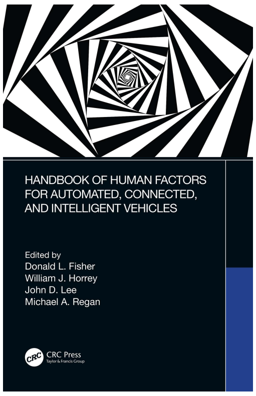

Handbook of Human Factors for Automated, Connected, and Intelligent Vehicles

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HMI Design for Automated, Connected, and Intelligent Vehicles

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15 HMI Design for Automated, Connected, and Intelligent Vehicles

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CONTENTS

KEY POINTS

- The guidance that is available on the design of HMIs, plus various SAE and ISO documents, generally reflects pre-2015 research conducted on driver information/safety systems that provided little or no automated driving capability or connectivity;
- Insofar as the existing guidance is relevant to ACIVs, the basic driver information needs, HMI considerations for transitions of control alerts and warnings, and high-level principles of message management are well understood and have been documented in a variety of sources.
- The development of more comprehensive and effective HMI guidelines will require a better understanding of the changing nature of driving and of the implications of these changes for HMI design.

15.1 INTRODUCTION

A key design element in advanced vehicles is the human–machine interface (HMI).[1] The HMI refers to displays that present information to the driver and controls that facilitate the driver's interactions with the vehicle as a whole and indicate the status of various vehicle components and sub-systems (Campbell et al., 2016). In the context of vehicle safety systems in particular, the HMI should effectively communicate information while managing driver workload and minimizing distraction (Jerome, Monk, & Campbell, 2015).

HMI design requirements for automated, connected, and intelligent vehicles (ACIV) must be determined in the context of many considerations, including their influence on safety, public perception and perceived value, the mix and behaviors of legacy vs. connected vs. automated vehicles (AV) over time within the vehicle fleet, and the degree and type of automation associated with the HMI (see also Noy, Shinar, & Horrey, 2018). In general, safe and efficient operation of any motor vehicle requires that the HMI be designed in a manner that is consistent with driver needs, limitations, capabilities, and expectations—a continuing challenge is to identify just what these are amidst the changing and uncertain landscape of advanced vehicle technology.

Despite these challenges, our objective in this chapter is to summarize what we do know (or at least, what we think we know) regarding HMI design principles for ACIV. Many of these principles are aimed at the important issues raised in the preceding chapters; i.e., how can the design of the HMI be used to increase trust (Chapter 4), manage workload (Chapter 6), and improve situation awareness (SA) in ACIV (Chapters 7 and 13). All these goals support the broader goal of safety—the safety of the drivers and occupants of ACIV, as well as the safety of all road users.

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[1] The literature generally uses the terms Human–Machine Interface (HMI) and Driver–Vehicle Interface (DVI) interchangeably; we will use HMI throughout this paper but view HMI and DVI to be synonymous for our purposes.

15.2 AUTOMATED VEHICLE HMI DESIGN

Considerable research has been conducted about how to design the HMI for vehicles with Level 0 and Level 1 automation (see Chapters 1 and 2 for a discussion of the levels of automation). Driver preferences, behaviors, and performance have been extensively studied using surveys, mock-ups, driving simulators, test tracks, and real-world driving; much of this research has been summarized and codified into design guidance (e.g., Campbell, Richard, Brown, & McCallum, 2007; Campbell et al., 2016), and into standards and best practices published by organizations such as the Society of Automotive Engineers (SAE) International and the International Standards Organization (ISO).[2] However, relatively few published research studies provide actionable insights into the questions surrounding how to design the HMI for vehicles with higher levels of automation. In many respects, this reflects the nascent level of maturity of the technology, but perhaps a broader challenge is the host of uncertainties surrounding the circumstances and scenarios in which automated driving system (ADS) HMIs will be fielded.[3] In particular, AV warnings may need to be richer and more carefully designed than the simpler hazard warnings that have been the focus of much of the published research. For example, driver warnings and even status information in AVs have the added long-term goals of aiding the driver to develop and maintain a functional mental model of the system, as well as supporting and increasing driver trust in the system. Information may also be frequently presented in situations where the driver is not fully engaged in the driving task and may be unaware of current conditions.

With these caveats in mind, we provide tentative design principles below for

- providing both basic status and mode information,
- identifying the key principles for the presentation of warning information,
- facilitating transfer of control (TOC), and
- supporting improved SA.

