# Rinse and repeat: behavior change associated with using partial automation among three samples of drivers during a 4-week field trial

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## Abstract

***Introduction:*** Partial automation is in its infancy. There is a need to understand driver behavior associated with the use of this technology, such as to what extent it differs from manual driving behavior or changes with use over time. In Reagan et al. (2021; *Transportation Research Part F*, *82*), volunteers driving a Volvo S90 with adaptive cruise control (ACC) and Pilot Assist, which couples ACC and continuous lane centering, were more likely to show visual-manual disengagement when using Pilot Assist in the second portion of a 4-week field trial compared with manual driving or relative to driving with Pilot Assist in the first portion.

***Method:*** We used the same analytical approach as Reagan et al. with three separate samples of drivers ($n_A = 10$, $n_B = 10$, $n_C = 9$). Using video data, we estimated the odds of conducting a visual-manual secondary activity or driving with both hands off the wheel across three automation modes (manual [no automation], ACC, Pilot Assist) and two study periods (period 1, weeks 1 and 2; period 2, weeks 3 and 4).

***Results:*** Participants exhibited higher odds of visual-manual distraction or driving hands-free in period 2 when using Pilot Assist relative to manual driving, but patterns differed noticeably across the groups. Pilot Assist use among groups A and B was associated with higher odds in the second period relative to the first, whereas group C exhibited a high level of visual-manual distraction and hands-free driving when using Pilot Assist throughout the 4 weeks of data collection.

***Discussion:*** Our findings suggest that drivers show reliably less attention to the road with the versions of partial automation we tested compared with manual driving that develops with time or is evident relatively early during drivers' initial trips with the automation. The results support arguments for driver-monitoring solutions that ensure adequate attention to the road. Differences among the samples in patterns of behavior change highlight the need to study factors that may further modify how drivers adapt their behavior when using partial automation such as driving exposure, willingness to use automation, and iterations of partial automation that differ in functional performance.

# 1. Introduction

Advanced driver assistance systems (ADAS) have come to represent such a large and evolving collection of crash avoidance or mitigation and driver comfort or convenience technologies that the term is a less useful descriptor than it once was. Design intent helps to classify ADAS and identify human factors concerns that might be expected based on their purpose for being equipped in a vehicle. Vehicles equipped with ADAS for crash avoidance or mitigation repeatedly show significantly lower crash outcomes than their unequipped counterparts whether they warn, intervene, or extend the driver's ability to see at night (Brumbelow, 2022; Cicchino, 2017, 2018a, 2018b, 2019; Highway Loss Data Institute [HLDI], 2023a; Leslie et al., 2021). Current concerns for crash avoidance ADAS include identifying implementations of a specific system that performs well in challenging conditions (e.g., a pedestrian detection system that works in dark conditions) and ensuring drivers keep systems activated (Cicchino, 2022; Insurance Institute for Highway Safety, 2022; Reagan et al., 2018).

In contrast, ADAS designed for comfort and convenience typically seek to alleviate the stress or boredom of driving. While instances of stress and boredom may also impact driving safety, systems may be more frequently designed for, and engaged by, the driver as a matter of convenience rather than a concern for safety. Examples include systems that automate parts of the driving task such as adaptive cruise control (ACC) and lane centering that provide continuous longitudinal and lateral vehicle control, respectively, and partial driving automation, which combines the two. The goal of the current study was to explore relationships between the use of ACC and partial driving automation with visual-manual secondary activity and steering-wheel-holding behavior.

Results from field research suggest that ACC use is associated with increased time headway and lower g-forces when braking relative to manual driving (e.g., Kessler et al., 2012), which aligns with safer driving behavior. However, other findings indicate ACC use is associated with increased secondary activity relative to manual driving (Grove et al., 2019; Reagan et al., 2022; Rudin-Brown & Parker, 2004) that highlight the opposing concern, that driver complacency can reduce driver readiness when hazards emerge that the technology cannot handle.

Researchers have begun to shift focus in recent years from ACC to partial driving automation, so relatively less work has focused on how automating lateral control might influence drivers. However, two early simulator studies suggest that automating the steering task may introduce concerns about driver readiness to resume control; these concerns are related to an attention degradation that is greater than that which has been observed with ACC (Carsten et al., 2012; Young & Stanton, 1997) and is in addition to concerns about response times associated with resuming manual control (Gershon et al., 2023). These findings are of particular importance, given that any implementation of ACC and even the most advanced partial driving automation system designs assume the driver must detect and avoid unexpected objects as well as detect and compensate for system failures. Federal investigations of fatal crashes of vehicles equipped with partial automation indicate that driver inattention when using partial driving automation had a major role in multiple crashes (e.g., National Transportation Safety Board [NTSB], 2017; 2020a; 2020b).

These crash investigation findings align with field research on vehicles equipped with ACC and partial driving automation systems that are instrumented with cameras and other sensors to study behavior change. In addition to the increase in the prevalence of visual-manual secondary activity relative to manual driving noted above with ACC use, naturalistic studies and field operational tests (FOTs) of volunteers driving with partial automation point to significant increases in time spent looking down or inside the vehicle and time spent driving with decreased steering wheel control (Gaspar & Carney, 2019; Ebel et al., 2022; Morando et al., 2021; Reagan et al., 2021).

The current study builds on Reagan et al. (2021), which used data from an FOT where volunteer participants received training on equipped ADAS and then were instructed to drive the study vehicles as they would drive their own vehicles for 4 weeks, using the ADAS at their discretion. That prior research reported an increase in the likelihood of visual-manual driver disengagement, defined as observable visual-manual interaction with in-vehicle or portable electronics or driving with both hands off the steering wheel, when using partial automation relative to manual driving. However, the increase was limited to the last 2 weeks of the data collection period. The results were based on a sample of 10 drivers and were partly accounted for by a large increase in the likelihood of hands-off-wheel behavior, a behavior receiving nominal research interest before the introduction of driving automation. The authors discussed that the increase in disengagement may indicate the development of complacency that builds after drivers become more comfortable using the technology. More highly controlled FOTs using protocols (e.g., routes, automation use) have found similar differences in measures of attentional demand between driving manually and driving with ACC or partial automation that were moderated by exposure to vehicle automation (McDonnell, Crabtree, et al., 2023; McDonnell, Simmons, et al., 2023; Naujoks et al., 2016).

A reality of current research on vehicle technology is the potential for the automation equipped in test vehicles to undergo non-researcher-controlled changes over the life of the vehicle. Automaker-provided software updates can fundamentally alter how ADAS performs, and this presents a challenge as well as an opportunity for researchers. Such updates complicate comparisons of samples of drivers and vehicles, but, if they are documented, there is a chance to study automation use and behavior as a function of design changes. In the current study, two dealer-delivered, unrequested software updates made during the FOT changed the functionality of the lane-centering subsystem and revised warnings displayed in the driver-vehicle interface, prompting the question of whether the changes influenced driver behavior.

