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Addressing Driver Disengagement and Proper System Use: Human Factors Recommendations for Level 2 Driving Automation Design

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Level 2 driving automation has the potential to reduce crashes; however, there are known risks when using these systems, particularly as they relate to drivers becoming disengaged from driving. This paper provides data-driven recommendations for Level 2 driving automation design using the best currently available methods to encourage driver engagement and communicate where and how a system can safely be used. Our recommendations pertaining to driver engagement concern driver management systems that monitor the driver for signs of disengagement and return the driver to the loop using a multimodal escalation process with attention reminders, countermeasures for sustained noncompliance to the attention reminders, 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 (ODD), driver responsibilities, and system limitations should be communicated and how these systems must be self-limited within the ODD. In addition, we discuss the benefits and limitations of training to emphasize the importance of making these systems intuitive to all users, regardless of training, to ensure proper use. These recommendations should be applied as a whole, because selectively adhering to only some may inadvertently exacerbate the dangers of driver disengagement.

Keywords: partial automation, ADAS, guidance, inattention, driver disengagement, distraction

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INTRODUCTION

Many new vehicles are equipped with technology designed to prevent crashes. For example, forward collision warning with automatic emergency braking warns the driver when a rear-end crash is imminent and provides emergency braking if the driver does not respond. This crash avoidance feature reduces rear-end crash rates by 50% (Cicchino, 2017). Beyond the transient warnings and automatic emergency braking capabilities of crash avoidance features, other more sophisticated driver assistance systems are also becoming increasingly available that assist with longitudinal or lateral vehicle control for extended periods. 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 various automakers, 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.

Safety Benefits and Unintended Consequences

Many Level 2 systems are marketed as driver convenience features, as opposed to safety features. The available data are difficult to interpret whether Level 2 systems have safety benefits above and beyond the crash avoidance features that act on similar crash scenarios; for instance, whether ACC has a rear-end crash reduction beyond that of automatic emergency braking. Insurance claims vary between automakers as to whether vehicles equipped with Level 2 systems have lower claims beyond the same vehicle models that are equipped with just crash avoidance systems or driver assistance packages with ACC (Highway Loss Data Institute [HLDI], 2017, 2019a, 2019c). These data, however, cannot attribute claim reductions to the use or disuse of these systems; they can only identify differences in claim rates as a function of the systems equipped within the same vehicle model type. Other data have shown that ACC, when combined with forward collision warning, is associated with increased headway and fewer harsh braking events relative to manual driving (European Commission, Joint Research Centre, 2012). By extension, it is possible that Level 2 systems might help to prevent situations in which crash avoidance systems would have to act, for example, by increasing headways, lowering speed, and limiting exposure to lane drifts.

Nevertheless, even if the safety benefit of Level 2 systems is a reduction in opportunities for conflict, it is unclear how significant such an effect would be within the systems' operational design domain (ODD). The ODD refers to the road conditions for which the driving automation is designed to operate in (SAE International, 2018). Most Level 2 system ODDs encompass only limited-access roads, which are the safest per vehicle mile traveled (Federal Highway Administration, 2019). A study by the Insurance Institute for Highway Safety (IIHS, 2016) showed that even higher levels of driving automation would have a limited safety impact within this ODD. They estimated that the maximum safety potential of a crash-free, highly autonomous system in this ODD (e.g., Level 4 driving automation, which is self-driving within its ODD restrictions) anticipates crash deaths and injury reductions to be only 17% and 9%, respectively.

There is currently a notable lack of U.S. federal regulation and guidance for the design and implementation of these systems, which has allowed a wide range of products to become available on the market that operate very differently despite being classified under the same umbrella as Level 2 driving automation (IIHS, 2018). Even though the automotive industry is racing to put more advanced vehicle features into production vehicles every year, the actual penetration rate of these technologies in the fleet of registered vehicles will take decades (HLDI, 2019b). Fortunately, the timeframe required for widespread adoption provides a unique opportunity now to implement design philosophies that are informed by empirical research to help Level 2 systems either offer convenience with safety benefits or convenience that is not at the cost of safety.

There is growing concern about the potential for unintended negative consequences with these systems, as documented in high-profile collision investigations and simulator, test track, survey, and on-road observation 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 (Biondi et al., 2018; Carsten & Martens, 2019; de Winter et al., 2014; Endsley, 2017a; Gold et al., 2015; Greenlee et al., 2018; Hergeth et al., 2016; Manzey et al., 2012; Merat et al., 2014). Mind wandering, fatigue, and longer and more frequent eye blinks tend to occur when using such systems (Körber et al., 2015). Drivers are also more likely to perform secondary nondriving tasks, such as using a smartphone or eating, when these systems are active (Carsten et al., 2012; Merat, Jamson, et al., 2012; Reimer, Pettinato, et al., 2016). Visual–manual distraction further impairs a driver's already strained ability to detect and react when the driving automation behaves inappropriately but does not alert the driver with an explicit takeover notification, which happens frequently in current production vehicles (Louw et al., 2019). In short, impaired vigilance, distraction, and the tendency to become cognitively 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 road conditions that exceed their operational boundaries (American Automobile Association, 2020; Insurance Institute for Highway Safety [IIHS], 2018). Given that Level 2 systems are in no way self-driving, the driver must rapidly intervene when the driving automation encounters conditions that it is unable to handle. Sometimes, however, this happens under fairly simple conditions that the driver might not anticipate to be outside the automation's operational constraints. Survey studies show that the public often has an inaccurate understanding about the limitations of these systems and what the driver's responsibilities are when operating Level 2 driving automation (Abraham et al., 2016; Teoh, 2020).

There is already evidence that driver disengagement and use of these systems outside their ODDs have resulted in fatalities (National Transportation Safety Board [NTSB], 2017, 2019, 2020). It is unknown whether these crashes are the tip of the iceberg and will become more frequent as these systems become more widespread, or whether they are outliers that are representative of extreme disengagement tendencies of only a few drivers. Regardless of which is the case, moving forward it is now a matter of what can be done to prevent crashes resulting from driver disengagement when using these systems.

Guidance Objectives

Technology should be designed and implemented in ways that minimize the possibility of negative unintended consequences, but it is clear from on-road functional testing that Level 2 systems vary substantially between automakers. The purpose of this paper is to summarize human factors design and implementation issues for Level 2 driving automation with the goal of making empirically grounded recommendations that could potentially be applied to vehicle ratings programs. While there could be any number of ways that Level 2 systems might be designed in theory, our recommendations center on the systems, strategies, and technological capabilities that are available today with the aim to encourage designs that could best prevent the worst case scenarios of driver disengagement, as seen with the Tesla Autopilot fatalities investigated by the NTSB (2017, 2019, 2020).