15.2.1 COMMUNICATING INFORMATION WITHIN A GIVEN MODE

When the driver is operating in a given level of automation (i.e., control is not being transferred between levels), the HMI must be designed appropriately for the level of automation.

15.2.1.1 Communicating AV System Status and Mode

Automation mode refers to the level and type of automation that is active at a particular time. This includes the specific driving functions (e.g., steering, speed maintenance, and/or braking) that are automated and other information that will aid the driver's understanding of the system's current operation. The status of automation refers to the information about the system overall, including mode, that is communicated to

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[2] Jeong and Green (2013) as well as Campbell et al. (2016) provide extensive lists and summaries of documents published by SAE and ISO that are relevant to HMI design.

[3] Automated Driving Systems are used in this chapter to refer to automated vehicles with one or more driver support features (SAE Levels 0–2) and automated driving features (SAE Levels 3–5).

TABLE 15.1
Principles for Presenting System Status Information in AV

Type of Status Information	What Information to Provide	Why Information Is Provided
System activation or on/off status	A display indicating which automation feature/function/mode is currently active.	To support driver awareness of current automation mode when the driver seeks this information.
Mode transition status	A display indicating that a TOC is occurring or that one will occur in the near future.	Under normal operating conditions, this information is presented to help drivers maintain awareness of the driving tasks.
Confirmation of successful transfer from automated to manual control	A display or message confirming for the driver that control has been transferred to the driver as they would expect, or communication of a failed/incomplete TOC if the transfer is unsuccessful.	To indicate a successful TOC from the automation system to the driver.
System fault or failure	A display or message indicating that part of the system has failed, is not functioning correctly, or that the system has reached some operational limit.	To alert drivers that they must intervene and reclaim control of driving tasks that have previously been performed by automation, due to a system fault or failure.

the driver. Appropriate feedback about automation status and mode is important for (1) maintaining driver's SA, (2) communicating if the driver's requests (e.g., a request for a TOC) have been received by automation, (3) informing drivers if the system's actions are being performed properly, and (4) informing drivers if problems are occurring (Toffetti et al., 2009).

Overall, vehicles should display the information that drivers need to maintain an understanding of the current and impending automation status and modes. Table 15.1 (from Campbell et al., 2018) shows the types of status information that can be provided to the driver about the automation and design considerations for presenting this information.

15.2.1.2 HMI Guidelines for AV Warnings

Past research and guidelines are available to support the design of visual, auditory, and haptic warnings (see e.g., Campbell et al., 2007; 2016; 2018). A note of caution is warranted here: few research studies are available to support the range of warning situations and conditions associated with Level 2–4 automation. In general, the utility of a particular warning approach may vary with the level of automation, the manner in which the automation is implemented, and the driver's level of engagement with the driving situation and conditions. Thus, we will focus here on three design parameters of warnings that are both well understood and highly applicable to AVs: selecting warning modality, reducing false and nuisance warnings, and using a staged (or graded) approach to warnings.

15.2.1.2.1 Selecting Warning Modality

The modality of warning presentations can impact driver responses and behavior. The type of modality that is appropriate for a message depends on the driving environment (e.g., expected vehicle/cab noise and vibration, hazard scenario, etc.), the criticality of the message (e.g., hazard versus non-hazard situations), the location of the visual displays (assuming those locations cannot be changed), and other factors. Most of the relevant literature (e.g., Kiefer et al., 1999) suggest that performance can be improved by combining auditory and visual messages when presenting warnings. In general,

