Addressing driver disengagement and system misuse: Human factors recommendations for Level 2 driving automation design

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Abstract

Currently available Level 2 driving automation has the potential to reduce crashes. However, there are known risks with drivers misusing these systems, particularly as they relate to drivers becoming disengaged from the driving task. The purpose of this paper was to summarize the human factors literature and make empirically supported design recommendations for Level 2 driving automation on the best methods to encourage driver engagement and communicate where the system can safely be used. Our recommendations pertaining to driver engagement concern driver monitoring systems that detect signs of driver disengagement, driver attention reminder methods, escalation processes, consequences for sustained noncompliance when monitoring systems have detected driver disengagement, and proactive methods for keeping drivers engaged with respect to driver-system interactions and system functionality considerations. We also provide guidance on how the operational design domain should be communicated and restricted. We advise you to consider these recommendations in a holistic context, as selectively adhering to only some may inadvertently exacerbate the dangers of driver disengagement and system misuse.

Keywords: Partial automation; ADAS; guidance; misuse; driver disengagement; distraction

Table 1.

Summary of recommendations for design philosophies to minimize driver disengagement and misuse

Topic	Recommendations
Driver monitoring	• Driver monitoring should use both direct and indirect methods for highest accuracy and reliability of detecting driver disengagement. • Direct methods include eye (glance and lid closure) and head orientation. • Indirect methods include steering wheel input, lane departure frequency, ignition cycle duration since start, and time it takes for the driver to respond to attention reminders.
Driver attention reminders and consequences for noncompliance	• Attention reminders should escalate in message urgency and increase the number of modalities used for alerts when the driver does not respond. • Visual-only alerts should be used in a brief initial phase. The next phase should include a dual-modality alert, preferably visual and seat tactile. It should then escalate to a tri-modal alert (visual, tactile, and audible). • All nonvisual alerts should be accompanied by a visual message for clarification. Nonvisual alerts should be unique for each type of warning. • Sustained or repeated instances of noncompliance should result in pulse braking, safe stop, and Level 2 system lockout until the next ignition cycle. • Drivers must not be allowed to deactivate or modify the attention reminders or escalation process.
Proactive strategies for keeping drivers engaged	• Encourage shared haptic control with the lane centering function, where the degree of lateral control support varies based on the driver's steering input, risk of lane departure, and the driver's attention to the road. • Allow steering input from the driver to override lane centering input without going into standby mode. • Prohibit partially automated systems from automating lane changing and overtaking functions.
Communicating the ODD	• The operational design domain (ODD) for Level 2 automation systems should be clearly defined and communicated to the driver. • Drivers should only be able to engage systems within the ODD.

1. Introduction

Many new vehicles are equipped with technology designed to prevent crashes. For example, forward collision warning with automatic emergency braking, which warns the driver when a rear-end crash is imminent and provides emergency braking if the driver does not respond, reduces rear-end crash rates by 50% (Cicchino, 2017). Beyond the warnings and automatic emergency braking capabilities of crash avoidance technologies, other more sophisticated driver assistance systems are becoming increasingly available that assist with longitudinal or lateral vehicle control. Adaptive cruise control (ACC) operates a vehicle's speed controls, maintaining a driver-set speed and automatically adjusting (slowing) to maintain a driver-set following distance when encountering a slower moving vehicle ahead in the same lane. Lane centering, called by different names by some manufacturers, provides sustained steering support to continuously keep the vehicle centered in the lane. SAE International's (2018) taxonomy refers to the simultaneous use of these features as Level 2 driving automation.

Level 2 driving automation could possibly prevent additional crashes by increasing headways, lowering speed, and limiting exposure to lane drifts. Yet, the potential for unintended negative consequences with these systems has been documented in simulator, test track, high profile collision investigations, and survey research. The more sophisticated and reliable the driving automation is, the harder it is for drivers to maintain the necessary vigilance to monitor the vehicle interface and roadway to detect vehicle notifications and hazards (Carsten & Martens, 2019; Gold, Körber, Hohenberger, Lechner, & Bengler, 2015; Merat, Jamson, Lai, Daly, & Carsten, 2014). Mind wandering, fatigue, and longer and more frequent eye blinks also tend to occur when using partial driving automation (Körber, Cingel, Zimmermann, & Bengler, 2015). Drivers are more likely to perform secondary nondriving tasks, such as using a smartphone, when these systems are active (Reimer, Pettinato, et al., 2016). Visual-manual distraction further impairs a driver's already strained ability to detect and react to silent system deactivations (i.e., when the driving automation deactivates but does not alert the driver with an explicit takeover notification), which happen frequently in current production vehicles (Louw et al., 2019). In short, impaired vigilance, distraction, and the tendency to become removed from the driving task are known as driver disengagement (Lee, 2014).

An issue with driver disengagement when using driving automation is that these systems often behave in ways that are unexpected when they encounter difficult road conditions that exceed their operational boundaries (Insurance Institute for Highway Safety [IIHS], 2018). Sometimes, this also happens under fairly simple conditions that the driver might not anticipate to be outside the automation's operational constraints. Regardless of the circumstances, when the automation encounters conditions it is unable to handle, the driver must rapidly intervene to avoid potentially catastrophic consequences; unfortunately, that ability diminishes with reduced driver engagement in the driving task.

