DRIVERS' RESPONSE TO AUTOMATION INITIATED DISENGAGEMENT IN REAL-WORLD HANDS-FREE DRIVING

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ABSTRACT

Driving automation features in the form of advanced driver assistance systems (ADAS) that can control the longitudinal and lateral vehicle kinematics on sustained bases (SAE Level2) are becoming increasingly available in consumer vehicles, making the study of drivers' behavioral adaptation and the impacts of automation central to driving safety. This study used real-world data to assess drivers' responses to automation-initiated disengagements by quantifying changes in drivers' moment-to-moment visual attention and vehicle control behaviors.

Fourteen drivers (36% female) drove for one-month each a Cadillac CT6 equipped with a data acquisition system that recorded driving kinematics, miles driven, automation use, GPS, and video of the driver and driving environment. Cadillac's Super-Cruise (SC) is one of the most advanced, commercially available partial automation systems that, when engaged, enables hands-free driving while directly monitoring the driver's head orientation.

A total of 265 SC initiated disengagement events were identified (mean=18.9; SD=16.5 per driver) across 5,514 miles driven with SC. In general, SC initiated disengagements were associated with substantial changes in glance distribution. Immediately after disengagement, the proportion of glances to the Road decreased from 83% to 68% and at the same time the proportion of glances to the Instrument Cluster increased substantially, from 8% to 27%. The period following SC initiated disengagement was also characterized by a 44% increase in the overall number of transitions between glance areas (from 845 transitions before to 1218 after the disengagement across events). The most dominant visual attention patterns after SC disengagements were Road to Instrument Cluster (57% increase) and Instrument Cluster to Road (222% increase). Linear quantile mixed-effects models were used to estimate glance duration before and after disengagements. Findings indicate that on-road glance duration following SC disengagement decreased significantly and was 4.86sec shorter in the 85th quantile ($Q15_{Before}$=0.5, CI=[0-2.24], $Q15_{After}$=0.43, CI=[0-2.11], *p*=.04; $Q50_{Before}$=2.02, CI=[0.8-3.24], $Q50_{After}$=1.45, CI=[1.02-1.88], *p*=ns; $Q85_{Before}$=6.63, CI=[2.06-11.2] to $Q85_{After}$=1.77, CI=[0-3.67], *p*<.001). Analysis of driver hands on-wheel behavior indicate that drivers adopted SC's hands-free feature to a substantial degree, taking both hands off the steering wheel more than 75% of the time SC was engaged. Takeover duration when driving hands-free was significantly longer (2.4sec) compared to driving with at least one hand on the steering wheel (1.8sec).

In conclusion, concerns over the phenomenon of driver out-of-the-loop, coupled with known limitations of partial automation systems, have led research to focus on driver response to automation-initiated disengagement and the ability to regain manual control. We find that real-world automation-initiated disengagements trigger substantial changes in driver glance behavior including shorter on-road glances and frequent transitions between the Road and the Instrument Cluster glance areas. This behavior pattern likely represents drivers' searching for information related to the disengagement or the automation state and may be shaped by the automation design. Higher levels of automation may introduce more substantial changes in visual and vehicle control behaviors during automation initiated-disengagements. This data provides useful information to designers charged with developing assistive and automated systems and empowers regulators and safety advocates with insights needed to better guide appropriate utilization of ADAS technologies.