- *Auditory warnings* are capable of quickly capturing the driver's attention and can be used to present short, simple messages (e.g., simple or complex tones or speech messages) requiring quick or immediate action, including high-priority alerts and warnings (Lerner, Kotwal, Lyons, & Gardner-Bonneau, 1996). The auditory mode may be particularly effective in getting the driver's attention in situations where the driver is distracted or not looking at the roadway or the instrument panel. Especially with higher levels of automation, the presentation of auditory warnings may have to be integrated/coordinated with other sound sources (e.g., entertainment systems) to aid the driver's perception and understanding of the warning.
- *Visual messages* are best for presenting more complex information (Deatherage, 1972) that is non-safety-critical and does not call for immediate action, including continuous information (uninterrupted presentation of information over a trip segment, a trip, or even a longer period of time), lower-priority information such as navigation instructions, or cautionary information. In this regard, visual messages presented through the HMI may be used to help drivers recover their SA after a period of disengagement by presenting information about surrounding vehicles, locations of potential hazards, or upcoming turns. If the visual display is presented in a standard location inside the vehicle (e.g., the instrument panel or the center stack) and requires the driver to look away from the roadway to acquire the message, it can be distracting.
- *Haptic/tactile messages* (like auditory warnings) are capable of quickly capturing the driver's attention and can be used if an auditory message is unlikely to be effective. Two types of haptic interfaces are discussed in the literature: *vibrotactile* and *kinesthetic*; these types of haptic interfaces have fundamental differences that impact how well drivers detect and understand haptic messages. *Vibrotactile interfaces* provide information to the driver using vibrations and may be included in seat belts, seats, foot pedals, and the steering wheel. *Kinesthetic interfaces* provide information by causing limb or body motion. Some examples of this type of haptic interface are when counterforces are applied through the accelerator pedal to "push back" the driver's foot, or when brake pulse displays cause a sudden jerky motion, or when steering wheel rotations cause the drivers hands and arms to move.
- Haptic/tactile warnings may be useful, for example, when delivering a takeover request. A recent study (Petermeijer, de Winter, & Bengler, 2016)

indicated that vibrotactile displays have the potential to grab driver's attention when the automation reaches its functional limits. In this case, sufficiently salient stimuli should be used to grab driver's attention, thus either high amplitude and high frequency vibrations or vibrating a large area might be required. In general, haptic messages can serve a similar function as auditory messages and can be useful when drivers are engaged in secondary tasks (e.g., listening to music or watching a video at a high volume) or using portable devices not under the control or purview of the vehicle.

- Critically, all forms of haptic or tactile warnings require physical contact with the driver to deliver information (but also see Gupta, Morris, Patel, and Tan (2013) for recent interest in non-contact haptic interfaces). Depending on the level of automation associated with the vehicle and the way the automation is implemented, the driver may not be in consistent contact with pedals, the steering wheel, or even portions of the seat.
- *Multi-modal feedback* is recommended for takeover requests to minimize the likelihood of misses and provide redundancy gains (Prewett, Elliott, Walvoord, & Coovert, 2012). Some research has found that visual–vibrotactile feedback is more effective compared with visual-only feedback (Prewett et al., 2012). A survey of 1,692 people found that multimodal takeover requests were the most preferred option in high-urgency scenarios, whereas auditory takeover requests were more preferred in low-urgency scenarios (Bazilinskyy, Petermeijer, Petrovych, Dodou, & de Winter, 2018).

15.2.1.2.2 Reducing False and Nuisance Warnings/Alarms

From Campbell et al. (2016), false alarms are alarms that indicate a threat when no threat exists. They should be avoided as they can cause driver distraction, lead to incorrect decisions and/or responses, and even increase driver's reaction time to true warnings. Nuisance alarms are alarms that correctly indicate a potential threat, but that the driver does not believe are warranted or needed, perhaps because the driver was already aware of the threat or believes that the threat will be resolved without driver intervention. Importantly, drivers may not necessarily make distinctions between false and nuisance alarms. Excessive false or nuisance warnings can increase workload and decrease the driver's trust in the AV system. Lerner et al. (1996) and Horowitz and Dingus (1992) provide some strategies for minimizing the frequency and impact of false/nuisance warnings, including

- Deactivate a warning device automatically when it is not needed during a particular driving situation (i.e., require the shift lever to be in reverse gear to place a backup warning device into the active mode).
- Allow the driver to reduce detection sensitivity to a restricted limit that minimizes false/nuisance warnings without significantly affecting the target detection capability of the device.
- Present a warning only after a target or critical situation has been detected as continuously present for some specified minimum time.

- Mitigate annoyance by allowing the driver to reduce warning intensity or volume.
- Change modality as the severity of the situation increases (e.g., warn first visually, then add auditory component as the severity increases).