Surveys indicate that the public has an inaccurate understanding of the limitations of and what the driver's responsibilities are when operating Level 2 driving automation (Abraham, Seppelt, Mehler, & Reimer, 2016; Teoh, 2020), which is likely to increase the risk of misuse. There is already evidence that system misuse has resulted in fatalities (National Transportation Safety Board [NTSB], 2017, 2019). It remains an open question whether such crashes are the tip of the iceberg as these systems become more widespread, or whether they are outliers more representative of extreme disengagement tendencies of very few drivers. Regardless, it is now a matter of what can be done to prevent crashes resulting from system misuse in the future.

Technology should be designed and implemented in ways that minimize the possibility of negative unintended consequences. IIHS has been driving improvements in vehicle design for 25 years, first by providing consumer information on crashworthiness, and more recently by encouraging the adoption of effective crash avoidance technology. Level 2 automation is a new opportunity for IIHS to encourage technology to be designed and used to result in positive driving behavior.

The purpose of this paper was to summarize the literature on human factors design and implementation issues for Level 2 driving automation with the goal of making recommendations that could potentially be implemented in an IIHS consumer information program. We chose to focus the scope of our recommendations on issues related to engagement in the driving task while using Level 2 automation and understanding safe use of these systems, two broad issues closely linked to the potential for unintended negative consequences with the systems (Carsten & Martens, 2019). The guidance provided is based on the available empirically supported literature, and therefore it does not contain recommendations for engineering specifications. Instead, the recommendations concern system design philosophies. We caution you to interpret the guidance holistically; selectively addressing only certain elements could inadvertently result in a Level 2 system that leads to higher rates of system misuse.

Our review does not make recommendations regarding characteristics of the driver vehicle interface, which is thoroughly covered in guidance from the National Highway Traffic Safety Administration (Campbell et al., 2018), except for where it applies to strategies for maintaining attention to the driving task. Other papers that we reviewed, which make human factors recommendations for the design and implementation of Level 2 automation (e.g., Cabrall, Eriksson, Dreger, Happee, & DeWinter, 2019; Consumer Reports, 2018; Seppelt & Victor, 2016), are more theoretical than concrete, cover some but not all of our areas of interest, and/or make recommendations without citing support from the literature. This paper is organized as follows: first we discuss strategies related to driver engagement with Level 2 driving automation, including strategies for detecting driver disengagement, followed by methods on how to return the driver's attention to the road when driver disengagement is detected, as well as approaches to proactively keep drivers engaged. We conclude by reviewing ways to design these systems to ensure that drivers use them within their operational design domains (ODD).

2. Driver monitoring

Driver monitoring systems are designed to detect when the driver is disengaged from the driving task while using Level 2 driving automation. These systems monitor surrogate behaviors that are indicators of driver disengagement. Upon detecting those behaviors, the monitoring system initiates a protocol to bring the driver back in the loop by delivering attention reminders (see Section 3 on driver attention reminders and consequences for noncompliance). Existing implementations of Level 2 driving automation include some form of driver monitoring; however, the strategies used vary in their efficacy to detect disengagement due to the types of driver behavior that they monitor.

In this section, we recommend that the ideal driver monitoring system should monitor a combination of eye gaze or head orientation, lane keeping, steering input, response timing after attention reminders initiation, and duration of the drive since the start of the ignition cycle to maximize accurate detection of disengagement and reduce deliberate misuse of the driving automation.

2.1. Direct methods for detecting driver disengagement

Driver monitoring methods for detecting driver disengagement can be direct or indirect (Rauch, Kaussner, Kruger, Boverie, & Flemisch, 2009). Direct methods normally utilize driver-facing optical or infrared cameras to capture overt behind-the-wheel behavior as it relates to visual attention, for example by monitoring the driver's head and eyes. Eye glance, head position, and eyelid closure are useful direct measures to capture when drivers are engaged in secondary visual-manual activities, such as interacting with a smartphone or the vehicle's infotainment system. Risk of a crash or a near-crash increases considerably when the driver looks away from the forward roadway for longer than 2 seconds (Klauer, Dingus, Neale, Sudweeks, & Ramsey, 2006), highlighting the value of monitoring where the driver is looking and for how long.

Unfortunately, even though eye gaze direction and dispersion (i.e., eye glance concentration in the center of the roadway versus spread more broadly across the roadway to include the forward periphery) have been shown to effectively capture driver disengagement (Dobres et al., 2016; He, Becic, Lee, & McCarley, 2011; Victor, Harbluk, & Engström, 2005; Victor et al., 2018), there are difficulties with using such methods for driver monitoring in production vehicles. Eye trackers require individual calibration to have the precision necessary to accurately determine where a person is looking in the scene (e.g., Crabb et al., 2010), which is complicated in the context of a moving vehicle over multiple drives with different drivers and environmental conditions. Head tracking serves as a useful, albeit coarse, proxy for eye glance behavior (Lee et al., 2018) and is predictive of driver disengagement (Gaspar, Schwarz, Kashef, Schmitt, & Shull, 2018; Radwin, Lee, & Akkas, 2017) and fatigue (Fridman, Lee, Reimer, &

Victor, 2016). Head tracking is used in the driver monitoring algorithms of some production Level 2 automation systems.