INTRODUCTION

Driving automation features in the form of advanced driver assistance systems (ADAS) are becoming increasingly available in consumer vehicles, making the study of drivers' behavioral adaptation and the impacts of automation central to driving safety. The Society of Automotive Engineers (SAE) defines a taxonomy of six automation levels, ranging from manual driving (i.e., SAE Level 0 - no driving automation) to fully self-driving vehicle under all conditions (i.e., SAE Level 5 - full automation) [1]. Partial automation systems (SAE Level 2) currently available in consumer vehicles can simultaneously control the longitudinal (e.g., adaptive cruise control) and lateral (e.g., lane centering) elements of the dynamic driving task on a sustained basis. When using partial automation, the driver delegates elements of operational control of the dynamic driving task over to the automation, while remaining responsible for monitoring, preforming object and event detection, and responding when needed. Essentially, with partial automation systems, driving has become a collaboration between driver and automation, where drivers are expected to maintain attention to events on the roadway and be ready to regain control of the vehicle at all times [2-4]. One such commercially available partial automation system is Cadillac CT6's Super Cruise (hereafter SC) which is a geofenced system that can be used only on mapped limited-access highways. When engaged, SC enables legs-free and hands-free driving while continuously monitoring the driver's visual attention using a camera-based Driver Monitoring System (DMS). Leveraging driver head-pose data derived from the DMS, SC supervises driver attention to the road through a series of escalating alerts designed to work in cohesion with features of the ADAS. SC and other partial automation systems have been associated with reports of increased driver comfort and reduced driving demand; however, the safety benefits of such systems are still debated as there is a potential for over-reliance [3, 5].

As driving demands are lowered by automation and the driver's role pivots toward monitoring, a task in which humans inherently underperform, drivers are more likely to experience challenges to maintain sufficient attention to the driving task and increased propensity for phenomena like driver out-of-the-loop (OOTL), cognitive underload, mode confusion, and distracted driving [6-8]. These concerns over driver inattention, coupled with known limitations of partial automation have led research to focus on time-critical, system-initiated disengagements where the automation issues an immediate takeover request and drivers are required to takeover either the lateral (steering) or both lateral and longitudinal (steering and speed) control [7-8]. The growing body of research that focuses on driver-automation interactions and system-initiated disengagement indicates that extended use of automation may result in slower hazard detection and longer reaction time to obstacles compared to manual driving [7, 9]. Driver attention monitoring and support systems are one mechanism intended to mitigate lapses in driver engagement by providing feedback to the driver or adapting the automation functionality in real-time [10-13]. Currently available driver monitoring systems use steering wheel torque-based sensors and/or driver facing cameras to track gaze and/or head position to infer driver state and intervene when a threshold for apparent inattention is exceeded. SC, for example, has a camera-based driver monitoring system that employs multimodal cues (visual, auditory, and haptic) to support driver attention on moment-to-moment basis.

While partial automation systems are increasingly available, the literature to date is limited by the lack of objective, real-world data on the extent to which drivers use partial automation, the context and frequencies in which the automation initiates disengagements, and how drivers respond to such events. Furthermore, in situations of automation-initiated disengagement events, it is still largely unknown to what extent the use of systems like SC, that allows hands-free driving, will impact driver ability to regain control in a timely manner. Naturalistic studies that directly and continuously record real-world driver behavior, capturing the use of automation and automation disengagements and driver takeovers, along with comprehensive, moment-to-moment driving data including vehicle speed, g-forces, engagement in non-driving related activities, driver visual attention patterns, traffic density, and other environmental conditions [4, 14-16] allow researchers to systematically address these gaps.

The current study used real-world driving data to characterize the occurrences of SC-initiated disengagement requests and to assess how drivers respond to these events. By quantifying changes in visual attention prior and immediately after SC disengagements, and analyzing the moment-to-moment distributional properties of driver glance and hand-on-wheel behaviors, this study provides insights on how drivers dynamically allocate their visual attention and the time it takes them to regain basic control following automation-initiated disengagement. The uniqueness of this paper comes from the large naturalistic driving dataset of consumers using Cadillac SC, a commercially available partial automation system that, when engaged, allows hands free driving. The findings from this paper can inform improvements in the design of assistive and automated vehicle technology as a whole, by enhancing knowledge on how drivers leverage automation under real-world operating conditions.

