest that accurate benefits estimation for partial automation will have to account for disbenefits introduced by complacency. This study provides support for the need for a more comprehensive consideration of factors such as changes in the odds of nondriving-related activities and hands-on-wheel behaviors when estimating safety benefits.

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