While eyelid closure is a measure most often used for detecting fatigue (e.g., Jamson, Merat, Carsten, & Lai, 2013; Poursadeghiyan et al., 2017), it can also be useful for identifying when the driver is looking down during a secondary task, such as when interacting with a smartphone. For example, Sigari, Fathy, and Soryani (2013) found that eye closure rate in conjunction with other eye-related behaviors is predictive of distraction. Eyelid opening (or, conversely, closure) behavior is less commonly used for driver monitoring in production vehicles.

An issue with direct methods of capturing driver disengagement concerns the camera equipment. Individual driver characteristics, such as facial hair, head gear, sunglasses, and seating position, as well as environmental ambient lighting conditions (e.g., glare and nighttime) can impair the camera's ability to capture overt driver behavior. Another concern is that having one's eyes on or head facing toward the road may not be an indicator of driver engagement in isolation of any other behaviors because drivers may be mind wandering (eye gaze tends to concentrate at the center of the roadway when mind wandering; He et al., 2011). Eyes on the road and hands on the wheel are also not perfect predictors of driver attention or involvement in the driving task. Victor et al. (2018) showed that drivers who overtrust the automation to perform in a certain way are less willing to take over when the automation behaves in an unexpected manner, even when explicitly instructed to have their eyes on the road or hands on the wheel. Although attention reminders encouraged drivers to keep their hands on the wheel and eyes on the road, some drivers still crashed into hazards while directly looking at them, which the authors concluded was due to overtrusting the automation.

2.2. Indirect methods for detecting driver disengagement

Indirect methods for detecting driver disengagement usually rely on the driver's interactions with the vehicle interface, such as the steering wheel, or how those interactions produce certain vehicle kinematic behaviors, such as lane departures. Many driver monitoring systems use hands-on-wheel behavior via capacitive touch or steering torque. The number and position of the hands a driver places on the steering wheel changes depending on workload (De Waard, Van den Bold, & Lewis-Evans, 2010; Fourie, Walton, & Thomas, 2011; Thomas & Walton, 2007; Walton & Thomas, 2005). Given that driving automation is designed to reduce driver workload, it is not surprising that hands-off-wheel time increases with the presence of driving automation and correlates with eyes-off-road time (Reimer, Pettinato, et al., 2016) and engagement of nondriving activities (i.e., distraction; Radwin et al., 2017). To date, there has been little research on the impact of the duration of a Level 2 system's allowance for hands-off-wheel time, but it is reasonable to assume that allowing the driver's hands to be off the wheel for an extended period would be ill advised. Although Naujoks, Purucker, Neukum, Wolter, and Steiger (2015) found no effect of permitted hands-off-wheel time, this was partially driven by the fact that most participants in that study kept their hands on the wheel in all conditions.

A significant limitation of the way the capacitive-touch-through-the-steering-wheel method is currently implemented is that it only requires the driver to intermittently tap or squeeze the wheel. These actions do not reliably indicate in-loop behavior, as the driver might do so in response to reminders absentmindedly while disengaged. That said, capacitive touch is not an inherently flawed indirect behavior if monitored differently and in conjunction with other behaviors. Capacitive touch monitoring should require the driver to have their hands consistently on the wheel with allowance for only brief disruptions. Steering torque also has value as part of a multimeasure algorithm because it assumes some degree of driver engagement if the driver is providing adequate input in a collaborative manner with the lane centering system (see Section 4 for driver copiloting with respect to shared haptic control). As with capacitive touch, though, drivers can still employ tactics to deliberately fool steering torque-based monitoring systems. It is important to consider that all behaviors arising from driver disengagement have the potential to be effective indicators for a monitoring system as long as the parameters used in the detection algorithm are finely tuned around constant engagement in the driving task.

There are interactions between direct and indirect measures that occur in response to driver distraction that support incorporating indirect measures into the driver monitoring detection algorithm to increase its accuracy. Peng, Boyle, & Hallmark (2013) found that time spent looking away from the road is related to variability in lane keeping. Given that many production vehicles have Level 2 driving automation systems with design philosophies of shared control, where the driver is expected to provide continuous steering input while the lane centering support is active, steering behavior might be a suitable indirect measure to include in the monitoring algorithms. We recommend that the driver monitoring systems use both direct and indirect methods to detect driver disengagement.

2.3. Timing of driver response

Timing aspects of direct and indirect measures could be incorporated into attention monitoring systems to refine driver disengagement detection accuracy. For example, Kuehn, Vogelpohl, and Vollrath (2017) showed that secondary activity while a driving automation system is on reduces the speed with which drivers return their eyes to the road, feet to pedals, and hands to the wheel after receiving a takeover request. This finding indicates that response timing to attention reminders of the behaviors captured could improve the driver monitoring algorithm accuracy. In addition, duration of the drive since the start of the ignition cycle might also be useful. Feldhütter, Gold, Schneider, and Bengler (2017) observed that, after 20 minutes with a driving automation system on, eye glances to the road became shorter and more frequent and takeover responses slowed, although without any other notable changes to takeover quality, possibly because the driving period was too brief. There is evidence from the fatigue literature that drive duration affects behind-the-wheel and lane keeping behavior (Anund et al., 2008), which argues that such a measure would be useful for calibrating system sensitivity to aberrant and distracted behavior.