METHOD

Participants

A total of fourteen drivers (36% female) with an average age of 42 years old (SD=13.3 years old) participated in the study. Drivers from the greater Boston area of Massachusetts were recruited through flyers and online advertisements. Potential participants were screened according to inclusion criteria that required them to pass background and driving record checks, and to have highway driving as part of their regular commute. Drivers were excluded if they had been involved in a police-reported crash or received two or more traffic violation convictions in the past year, or had other risk markers (e.g., selected criminal records, or previous license suspension). Participants were provided with an MIT owned vehicle for one month along with paid tolls and a monetary incentive of $50 to complete a post drive interview. Participants received training on the available automation features including Adaptive Cruise Control (ACC, SAE Level 1) and the SC (SAE Level 2) systems. The training session started with a 30-minute static in-vehicle instruction period followed by an hour of on-road training. During the training drive, participants were familiarized with and were asked to interact with the different automation systems.

Data Source and Data Reduction

Data were drawn from the ongoing MIT Advanced Vehicle Technology (MIT-AVT) naturalistic data collection effort. As part of the study, participants drove MIT's instrumented 2018 Cadillac CT6 vehicles for a period of one month each (between April 2018 and May 2019). The study vehicles were instrumented with RIDER (Real-time Intelligent Driving Environment Recording) data acquisition system (Fridman et al. 2019) that continuously collected data from: (i) Controller Area Network (CAN) bus to determine vehicle kinematics, driver interaction with the vehicle controllers, and the state of in-vehicle automation systems, (ii) Global Positioning System (GPS) to record location; and (iii) four 720p video cameras that continuously captured (30 fps) the driver's face, vehicle cabin, instrument cluster, and the view of the forward roadway (See Figure 1). Together, these multiple data sources and data types provided rich and comprehensive data related to the vehicle state, driving environment, driver behavior, and the use of automation.

Figure 1. **Example of hands-free, legs-free driving in the Cadillac CT6 with SC engaged as captured by the four RIDER cameras, including: the driver's face, in cabin view, instrument cluster, and the view of the forward roadway.**

Automation initiated disengagement, operationally defined as an event where the automation (SC) issued an immediate takeover request triggered by conditions such as: (i) a failure of the automation system (e.g., sensing, computation, and planning), (ii) changes in the operational design domain (ODD), like entering a construction zone, and (iii) driver behaviors like accelerating beyond the ACC braking authority. To identify these events, a filter was run over the continuous CAN data and each flagged event was evaluated by experienced coders who viewed a video segment of 10sec before and 10sec after SC initiated the disengagement. Coding employed a systematic protocol to validate the occurrence and annotate the context of the disengagement events.

Measures

Glance Location

Each SC disengagement event was manually annotated capturing the driver's glance location at a frame-by-frame level at 30 fps. Glances were classified according to the following categories: (i) Road (any glance directed outside the windscreen); (ii) Instrument Cluster (any glance to the instrument cluster or steering wheel region); (iii) Down & Center Stack (any glance to the center stack, the in-car multimedia touch-screen, or down when looking at a smartphone or other object in the lap region); (iv) Mirrors (any glance to the left, right windows or mirrors, and rearview mirror). When a glance did not fall under the categories listed, it was annotated as Other. The Other category contains non-specific glances away from the road. For example, over the shoulder glances, glances towards objects positioned at head level or higher, but also those rare moments when the eyes were closed for longer than a typical blink duration (0.3sec). If the driver's eyes were temporarily not visible due to lighting conditions, etc., glances were coded as Not available. The Other and Not available glance categories were excluded from the glance analysis. Lastly, following ISO 15007-1:2014, a single glance consisted of the transition time toward an area of interest and the subsequent dwell time on that area.