In the present work, considerable group differences in driving exposure combined with wide variability in the use of ACC or partial automation across the three samples that became apparent after data collection further motivated us to determine if the behavior observed in Reagan et al. (2021) would be observed among additional samples of drivers. Using the same analytical approach as Reagan et al. (2021), we compared participants' visual-manual secondary activity and hands-off steering wheel behavior when driving with ACC or partial driving automation with manual driving, with comparisons focused on differences in behavior during the first 2 weeks (period 1) and second 2 weeks (period 2) of data collection.

## 2. Method

### 2.1 Vehicles and systems

Two model year 2017 Volvo S90 sedans served as the FOT vehicles. Each was equipped with Volvo's Pilot Assist partial driving automation system that pairs the longitudinal control provided by ACC with continuous lateral control. The owner's manual states that ACC and Pilot Assist are primarily designed to provide more relaxed driving on long trips on highways (the Pilot Assist description adds "other limited-access roads") in an even flow of traffic but are not geofenced (Volvo Cars Corporation, 2017). In Volvo's implementation of the automation, ACC can be activated as a stand-alone system, but the lane-centering feature can only be used with ACC engaged. Although ACC and Pilot Assist provide sustained inputs to control the vehicle, the driver is ultimately responsible for maintaining speed, a safe following distance, and lateral control, and the vehicle owner's manual emphasizes this in multiple places. Pilot Assist was designed with the intent that drivers would primarily keep one or both hands on the steering wheel, and the system issues visual and auditory warnings that instruct the driver to steer when torque sensors on the steering wheel detect that the driver has removed their hands from the wheel for an extended period.

The study vehicles were instrumented with multiple cameras and sensors for recording data on system use and driver behavior. Machine vision determined the system state by viewing video footage of the instrument panel showing status icons. A top-down camera angle was used for recording driver behavior. GPS recorded location and speed.

Each S90 received software updates to the Pilot Assist system in June 2017 and July 2018 during routine maintenance at a Volvo dealership service department. The documentation provided by the dealership verified that the update occurred but provided little detail of what changed as a result. On a test drive after the 2017 update, a researcher with prior experience using Pilot Assist in both S90s noted that the automated steering was engaged more continuously on road sections where it previously became inactive due to system limits (e.g., when passing exits that did not have lane lines, under tunnels, through curves). The July 2018 update included changes to the in-vehicle displays associated with Pilot Assist warnings to return hands to the wheel when the steering-wheel torque sensor detected no hands on the wheel after a period of time. This latter update altered the iconography by adding the image of two hands holding a steering wheel to the visual component that also included the text instruction for the driver to "Apply Steering." The second update also added escalations to confer urgency through color and sound (e.g., the Apply Steering icon changed from amber to red as the warning progressed, and the auditory component of the warning added repeating tones that escalated to pulsing tones as the warning continued, which was not present before the update). The Appendix describes the software updates in more detail.

Volvo representatives indicated that the increased availability of lane-centering support summarized by the researcher was consistent with the automaker's intention to improve the driver experience with the automation. They reported that the updates also included a change to promote driver-in-the-loop behavior by increasing the amount of manual steering input permitted by the system before lane-centering support becomes inactive (Volvo Cars Corporation, personal communication, November 2023).

## 2.2 Participants

Data analysis was based on 29 participants who were recruited from the adult driving population in the greater Boston area in Massachusetts. The initial 20 participants reported commuting 5 days a week with at least 30 minutes of highway driving each way and that they did not own an S90. The criteria for driving exposure was changed to mileage for the final nine participants to a self-reported minimum weekly total of 100 miles of highway driving while commuting 3 to 4 times per week. The unrequested software updates led us to stratify our sample into three groups: group A ($n$ = 10), who participated before either software update; B ($n$ = 10), who participated between the 2017 and 2018 updates; and C ($n$ = 9), who participated after both software updates were completed. Given that a central focus of this work was behavior change across the first and second periods of the study, an additional inclusion criterion was that participants needed to have logged trips in each period. Group C initially included a tenth participant who did not make any trips on limited-access roads in the second study period, and we excluded their data from the analysis.

Data collection for each group occurred from November 2016 to June 2017 (group A), from June 2017 to March 2018 (group B), and from July 2018 to May 2019 (group C). The participants were highly educated (all reported a minimum of some college courses and 17 had taken or completed graduate coursework) and middle-aged ($M_A = 47.0$, $SD = 16.0$; $M_B = 47.3$, $SD = 11.9$, $M_C = 41.7$, $SD = 14.4$) with six males in each group, four females in groups A and B, and three females in group C. Prior to enrolling, most participants (n = 22) indicated they had never driven a vehicle with ACC, three in group A reported having driven a vehicle with ACC a couple times per year, one in group C reported doing so a couple times per week, and three (two in group B, one in group C) reported driving a vehicle with ACC a couple times per day.

## 2.3 Procedure

Participants met with a researcher for an approximately 90-minute one-on-one training session for the assigned vehicle prior to starting the 4-week trial. Training began with an overview of basic settings, displays, controls, instrumentation, and summaries of ADAS equipment while the vehicle was parked and ended with a drive on a limited-access road to ensure all participants experienced ACC and Pilot Assist with a researcher present. The researcher answered questions and verified that all were able to use the automation while driving.

Participants in groups A and B had overviews of ACC and Pilot Assist that were largely from Volvo scripts taken from owner manuals and online videos that emphasized operational design domains and limitations of the automation. This was followed by a training drive where the researcher prompted A and B participants to activate, cancel, and resume ACC and Pilot Assist when they felt comfortable. Participants in group C received overviews of ACC and Pilot Assist that emphasized the potential benefits of using the systems, and a researcher drove and demonstrated using the automation before having the participant drive and demonstrate to the researcher that they could engage, cancel, and resume ACC and

Pilot Assist. Participants began their 4-week trial after the training and demonstration drive, with the instruction to use the research vehicle as they would drive their own vehicle. Participants provided demographic data and completed surveys on their attitudes toward technologies at the start and end of the 4-week trial.

Secondary activities requiring visual-manual resources and driving without manual steering wheel control were the behaviors of interest. Trained analysts coded the prevalence of visual-manual cellphone use, visual-manual interaction with the center stack or steering wheel controls, and traditional visual-manual tasks (i.e., eating, drinking, personal grooming and hygiene, interacting with objects, reading or writing on a non-electronic medium). Eating and drinking, grooming, reaching for an object, and reading or writing on a non-electronic medium were included in the current coding scheme, whereas in Reagan et al. (2021), the prevalence of these traditional visual-manual tasks were grouped with voice-based tasks.