3. Driver attention reminders and consequences for noncompliance

Depending on what a driver monitoring system's criteria are for establishing driver engagement in the driving task when the Level 2 driving automation is active, attention reminders may include alerting the driver to return hands to the wheel or eyes or head orientation back to the forward roadway. If the driver complies by performing whatever behavior the system requires, the attention reminders will desist. Attention reminders have been shown to help keep drivers engaged in the driving task. Gaspar et al. (2018) showed that audible and visual prompts given by vehicle monitoring of driver head position improved situation awareness, time spent looking at the center of the roadway, and takeover responses when the driving automation suddenly disengaged. Similarly, Atwood, Guo, and Blanco (2019) found that attention reminders modified driver behavior over the course of their study with fewer threshold instances of driver disengagement toward the end (i.e., fewer reminders were initiated).

All driver monitoring systems should use attention reminders that escalate in urgency. We recommend that escalation procedures begin with a brief visual-only phase, on the scale of seconds, which should be followed rapidly by subsequent phases that use dual-modal alerts and then tri-modal alerts. Nonvisual alerts should be paired with visual alerts that clarify their meaning. For the final phases of escalation when faced with sustained driver noncompliance, we recommend that manufacturers employ vehicle kinematic responses such as pulse braking, a safe stop, and lockout strategies where the driver cannot reengage the driving automation until the start of the next ignition cycle. Given the purposeful selection of specific alert methods and consequences for driver noncompliance, drivers must not be allowed to modify or deactivate the attention reminders or escalation process.

3.1. Escalation of alert modalities

Escalation procedures involve an additive process whereby more alert modalities are included and message urgency increases with each progressive phase; for example, audible alert volume increases or timbre changes, visual icon color changes from green to yellow to red, text-based instructions change in phrasing, and tactile alert vibration increases in frequency or amplitude (Cao, Theune, & Müller, 2010; Politis, Brewster, & Pollick, 2013). Escalating attention reminders are needed because such reminders must balance delivering notifications that bring the driver back into the loop in a timely manner with avoiding annoyance, which could lead to drivers disusing the system (Reagan, Cicchino, Kerfoot, & Weast, 2018).

Weighing the consequences of driver annoyance and alert effectiveness, many manufacturers use a visual alert in the first phase of driver attention reminders. This approach is appropriate as long as the visual-only initial phase is short before quickly escalating to multimodal phases. It must be brief because drivers who are truly disengaged from driving are unlikely to notice a visual alert in the first place, and Zhang, de Winter, Varotto, Happee, and Martens (2019) found that drivers have slower takeover responses to visual-only alerts when compared with audible or tactile alerts.

Although most automakers use small icons for their visual notifications, the initial phase could utilize strategies that increase the visual conspicuity and detection rate of alerts, thus potentially avoiding escalation and reducing annoyance for drivers that are already in loop. Possible strategies include temporarily fading out all other competing information in the interface, using larger and higher contrast icons, and using unconventional locations for visual alerts that could be within a distracted driver's line of sight, for example, through a large LED in the steering wheel. With humans being particularly sensitive to visual motion (McKee & Nakayama, 1984), it is also possible that attention reminders escalating from static to dynamic motion-based alerts may also be effective in capturing attention, although this remains to be demonstrated.

The purpose of single-modality tactile vibrations or audible alerts may be confusing without clarification from visual notifications and messages. Morando, Victor, Bengler, and Dozza (2019) found that many drivers initially default to looking at the instrument cluster when they receive unexpected audible takeover requests, even though the instrument cluster in their study contained no relevant information about the driving automation's operation status. This automatic impulse highlights an opportunity for the vehicle to clarify the purpose of the audible alert through a visual notification, given that the authors found audible alerts alone do not universally lead drivers to resume control. Therefore, we recommend using a combined visual-auditory or visual-tactile notification in the subsequent phase after the initial visual-only alert phase. In effect, an audible or tactile alert serves to capture the driver's diverted attention and visual messages help the driver reorient back to the task of driving. Nonvisual alerts should be distinct for each type of message or notification.

Audible alerts should require the infotainment system to automatically reduce volume and the climate control to reduce the airflow to ensure they are heard by the driver. A visual-tactile alert may be perceived as less annoying and more urgent than a visual-audible alert (Politis et al., 2013); however, the method of tactile feedback delivery used may matter because a driver with hands off the steering wheel will not detect alerts through it, and therefore static seat vibrations would likely be more effective. Petermeijer, Cieler, and de Winter (2017) have shown that static seat vibration is an effective alert modality for capturing driver attention.

Regardless of the alert modality combinations used in the subsequent escalated phases, it is imperative that notifications be easily detected, concise, and intuitive (Campbell et al., 2016). Response time will increase if a driver has difficulty recognizing and understanding the alerts, which would detract from the purpose of the attention reminder (Petermeijer et al., 2017). To this point, visual messaging should be succinct to reduce the time drivers spend looking away from the road (Hoffman, Lee, McGehee, Macias, & Gellatly, 2005), but persist long enough on display to be read by a driver whose attention may have been otherwise diverted from the interface at the time of the alert.