Steering Wheel Control Level

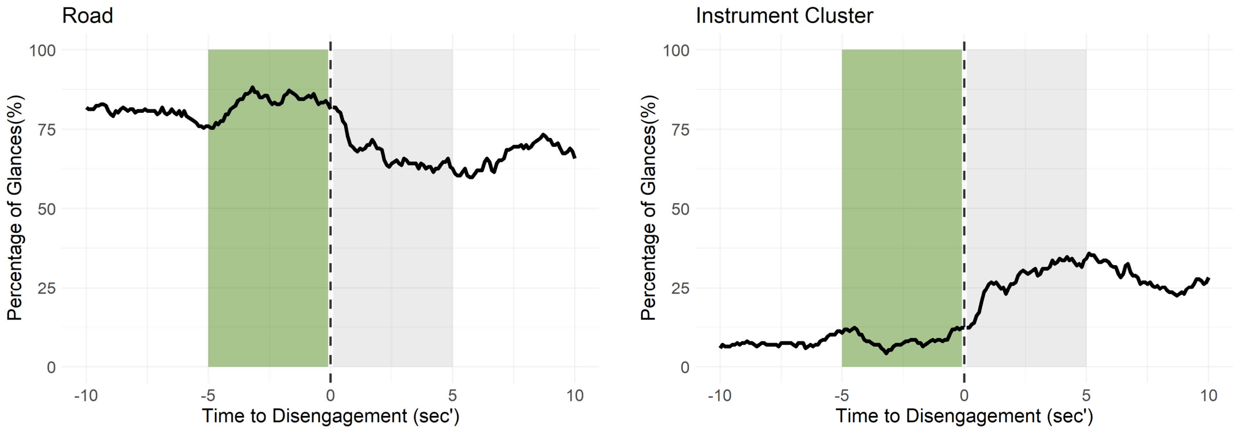
A driver's hand position relative to the steering wheel was manually annotated frame-by-frame at 30 fps and included the following labels: (i) No hands (driving hands free with no hand on the steering wheel); (ii) One hand (driving with one hand on the steering wheel); and (iii) Two hands (driving with two hands on the steering wheel); and (iv) Not visible (used when the driver's hands were momentarily not visible or in poor video quality).

RESULTS

During the data collection period and within the study sample, 265 SC initiated disengagement events were identified (mean=18.9; SD=16.5; range= 0 to 52 events per driver) across 5,514 miles driven with SC engaged. The analysis below included only disengagement events for which drivers' eyes and hands were visible and SC was engaged for at least 10sec before the disengagement (n=187). Following disengagement, the transition in the automation state was primarily to ACC (89%); only in a limited number of the disengagement events was the transition directly to manual driving (11%). During the evaluated 10sec after SC disengagement, drivers may or may not have reengaged SC.