Manual steering wheel control was coded separately from secondary activity, with analysts noting whether participants had both hands off the steering wheel for every moment of the drive. During data screening, unique hands-free driving behavior was observed for one participant in group C who had multiple epochs of driving with no manual steering wheel control for over 20 seconds during manual or ACC-assisted driving (i.e., when automated lane centering was off) and a vehicle speed over 55 mph. A closer inspection of the video of these cases indicated that the participant steered intermittently with their leg throughout each epoch. Given that the original intent of coding steering wheel control was to differentiate moments when a participant was or was not providing human steering input, steering with a leg or knee was coded the same as steering with hands. The coding team noted that low contrast between driver apparel and the vehicle interior combined with the 1-Hz analytical sampling rate (downsampled from 30-Hz video recordings) made it challenging in some video segments to accurately differentiate steering with a knee or leg from driving with no manual control. Despite the anomalous behavior of this one participant, we henceforth use the term "both hands off the wheel" to maintain consistency with Reagan et al. (2021).

Behaviors had to last for at least 500 ms to be coded as occurring. Video with poor resolution (e.g., low light/night conditions) was excluded, and the dataset was further limited to driving that occurred on limited-access roads when the vehicle speed was over 25 mph. The resulting dataset was downsampled at 1 Hz with binary indicators for individual behaviors. The frequencies which coders observed the behaviors for each group of participants are listed in Table 1.

**Table 1**

Percent of time behavior was observed when driving on limited-access roads at speeds over 25 mph

| Behavior | Group A | Group B | Group C |
|---|---|---|---|
| Holding cellphone | 1.9 | 0.8 | 9.0 |
| Handheld cellphone conversation | 0.3 | 1.7 | 0.4 |
| Manipulating cellphone | 1.1 | 0.4 | 0.5 |
| Reaching for cellphone | 0.2 | 0.1 | 0.4 |
| Manual center stack interaction | 1.3 | 1.6 | 1.6 |
| Manual interaction with controls on steering wheel | 0.7 | 0.9 | 2.7 |
| **Subtotal: Visual-manual cellphone or in-vehicle interface use** | **5.4** | **5.5** | **14.4** |
| Eating or drinking | 4.7 | 2.6 | 4.1 |
| Personal grooming and hygiene | 3.0 | 3.0 | 3.4 |
| Interacting with object | 0.3 | 0.7 | 0.8 |
| Reaching for object | 0.2 | 0.1 | 0.2 |
| Reading or writing | 0.0 | 0.0 | 0.3 |
| **Subtotal: Traditional visual-manual tasks** | **8.1** | **6.4** | **8.4** |
| **Total: Visual-manual tasks** | **13.4** | **11.8** | **22.6** |
| Both hands off steering wheel | 0.6 | 0.1 | 0.7 |
| Hands-free voice conversation | 1.4 | 0.3 | 9.4 |
| Voice-based in-vehicle interface | 0.4 | 0.1 | 0.2 |
| Other tasks (e.g., passenger interaction, singing) | 14.8 | 6.4 | 6.5 |

*Note*. Bolded values indicate aggregation across secondary behaviors. Sums of individual values may not equal aggregated totals, as drivers may have engaged in multiple behaviors at once.

## 2.4 Analysis

Prior to the main analysis, logistic regression assessed the odds of driving with the assistance of ACC or Pilot Assist versus driving manually as a function of participant group and study period, with participant included as a repeated measure to control for multiple observations of the same driver.

The main analyses were based on Reagan et al. (2021) and assessed whether participants showed changes in the percentage of time with visual-manual secondary activity or with no manual steering wheel control depending on specific combinations of the following two independent variables: automation mode, which had three levels (manual [no automation], ACC, or Pilot Assist) and study period, which had two (period 1 or 2). Linear combinations of parameter estimates produced from logistic regression models estimated the likelihood of driving with visual-manual distraction or driving with both hands off the wheel across the three automation modes within each study period or a given automation mode as a function of the study period. Specifically, the following seven comparisons were made for each participant group:

1. Driving manually in period 2 relative to period 1.
2. Driving with ACC in period 2 relative to period 1.
3. Driving with Pilot Assist in period 2 relative to period 1.
4. Driving with ACC relative to manual driving in period 1.
5. Driving with ACC relative to manual driving in period 2.
6. Driving with Pilot Assist relative to manual driving in period 1.
7. Driving with Pilot Assist relative to manual driving in period 2.

The comparisons were made for each of the five dependent measures. Cellphone manipulation and driving with both hands off the wheel represent individual behaviors, whereas the other three aggregated across secondary tasks. "Visual-manual use of electronics" combined visual-manual cellphone activity with manual use of the center stack and driver-vehicle interface controls on the steering wheel, and "traditional visual-manual tasks" aggregated eating or drinking, reading or writing, personal grooming, and reaching for an object. "Combined visual-manual activity" aggregated visual-manual interaction with cellphones, vehicle interfaces, and traditional visual-manual tasks. The threshold for statistical significance was a *p* value less than 0.05. Results presented for each comparison represent odds ratios and 95% confidence intervals (CIs) that were converted to indicate the percent change in the odds by subtracting 1 from each odds ratio value and multiplying the difference by 100.

# 3. Results

## 3.1 Driving exposure and automation use by software version and study period

The analytical dataset included a total of 139.9 hours of driving on limited-access roads at speeds over 25 mph across the 29 participants. The machine vision algorithm indicated that participants drove manually (i.e., unassisted by ACC or Pilot Assist) more than three fifths of the time. For less than 1 % (0.7%) of total driving time, Pilot Assist was turned on but was temporarily inactive. Given that the inactive state can result from a driver- or system-initiated event and because it comprised a nominal amount of the data, data points from when the system was on but inactive were removed from further analysis. The resulting dataset included 138.8 hours, and with a mean vehicle speed of 62.1 mph, the data used for the final analysis represent 8,619.5 miles of driving data.

Table 2 shows that group C participants drove more than twice as long overall than those in groups A or B. The table also indicates that each group drove more hours in period 1 than in period 2. Participants spent the majority of time driving manually compared with driving with ACC or Pilot Assist, with automation use in period 1 greater than that in period 2. Also, group C had noticeably more ACC and Pilot Assist use than group A or B. Logistic regression estimated that participants in groups A and B had significantly lower odds of using ACC or Pilot Assist than those in group C ($OR_A$ = 0.76, 95% CI = 0.64 to 0.91; $OR_B$ = 0.72, 95% CI = 0.59 to 0.89). The higher odds of ACC or Pilot Assist use estimated for group A relative to group B was not statistically significant (*OR* = 1.06, 95% CI = 0.87 to 1.28). Participants also had significantly lower odds of using ACC or Pilot Assist in period 2 relative to period 1

(*OR* = 0.90, 95% CI = 0.85 to 0.95), after holding differences in automation use between the subsamples constant.

**Table 2**

Hours of driving exposure by study period, driver group, and automation mode

| | Period 1 | | | Period 2 | | | |
|---|---|---|---|---|---|---|---|
| Group | Manual | ACC | Pilot Assist | Manual | ACC | Pilot Assist | Total[a] |
| A | 15.9 | 2.4 | 1.6 | 13.6 | 0.9 | 1.0 | 35.6 |
| B | 14.6 | 1.3 | 2.4 | 9.2 | 0.8 | 0.6 | 28.9 |
| C | 15.6 | 7.6 | 18.0 | 17.1 | 8.2 | 7.9 | 74.3 |

*Note*. ACC = adaptive cruise control.