Moreover, it is important to not overwhelm the driver in the initial phases by incorporating too many alert modalities and messages at once. Politis et al. (2013) showed that increasing the number of modalities used to communicate a warning increases perception of both urgency and annoyance among drivers but also lowers reaction times to critical events. Unsurprisingly, the combination of audible, visual, and tactile alerts together leads to perceptions of highest urgency. This alert strategy therefore should be incorporated in the later phases of the escalation procedure, whereas dual-modal alerts would be more effective than a single-modal alert and less annoying than the tri-modal alerts for earlier phases.

3.2. Strategies to address sustained noncompliance

Some manufacturers use physical vehicle kinematic strategies later in the escalation process to get potentially fatigued drivers to resume control, for example, through pulse braking. Although accelerator (Adell & Várhelyi, 2008) and brake pedal pulsing (Riley, Kuo, Nethercutt, Shipp, & Smith, 2002) are possible forms of haptic feedback, a pulse-braking strategy that relies on the vehicle's physical motion has the most promise to alert an unresponsive driver. This is because not only is the human vestibular system remarkably sensitive to changes in self-motion (MacNeilage, Banks, DeAngelis, & Angelaki, 2010), but it is also likely that the driver might have his or her feet off the pedals while ACC is on (Rudin-Brown & Parker, 2004). Another potential vehicle response is for ACC to extend the time headway while the driver is detected to be disengaged to increase the safety margin. The increased safety margin might improve the chances of a safe reaction time once the driver is brought back into the loop, allow more time for ACC to respond to hazards in front, or give more time for an autosteering system to intervene.

A final phase strategy that some manufacturers employ involves a safe stop, where the vehicle activates the hazard-warning lights and brings the vehicle to a stop. This approach contrasts with another approach where the Level 2 system is simply deactivated when the driver does not comply with attention reminders. Abrupt deactivation can have perilous consequences if the driver is unable to regain control in time; thus, we do not recommend such an approach. Emergency services may also be called after coming to a complete stop, given that a driver who endures the entire escalation procedure without taking over might be incapacitated.

In the future, driving automation might play a more significant role in safe stop protocols. Hyundai Mobis (Agnew, 2018) proposed the "Departed Driver Rescue and Exit Maneuver" concept where higher level driving automation (i.e., Level 4) could take over when the driver is incapacitated and safely depart the roadway to bring the vehicle into a minimal risk condition, such as pulling over to the shoulder. The driver and roadway would be monitored passively while the driver is in control of the vehicle, and the fully automated capabilities of the system would only be invoked under these specific conditions. This concept could plausibly be applied to an unresponsive driver using Level 2 driving automation.

Another consideration is to have a lockout consequence for sustained noncompliance in the last phase of the escalation procedure. The purpose of an escalation procedure is to discourage driver disengagement and, therefore, drivers who deliberately misuse the driving automation should be penalized with the system becoming unavailable for the rest of the drive. The ideal method of discouragement would be to combine a safe stop and lockout protocol for the final phase of the escalation procedure where the driver would be able to resume control of the vehicle at any time during the safe stop procedure, but once that procedure is completed or overridden, the system would be in lockout mode for the remainder of the drive. Alternatively, another possibility would be to invoke the lockout when the driver elicits a maximum number of escalation instances, even if he or she never reaches the final stage of the escalation process, in order to prevent repetitive system misuse.

Although the interface is limited in terms of how it can communicate the nature and purpose of the lockout, drivers who deliberately misuse the driving automation will learn through experience about the lockout consequences and may be less inclined to misuse the system over time. In a closed course study using a vehicle with a prototype Level 2 system, Llaneras, Cannon, and Green (2017) found that participants had few instances where the escalations reached the point of lockout, which indicates that an escalation procedure effectively deters most drivers who might be prone to misusing the system. That there were still individuals who experienced a lockout highlights the necessity of including a lockout phase.

4. Proactive strategies for keeping drivers engaged

Although driver monitoring and attention reminders increase driver engagement while using driving automation, reminders are reactionary to driver behavior and do not guarantee that a driver will continuously stay engaged. Numerous proactive strategies have been recommended to keep drivers engaged by increasing situational awareness of present traffic conditions and staying in loop in the physical task of driving, while also minimizing in-vehicle opportunities for distraction. However, some strategies that have been suggested are unrealistic for modern production vehicles and real-world driving conditions, such as imposing secondary tasks through gamification to maintain cognitive arousal (Cabrall et al., 2019), which would add unsafe cognitive burden, or using adaptive automation that tailors system functionality to individual driver characteristics, such as experience or age (Saffarian, de Winter, & Happee, 2012), which goes beyond current in-vehicle driver recognition software capabilities and also introduces privacy concerns for operators.

The proactive driver engagement strategies that we recommend in this section seek to encourage driver involvement by sharing control with automation that adapts its behavior to the driver's input and maintaining driver situational awareness by limiting the functionality of Level 2 systems, whereby the systems are not allowed to do automated overtaking and lane changing. Shared control between the driver and automation would include allowing steering input from the driver to override lane centering input without deactivating the system. Another recommended design philosophy would be to incorporate a protocol that incentivizes the driver to behave safely in order to earn the ability to activate the system in the first place.