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 that are closely linked to the potential for unintended negative consequences with the systems (Carsten & Martens, 2019). Although this paper does not contain a comprehensive literature review of all the studies performed in the automotive human factors field, the guidance provided is based on currently available data. As such, it does not contain recommendations for engineering specifications, such as precise timing thresholds for how long a behavior might occur before it is classified as disengagement or how long each phase of the attention reminder process should last. There is a lack of consistent data on many of these design aspects due to the complexity of the driving task in dynamic road environments, and therefore our recommendations concern high-level design philosophies from a comprehensive system's perspective. The guidance must be interpreted as a whole because selectively addressing only certain elements could inadvertently result in a Level 2 system that leads to higher rates of driver disengagement.

Our paper does not make recommendations about vehicle interface characteristics, which is thoroughly covered in the guidance from the National Highway Traffic Safety Administration (Campbell et al., 2018; National Highway Traffic Safety Administration [NHTSA], 2017), except for where it applies to strategies for managing a driver's attention to the driving task. Other important papers have made human factors recommendations on the design and implementation of Level 2 driving automation (e.g., Banks et al., 2018; Cabrall et al., 2019; Consumer Reports, 2018; Endsley, 2017a, 2017b, 2018; Eriksson & Stanton, 2017; Seppelt & Victor, 2016); however, they were more theoretical than concrete, covered some but not all of our areas of interest, and/or made recommendations without citing empirical data. This paper seeks to build upon that body of work and is organized as follows. We discuss methods for detecting driver disengagement, followed by methods on how to return the driver's attention to the road when the driver is detected to be out of the loop, and proactive driver management strategies to keep drivers engaged. We also cover the potential benefits and limitations of training and consumer information strategies. This paper concludes by recommending ways that these systems could be designed to communicate to drivers and self-limit where and how these systems should be used in order to help ensure that drivers use them safely and within their ODD.

MONITORING FOR SIGNS THAT THE DRIVER IS OUT OF THE LOOP

Driver monitoring systems (DMS) are designed to detect when the driver is disengaged from the driving task while using Level 2 driving automation. Upon detecting driver disengagement, the DMS initiates a protocol to bring the driver back in the loop by delivering attention reminders (see the section "Driver Management Strategies" for attention reminders and countermeasures 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. The reason for this variation is that driver disengagement is a theoretical construct and what these systems actually monitor are surrogate behaviors that are indicators of driver disengagement. Although some behaviors are more reliable indicators that the driver has become disengaged, no single behavior can be the basis for a robust DMS because of cognitive phenomena inherent to humans and limitations of in-vehicle monitoring equipment, which we elaborate upon below.

In this section, we recommend that the ideal DMS should monitor a combination of eye gaze or head orientation, steering input, the time it takes drivers to respond to attention reminders, and the duration of the drive since the start of the ignition cycle to maximize accurate detection and reduce opportunities for driver disengagement. Driver drowsiness is generally detected through eyelid closure using, for example, the PERCLOS method (Federal Highway Administration, 1998); however, other drowsiness monitoring strategies have not yet been implemented. In addition, the sustained lateral support from the driving automation prevents the DMS from being able to detect drowsy-related lane drifts. Nevertheless, many of our high-level recommendations that address driver disengagement also would apply to driver drowsiness.

Monitoring the Driver's Visual Attention

For simplicity's sake, driver monitoring methods for detecting driver disengagement can be classified as direct or indirect, even though technically all behind-the-wheel behaviors are indirect indicators of disengagement from the driving task (Rauch et al., 2009). Direct methods normally utilize driver-facing optical or infrared cameras to capture overt behind-the-wheel behavior as it relates to visual attention. Eye glance and head position are useful measures for capturing 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 s (Klauer et al., 2006), highlighting the value of monitoring where the driver is looking and for how long.

Even though eye gaze direction and degree of dispersion (i.e., eye glance concentration in the center of the roadway versus spread more broadly across the roadway to include the forward periphery) are effective indicators of driver disengagement (Dobres et al., 2016; He et al., 2011; Victor et al., 2005, 2018), it is difficult to use those measures for driver monitoring in production vehicles at present. Some 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). Calibrating the equipment to a driver before each drive is complicated, although not impossible, in the context of a moving vehicle over multiple drives with different drivers and environmental conditions, and ambient lighting conditions (e.g., glare) can also affect the camera equipment. In addition, while eyelid closure is a measure most often used for detecting drowsiness, for example with PERCLOS (e.g., Jamson et al., 2013; Poursadeghiyan et al., 2017), it is also useful for identifying when the driver is looking down during a secondary task, such as when interacting with a smartphone. Sigari et al. (2013) found that eye closure rate in conjunction with other eye-related behaviors is predictive of distraction.

Head tracking serves as a simpler, albeit coarser, proxy for eye glance behavior (Lee et al., 2018) and is predictive of driver disengagement (Gaspar et al., 2018; Radwin et al., 2017) and drowsiness (Fridman et al., 2016). A limitation of head tracking on its own is that the DMS may not be able to identify when the driver is looking away if his or her head is facing forward, which argues for the need for a DMS to incorporate eye gaze (Fridman et al., 2016). At the time of publication, head tracking is currently used in the driver monitoring algorithms of some production Level 2 automation systems.

The problem with a DMS that only monitors eye glance or head orientation toward the forward roadway is that these behaviors on their own may not always capture driver disengagement. Mind wandering often results in the driver's eye gaze concentrating near the center of the roadway while he or she is cognitively removed from driving (He et al., 2011). Moreover, just because the driver's head and gaze are directed toward an object does not guarantee that he or she consciously perceives it. This is known as the "looked-but-failed-to-see" phenomenon, and it accounts for the fact that drivers sometimes crash into the things that they were looking at (Koustanaï et al., 2008).

Monitoring the Driver's Hands on the Steering Wheel

Indirect methods for detecting driver disengagement usually rely on the driver's interactions with the steering wheel or on how those interactions produce certain vehicle kinematic behaviors, such as lane departures. Many DMS at present 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 et al., 2010; Fourie et al., 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 driving-unrelated activities (Radwin et al., 2017).

A significant limitation about the way the capacitive touch method is currently implemented is that it only requires the driver to intermittently tap or squeeze the steering wheel. These actions do not reliably indicate in-loop behavior, as the driver might do them 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 constantly 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, which we discuss further in the section "Proactive Strategies for Keeping Drivers Engaged." As with capacitive touch, though, drivers can 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.

Using Multiple Driver Monitoring Strategies Simultaneously

We recommend against a hands-free driver monitoring strategy for Level 2 systems with the current capabilities and functional performance that have been observed to date (American Automobile Association, 2020; IIHS, 2018). The rationale for this position is that a driver must be able to respond quickly when the system behaves in a way that he or she might not expect and having one's hands on the wheel facilitates the speed with which a driver is able to react. Consequently, the most effective driver monitoring strategy for currently available Level 2 systems would be to monitor both the driver's visual attention and hands on wheel.