[a]Values in the Total column may not match sums of cells in the associated row due to rounding.

Table 3 indicates that the number of individual trips with travel on limited-access roads aligned with the number of hours driven. As examples, group C had the most individual trips, and each group made fewer trips in the second period than in the first period. Across the 29 drivers, the average amount of data associated with a single trip represented 13.0 minutes or 13.3 miles of travel on limited-access roads at speeds over 25 mph.

**Table 3**

Number of trips overall, by driver group and study period

| | Trip count | Median *(SD)* | Range of trips per participant |
|---|---|---|---|
| Group A | | | |
| Period 1 | 107 | 12 (4) | 5–16 |
| Period 2 | 103 | 11 (3) | 6–14 |
| Group B | | | |
| Period 1 | 105 | 11 (5) | 3–16 |
| Period 2 | 66 | 5 (3) | 4–13 |
| Group C | | | |
| Period 1 | 147 | 18 (7) | 7–27 |
| Period 2 | 122 | 13 (6) | 2–22 |
| Overall | | | |
| Period 1 | 359 | 12 (6) | 3–27 |
| Period 2 | 291 | 10 (5) | 2–22 |
| Overall total | 650 | 21 (10) | 8–45 |

## 3.2 Visual-manual distraction and driving with both hands off the wheel

Table 4 displays the percentage of time that participants were coded with visual-manual distractions or as driving hands-free. The percent of time driving with combined visual-manual activity varied from 5.7% to 33.7% across the automation modes, study periods, and participant groups. For groups A and B, combined visual-manual activity in period 1 was more prevalent when driving manually than with Pilot Assist, whereas the reverse was true for period 2. Indeed, group A and B's levels of combined visual-manual activity with Pilot Assist in period 2 were more than 3 times the levels observed with Pilot Assist in period 1. Combined visual-manual activity was most prevalent among participants in group C, with higher percentages for each automation mode within each study period relative to groups A and B. Participants in group C were observed with combined visual-manual activity when using Pilot Assist about one third of the time in both periods, which was about twice as often as compared with driving manually in either period. Within each group and period, the prevalence of the four measures of visual-manual distraction when using ACC was either in between or less than the levels observed for the other automation modes within each study period, with the exception of period 1 among participants in group B.

Table 4 shows a very low prevalence of driving hands-free. The large period-to-period (1,140%) increase in the percentage of time drivers had both hands off the wheel when group A participants drove with Pilot Assist was very different from group B participants who were coded as having all but constant manual contact with the wheel when using the system (99.9% in period 1, 100% in period 2). Group C's hands-off-wheel time when driving with Pilot Assist in period 2 was 33% greater than in period 1.

**Table 4**

Percent of time behavior was observed by participant group, period, and automation mode

| | Period 1 | | | Period 2 | | |
|---|---|---|---|---|---|---|
| | Manual | ACC | Pilot Assist | Manual | ACC | Pilot Assist |
| Group A | | | | | | |
| Combined VM activity | 12.1 | 7.6 | 5.7 | 16.8 | 9.8 | 18.8 |
| VM cellphone or vehicle interface use | 4.2 | 6.1 | 4.3 | 6.4 | 5.0 | 9.5 |
| Traditional VM tasks | 7.9 | 1.5 | 1.5 | 10.5 | 4.8 | 9.2 |
| Cellphone manipulation | 0.3 | 0.1 | 1.3 | 1.7 | 1.1 | 6.3 |
| Both hands off wheel | 0.3 | 0.6 | 0.5 | 0.6 | 0.2 | 6.2 |
| Group B | | | | | | |
| Combined VM activity | 12.8 | 14.7 | 7.4 | 9.6 | 16.3 | 24.7 |
| VM cellphone or vehicle interface use | 6.7 | 8.8 | 6.7 | 3.2 | 2.9 | 1.3 |
| Traditional VM tasks | 6.2 | 6.2 | 1.1 | 6.4 | 13.9 | 24.0 |
| Cellphone manipulation | 0.4 | 1.8 | 0.6 | 0.3 | 0.0 | 0.0 |
| Both hands off wheel | 0.1 | 1.3 | 0.1 | 0.1 | 0.1 | 0.0 |
| Group C | | | | | | |
| Combined VM activity | 15.2 | 18.7 | 31.8 | 18.7 | 17.9 | 33.7 |
| VM cellphone or vehicle interface use | 7.7 | 11.1 | 24.2 | 8.5 | 8.5 | 27.6 |
| Traditional VM tasks | 7.6 | 7.7 | 7.8 | 10.3 | 9.5 | 6.6 |
| Cellphone manipulation | 0.4 | 0.2 | 0.8 | 0.7 | 0.1 | 0.4 |
| Both hands off wheel | 0.1 | 0.1 | 1.5 | 0.1 | 0.3 | 2.0 |

*Note*. ACC = adaptive cruise control; VM = visual-manual.

Table 5 presents the average length of time of a single epoch for each dependent measure broken out across participant group, study period, and automation mode. The length of each instance of the behavior was estimated by summing consecutive data points from the start to end of each event. Limiting analysis to driving over 25 mph introduced a challenge associated with the intermittent occurrence of driving speeds fluctuating above and below the 25-mph cutoff coupled with ongoing secondary activity. To address this, we created a buffer such that if vehicle speed went below 25 mph for 2 seconds or less then we would treat the data as if speed stayed above 25 mph, but ended the epoch if speed remained below 25 mph for longer than 2 seconds.

Overall, the patterns of mean epoch length aligned with the proportions in Table 4. For example, mean epoch lengths associated with combined visual-manual activity among group A and B when driving manually in period 1 ($M_A$ = 16.9 seconds, $M_B$ = 14.1 seconds) were longer relative to Pilot Assist use during the same period ($M_A$ = 8.6 seconds, $M_B$ = 5.9 seconds), but the reverse was evident in period 2 with longer visual-manual tasks in Pilot Assist mode ($M_A$ = 15.9 seconds, $M_B$ = 20.3 seconds) than during manual driving ($M_A$ = 13.9 seconds, $M_B$ = 11.1 seconds). However, among group C, the mean length of combined visual-manual-activity epochs were longer when using Pilot Assist compared with driving manually in both periods. The average length of an epoch of driving with both hands off the wheel when using Pilot Assist in period 2 relative to period 1 doubled for participants in group A from 5.4 to 11.1 seconds but was slightly shorter for drivers in group C (4.1 vs. 3.8 seconds). Within each participant group, epochs of combined visual-manual activity associated with ACC use tended to be shorter than or fall between epoch durations associated with driving manually or with Pilot Assist.