4.1. Shared haptic control and automation that adapts to the driver

Participating in decision-making, action selection, and action implementation while using driving automation can help keep drivers in the loop (Onnasch, Wickens, Li, & Manzey, 2014). One way to encourage such interaction is through shared haptic control, which is automation that allows for inputs by both the driver and the system with the design intent of limiting errors arising from driver disengagement (Mulder, Abbink, & Boer, 2012). In this framework, steering control can be considered to exist on a continuum between total manual control and total system control. Shared haptic control of steering fits in the middle of this continuum and can take different forms, depending on the amount of control authority exerted by the system and input required by the driver. An ideal shared controller should adapt to the individual's steering input, as opposed to forcing an authoritarian input from the system that overrides the driver's input, even if that input adapts to road conditions.

Through implicit haptic feedback via the steering wheel, this shared control method of interaction can help to ensure that the driver is always aware of the lane centering system's activity, keep the driver engaged in the driving task by requiring input from him or her, and allow the driver to rapidly detect and intervene further if the system were to encounter situations it is unable to handle (Merat & Lee, 2012; Saffarian et al., 2012). The advantages of such a system highlight the potential disadvantage of a hands-free Level 2 driving automation system, because the interaction between the driver and the steering wheel would help to keep the driver in the loop if a shared control design philosophy were utilized.

Adaptive automation is a form of shared haptic control that provides more authoritative assistance when it is needed, but no or less assistance when it is not. From the robotics literature there is evidence that adaptive automation helps to reduce overall operator workload and improves trust when compared with conditions of no automation or nonadaptive automation (de Visser & Parasuraman, 2011). Using an air traffic control system with simulated shared control, Clamann, Wright, and Kaber (2002) also found that it was more beneficial when adaptive automation interacted with operators on lower (i.e., psychomotor) than higher (i.e., cognitive) function levels, which is an argument in favor of an adaptive shared haptic control mechanism through steering in the automotive context as it relies on psychomotor functions. In the driving automation context, a shared controller could act as an assistive system by amplifying the driver's input as long as driver state is normal and there is no risk of lane departure, but give more authoritative haptic steering feedback when the driver is detected as disengaged and there is a risk of lane departure (Benloucif, Sentouh, Floris, Simon, & Popieul, 2019). Yet, Benloucif et al. (2019) noted a potential limitation with shared control after observing that some participants tended to give too much control to a shared control automated lane keeping system while performing a secondary task. This finding underscores the importance of having countermeasures in place for driver disengagement as described in Sections 2 and 3.

Shared haptic control can benefit beyond increased driver engagement with respect to driver acceptance of lateral vehicle support. A system that adapts its input tends to behave more similarly to manual driving behavior than a nonadaptive controller under challenging road conditions, such as curves (Mulder et al., 2012), which has the potential to increase driver satisfaction and minimize uncomfortable automation control experiences. The assistive nature of the system would not be compromised with a shared controller, as studies have demonstrated that lane keeping with a shared control system is improved relative to manual driving (Benloucif et al., 2019; Mulder et al., 2012).

Some current systems cancel the lane centering functionality when the driver provides steering input. Because of the advantages of shared haptic control of steering, we recommend that systems allow drivers to override lane centering input by steering without going into standby mode. An added advantage to lane centering remaining active when the driver steers comes from the consistency of this behavior with the functionality of other systems designed to keep drivers from departing their lanes. Consistency between the designs of legacy and replacement technologies allows users to leverage their existing expectations and understanding (i.e., their mental model) of the legacy system to promote appropriate use of the new system (Vandenbosch & Higgins, 1996; Zhang & Xu, 2011). Lane departure prevention systems that intervene with transient steering support when drivers depart their lanes remain turned on until they are intentionally turned off through a button push or menu. Drivers can override the input of such systems by steering and they will remain engaged, and drivers who have experienced lane departure prevention may expect a similar response from a lane centering system.

4.2. Limiting the functionality of Level 2 driving automation

As highlighted by the advantages of sharing control with adaptive automation, taking too much of the workload away from the driver encourages disengagement and generally poorer vehicle control. Some Level 2 systems offer lane change assistance where, once the driver has activated the turn signal, the vehicle will judge the appropriate gap in traffic in the adjacent lane and then will automatically adjust speed and change lanes. Banks and Stanton (2015) recommended against allowing the driving automation to offer the ability to automatically perform overtakes, so that drivers must rely on their own ability and situational awareness to perform complex maneuvers. By that logic, it is reasonable to likewise discourage simpler automatic lane changing functionality in partially automated driving systems that still require the driver to be in the loop.

4.3. Rewarding appropriate driving behavior with driving automation access

Similar to the system lockout consequences described in Section 3.2, a hypothetical way to keep drivers engaged is by having drivers "earn" the ability to use the driving automation based on good behavior. For example, if the driver fails to control the vehicle safely before the driving automation would normally be available, the system does not become available for activation at all. Likewise, if the driver demonstrates acceptably safe vehicle control and behind-the-wheel behavior (e.g., keeping eyes on the road), the driving automation will become available when in its ODD and it will remain available under those conditions unless the driver starts behaving in an unacceptable manner.