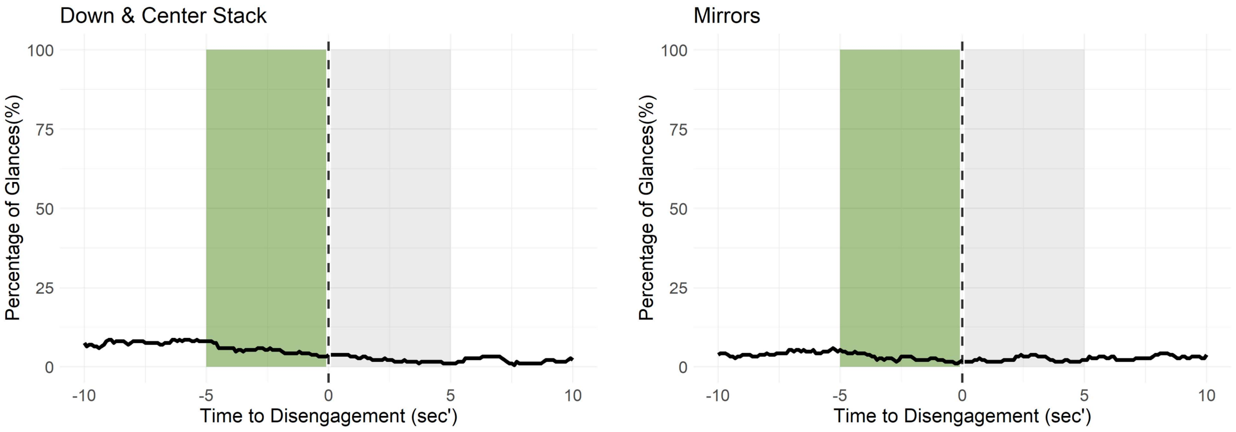
Glance Behavior

Figure 2 shows the time course of glance behavior from 10sec before to 10sec after SC initiated disengagement, across the evaluated glance areas. In general, SC initiated disengagements were associated with substantial changes in glance distribution. During the transition phase (i.e., in the 5sec around the disengagement), the distribution of glances prior to the disengagement (highlighted in green) were 83% (SD=3%) directed to the Road and only 8% (SD=2%) to the Instrument Cluster. Immediately following SC disengagement (highlighted in gray), glance proportions to the Road decreased substantially (68%, SD=6%) and the proportion of glances to the Instrument Cluster increased by 19% (27%, SD=6%) (see Figures 2a and 2b). This shift in glances towards the Instrument Cluster may capture drivers' search for information related to the reason for disengagement and/or to SC state. At the start of the transition phase, the average proportion of glances to the Down & Center Stack area was 5% (SD=1%), and this value decreased to 2% (SD=1%) in the 5sec after the disengagement (Figure 2c). The proportion of glances to the Mirrors showed a slightly decreasing trend as well.



(a)

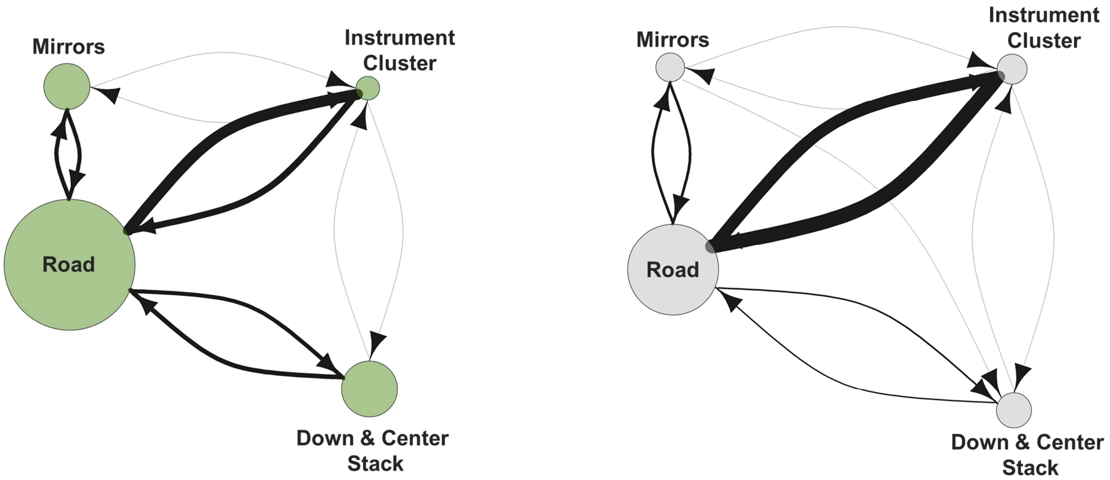
(b)



(c) (d)

Figure 2. **Proportions of glances to the different areas at any given time during SC initiated disengagement events. SC initiated disengagement is at 0sec, marked with black dashed line. The shaded bands indicate the intervals of the transition phase starting 5sec before (highlighted in green) and 5sec after (highlighted in gray) SC initiated disengagement.**