**Table 5**

Mean (SD) epoch duration (seconds) of visual-manual distractions or driving with both hands off wheel

| | Period 1 | | | Period 2 | | |
|---|---|---|---|---|---|---|
| | Manual | ACC | Pilot Assist | Manual | ACC | Pilot Assist |
| Group A | | | | | | |
| Combined VM activity | 16.9 (42.5) | 10.9 (20.1) | 8.6 (14.1) | 13.9 (31.4) | 9.8 (12.5) | 15.9 (21.4) |
| VM cellphone or vehicle interface use | 12.3 (25.6) | 16.3 (26.2) | 13.8 (19.6) | 12.2 (18.6) | 14.1 (17.2) | 13.3 (20.6) |
| Traditional VM tasks | 19.7 (51.6) | 4.3 (2.8) | 4.0 (2.4) | 13.8 (36.8) | 7.1 (8.4) | 19.8 (22.6) |
| Cellphone manipulation | 7.1 (8.5) | 2.4 (1.1) | 37.5 (24.7) | 16.1 (16.5) | 7.2 (11.6) | 32.9 (29.3) |
| Both hands off wheel | 1.7 (1.0) | 3.8 (5.3) | 5.4 (3.2) | 2.2 (1.4) | 1.5 (0.6) | 11.1 (21.2) |
| Group B | | | | | | |
| Combined VM activity | 14.1 (35.4) | 8.7 (15.0) | 5.9 (9.1) | 11.1 (25.0) | 11.5 (35.9) | 20.3 (56.1) |
| VM cellphone or vehicle interface use | 16.6 (48.2) | 9.7 (13.1) | 6.6 (9.9) | 9.4 (15.8) | 4.8 (3.5) | 4.8 (3.3) |
| Traditional VM tasks | 11.3 (19.2) | 6.1 (8.5) | 3.1 (4.3) | 11.8 (29.0) | 14.0 (42.8) | 22.2 (59.4) |
| Cellphone manipulation | 12.7 (16.7) | 20.8 (24.2) | 7.3 (6.2) | 12.5 (14.9) | — | — |
| Both hands off wheel | 2.0 (0.9) | 5.2 (4.1) | 2.0 (0) | 1.8 (0.6) | 2.0 (—) | — |
| Group C | | | | | | |
| Combined VM activity | 9.9 (36.5) | 9.7 (33.4) | 19.0 (56.5) | 13.2 (50.7) | 8.5 (23.7) | 17.7 (52.8) |
| VM cellphone or vehicle interface use | 9.3 (19.5) | 8.7 (14.3) | 23.7 (66.6) | 11.5 (35.9) | 7.2 (18.8) | 24.2 (64.1) |
| Traditional VM tasks | 10.1 (47.7) | 10.3 (49.9) | 9.6 (29.9) | 13.2 (58.5) | 9.3 (26.3) | 6.5 (22.3) |
| Cellphone manipulation | 15.5 (12.1) | 9.0 (7.2) | 20.2 (17.7) | 9.5 (13.2) | 25.0 (—) | 14.7 (8.6) |
| Both hands off wheel | 1.9 (1.0) | 3.0 (2.3) | 4.1 (4.6) | 1.8 (1.0) | 7.7 (13.4) | 3.8 (5.1) |

*Note*. ACC = adaptive cruise control; VM = visual-manual.

A dash in place of a mean value indicates no cases of the behavior or a single case of the behavior in place of the standard deviation.

## 3.3 Modeling the odds for visual-manual distraction and driving with both hands off the wheel

***3.3.1 Pilot Assist.*** Table 6 provides odds ratios and 95% CIs that resulted from modeling the association between automation mode and study period on visual-manual distractions or driving with both hands off the wheel for the three participant groups. Among groups A and B, there was a similar relationship between study period and the odds of conducting a visual-manual activity or driving with both hands off the wheel when driving with Pilot Assist relative to manual driving. During period 1, Pilot Assist was associated with lower odds of most measures of visual-manual distraction compared with manual driving, although only the −54% (group A) and −73% (group B) lower odds of traditional visual-manual tasks were significant. Participants in group A did have higher odds of cellphone manipulation and driving without steering associated with Pilot Assist use relative to manual driving in period 1, but only the 278% increase in the odds of driving with both hands off the wheel was significant. In period 2, Pilot Assist was associated with significant increases in the odds of traditional visual-manual tasks (36%), cellphone manipulation (235%), and driving with both hands off the wheel (1,639%) among group A and of combined visual-manual activity (232%) and traditional visual-manual tasks (485%) among group B.

Group C's results were characterized by higher odds of most measures of visual-manual distraction and driving with both hands off the wheel when driving with Pilot Assist compared with manual driving in both study periods, but differences were most pronounced in period 1. Specifically, Pilot Assist use in period 1 was linked to higher odds than manual driving across the five outcome measures, with significant increases of 125%, 100%, 64%, and 1,030% for combined visual-manual activity, traditional visual-manual tasks, cellphone manipulation, and driving with both hands off the wheel, respectively. In period 2, Pilot Assist use for group C was associated with higher odds of combined visual-manual activity, visual-manual use of electronics, and driving with both hands off the wheel relative to driving manually, but only the 744% increase for driving with both hands off the wheel was significant. These results coincided with slightly lower odds of traditional visual-manual tasks (−6%) and cellphone manipulation (−1%) relative to manual driving that were not significant.

For groups A and B, there were higher odds of measures of visual-manual distraction or driving with both hands off the wheel in period 2 relative to period 1 with Pilot Assist that were greater in magnitude than changes in manual or ACC modes. In group A, the use of Pilot Assist in period 2 was associated with higher odds for each outcome measure, but only the higher odds of traditional visual-manual tasks (356%) and driving with both hands off the wheel (855%) were significant, yet each of the odds ratios were greater than the parallel estimates for manual or ACC-assisted driving. For group B, the significantly higher odds of combined visual-manual activity (337%) associated with Pilot Assist driving in period 2 relative to period 1 was likely due to the significantly higher odds of traditional visual-manual tasks (2,270%), as there were significantly lower odds of visual-manual activity with electronics (−60%) when using Pilot Assist in period 2. Group C participants had significantly higher odds of each measure of visual-manual distraction and driving with both hands off the wheel during manual driving in period 2 relative to period 1, whereas the odds of the measures of visual-manual distraction or driving with both hands off the wheel associated with Pilot Assist use in period 2 did not change significantly compared with period 1.

***3.3.2 ACC.*** Within each group, period 2 ACC use was associated with higher odds of combined visual-manual activity and traditional visual-manual tasks compared with period 1, although only the higher odds of traditional visual-manual tasks were significant across samples. Period 2 ACC use was also associated with lower odds of visual-manual use of electronics among each participant group, although only the reductions estimated for groups B (−29%) and C (−42%) were significant. Among group A participants, there were significantly higher odds of cellphone manipulation (495%) when using ACC in period 2 compared with period 1, but there were lower odds of cellphone manipulation when using ACC relative to manual driving in both periods, although the comparisons were not significant. Among group C participants, the odds of cellphone manipulation with ACC in period 2 were −20% lower than in period 1, and relative to manual driving, the odds of cellphone manipulation with ACC use were 9% higher in period 1 and −37% lower in period 2, but the comparisons were not significant.