Another problem that is inherent to a Level 2 system that is designed to allow drivers to take their hands off the wheel for prolonged periods of time, even when it incorporates a DMS that monitors visual attention via the driver's eyes or face, is that it can produce expectations that the driver is allowed to perform other tasks while receiving assistance from the driving automation. Carsten et al. (2012) showed that lateral support capabilities of driving automation tend to encourage more driver disengagement and secondary activity than the longitudinal support, and this tendency persists when using higher levels of driving automation that have the two functionalities integrated.

Hand-on-wheel based DMS offer the additional benefit of information feedback through physical contact with the steering wheel, which a hands-free DMS lacks. The physical feedback from the vehicle's lateral positioning cues through the steering wheel can help support the driver's situational awareness of the Level 2 driving automation's behavior and thereby increase the speed with which the driver can detect situations requiring further intervention when the system encounters situations it cannot handle (Endsley & Kiris, 1995; Petermeijer et al., 2015). Even with geospatial mapping restrictions to self-limit where the driving automation might be used, which we discuss further in the section "Aiding Driver Understanding and Safe Use of the Automation," all Level 2 systems can behave suddenly in ways that are unexpected. Moreover, the operational requirement for Level 2 driving automation from automakers is that the driver is responsible at all times for the vehicle's performance, which underscores the importance of requiring the driver to remain physically connected with the driving task. In essence, the physical contact with the steering wheel and shared control with the lateral support of the Level 2 system help to keep the driver in the loop of the driving task (Mulder et al., 2012).

Unsurprisingly, because multiple related yet distinct behaviors occur when a driver is disengaged from the driving task, there are interactions that occur between direct and indirect measures that support the importance of a DMS integrating both types of methods into its detection algorithm to increase its accuracy. Peng et al. (2013) found that time spent looking away from the road is related to variability in lane keeping. Morando et al. (2020) also reported that drivers spend less time looking at the road and more time with both hands off the wheel, often to manually manipulate an object such as a smartphone, when using a Level 2 system than when manually driving. Given that many production vehicles have Level 2 driving automation with design philosophies of shared control, where the driver is expected to provide continuous steering input while the lane centering system is active, the driver's steering behavior is a suitable measure to include in the monitoring algorithms along with direct visual monitoring of the driver's eye gaze or head orientation.

Timing Elements to Refine Driver Disengagement Detection Accuracy

Timing aspects of direct and indirect measures could be incorporated into DMS algorithms to refine driver disengagement detection accuracy. For example, Kuehn et al. (2017) showed that secondary activity while using driving automation 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 the time it takes drivers to respond to attention reminders could improve the DMS algorithm detection accuracy, as too could the duration of the drive since the start of the ignition cycle. Feldhütter et al. (2017) observed that, after 20 min with a driving automation system on, eye glances to the road became shorter and more frequent with less time looking at the road overall and takeover responses slowed, although without any other notable changes to takeover quality, possibly because the driving period was too brief. There is also 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.

Limitations of Any DMS

Although we recommend that the DMS use both direct and indirect methods to detect driver disengagement, eyes on the road and hands on the wheel are not perfect indicators of driver attention or involvement in the driving task. In addition to the issues of mind wandering, looked-but-failed-to-see phenomena, and deliberate system misuse, overtrust in the driving automation also presents a risk. 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 or when informed about the system's limitations. 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. Given the limitations of any driver monitoring strategy, later in the paper we discuss proactive strategies to help keep drivers engaged in the driving that ought to be included in addition to a robust DMS for any Level 2 system. Then, in the section "Aiding Driver Understanding and Safe Use of the Automation," we provide recommendations associated with driver training, dynamic interfaces that communicate the vehicle's performance and the driver's roles and responsibilities in real time to improve the driver-driving automation interaction, and system restrictions to be operable only within the ODD.

DRIVER MANAGEMENT STRATEGIES

The DMS is part of an overall driver management strategy to keep the driver in the loop of the driving task. Attention reminders are typically used in the first phase of the driver management response to when the driver becomes disengaged from the driving task. Depending on what a DMS's criteria are for identifying driver disengagement when the Level 2 driving automation is active, attention reminders may include alerting the driver to return hands to the wheel or eyes back to the forward roadway. If the driver complies by performing whatever behavior the system requires, the attention reminders will desist; if the driver does not comply, the driver management strategy should escalate. Attention reminders have been shown to be effective in managing driver engagement in the driving task. Gaspar et al. (2018) showed that audible and visual prompts given by vehicle monitoring of driver head position improved situational awareness, time spent looking at the center of the roadway, and takeover responses when the driving automation suddenly disengaged. Similarly, Atwood et al. (2019) found that attention reminders modified driver behavior over the course of their study with fewer threshold instances of driver disengagement (i.e., fewer reminders were initiated) toward the end than in the beginning.

This section contains recommendations on how attention reminders could most effectively be used to manage driver engagement. We discuss strategies in which attention reminders ought to escalate in urgency and utilize alerts with multiple modalities when the driver does not react. Guidance is also provided on how the system should respond when faced with sustained driver noncompliance by using vehicle kinematic behavior, a vehicle stopping procedure, emergency services notification, and system lockout where the driving automation becomes inaccessible for the remainder of the drive. Given the purposeful implementation of specific alert methods and countermeasures for driver noncompliance, we recommend that drivers must not be allowed to modify or deactivate any aspect of the driver management system.

Alert Escalation When the Driver Does Not Comply

All driver management strategies should use attention reminders that escalate in urgency. The escalation procedure should use 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 to become more directive, and tactile alert vibration increases in frequency or amplitude (Campbell et al., 2018; Cao et al., 2010; Politis et al., 2013). Escalating attention reminders should employ urgency mapping strategies because these alerts must balance the need to bring the driver back into the loop in a timely manner while avoiding annoying, distracting, or overwhelming the driver, which could lead to drivers disusing the system (Reagan et al., 2018). Calibrating the urgency of alerts to be appropriate for the driving situation and driver state should help to facilitate quicker driver adherence to the attention reminders while reducing perceived annoyance (Marshall et al., 2007). The goal of this paper is not to recommend particular alert design specifications beyond discussing the merits of utilizing different alert modalities for the various phases of the escalation process, though. Prior research has investigated the efficacy and application of urgency mapping among a range of single and multimodal alert designs, mostly in the context of driver alerting strategies for hazard avoidance maneuvers (e.g., Baldwin & Lewis, 2014; Campbell et al., 2018; Fagerlönn, 2011; Gonzalez et al., 2012; Gray, 2011; Ho et al., 2007; Marshall et al., 2007; Wiese & Lee, 2004).