15.2.1.2.3 Using Staged Warnings

A considerable body of research supports the value of staged warnings in the automotive environment for aiding both driver's comprehension of, and response to, a threat or hazard, as well as increased comprehension of system operation (e.g., Lerner et al., 1996; General Motors Corporation & Delphi-Delco Electronic Systems, 2002; Lee, Hoffman, & Hayes, 2004; Mendoza, Angelelli, & Lindgren, 2011). Staged (or graded) warnings may include two or more stages of cautionary information that increase in urgency proportionally (in terms of timing and perhaps modality) with the criticality of the hazard situation prior to the presentation of a warning indicating an imminent hazard. For example, in a collision warning application, a one-stage warning system may provide only an imminent collision warning (i.e., the warning requires immediate corrective action), while a two-stage system provides a cautionary collision warning (i.e., the warning requires immediate attention and possible corrective action) to cue the driver, followed by a separate imminent collision warning (see also Campbell et al., 2016).

The Cadillac Super Cruise™—a Level 2 vehicle—from General Motors provides a recent example of a staged warning.[4] If the system detects that the driver is not attending to the roadway, it provides a series of warning lights on the steering wheel, audible alerts, and/or a vibration in the seat. Only if the driver fails to respond appropriately to these alerts does the system apply the vehicle's brakes until it stops.

Two- or multi-stage warnings have the benefit of providing continuous information to the driver, provide more time for the driver to recognize and respond to an emerging threat, and may help drivers in developing a functional and coherent mental model and better awareness of the operation and limits of the automation system (Campbell et al., 2016).

15.2.2 CONVEYING INFORMATION ABOUT THE TRANSFER BETWEEN THE DRIVER AND THE ADS

The HMI must also be designed to facilitate the TOC between the ADS and the driver; note that there are two types of TOC: (1) from the driver to the system and (2) rom the system to the driver. A recent naturalistic driving study collected 454 hours of autopilot use from Tesla drivers and found a total of 16,422 transfers of control (Reimer, 2017). In the study, the number of transfers from the human driver to the system was 8,211, and the number of transfers from the system to the human driver was 8,253. Furthermore, transfers from the system to the human driver split into two categories: (1) transfers initiated by the human drivers ($n = 8{,}211$) and (2) transfers initiated by the system ($n = 42$) (Reimer, 2017). Much of the literature in this area is

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[4] https://www.consumerreports.org/autonomous-driving/cadillac-super-cruise-may-lead-to-safe-hands-free-driving/

concerned with a system-initiated TOC when the driver is unengaged or has low SA; many relevant scenarios here involve a potential hazard. However, TOC is an issue with AVs even when the driver is situation aware. Imagine that a driver is monitoring the dynamic driving task with their hands on the wheel and feet on the pedals. Automatic emergency braking could be too slow to avoid a child who suddenly runs out into the street, but a steering maneuver initiated by the driver may successfully avoid the hazard. Will the driver recognize this while in Level 2, as well as he or she does in Level 0 or 1? And, if not, how can the HMI be used to support the correct decision? If the driver is unengaged when the TOC request is made, this poses additional burdens on the HMI. Augmented reality head-up displays (HUDs) have been proposed as one solution to highlight the areas that pose potential threats or are of central concern to the immediate driving task (i.e., contain safety-critical traffic information). In general, the HMI needs to be designed to support all these situations; some general guidance for TOCs is presented below.[5]

15.2.2.1 HMI Design Issues for TOC to and from the Driver

15.2.2.1.1 TOC from the Driver to the System

This reflects a series of operations through which the driver transfers responsibility for performing part of or the entire driving task to the automated system. Providing appropriate information through the HMI is important during these transfers to maintain a driver's trust in the system and to help drivers maintain awareness of driving tasks and the broader driving situation. In general, the system should aid the transition from manual to automated driving by acknowledging a driver's request to engage the automation and providing information about the status of the TOC throughout the process. The following principles can be used to support this goal:

- The current system status should always be provided (Toffetti et al., 2009).
- Automation engagement requests should be acknowledged upon receipt to prevent duplicate or conflicting inputs from the driver and to prevent the driver from releasing control of the vehicle without the automation being activated.
- Feedback acknowledging a driver automation activation request should be provided within 250 ms of the driver's input (ISO 15005, 2002; AAM, 2006).
- If the transfer was successful, a notification should be provided to the driver along with an updated automation status display.
- If the transfer was unsuccessful, the driver should be provided with a notification as to the failure of the automation to engage and the reason why the automation did not engage (Tsao, Hall, & Shadlover, 1993; Merat & Jamson, 2009).

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[5] Research on this topic is limited. These principles are perhaps most relevant to transitions occurring in lower levels of automation; i.e., Level 3 or below.