Such a mechanism for driving automation currently does not exist in any production vehicle and it is unclear what driving behavior-related criteria would be necessary, or even feasible, to determine whether the driver's vehicle control and behind-the-wheel behavior are "acceptable". Nevertheless, if the intent behind automation in the vehicle is to improve driver behavior, it is important to incorporate incentivizing strategies into the operation of those systems and those strategies may be most effective for keeping drivers in loop. Other incentivizing strategies for shaping driver behavior could require seatbelt use or keeping the crash avoidance systems on. Systems could also potentially incentivize positive behaviors while they are in use. For example, systems capable of sign recognition or linked to GPS-based speed limit databases could restrict setting ACC's speed above the speed limit. Such strategies may discourage system use, but the safety benefits associated with higher belt use, safer speeds, and use of crash avoidance systems could possibly outweigh the disbenefits of automation disuse.

4.4. Restricting other in-vehicle systems

Another concern about keeping the driver in the loop has to do with the vehicle's infotainment system. Although secondary systems offer convenience and assistance, they also risk distracting the driver with submenu navigation challenges and the number of options and functionalities available through peripheral applications. Donmez, Boyle, and Lee (2003) suggested that the infotainment and navigation systems could be designed to have a form of temporary lockout or impose access limitations when the driving automation is on to minimize distraction. Some automakers do this with, for example, vehicle settings submenus and on-board digital owner manual access. However, restricting infotainment system functionality too much might encourage drivers to rely more on smartphones, which could lead to longer eyes-off-road time than when using the infotainment interface (e.g., Reimer, Mehler, Reagan, Kidd, & Dobres, 2016).

4.5. Vehicle interface communication of system confidence

Evidence from driving simulator studies suggests that displaying information about system confidence has the potential to improve driver vigilance for monitoring the vehicle interface and understanding changes in the driving automation's operating status. System confidence refers to the degree to which the driving automation's algorithms have the necessary information and traffic or road conditions to operate (i.e., it displays when the system approaches its operational limits). Stockert, Richardson, and Lienkamp (2015) found that participants had higher driving engagement and takeover readiness, and also spent less time performing the secondary experimental task, when the vehicle interface constantly displayed system confidence information. Similarly, Seppelt and Lee (2019) reported that constant interface communication about ACC confidence was more beneficial than discrete warnings, as the system confidence notifications improved understanding of ACC's limitations and takeover responses in response to ACC failures. Performance on a secondary task was unaffected by the presence of system confidence information, indicating that the constant notification does not increase the driving task load or act as a distraction; instead, it appears to help drivers better manage their attention when monitoring the interface for changes to the driving automation's operating status.

Despite the potential merits of displaying system confidence in the interface, there are legal considerations for incorporating such information into the interface that automakers may oppose, such as manufacturer liability for when there is a mismatch between the vehicle's system confidence display and the driving situation. Another concern is that in the real world, some drivers may shift their vigilance to focus on the system confidence display over time at the cost of monitoring the forward roadway less, consequently leading to misuse of the driving automation. It is also unclear whether system confidence could be estimated accurately in the first place, or if such an estimate would be predictive of system performance either at the moment of notification or within a short distance or time in the future. The latter concern would apply even to a binary indicator of "confident" and "not confident". In light of these concerns, we do not recommend incorporating system confidence into the driving automation's visual interface.

5. Communicating the ODD

A driving automation system's ODD refers to the operating conditions under which the system was designed to function (SAE International, 2018). It is important for drivers to understand the constraints for the driving automation in their vehicle in order to understand its functional capabilities and limitations (Lee & See, 2004; SAE International, 2018). Understanding where (i.e., road environments with specific characteristics concerning, for example, lane line delineation, curvature, speed limits, and traffic conditions) and how the driving automation's features should be used, in turn, informs the driver about his or her roles and responsibilities for operating the vehicle while the systems are engaged within their ODDs as well as when they depart their ODDs. We recommend that the ODD, which is also known as the intended operational environment for L2 systems (US DOT, 2018), should be clearly defined, effectively communicated to the driver, and that drivers should be unable to engage the systems outside of the ODD.

5.1. Clearly defined ODD

Performance of Level 2 features varies with roadway and traffic characteristics. On-road testing has revealed that systems perform best on open freeways and can be challenged by the curves, hills, and intersections that typically appear most often on rural and urban surface streets (American Automobile Association, 2018; IIHS, 2018). In turn, the roads on which Level 2 systems are used affect how well drivers enjoy driving with them. Drivers more frequently report higher comfort and fewer instances of unexpected and undesirable system behavior when using Level 2 systems on interstates, freeways, and expressways compared with other road types (Kidd & Reagan, 2018; Reagan, Cicchino, & Kidd, 2020). Limiting system use to roadway types where Level 2 automation performs well would reduce the demands for monitoring the vehicle interface and decrease the likelihood of the system behaving unexpectedly and requiring driver intervention. However, where systems should be used is not always clearly defined. Specifications of where systems should be used in owner manuals can vary across automakers, sometimes do not capture all situations where systems struggle, and at times use ambiguous wording (Reagan, Kidd, & Cicchino, 2017; Wright, Svancara, & Horrey, 2020).

5.2. Self-limiting the ODD

Although most Level 2 systems are designed primarily to operate on limited-access roads, drivers are nevertheless sometimes able to engage them in a variety of environments. There is large individual variability in drivers' use of ACC and Level 2 automation on other road types (Reagan, Hu, et al., 2019), which highlights that system limitations are not currently being well-communicated to drivers. This study supports the notion that the two fatal crashes involving use of Level 2 systems outside of the intended ODD (NTSB 2017, 2019) may not be anomalies, as there appears to be a segment of the driving population with a proclivity to misuse driving automation.