Figures 3a and 3b summarize driver visual attention patterns, capturing both the number of transitions (normalized proportion of transitions indicated by the edge width) and the mean duration spent in each glance area (indicated by the relative size of the vertex) in the 10sec before and 10sec after SC initiated disengagement. Overall, the number of transitions between glance areas following SC disengagement increased by 44%, from 845 transitions before the disengagement to 1218 after the disengagement across all events. The most prevalent visual attention patterns following SC initiated disengagement were Road → Instrument Cluster and Instrument Cluster → Road, which increased by 57% (from 262 to 412 transitions) and by 222% (from 156 to 503 transitions), respectively. In-parallel, the number of transitions from the Road → Down & Center Stack decreased by 45% (from 99 to 54) and the number of transitions from Road → Mirrors decreased by 10% (from 103 to 93) (see Figures 3a and 3b). All glances to all off-road areas, before and after SC initiated disengagements, were most likely to return to the Road before transitioning elsewhere. Figures 3a and 3b also illustrate that, on average, the time drivers spent in each glance area changed before and after SC initiated disengagements. The mean duration of glances to the Road decreased and was 2sec shorter following the disengagement. The mean durations of glances to the Mirrors and the Down & Center Stack areas decreased from 0.79sec to 0.68sec and from 1.34sec to 0.89sec respectively, and the glance duration to the Instrument Cluster increased slightly following the disengagements (from 0.71sec to 0.84sec).



(a) (b)

Figure 3. **Transition plots showing the number of transitions (edge width - normalized proportion of transitions) and the mean duration spent in each glance area (vertex size) in the (a) 10sec before and (b) 10sec after SC initiated disengagement.**

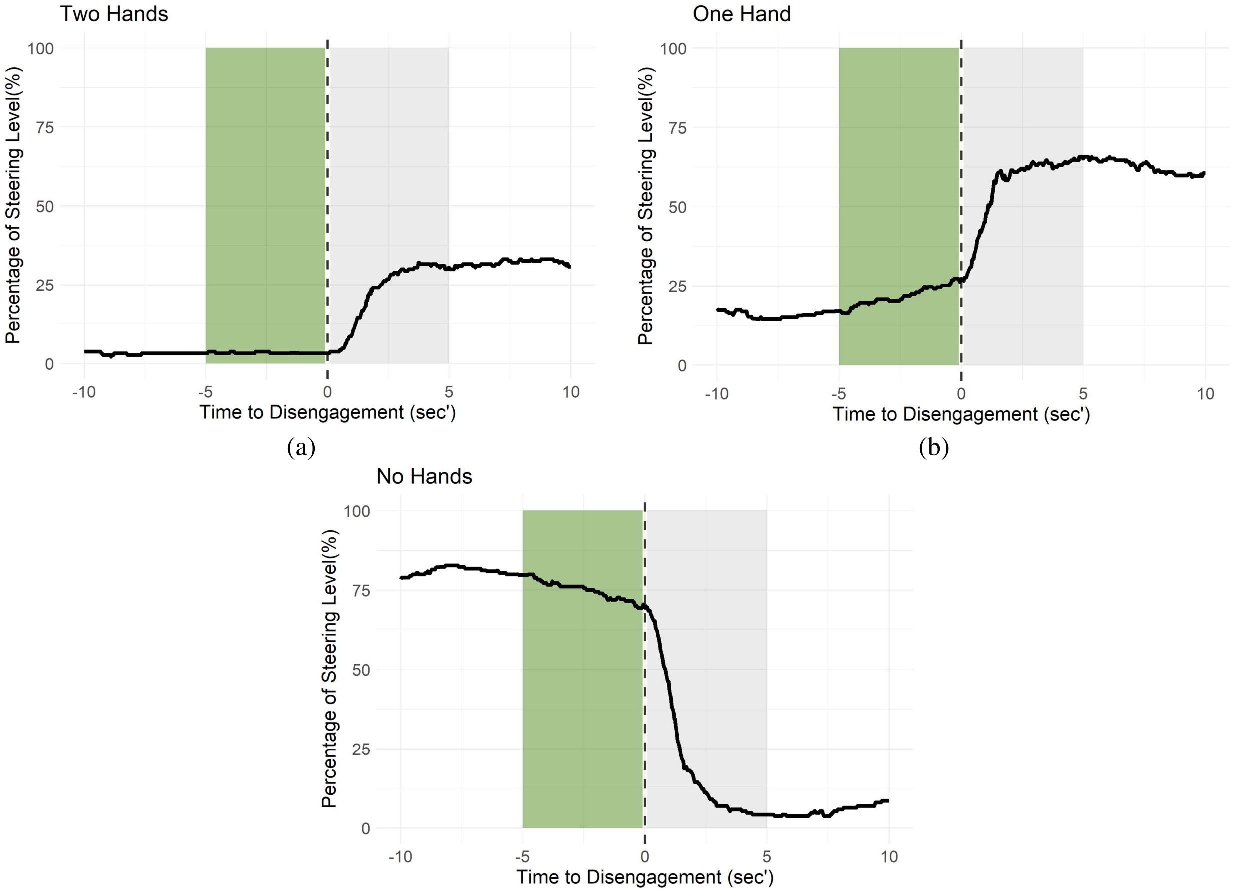
Linear quantile mixed-effects models with subject specific random intercept were used to estimate variations in the duration of glances to the Road and to the Off-Road glance areas (i.e., aggregated across Mirrors, Instrument Cluster, and Down & Center Stack) before and after SC disengagement and across the 15th, 50th and 85th quantiles [17]. The duration of long glances to the Road decreased significantly and was 4.86sec shorter following the disengagement ($Q15_{Before}$=0.5, CI=[0-2.24], $Q15_{After}$=0.43, CI=[0-2.11], *p*=.04; $Q50_{Before}$=2.02, CI=[0.8-3.24], $Q50_{After}$=1.45, CI=[1.02-1.88], *p*=ns; $Q85_{Before}$=6.63, CI=[2.06-11.2] to $Q85_{After}$=1.77, CI=[0-3.67], *p*<.001) (Figure 4a). Off-Road glance duration did not change significantly following SC initiated disengagements in any of the evaluated quantiles (see Figure 4b). Analysis of the glance duration for the individual off road glance areas did not yield any significate difference between the period before and after SC initiated disengagements.