- The use of uni- or multi-modal notifications and messages should be based on the context of the situation.
- Distinctive messages should be used for successful and unsuccessful TOC events.

15.2.2.1.2 TOC from the System to the Driver

This reflects a series of operations through which the automated system transfers responsibility for performing part of or the entire driving task back to the driver. Importantly, this form of TOC can range from gradual and expected by the driver to immediate and completely unexpected. In general, the system should aid the transition from automated to manual driving by providing information about the need for the driver to take over vehicle control. The following principles can be used to support this goal:

- The driver should be provided with information on when they need to take control (Gold, Damböck, Lorenz, & Bengler, 2013; Blanco et al., 2015).
- The driver should be provided with information on how to take control if a specific control input is required (Toffetti et al., 2009).
- The driver should be provided with information on why the driver needs to take control. For time-critical situations, this may be a simplified "take control" message. For less time-critical situations, more information (e.g., upcoming system limits; Naujoks, Forster, Wiedemann, & Neukum, 2017) may be provided.[6]
- The current system status should always be provided, allowing the driver to validate the disengagement (Sheridan & Parasuraman, 2005).
- Notifications and messages related to a "take control" message should be multi-modal (Blanco et al., 2015; Toffetti et al., 2009; Brookhuis, van Driel, Hof, van Arem, & Hoedemaeker, 2008).

15.2.2.2 HMI Solutions for SA Support: Improve SA for Both Normative and Time-Critical Driving Situations

A consequence of automated driving may be a loss of SA by the driver (see also, this Handbook, Chapters 7, 13). Disengagement from the active control loop and/or a focus on non-driving activities while the vehicle is being controlled by automation may lower the driver's attention to and awareness of numerous aspects of the driving task, including traffic control devices, signs, other vehicles, and potential hazards. There may also be situations where the demands on the driver are too great to expect the driver to be able to assume control of the vehicle in the time available (see e.g., this Handbook, Chapter 6). As discussed in the previous sections, in Levels 2–3 systems, the system and the human driver may transfer control of the vehicle back and forth during driving as needed. When the system initiates the transition, the driver has to transition from being a passive monitor/supervisor in a vehicle being driven by the automated system to becoming an active controller of the vehicle. In this case, the driver must become fully engaged and takeover vehicle control in a timely manner.

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[6] The driver's ability to take control may be faster and easier with lower levels of automation.

AV designers may assume drivers would perform their allocated roles (e.g., monitoring the driving situation and the system) and maintain their SA in automated driving, but recent fatal crashes (e.g., the self-driving Uber accident in Tempe, AZ) demonstrated the frailty of such assumptions (e.g., the driver watching a video instead of monitoring during automated driving). During the takeover phase, the human driver may have to identify the current situation, surroundings, and required actions in a very short period of time. If the human driver is totally disengaged and does not pay attention to the roadway environment (e.g., engaging in secondary tasks, sleeping, etc.) during automated operation, it will take a relatively longer time to build up SA to an appropriate level for intervention. In worst cases, drivers may not be able to take over within the available time or may contribute to other errors.

Proactive HMIs could help driver's attention management and takeover performance by incorporating information about driver state (e.g., overall readiness, glance history, secondary task activity, etc.; see also this Handbook, Chapter 11) and immediate tactical demands into an alerting approach that helps direct the driver's attention to time-critical information. Future vehicle designs may be able to use an advanced, proactive HMI that can help drivers re-engage with the driving task through information that is tailored to their specific information needs. For example, the HMI can be used to directly provide critical information to the driver or to help direct the driver's attention to critical information and/or information elements in the roadway environment. This could include timely presentation of attentional cues, alerts, or critical roadway information (e.g., missed guide signs or temporary roadside messages; see also principles for designing to support SA developed by Endsley, 2016). This could include design features such as an HUD with augmented reality capabilities that could be integrated with a driver state monitoring system to present such information. In the short term, the proactive HMIs can help drivers' takeover performance and decrease takeover time, and in the long term, this could improve driver trust and prevent potential misuse and disuse of AVs (Parasuraman & Riley, 1997).