Many automakers use a visual alert in the first phase of driver attention reminders, which is appropriate so as not to annoy the driver if it is a false alarm 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 et al. (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 better utilize strategies that increase the alert's visual conspicuity to prevent unnecessary escalation if the driver is already in the loop. Possible strategies include temporarily fading out all other competing information in the interface that is not relevant for time-critical tasks, 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 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.

Our recommendations in the earlier section "Monitoring for Signs That the Driver is Out of the Loop" encourage DMS designs that are less prone to false alarms, which should help to improve the effectiveness and driver acceptance of the attention reminders. If the DMS detects that the driver has become disengaged from the driving task, the visual alert should be initiated as soon as possible, to be followed by other alert modalities shortly after. While it remains unclear how long would be appropriate for each phase of the attention reminder escalation process, the vehicle logs for the fatal crashes that occurred while using Level 2 driving automation as reported by the NTSB show that those drivers had been allowed to take their hands off the wheel for more than 10 s at a time (NTSB, 2020), with a recorded instance of even more than 5 min (NTSB, 2017), before alerts were initiated. Those permitted durations of driver disengagement were far too long. The crashes highlight the need for these systems to permit only brief interruptions, on a scale of a few seconds, to ensure the driver remains in the loop.

If the driver is disengaged from the driving task, he or she will probably not respond to the initial visual alert, which requires the escalation process to then include the addition of a tactile or audible alert. Morando et al. (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 an audible or tactile alert through a visual message, given that the authors found nonvisual 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.

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 matters because a driver with hands off the steering wheel will not detect vibrations through it. Petermeijer et al. (2017) have shown that static seat vibration is an effective alert method for capturing driver attention. Seat vibration also has a social advantage over an audible alert when passengers are present because the driver will be able to comply with the alert while unnoticed by the other occupants. This benefit of a driver-targeted tactile alert might avoid the potential embarrassment of being perceived as having done something wrong, which would minimize the driver's annoyance with an escalated bimodal alert (Carsten et al., 2020). While this strategy has the potential to encourage system use, it is worth noting that if the driver were not to comply with the visual–tactile alert, further escalation would be necessary to include audible alerts as well as other countermeasures for noncompliance that we discuss in section "Addressing Sustained Driver Noncompliance".

It is important to not overwhelm or startle the driver in the initial phases by incorporating too many alert modalities and messages at once, though. 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 trimodal alert strategy therefore should be incorporated in the later phases of the escalation procedure, whereas bimodal alerts would be more effective than a unimodal alert and less annoying than the trimodal alerts for earlier phases (Figure 1).

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 avoid confusion and improve response time, nonvisual alerts should be distinct for each type of message or notification. Visual messaging should be succinct and directive to reduce the time drivers spend looking away from the road (Hoffman et al., 2005), and 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.

Addressing Sustained Driver Noncompliance

We recommend that driver management systems use additional countermeasures when the driver has not responded to the multimodal attention reminders. If the driver has not responded to the escalated alerts, it is possible that he or she may be incapacitated (e.g., asleep) or deliberately using the system to remain out of the loop. Some automakers use physical vehicle kinematic countermeasures to get drivers to resume control, for example, through pulse braking. Although accelerator (Adell & Várhelyi, 2008) and brake pedal pulsing (Riley et al., 2002) are possible forms of haptic feedback, a pulse braking strategy that relies on abrupt physical vehicle accelerations 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 et al., 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). Although one might wonder whether pulse braking slows the vehicle enough to risk being rear-ended by a following vehicle, IIHS testing has shown that pulse braking is so rapid and brief that, while detectable in its

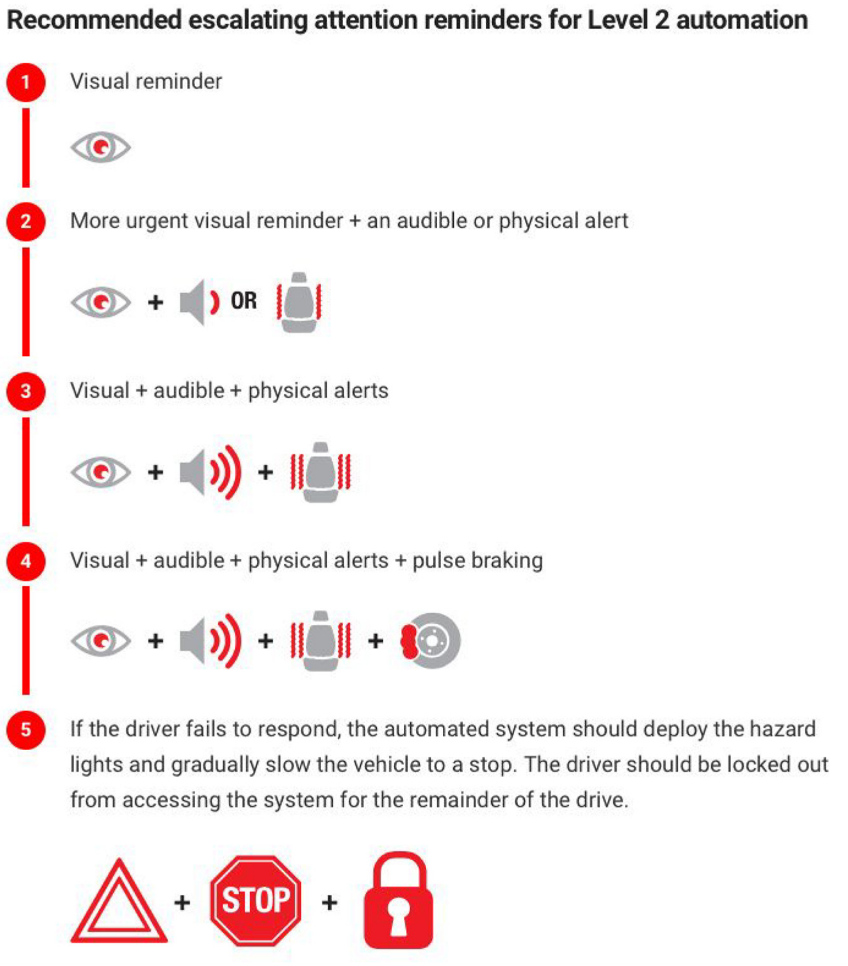

Figure 1. Escalation procedure of attention reminders and possible consequences for driver noncompliance.

acceleration, it does not significantly change the vehicle's overall speed (https://techdata.iihs.org). Another useful vehicle response strategy is for ACC to extend the headway time when the driver is detected to be disengaged. This not only encourages the driver to resume control to bring the vehicle back to the original set speed, but it also has the possible benefit of increasing 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 or automatic emergency braking to respond to hazards in front, or give more time for an autosteering system to intervene.