(a) **(b)**

Figure 4. **Estimated mean glance duration 10sec before and 10sec after SC initiated disengagement across the 15th, 50th, and 85th quantiles, (a) to the Road, and (b) to the Off-Road glance areas.**

Steering Wheel Control Level

Figure 5 shows the percentage of steering wheel control levels expressed by hand on wheel position, across all events during the 10sec before and 10sec after SC initiated disengagements. We find that prior to SC initiated disengagement, on average, drivers drove hands-free 78% of the time and rarely had both hands on the steering wheel (3%). During the transition phase (i.e., in the 5sec around the disengagement), drivers' percentage of steering control level changed dramatically. While at the beginning of the transition phase the proportion of No Hands on the steering wheel was still about 75%, it dropped shortly after SC disengagement to 21% on average. Meaning, shortly after the onset of the disengagement, drivers increased their level of steering wheel control by 54%, grabbing the wheel with at least one hand. A linear mixed-effects model with a driver-specific random intercept was used to assess the relationship between level of steering wheel control and the time it took drivers to takeover in response to SC initiated disengagement. The analysis compared steering wheel control levels (hands-free vs. driving with at least one hand on the steering wheel) at the onset of the disengagement request and the succeeding takeover duration. The disengagement duration from its onset is dictated by the time it takes the driver to resume steering control (i.e., active steering that is reflected by a change in the automation state). On average, the takeover duration when driving hands-free was significantly longer (2.4sec) compared to driving with at least one hand on the steering wheel (1.8sec) [$\chi^2(1)$=4.97, *p*=.026].