Regarding manual steering wheel control, participants in group A had significantly higher odds of driving with both hands off the wheel when using ACC relative to manual driving during period 1 but lower odds during period 2. These changes reflect the lower odds of driving with both hands off the wheel with ACC in period 2 relative to period 1 but significantly higher odds when driving manually. The higher odds of driving with both hands off the wheel when participants in group C used ACC in period 2 relative to ACC use in period 1 or manual driving in period 2 were not significant. Inspecting the data at the participant level indicated that the results for group C were driven by the participant with the anomalous steering behavior, who accounted for 87% of the hands-free behavior when ACC was used in period 2.

**Table 6**

Odds ratios (95% confidence intervals) associated with visual-manual distraction or driving with both hands off the wheel by study period and driving mode

| | Combined VM activity | VM use of electronics | Traditional VM tasks | Cellphone manipulation | Both hands off steering wheel |
|---|---|---|---|---|---|
| Group A | | | | | |
| Period 2 vs. 1, manual | **1.39 (1.04, 1.85)** | 1.14 (0.67, 1.93) | **1.55 (1.08, 2.23)** | **3.96 (2.81, 5.57)** | **2.07 (1.09, 3.97)** |
| Period 2 vs. 1, ACC | 1.15 (0.90, 1.46) | 0.70 (0.30,1.61) | **1.79 (1.39, 2.30)** | **5.95 (1.75, 20.3)** | 0.27 (0.03, 2.42) |
| Period 2 vs. 1 Pilot Assist | 3.28 (0.96, 11.2) | 2.16 (0.17, 27.8) | **4.56 (2.32, 8.96)** | 6.57 (0.04, 1065.0) | **9.55 (2.73, 33.4)** |
| ACC vs manual, Period 1 | **0.73 (0.58, 0.92)** | **0.67 (0.54, 0.84)** | 0.82 (0.61, 1.11) | 0.43 (0.15, 1.22) | **2.35 (1.49, 3.68)** |
| ACC vs manual, Period 2 | **0.60 (0.46, 0.79)** | 0.41 (0.16, 1.06) | 0.95 (0.74, 1.22) | 0.65 (0.12, 3.62) | 0.30 (0.03, 3.19) |
| Pilot Assist vs. manual, Period 1 | 0.51 (0.17, 1.51) | 0.55 (0.11, 2.65) | **0.46 (0.23, 0.92)** | 2.02 (0.02, 167.7) | **3.78 (1.40, 10.2)** |
| Pilot Assist vs. manual, Period 2 | 1.21 (0.84, 1.76) | 1.04 (0.41, 2.63) | **1.36 (1.00, 1.85)** | **3.35 (1.54, 7.28)** | **17.4 (3.44, 87.9)** |
| Group B | | | | | |
| Period 2 vs. 1, manual | 0.87 (0.59, 1.30) | 0.68 (0.44, 1.04) | 1.11 (0.55, 2.22) | | |
| Period 2 vs. 1, ACC | 1.75 (0.91, 3.37) | **0.71 (0.55, 0.93)** | **2.65 (1.00, 7.04)** | | |
| Period 2 vs. 1 Pilot Assist | **4.37 (1.20, 15.8)** | **0.40 (0.29, 0.56)** | **23.67 (7.18, 78.0)** | | |
| ACC vs manual, Period 1 | 1.00 (0.51, 1.95) | 0.86 (0.39, 1.91) | 1.31 (0.73, 2.34) | | |
| ACC vs manual, Period 2 | **2.01 (1.62, 2.50)** | 0.91 (0.51, 1.62) | **3.13 (2.15, 4.55)** | | |
| Pilot Assist vs. manual, Period 1 | 0.66 (0.26, 1.70) | 1.00 (0.31, 3.17) | **0.27 (0.18, 0.42)** | | |
| Pilot Assist vs. manual, Period 2 | **3.32 (2.03, 5.45)** | 0.59 (0.30, 1.16) | **5.85 (2.99, 11.4)** | | |
| Group C | | | | | |
| Period 2 vs. 1, manual | **1.53 (1.26, 1.86)** | **1.28 (1.03, 1.59)** | **1.75 (1.29, 2.38)** | 1.39 (0.99, 1.96) | **1.55 (1.09, 2.22)** |
| Period 2 vs. 1, ACC | 1.15 (0.64, 2.04) | **0.58 (0.37, 0.90)** | **2.64 (1.31, 5.29)** | 0.80 (0.45, 1.44) | 2.62 (0.10, 70.3) |
| Period 2 vs. 1 Pilot Assist | 0.91 (0.69, 1.21) | 0.98 (0.78, 1.24) | 0.82 (0.57, 1.19) | 0.84 (0.67, 1.04) | 1.16 (0.26, 5.14) |
| ACC vs manual, Period 1 | **1.23 (1.11, 1.37)** | **1.41 (1.16, 1.73)** | 0.97 (0.65, 1.44) | 1.09 (0.86, 1.38) | 1.00 (0.61, 1.67) |
| ACC vs manual, Period 2 | 0.92 (0.58, 1.47) | 0.64 (0.41, 1.00) | 1.46 (0.84, 2.52) | 0.63 (0.32, 1.22) | 1.70 (0.12, 23.5) |
| Pilot Assist vs. manual, Period 1 | **2.25 (1.10, 4.58)** | 2.01 (0.83, 4.84) | **2.00 (1.22, 3.29)** | **1.64 (1.08, 2.49)** | **11.3 (5.52, 23.2)** |
| Pilot Assist vs. manual, Period 2 | 1.34 (0.69, 2.59) | 1.54 (0.59, 4.01) | 0.94 (0.65, 1.35) | 0.99 (0.80, 1.22) | **8.44 (2.55, 27.0)** |

*Note*. ACC = adaptive cruise control; VM = visual-manual. Statistically significant effects are bolded.

The blank cells indicate that the SAS GENMOD procedure experienced estimation errors in generating model results due to low prevalence of behavior across experimental conditions.

# 4. Discussion

## 4.1 Summary

The current field test study found that over 4 weeks, three samples of adult drivers developed different patterns of behavior associated with using the Pilot Assist partial driving automation system despite driving in the same metropolitan area, sharing demographic characteristics, and using research-institute-owned 2017 Volvo S90s in lieu of their own vehicles. Changes in Pilot Assist software that enhanced key operating characteristics of the assistance system likely influenced the observed behaviors, despite potential confounds such as sample-wide differences in driving exposure. These results provide a clear illustration of the complexities involved in studying ADAS where dealer-installed or over-the-air software updates change underlying operating characteristics or interface elements over the lifetime of the vehicle.