Pulse braking with multimodal attention alerts should be adequate to rouse a drowsy or distracted driver, but if the driver endures the entire escalation procedure without resuming control then it is likely that he or she might be incapacitated. A strategy that some automakers employ when the driver is nonresponsive is to activate the hazard-warning lights and bring the vehicle to a stop. Some systems also use loud alarms and place a call to emergency services during this procedure, which we recommend. This strategy contrasts with another approach where the Level 2 system is simply deactivated when the driver does not comply with attention reminders. We do not recommend an abrupt deactivation of the Level 2 system as a countermeasure to driver unresponsiveness because such a strategy could have perilous consequences if the driver is unable to regain control in time.

While it would be ideal for the vehicle to be brought to a stop on the shoulder or to exit the road entirely to find a place to stop, such a complex and situation-dependent maneuver is beyond the technical capabilities of currently available Level 2 systems. However, 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 in the future.

The final countermeasure for sustained noncompliance that we recommend is to have a system lockout in the last phase of the escalation procedure. The purpose of an escalation procedure is to discourage driver disengagement while using the system and, therefore, repeated instances of detected driver disengagement should result in the system becoming unavailable to the driver until the next ignition cycle. The system lockout should also occur when the vehicle stopping procedure for the unresponsive driver scenario is invoked. During the stopping procedure, the driver must be able to resume control of the vehicle at any time; but, once the stopping procedure is completed or has been overridden, the system should be inaccessible until the next ignition cycle.

Although the interface is limited in terms of how it can communicate the nature and purpose of the lockout, drivers will learn through experience about the lockout consequences and may be less inclined to continue behavior that elicits the escalation procedure over time. In a closed course study using a vehicle with a prototype Level 2 system, Llaneras et al. (2017) found that participants had few instances where the escalations reached the point of lockout, which supports the efficacy of an escalation strategy. That there were still individuals who experienced a lockout highlights the necessity of including a lockout countermeasure.

PROACTIVE STRATEGIES FOR KEEPING DRIVERS ENGAGED

Even though driver monitoring and attention reminders increase driver engagement while using driving automation, they 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 could add unsafe cognitive burden in certain situations, or using adaptive automation that tailors system functionality to individual driver characteristics, such as experience or age (Saffarian et al., 2012), which goes beyond current in-vehicle driver recognition software capabilities and also introduces privacy concerns for operators.

The proactive driver management strategies that we recommend in this section seek to encourage driver involvement by sharing control with automation that adapts its lane centering behavior to the driver's steering input and to maintain 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 the system's lane centering support without deactivating the system. A hypothetical design philosophy that may have merit is a protocol that incentivizes the driver to behave safely in order to earn the ability to activate the system in the first place.

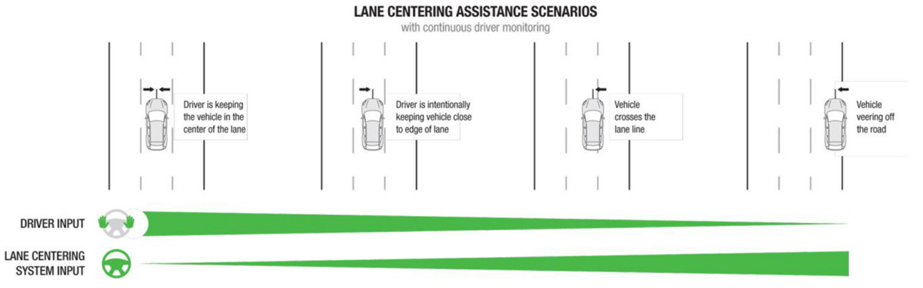

Figure 2. Examples of scenarios demonstrating the different degrees of steering assistance through shared haptic control with the lane centering system. *Note*: These scenarios exemplify the nature of adaptive automation and do not represent all possible scenarios.

Sharing Control With the Driving Automation

Participating in decision-making, action selection, and action implementation while using driving automation can help keep drivers in the loop (Onnasch et al., 2014). One way to encourage such interaction is through shared haptic control, which is when the automation is designed to integrate input from both the driver and the system with the intent of limiting errors that can arise from driver disengagement (Mulder et al., 2012). In the framework of shared haptic control as a form of adaptive automation, steering control can be considered to exist on a continuum between total manual control and total system control. Collaborative steering fits in the middle of this continuum as it modifies the amount of lane centering support given based on the driver's required steering input, the driver's state, and the road conditions (Figure 2). This strategy sits in contrast to the authoritarian control of some lane centering systems, which at times overrides or resists the driver's input and can lead to frustrating experiences by the driver (Reagan et al., 2020), or risks drivers learning to relinquish control to the lane centering system entirely even though the hands-on-wheel design philosophy requires the driver to be involved in steering at all times. Many Level 2 systems currently available in production vehicles lean toward the more authoritarian strategy for lateral support, whereas some systems have a more collaborative steering design for the lane centering functionality—the latter of which we encourage automakers to implement, although we recommend taking the strategy further in design to ensure the driver continuously participates in the driving task.

As described in the earlier section "Monitoring for Signs That the Driver is Out of the Loop," the information feedback that the driver receives through the physical connection of the steering wheel by sharing control with the lane centering system helps to keep the driver in the loop, which highlights the potential disadvantage of a hands-free Level 2 driving automation system. 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 his or her regular steering input, 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). However, we emphasize that any form of shared haptic control could only be effective in keeping drivers engaged in the driving task if it is also paired with a robust DMS and effective driver management strategy. In the absence of a robust driver management system, adaptive automation could easily be misused as drivers might intentionally give over responsibility to the driving automation so that it provides more support while the driver is disengaged (Benloucif et al., 2019).

Adaptive automation acts as an assistive system by amplifying the driver's input as long as the driver's state is normal and there is no risk of a lane departure, but it will give more authoritative haptic steering support when the driver is detected to be out of the loop and there is a risk of a lane departure (Benloucif et al., 2019). In other words, as shown in Figure 2, the shared control with the lane centering system will give priority to the driver's steering as long as the driver is actively steering the vehicle to keep it within the boundaries of the lane, even when the vehicle is not perfectly centered (e.g., when the driver is intentionally giving more space to one side of the lane for a large truck in the neighboring lane or a construction zone). Shared haptic control with the lane centering system is distinct from a simpler lane departure prevention system, because the lane centering system provides sustained lateral support to keep the vehicle within the lane, although the degree of support depends on the circumstances of the driver and road conditions.

Shared haptic control also has a potential benefit beyond increased driver engagement with respect to driver acceptance of lateral vehicle support. A system that adapts the degree of its support to the driver's steering tends to behave more similarly to manual driving behavior than a nonadaptive system 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 benefit of the system would not be compromised with a shared control design philosophy, 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 lane centering systems in production vehicles cancel or go into standby mode when the driver provides steering input, which acts as a form of punishment for the driver's steering participation and as a result encourages drivers to relinquish control to the Level 2 system, despite its operational requirements (Shutko et al., 2018). Contrary to a penalizing strategy with the deactivation of the system, we recommend that these systems allow drivers to override lane centering support by steering without the system going into standby mode; instead, the system should allow the driver's overriding input and resume support immediately once the driver's input has reduced, based on the road conditions.