(a) (b)

(c)

Figure 5. **Percentage of steering wheel control levels across time and hand position. SC disengagement is at 0sec and marked with a black dashed line. The shaded bands indicate the interval of the transition phase starting 5sec before (highlighted in green) and 5sec after (highlighted in gray) SC initiated disengagement.**

DISCUSSION

This study provides new objective insights on how drivers behave with partial automation system that allows drivers to drive hands free. The study findings capture naturalistic utilization of Cadillac's SC through shifts in attention and hand position during automation-initiated disengagements and transitions of control. Cadillac SC was one of the first systems to use a driver facing camera to infer driver attentional state and issue multimodal alerts when a threshold for apparent inattention is exceeded. Driving safety research has long been concerned with the driver's ability to maintain adequate attention to the driving task when using automation and to regain vehicle control in response to a potential hazard or following automation-initiated disengagement requests [18-19]. Similar to previous studies that focused on driver visual attention when driving with partial automation, we also find that the distributions of glances prior to SC initiated disengagement were relatively stable with glances primarily directed to the Road and to the Down & Center Stack area, and only a limited proportion of glances were directed towards the Instrument Cluster [3, 20]. Our results extend the understanding of drivers' glance behavior around automation-initiated disengagements, indicating that shortly after SC disengagement, there was a sharp and substantial decrease in the proportion of glances that drivers directed to the Road along with an increase in the proportion of glances towered the Instrument Cluster, which lowered attention to all other glance areas. Glances to Down & Center Stack areas are often associated with non-driving related activities, as drivers may glance down when using a smartphone or glance to the center stack while interacting with the infotainment touchscreen.

As part of a driver's response to SC initiated disengagement, the proportion of glances to the Down & Center Stack areas diminished almost to zero and remained low for the rest of the evaluated period. Changes in driver glance behavior following the disengagement were also evident in more frequent transitions between a limited number of glance areas and in that long on-road glances were shorten by 73%. Taken together, these changes in glance behavior resulted in an overall lower and more fragmented visual attention to the Road during a sensitive and possibly time-critical driving situation. This shift in glance behavior is consistent with information seeking behavior that may capture drivers' search for information related to the reason for the disengagement and/or the automation state.

Adequate control of the steering wheel is critical both to correct lateral position in normal driving and to evade emergency situations. There is limited quantitative information on how drivers maintain control of the steering wheel during manual or automated driving, especially when using partial automation systems that allow hands free driving. The current analysis found that drivers adopted the SC's hands-free driving feature to a substantial degree, taking both hands off the steering wheel more than 75% of the time when SC was engaged. When both hands were off the steering wheel, the response to SC initiated disengagement requests took on average an additional 0.6sec for drivers to regain control and actively resume steering which is an increase of 33% compared to drivers who had at least one hand on the wheel. The significance of this time interval should be evaluated in the context of readiness to respond and considering the design of SC which continues its lane-centering support until the driver actively steers.

Limitations and Future Directions

Limitations to the current study include a volunteer sample of drivers that were enrolled for one-month. Driving context was not investigated, although driver visual response has been shown to depend on, for example, the presence of a lead vehicle. Future research could study the interplay between driver behavior and the complexity of the traffic situation. Future work may also consider different types of, and reasons for, system-initiated disengagement. Furthermore, as increases in inattention and distraction may become more pronounced after prolonged periods of automated driving, future work may benefit from longer periods of study to better estimate the longer-term use of automation and document more instances of automation-initiated disengagements. This study provides a reference point for looking at the response behaviors when interacting with other system designs and implementations (e.g., Tesla's Autopilot or Ford's Blue Cruise). Future research should evaluate how the use of partial automation and the characteristics of driver attention monitoring and support systems may impact the way glance behavior and steering wheel control intertwin.

CONCLUSIONS

As driver behavioral adaptation to automation is complex and hard to predict, developing human-centered automated systems will benefit from an evolutionary process that builds upon insights on how drivers use currently available ADAS in real-world settings. The use of partial automation is changing and reshaping drivers' visual and vehicle control behaviors, including the response to automation-initiated disengagements. Based on the observed trends, it is likely that the use of higher levels of automation will introduce even more substantial changes in visual and vehicle control behaviors during automation disengagements. As the performance of automation depends on the interaction between the human and the system, we hope that the data provides useful information to designers charged with developing assistive and automated systems and empowers regulators and safety advocates with data needed to objectively assess how to guide appropriate utilization of such technology.

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