Building on Reagan et al. (2021), which analyzed an earlier version of group A's data, samples in the current study had higher odds of visual-manual distraction or driving with both hands off the wheel when using Pilot Assist relative to manual driving that was either apparent throughout the 4 weeks of data collection (i.e., group C) or primarily limited to the second period of the study that considered the last 2 weeks (groups A and B). Our findings suggest that driver disengagement when using partial automation is greater than when driving without it, with differences evident despite software updates that changed system characteristics and wide variation in the samples' commuting patterns and propensity to use automation.

The current dataset was limited to driving on limited-access roads, which accounts for about a third of miles traveled in the United States (Federal Highway Administration, 2023). With this in mind, group C's driving exposure was double that of A or B **and** the group had significantly higher odds of using ACC and Pilot Assist compared with the other samples. Several factors may have contributed to differences in automation use including the software updates that affected Pilot Assist, although the pattern of disuse among group B, which drove the S90s after the initial update described in the *Method* section, was strong enough to suggest that a specific software update had little influence on automation use. Changes to the participant training and participant recruitment criteria may also have influenced the propensity to use automation or engage in secondary activity. Isolating the variance in automation use attributed to these various factors would require data collection beyond the scope of the current study. It is important to note that the influence of automation on safety, regardless of its directionality, will be limited to where and how much it is used and so will be most heavily weighted by those who commute and use ADAS similarly to participants in group C.

## 4.2 Behavior change across study periods, partial automation versus manual driving

Regarding the relationship between partial automation use and driver attention, Reagan et al. (2021) concluded that increased driver disengagement that was limited to Pilot Assist use in period 2 reflected a reallocation of attentional resources away from the driving task. This was characterized as a behavior that occurred only after the drivers used automation enough to develop trust, and differences in behavior with versus without the automation were likely accentuated by the subset of drivers who used the automation cautiously before making a value judgment about it and ultimately deciding on disuse. In the current study, despite group B's low exposure and use of automation, the sample's pattern of behavior change with Pilot Assist use from periods 1 to 2 supports the conclusion by Reagan et al. However, the prevalence of combined visual-manual activity when group C used Pilot Assist in period 1, which was twice as common compared with their manual driving in period 1, was 4 to 5 times more frequent than it was when group A or B drove with Pilot Assist in period 1. This suggests that partial automation may compel more immediate behavioral adaptations for some drivers.

The pattern of results among groups A and B were consistent with McDonnell, Crabtree, et al. (2023) who found that drivers naïve to partial automation exhibited comparable levels of workload when driving manually or with the system engaged on test drives immediately after an introduction to the vehicle and system. McDonnell, Simmons, et al. (2023) retested the same participants on the same routes after they drove the study vehicles on open roads as their own for a 6-week period and saw differences in workload depending on their use of partial automation and the complexity of the interstates they drove on. In contrast to our current findings of increased secondary activity that implies workload reductions, McDonnell and colleagues reported a higher workload with partial automation after exposure relative to manual driving. The authors saw that workload with partial automation was lower on the post-familiarization drive than the initial test drive but only on the low-complexity interstate.

The higher level of visual-manual distraction observed when group C in the current study used Pilot Assist was even less consistent with the higher workload with partial automation finding reported by McDonnell, Simmons, et al. (2023). The workload reduction associated with low-complexity interstate driving reported by McDonnell, Simmons, et al. and the increased secondary-task involvement observed when drivers with prior ACC experience drove with partial automation reported by Naujoks et al. (2016) may point to different levels of spare attentional capacity for drivers with high exposure to interstate driving compared with those who drive on interstates infrequently. We echo the call by Naujoks and colleagues for research to identify factors such as route familiarity or previous exposure to ADAS that may moderate how behavior adapts to automation use over time.

The higher odds of secondary activity or driving with both hands off the wheel associated with Pilot Assist use occurred with noteworthy between-group variability for specific behaviors. Groups A and C manifested behavior change through higher odds of driving hands-free with Pilot Assist relative to manual control. The increase in the odds of cellphone manipulation associated with group A’s Pilot Assist use during period 2, which was concerning given the elevated crash risk associated with visual-manual phone behaviors (e.g., Dingus et al., 2016; Guo et al. 2017; Kidd & McCartt, 2015), was not observed among the B and C samples. Indeed, cellphone manipulation was noticeably less prevalent overall among B or C participants. The government of Massachusetts enacted a statewide ban on handheld cellphone use in 2019 that took effect in 2020. The legislation became effective after data collection finished, but media reports of earlier efforts may have influenced the cellphone use of groups B and C (e.g., Suntrup, 2017).

In contrast to groups A and C, group B participants rarely drove hands-free when using Pilot Assist but showed adaption to the automation in the 22-times higher odds of conducting traditional tasks like grooming or eating when using Pilot Assist in period 2 compared with period 1. This change coincided with significantly lower odds of visual-manual use of electronics among the group. The diverging changes in behavior may reflect low driving exposure and automation use or factors such as risk perception and mitigation.

The increases in measures of visual-manual distraction and driving with both hands off the wheel associated with each group's Pilot Assist use supports concerns about driver readiness to detect and respond to hazardous events that emerge during trips. Although the crash risk associated with some individual behaviors included in our measures is unclear, visual-manual inattention has been repeatedly shown to increase crash risk during manual driving (Dingus et al., 2016). Drivers tend to engage in visual-manual activity when they detect the absence of looming threats, but the longer they look away from the forward road, the more likely it becomes that a crash threat emerges that they fail to detect (Victor et al., 2014). Schwarz et al. (2023) recently illustrated drivers' propensity to fall out of the loop when using partial automation by engaging in visual-manual secondary activity and then failing to recover from an unexpected failure despite instructions to remain vigilant for such an occurrence. Combined with the well-publicized crashes pointing to driver inattention with the use of partial driving automation, this work provides additional evidence on the need to deploy safeguards with partial automation to ensure drivers attend to the road (Mueller et al., 2021).

Driving without holding the steering wheel is a new phenomenon afforded by lane-centering automation. The increased odds of driving with both hands off the wheel among groups A and C in periods 1 and 2 are curious when considered together with the average durations of individual epochs of driving with both hands off the wheel (Table 5). Among group A, mean hands-free epoch length with Pilot Assist during period 2 (11.1 seconds) was twice as long as period 1 (5.4 seconds) but there was little difference in mean duration across the periods (4.1 seconds vs. 3.8 seconds) when group C participants used Pilot Assist. It is likely that the software updates contributed to these patterns. Volvo representatives believe that the shorter hands-off-wheel epochs among group C participants would be consistent with design expectations, given that the updates allowed more manual steering input while maintaining automated lane centering, and given that the increased saliency of the revised hands-on-wheel reminder from the second update was clearly intended to promote manual steering. The safety relevance associated with the increase in hands-free driving is unknown.