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, such as lane departure prevention systems. Lane departure prevention systems remain quietly active in the background outside of the driver's awareness until the vehicle departs the lane or road, and then the system provides temporary assistance to nudge the vehicle back into the lane. The driver does not have to continuously activate or deactivate the lane departure system to receive its assistance, and he or she can override the input of that system by applying steering torque at any time. It is likely that drivers who have experienced lane departure prevention may expect a similar response from lane centering system. Furthermore, 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).

Limiting Automated Capabilities of Level 2 Systems

Some Level 2 systems offer automated 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. Some of these systems can also perform automated overtaking maneuvers. The problem with automating either aspect of the driving task is that they are both high-risk maneuvers that require the driver to be situationally aware of what is happening around the vehicle. Requiring a simple lever press by the driver, as is currently required by most Level 2 systems that have these features, contains no inherent check by the system to ensure the driver is engaged in the driving task when he or she initiates these maneuvers.

The difficulty that a driver can have with maintaining the necessary vigilance to be engaged in the driving task when using a Level 2 system increases the chance that these features could be activated without the driver being fully aware of the road environment, thereby potentially allowing the system to make the maneuvers when it is not safe to do so (Banks & Stanton, 2015). Furthermore, in the absence of a robust driver management system, there is also the risk that the driver might intentionally give the vehicle full responsibility of the lane changing or overtaking maneuvers, even though that would go against the fundamental operational requirement that the driver be in full control at all times when using the system. While it remains to be demonstrated how risky these automated lane changing or overtaking features are in general, we recommend that only Level 2 systems that have robust visual attention-based DMS should offer these features; ideally, such a DMS would have the ability to detect whether the driver has made one or more mirror checks or over-the-shoulder checks before performing the maneuver.

Rewarding Appropriate Driving Behavior With Driving Automation Access

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 would not be available for activation at all. On the other hand, if the driver demonstrates acceptably safe vehicle control and behind-the-wheel behavior (e.g., keeping eyes on the road), the driving automation could become available when in its ODD and it could remain available under those conditions unless the driver starts behaving in an unacceptable manner. This form of positive reinforcement is the reverse strategy to the system lockout punishment described in the section "Addressing Sustained Driver Noncompliance".

Such a mechanism for driving automation accessibility currently does not exist in any production vehicle. 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 the loop. Other incentivizing strategies for shaping driver behavior could require seatbelt use or keeping the crash avoidance systems on. We recommend that all currently available Level 2 systems not be accessible if the driver has disabled the crash avoidance features. Within the Level 2 system's ODD of limited-access roads, traffic conditions can change abruptly, requiring rapid deceleration from high speeds to avoid collision with slowing vehicles ahead. Automatic emergency braking can bring the vehicle to a stop far more quickly than ACC (IIHS, 2018). Lateral collision prevention systems also help drivers under circumstances in which their situational awareness might be strained, as when using Level 2 systems, by alerting the driver or preventing the vehicle from entering occupied spaces when making a lane change.

Another hypothetical design could also involve incentivizing positive behaviors while the driving automation is in use. For example, systems capable of sign recognition or linked to GPS-based speed limit databases could restrict setting ACC's settable 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.

Restricting Access to 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 functionalities available through peripheral applications. Donmez et al. (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 already by limiting access to vehicle settings submenus and the on-board digital owner manual while the vehicle is moving. 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, et al., 2016).

AIDING DRIVER UNDERSTANDING AND SAFE USE OF THE AUTOMATION

It is important for drivers to understand the driving automation constraints in their vehicle (Lee & See, 2004; SAE International, 2018). Understanding where (i.e., road environments with specific characteristics concerning, e.g., 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. In this section, we recommend that the ODD, which is also known as the intended operational environment for Level 2 systems (U.S. Department of Transportation, 2018), should be clearly defined and effectively communicated to the driver, and that drivers should be unable to engage the systems outside of the ODD.

Limitations of Training to Safely Operate a Level 2 System

The marketing of these systems often misleads consumers to overestimate what the functional capabilities are for Level 2 driving automation, which undermines understanding about its limitations and creates inappropriate expectations about where and how these systems can be used (Teoh, 2020). Accurate representation of these systems is necessary from an ethical marketing perspective, but it is not enough to ensure appropriate use and expectations. While the design characteristics that we have recommended so far in this paper can help to keep drivers engaged, on their own these strategies do not ensure that the driver understands what the system functional limitations are.

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 to use Level 2 systems safely (Casner & Hutchins, 2019). Hypothetically, adequate driver training could, in tandem with robust driver management design, increase driver engagement and proper use of the system by better calibrating a driver's trust in the system to its capabilities. The degree and accuracy of the information drivers receive about the limitations of advanced driver assistance systems affects how they interact with and trust those systems later on (Beggiato & Krems, 2013; Körber et al., 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.

It is unclear, though, how training could be comprehensively and accurately delivered to drivers of vehicles equipped with Level 2 systems. Drivers say that they would prefer to learn about their vehicles at dealerships, but dealership personnel frequently lack knowledge about the technologies on the vehicles they sell (Abraham, Reimer, & Mehler, 2018; Abraham et al., 2017), and this strategy would not be applicable to nondealership used vehicle sales. It is also not realistic to expect staff at rental agencies to have the necessary knowledge about all the vehicles in their fleet or to have the time to inform their customers at the time of vehicle pick up. Training also might be limited in the long run due to frequent or significant system functionality and interface updates (Endsley, 2017a).

In addition to owner manuals, automakers are making consumer information content more readily available through Internet streaming services. The content varies considerably between automakers, but generally includes, for example, instructional videos and information guides about brand-specific vehicle technologies. These online resources have the potential to help inform consumers about their roles and responsibilities when using Level 2 systems; however, this strategy relies not only on consumers proactively seeking out these resources, but also that those consumers access appropriate content only. The aforementioned concerns about accurate and appropriate advertising are relevant for any consumer information content, including the online content developed by the automakers and other consumers. Alternatively, the consumer could hypothetically access similar content through a self-administered training tool developed by the automaker via the infotainment system when he or she is behind the wheel. While this strategy could have merit to help inform appropriate use and understanding of a Level 2 system in real time, the nature of the information delivery would have to be considered carefully so as not to distract the driver. In light of all these considerations, Level 2 system design should not assume that drivers will receive any education or have any familiarity with the driving automation before getting behind the wheel.