In addition to the considerable variation in clarity and thoroughness among owner manuals, it is unrealistic to expect all drivers to consult the owner manual before operating a vehicle with Level 2 features and to remember an exhaustive list of all the subtle nuances of the environmental conditions that systems may struggle to cope with. We recommend that automakers design systems so that they cannot be used outside of the ODD when the technological capabilities to do so exist. As an example, some automakers use GPS information or infrastructure conditions to lock out system use outside the ODD. The majority of drivers expect that a system will communicate where it should not be used by not allowing the driver to engage the system (Teoh, 2020). Part of that communication could include notifying the driver when the vehicle approaches the boundary of its ODD; for example, using GPS mapping to self-limit the vehicle's ODD, the system will recognize its exact position on a road and could alert the driver that it will become unavailable as it approaches the end of its mapped infrastructure. Although some drivers may wish to learn system limits by testing it under a variety of conditions (Sullivan, Flannagan, Pradhan, & Bao 2016; Teoh, 2020), such a strategy puts the driver and other road users at risk. In 2017, the NTSB recommended that automakers incorporate system safeguards to limit the use of automated vehicle control systems to the conditions for which they were designed, and that the National Highway Traffic Safety Administration (NHTSA) develop a method to verify that automakers have done so. Currently, NHTSA (2017) proposes self-limiting ODDs, but only for highly automated vehicles (Level 3 and above).

6. Discussion

The sophistication of currently available Level 2 systems is undeniable, and the task now is to realize their potential safety benefits while minimizing known risks. The guidance provided in this paper concerns the overall nature of how drivers interact with Level 2 driving automation. Driver disengagement is an issue regardless of the presence of driving automation, but partially automated systems have the potential to exacerbate the problem. System intervention is therefore needed to alter the driver's interaction with the automation to ensure the driver remains in loop with the driving task. This intervention requires modification of the driving environment (i.e., the vehicle) through the implementation of adaptive driving automation with driver monitoring. Consequently, we emphasize a holistic approach as opposed to selectively adhering to only some of the recommendations, which are summarized in Table 1. For example, designing these systems to be adaptive with their input by providing greater support when drivers are disengaged than when they are actively participating in the driving task could, in fact, encourage drivers to misuse them if automakers do not also include reliable driver monitoring systems and escalation processes with consequences for noncompliance.

Given the difficulties drivers face with maintaining vigilance, vehicles with Level 2 driving automation should have monitoring systems that detect when the driver is disengaged from the driving task using both direct and indirect detection methods. Once driver disengagement is detected, the monitoring system should initiate a series of escalating alerts to bring the driver's attention back to the task of driving. If faced with sustained noncompliance from the driver, the vehicle should engage protocols designed to bring the vehicle into a minimal risk condition (SAE International, 2018), which should in turn discourage deliberate misuse. Moreover, Level 2 driving automation should be designed to keep the driver engaged in the driving task while the systems actively provide support. The method of system support should be similar to legacy systems that the Level 2 automation replaces to take advantage of the familiarity drivers may have already established with respect to system operation and expectations. Even with clear system communication and varied methods to keep the driver engaged in the driving task, there is still the potential for unintentional as well as deliberate misuse and, consequently, these systems should be functionally restricted to operate only within their ODD.

A topic that was not discussed in this paper is the role of driver training in safe operation of Level 2 systems. It has been suggested that training on what the technology does, what the driver's role is, and how driver behavior changes while using automation is necessary for drivers using partial automation (Casner & Hutchins, 2019). The design characteristics we recommend can help keep drivers engaged, but it would be difficult to ensure that drivers understand a system's functional limitations through design itself.

Driver training could, in tandem with system design, increase driver engagement and proper use of the system by more closely calibrating a driver's trust in the system to its capabilities. Manipulating the information provided to drivers about the limitations of advanced driver assistance systems that they later experience significantly affects subsequent interactions with and trust in the systems (Beggiato & Krems, 2013; Körber, Baseler, & Bengler, 2018).

Victor et al. (2018) similarly found that providing drivers with more detailed information about a system's limitations combined with attention reminders decreased the number of crashes with unexpected objects on a closed course, although these interventions did not eliminate them. Yet, the question of how training could be comprehensively and accurately delivered to drivers of vehicles with partial automation is a challenging one. For instance, drivers say that they would prefer to learn about their vehicles at the dealership, but dealership personnel can lack knowledge of the technology on the vehicles they sell (Abraham, Reimer, & Mehler, 2018; Abraham, McAnulty, Mehler, & Reimer, 2017), and this strategy would not cover non-dealership used vehicle sales. It thus remains crucial for vehicle design to accommodate the human element, to the extent possible, without assuming that drivers will receive education before getting behind the wheel.

As described by the Highway Loss Data Institute (2019), current technologies will be available for decades to come as they slowly penetrate the registered vehicle fleet. The slow uptake of Level 2 automation systems offers designers the opportunity to now refine them by incorporating the human factors recommendations discussed in this paper. Doing this before these technologies become commonplace will help maximize potential safety benefits.

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