Reagan et al. (2021) noted the prevalence of hands-free driving with a system designated as "hands-on" was concerning. Observations of increased hands-free driving with hands-on systems in the current study, as well as in Morando et al. (2021) in Tesla vehicles and in the qualitative work of Nordhoff et al. (2023), suggest that this observation of use beyond the design intent extends across different samples of volunteers borrowing research vehicles to samples of vehicle owners driving hands-on systems implemented by other automakers. Indeed, Morando and colleagues observed a much higher proportion of hands-free driving than the current work, and Nordhoff et al.'s summaries of interviews of Tesla owners about their experience with Autopilot or Full Self-Driving indicate that some of the misuse associated with hands-free driving includes blatant violations of safe use, such as defeating sensors to avoid alerts to steer manually. The co-occurrence of increased odds of hands-off-wheel behavior and secondary activity in the current study strengthens the case for deploying partial automation with safeguards that ensure drivers are effectively supported and positioned to respond to critical events when needed. Combining proactive (cooperative steering) and reactive countermeasures (multimodal attention reminders that are triggered by monitoring of eyes and hands) may be an effective strategy, given that partial automation functionality assumes considerable involvement by the human operator (see Campbell et al., 2016; Mulder et al., 2012). Future research may also benefit from deeper insight into the role of feature lockouts and other punitive measures on driver engagement.

## 4.3 Behavior change across study periods, ACC versus manual driving

In the current study, results associated with ACC indicate participants' adaptation across the two study periods was more modest than that observed with the partial automation and the directionality was inconsistent. For example, the most concerning finding regarding ACC is likely the significantly higher odds of cellphone manipulation in period 2 relative to period 1 for group A, although ACC was tied to lower odds of manipulation than manual driving. Similarly, there were significantly higher odds of traditional visual-manual tasks associated with ACC use in period 2 relative to period 1 for each group, with odds ratios higher than manual driving but lower than Pilot Assist.

The higher odds ratios of driving with both hands off the wheel estimated for group C's ACC use in period 2 were driven by one participant. This case of behavior is noteworthy given its occurrence in a vehicle with automated lane centering. The prevalence of this type of steering with ACC use and manual driving is not well known, but its occurrence in the current FOT illustrates the utility of reporting steering wheel behavior in manual and ACC modes for comparison's sake (see Reagan et al., 2022).

## 4.4 Conclusion

Partial driving automation systems in consumer vehicles emerged nearly a decade ago amid enthusiasm about the predicted imminent availability of vehicle automation that would be a panacea for crashes due to human error. Presently, technological hurdles have limited the deployment of highly automated vehicles to pilots of driverless ride-hailing services and commercial trucking. Embarrassing and sometimes fatal automation failures associated with test or consumer vehicles have garnered significant media attention and coincided with increased skepticism toward automation from consumers (Lee et al. 2021; Othman, 2023) and scrutiny by regulators (National Highway Traffic Safety Administration, 2023).

Despite these developments, it is unclear whether drivers are safer when using partial driving automation compared with driving manually. Fatal crash investigations involving partial automation are not representative of all equipped vehicles, and the potential for disuse does not imply a guaranteed increase in crash risk. The lack of clarity about the net effects on safety also partly reflects that only about 4% of registered vehicles in the United States in 2022 were estimated to be equipped with ACC and lane centering (Highway Loss Data Institute, 2023b). All things being equal, conducting a visual-manual secondary activity when supported with ACC and lane centering should be safer, but it remains to be demonstrated and is potentially countered by the evidence of misuse. Ultimately, the safety of this technology will largely depend on whether support for inattention outweighs the risk that drivers will increase their secondary activities because they perceive they are being supported.

Ensuring the safe deployment of partial automation will be complicated by the pacing of technological advancements, as exemplified by the software updates documented in the current study. Similarly, implementations of partial automation that change lanes or navigate intersections with traffic control devices are already available to consumers. These advanced features may introduce a different set of safety concerns than those about the systems that more closely meet the operational definition of partial automation (SAE International, 2021). As illustrated in the interviews by Nordhoff et al. (2023) and the survey work of Mueller et al. (2023), near-term concerns with automation range from implementing immature systems in a consumer vehicle that subsequently fail at critical moments to issues associated with overtrusting highly reliable but imperfect automation, and the potential for misuse appears to extend across different automakers' implementations but at significantly different levels.

Providing functionality with partial automation that goes beyond SAE International's definition seems to exemplify the term "oxymoron," but it reflects gaps in the current regulatory framework. Test programs that rate systems based on how well they ensure appropriate driver use of automation and attention to driving may help to limit human factors errors with partial automation in the absence of regulations, while encouraging manufactures to implement potentially better safeguards that aim to advance both the convenience and safety benefits of partial automation. Continuing to collect data and conduct analyses similar to those in the current effort can inform whether changes implemented to improve systems are occurring. In that vein, data from the current study can serve as a benchmark for a less-refined version of the automation.

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# 7. Appendix

## 7.1 June 2017 software update

The following details were provided by a researcher who was experienced driving both of the study vehicles (2017 Volvo S90 sedans) before and after the June 2017 software update.

- The Pilot Assist icon (a steering wheel) that is green when actively providing support and gray when turned on but temporarily inactive appears brighter in both active and inactive states.
- The sequence for hands-on-wheel warnings is the same as it was before the update but may possibly be reduced.
- After the update, the S90s were driven on an approximate 60-mile route on limited-access roads where they had been driven frequently before the update, where Pilot Assist was known to become inactive due to conditions such as poor lane markings, low-light conditions (e.g., tunnels), and sharp curves, and Pilot Assist was available nearly continuously on an approximate 60-mile drive on limited-access roads.

## 7.2 July 2018 software update

The July 2018 software update that included the change to the "Apply Steering" icon was consistent with online documentation from Volvo Cars for owners about a global update issued in May 2018.

The following link for Volvo owners residing in the U.S. describes the post-update changes only:

https://volvo.custhelp.com/app/answers/detail/a_id/10141/

The following table summarizes differences before and after the update and was adapted from the following link for Volvo owners residing in Canada:

https://www.volvocars.com/en-ca/support/topics/article/72f5da56962e016cc0a8015108ed6a92

**Differences before and after the 2018 Volvo S90 software update for Volvo owners residing in Canada**

| Updated feature | Before update | After update |
|---|---|---|
| Appearance and sound for messages stating that Pilot Assist use requires hands on the steering wheel. | 1. Pilot Assist icon lights orange in the driver display with a text message asserting the driver must steer.<br>2. If the driver does not steer, the message remains and a warning signal sounds.<br>3. If the driver still does not steer, a sustained signal sounds, Pilot Assist turns off, and the message stating the driver must steer remains. | 1. An orange icon depicting **two hands holding a steering wheel** lights in the driver display with a message that prompts the driver to actively steer.<br>2. If the driver does not steer, the icon turns red and a warning signal sounds and is repeated.<br>3. If the driver still does not steer, the icon turns red, a warning signal sounds and is repeated.<br>4. If the driver still does not steer, more sustained warning sounds are issued in short pulses over a period, Pilot Assist switches off, and a text message stating it has been canceled appears with the red icon in the driver display. |