Communicating to Drivers Where to Use Level 2 Systems

On-road testing has shown that Level 2 systems perform optimally on limited-access roads 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, 2020; IIHS, 2018). Unsurprisingly, the roads where drivers use the driving automation affect how well drivers enjoy driving with these systems. Drivers more frequently report greater 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 et al., 2020). Nevertheless, individual variability is high for ACC and Level 2 system usage rates on other road types (Reagan et al., 2019), which shows that system limitations are not currently being communicated well to drivers. It is also likely that recent fatal crashes involving the use of Level 2 systems outside of their intended ODD (e.g., NTSB, 2017, 2019) may not be anomalies, as there appears to be a segment of the driving population with a proclivity to use driving automation in more complex environments that are outside the ODD.

Drivers often seek information about their vehicles through the owner manual (Abraham et al., 2018), but these documents often vary significantly across automakers in terms of specifying where Level 2 systems should be used, sometimes do not capture all situations where the systems struggle, and at times use ambiguous wording (Reagan et al., 2017; Wright et al., 2020). Although we recommend clarity and thoroughness in owner manuals because they will continue to serve as important reference material to drivers, it is impractical to expect all drivers to consult these documents before operating a vehicle with Level 2 driving automation. It is also unfeasible to require drivers to remember an exhaustive list of all the subtle nuances of the road conditions that systems may struggle to cope with.

Part of the solution is to utilize the vehicle interface to communicate to the driver in real time about what the Level 2 system is doing and what the driver needs to do in response to the dynamic feedback, which is known as automation transparency (Endsley, 2017a, 2017b). Visually displaying constant information about (a) changes in the system confidence to handle current road conditions, (b) the purpose of the displaying system confidence to inform the driver's role, and (c) the process of reaching the system's boundaries has the potential to improve driver vigilance for monitoring the vehicle interface and to know when to intervene. System confidence refers to the degree to which the driving automation's algorithms have the necessary information and appropriate traffic or road conditions to operate in. This information would also show environmental considerations for system operation, for example, with rain compromising sensor capabilities resulting in system performance degradation. Having the vehicle interface display information about when and why the system approaches its operational limits and what the driver must do in response to that information altogether would help to reinforce the driver's understanding about the boundaries of the system's ODD.

An example of such an interface is one that shows the dynamics of the headway time, range rate (relative velocity between the vehicle and a vehicle ahead), and time-to-collision as used in Seppelt and Lee (2007, 2019). This type of display describes the ACC component of the Level 2 system by capturing its system state and current settings, as well as warning the driver when the road conditions exceed its braking authority. Current ACC systems typically have gradual decelerations (on average approximately between 0.2 to 0.3 g; IIHS, 2018) in response to changing traffic conditions; however, even within the ODD, the dynamic road conditions can rapidly reach the upper bounds of the system's limit, thereby requiring driver intervention to brake beyond ACC's capabilities or to proactively disengage ACC to avoid system exceedance. To this end, the interface used in Seppelt and Lee's (2019) study also contained discrete visual and auditory warnings to notify the driver to a rapid change in vehicle performance when it reached its operational limits. These warnings facilitated decision-making for when to take over because the continuous system feedback provided the necessary contextual information to understand the purpose of the warning.

Using these types of interfaces has been shown to improve driver engagement and takeover readiness with also less time spent performing secondary tasks (Stockert et al., 2015). Constant interface communication about ACC confidence appears to be more beneficial than discrete warnings in terms of driver takeover behavior in response to ACC failures (Seppelt & Lee, 2019). Moreover, performance on a secondary task does not seem to be affected 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 helps drivers better manage their attention when monitoring the interface for changes to the driving automation's operating status that require the driver to intervene. Another advantage of this type of interface is that it has the potential to reduce mode confusion, where drivers confuse the operating status of the Level 2 system to be in a mode that it is not; for example, by assuming the system is on and providing active support when in fact it is on standby mode.

A word of caution about these displays that Seppelt and Lee (2019) note: if the display is merely an indicator of system confidence, the information could be interpreted in a number of ways from which drivers may learn to over rely on the display or they may not use it at all if they perceive the system to be unreliable. The driver needs a sense of process and purpose about the system degradation and the method of communication to understand what system boundary is being exceeded or what performance element is not being maintained for the given road conditions. Incorporating all of this information into a simple, comprehensive display reinforces understanding about the limitations of the Level 2 system and its ODD and also helps to contextualize the displayed information to better facilitate driver decision-making.

It is for these reasons why a similar interface specific to the lane centering system might be difficult for developers, because the road conditions change abruptly at high speeds within the ODD. Lane centering functionality of currently available Level 2 systems often struggles to handle road conditions because of limitations of line of sight for the forward mounted cameras. The system's limited ability to detect road conditions far enough ahead would constrain an interface's ability to reliably and intuitively communicate the necessary information about lane centering performance, purpose, and driver's role. Nevertheless, even an interface primarily concerned with ACC's performance, purpose, and driver's role would serve as a proactive strategy to keep the driver engaged in the loop, especially if the other proactive design considerations discussed in this paper were implemented.

Self-Limiting Where Level 2 Systems May Be Used

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 NHTSA develop a method to verify that automakers have done so. Currently, the National Highway Traffic Safety Administration (NHTSA, 2017) proposes self-limiting ODDs, but only for highly automated vehicles (Level 3 and above). Limiting system use to roadway types where Level 2 automation performs well would reduce the demands on the driver to monitor the vehicle interface and decrease the likelihood of the system behaving unexpectedly and requiring driver intervention. Some automakers use GPS information or infrastructure conditions to lock out a driver's ability to operate the system outside the ODD.

Most drivers expect that a system will self-limit where it should not be used by not allowing the driver to engage the system (Teoh, 2020). Part of how a system restricts access beyond its ODD could include notifying the driver when the vehicle approaches the boundaries; 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 et al., 2016; Teoh, 2020), such a strategy puts the driver and other road users at risk.

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. Compounding the issue is the fact that these systems are often marketed to have more sophisticated autonomous capabilities than are possible with Level 2 driving automation, which leads to consumers having inappropriate expectations about what the system capabilities and limitations are (Teoh, 2020).

Safeguard design considerations are needed to ensure that the driver remains in the loop of the driving task and uses the driving automation within the operating conditions for which it was designed. The interrelated elements needed for the design of a robust driver monitoring and management system that integrates the automation's functional performance and driver–vehicle interactions underscore the importance of considering the guidance presented in this paper in a holistic manner (as summarized in Table 1), as opposed to considering the various aspects in piecemeal fashion. 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 become disengaged if automakers do not also have driver management designed into the driving automation. Nevertheless, the guidance provided in this paper is based on a synthesis of and extrapolation from currently available data. These recommendations will hopefully be subjected to continued empirical evaluation in both simulated and actual driving conditions.

This paper reviews a variety of driver management strategies, some of which proactively encourage driver engagement and others penalize driver disengagement. These strategies help to shape behavior in different ways and, while both are necessary, it is preferable to utilize the proactive and rewarding strategies before the reactive penalizing ones. Proactively encouraging shared control with the driving automation should reduce opportunities for driver disengagement while simultaneously improving a driver's general experience with the system. Part of this strategy involves an interface that reduces opportunity for mode confusion by clearly communicating the Level 2 system's operating status, current settings, and when it approaches its operational boundaries while informing the driver about his or her role in the vehicle's behavior. To further ensure appropriate and safe use, these systems ought to be functionally restricted to operate only within their ODD. Nevertheless, there is the chance that the driver could still fall out of the loop, which is dangerous with the current capabilities of Level 2 systems; therefore, the vehicle must monitor

TABLE 1: Summary of Recommendations for Design Philosophies to Minimize Driver Disengagement and to Aid Understanding of Where the Level 2 Systems Should Be Used.

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 head orientation. • Indirect methods include steering wheel input, duration since start of the drive, and time it takes for the driver to respond to attention reminders.
Driver management	• 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 bimodal alert, preferably visual and seat tactile. It should then escalate to a trimodal 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 instances of noncompliance should result in pulse braking, ACC headway distance increase, vehicle stopping protocol, 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, unless the system has a robust visual attention-based DMS. • Drivers should only be able to engage Level 2 systems if crash avoidance systems are on.
Aiding driver understanding and safe use of the automation	• The ODD for Level 2 driving automation systems should be clearly defined and communicated to the driver in all consumer information content, including the owner manual. • A dynamic vehicle interface should communicate the system's performance, ODD restrictions, and the driver's role for the current road and traffic conditions in real time. • Drivers should only be able to engage Level 2 systems within the ODD. • Automakers must advertise their Level 2 systems accurately, not use misleading names that imply greater autonomous capability than is feasible for the systems, and transparently describe the driver's roles and responsibilities when using the systems.

Note. ACC = adaptive cruise control; DMS = driver monitoring system; ODD = operational design domain.

the driver for signs of disengagement through eye gaze or head orientation and hands on the wheel. If the driver is detected to be out of the loop, the driver management systems involving attention reminders and countermeasures should be utilized to actively discourage driver disengagement and to return the driver back to the driving task as quickly as possible.

Although one could argue that forcing the driver to be engaged negates the idea of having driving automation support the driving task, the capabilities and limitations of the systems that are available today require the driver to be fully in the loop because he or she is responsible for the vehicle's performance at all times and must rapidly intervene when it reaches its operational boundaries. This supports the recommendation for limiting the functional capabilities of the Level 2 system to not be able to automatically change lanes or overtake, unless the system has a robust visual attention-based DMS. The absence of those automated features does not inconvenience the driver or make the driving task more difficult, given that all currently available forms of driving automation are designed for the driver to be in supervisory control. Moreover, the argument that the automation of lane changing or overtaking in general improves the safety of those maneuvers has yet to be empirically supported. Lateral collision prevention systems, on the other hand, have established safety benefits and underscore the importance of a driver not being able to use the Level 2 system if the crash avoidance features are turned off.

Certain driver management strategies could be more effective in encouraging the use of Level 2 systems than others. Proactive strategies, such as shared haptic control, require the driver to constantly participate in steering, but the lane centering support makes the overall task easier by requiring less effort from the driver. With the current functional limitations of these systems, the driver's constant steering participation should reduce the number of uncomfortable situations where the lane centering system behaves in a way that is unexpected, which should increase the likelihood of its use. Furthermore, an interface that communicates to the driver about what the system is doing and what the driver must do helps to keep the driver informed without distraction.

Likewise, reactive strategies in response to detected driver disengagement can help to encourage appropriate and safe use of the system with minimal driver frustration if the strategies are scaled according to the driver's state and driving conditions. Specifically, attention reminders should be initiated quickly after driver disengagement is detected, but the initial phase of the alert should be visual in case the alert is a false alarm. Should the driver not respond, the visual alert should then be paired with seat vibration to be driver-focused, which should help to avoid social ramifications when other occupants are present. Countermeasures, such as pulse braking, ACC headway increase, vehicle stopping procedures, and system lockouts, are necessary if the driver does not respond to the attention reminders because Level 2 systems are not fully autonomous. While those final phases of the escalation procedure, particularly the system lockout, might be undesirable from a driver's point of view, there is evidence that some drivers will deliberately misuse these systems, which can have fatal consequences. However, opportunities for disengagement should be reduced if the proactive strategies that we have outlined in this paper are designed into Level 2 systems to help facilitate driver engagement, which should lower the likelihood of a driver ever reaching the final phases of the escalation procedure. This in turn should decrease driver frustration and confusion when using these systems and increase system usage rate.

Next Steps for Evaluating the Safety Benefits or Limitations of Level 2 Systems

It is unclear from the data available what the safety benefits and limitations are for Level 2 driving automation. Current Level 2 systems vary in terms of vehicle functional performance and driver management strategies (American Automobile Association, 2020; IIHS, 2018), both of which interplay to have consequences for overall vehicle and driver behavior. Multiple data sources are therefore needed to understand the positive, neutral, or negative safety effects that these systems have on vehicle-related fatalities, injuries, property damage, and driver behavior.

A universal vehicle identification number (VIN) database that contains the specific types of crash avoidance systems and Level 2 systems equipped on every vehicle would facilitate identifying which vehicles are equipped with these systems in order to examine the effects of Level 2 driving automation on crashes. Although crash data can provide some information about crash circumstances, they do not capture system activity state at the time of the crash, which requires information from the automaker. Unfortunately, event data recorders collect only a few seconds before and after the crash about what the driver and vehicle were doing; however, automakers are not required to collect information about the state of the automation. Automakers need to have longer stored data logging periods of driver monitoring as well as of crash avoidance system and Level 2 system activity to capture what happened leading up to and at the time of a crash.

While these data sources provide information about the scope and details of crashes, longitudinal naturalistic data can enhance our understanding of the circumstances that lead to crashes in the first place as well as high-risk situations that do not always result in a crash, such as near misses or dangerous behind-the-wheel behavior. In addition, naturalistic studies are uniquely positioned to show how regular driving with these systems might be affected, for example, by potentially reducing the number of conflicts that normally activate crash avoidance systems, such as automatic emergency braking, as well as whether there are other unintended consequences related to system use that have a bottom line in crash effects. Naturalistic data also reveal what these systems are like to live with and how driver-system interactions evolve over time. The lessons learned from these different types of data are crucial to inform the designs of Level 2 systems as well as to encourage effective and data-driven federal regulation and guidance. Moreover, in the future, these data could be used to determine whether our recommendations have helped to improve the overall safety of Level 2 system designs.

Current technologies will be available for decades to come as they slowly penetrate the registered vehicle fleet (HLDI, 2019b). The slow uptake of Level 2 driving 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 their potential safety benefits.

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