15.3 CONNECTED VEHICLE HMI DESIGN

Connected vehicles (CV) wirelessly receive basic safety messages (BSM) from, and broadcast to, a range of sources and sinks in their environment including other vehicles and road users (Harding et al., 2014; ITS JPO, 2018). BSM packets contain information on position, heading, and speed of nearby connected road users (e.g., vehicles, motorcycles, pedestrians, etc.). The safety of the ego-vehicle movement is estimated using projections of others' movements as well as data on non-connected proximal objects using on-board short-range sensors. In addition, CV technologies allow for the linkage of nomadic devices (e.g., mobile phones, wearables, etc.) and cellular telematics (e.g., wireless updates of in-vehicle software), creating the potential for a veritable in-vehicle cockpit featuring various types of information, displays, and controls. Thus, while the central focus of the CV HMI is safety-relevant information, it is important to consider that it also serves as a medium for infotainment and entertainment services.

CV technologies can exist at any level of automation, with basic technologies already available in a substantial portion of the current fleet (e.g., Bluetooth connectivity to personal devices). The central design challenge of CV HMIs is the balance between the driver's access to information and the need for minimal distraction away from activities critical for safe vehicle control (Jerome et al., 2015; this Handbook, Chapters 6, 9). CV HMIs are also available to a variety of road users (pedestrians, bicyclists, and motorcyclists) via personal devices and roadway infrastructure (e.g., pedestrian flashing beacons). Each of these interfaces serves the safety purpose of alerting the user to potential path intrusions. However, the interface and information design considerations vary based on where and how they are being used (for related discussions in this Handbook, see Chapters 7, 13).

Currently, CV technologies are still in the developmental phase (Harding et al., 2014). The design features of CV HMIs, particularly the content and location of information provided to the vehicle occupants, will evolve with advancements in communication standards, infrastructure design, and vehicle technologies. Below, we discuss basic HMI design guidelines for the key configurations associated with CVs, with the expectation that these will change with related technological advancements.

15.3.1 Vehicle-to-Vehicle (V2V) Information

The display real estate within the vehicle is limited, and safety critical information should be prioritized and salient. Much of this information is related to potential path intrusions by other road users. In this section, we will specify design requirements for displaying safety-relevant vehicle-to-vehicle (V2V) information. V2V information is primarily intended to provide an *omni-directional awareness of other vehicles* (NHTSA, 2017) to help drivers plan maneuvers (e.g., overtaking, merging, etc.), respond to unexpected incursions (e.g., sudden deceleration of lead vehicle), and monitor the movement of traffic.

15.3.1.1 HMI Design for Status of CVs

Drivers perform a variety of driving tasks while navigating in the midst of other vehicles, including lane changes, selecting and maintaining following distances, and overtaking other vehicles. Knowing the positions and movements of other vehicles can enhance the driver's SA and help in smooth execution of vehicle control. V2V technologies extend the amount of information available beyond the limits of the driver's perceptual capabilities and on-board sensors and cameras. This makes them particularly useful in warning the driver of hazards in difficult terrain and visibility, adverse weather conditions, and challenging traffic situations (NHTSA, 2017; Harding et al., 2014). CV HMIs can also provide traffic status information intended for use by the driver in preparation for upcoming maneuvers. Upcoming turns, distance to a destination, and relative positioning of the ego vehicle to a lead vehicle are some of the most commonly provided safety-relevant information. Status information is particularly safety-critical in situations when the driver is preparing to execute potentially demanding maneuvers and may want to survey the status of nearby traffic. Generally, continuous traffic status indications must be minimally intrusive during normal driving to prevent overloading the driver with non-critical information.

Two primary design considerations for provision of status information in CVs are listed below:

- Consider the provision of a display indicating the position and movements of the hazards in situations where the hazards may be hidden or hard to identify from the driver's viewpoint. This information is relevant in unexpected situations (e.g., pedestrian in a limited access highway) or in limited visibility. The driver must be given sufficient time to perceive and process the information on the display, without the risk of inopportune distraction.
- In certain situations, the CV HMI may provide integrated traffic status information (e.g., vehicle movements, traffic signal status, changes in traffic flow relative to planned maneuvers of the ego vehicle) to advise the driver of the safety risks of executing specific maneuvers; for example, see ISO 17387 (2008) and SAE (2010) for standards related to lane change coverage status information. One example is executing a lane change and checking for vehicles encroaching the blind spot. CV HMIs can provide a comprehensive display of the traffic along with advisory information on the safety of executing the lane change (Campbell et al., 2016).

Status information can also be useful in the case of heavy vehicles, such as automated truck platoons. The lead platoon vehicle communicates its movements to following vehicles through V2V communication; these followers can choose to enter or leave the platoon at will (Bergenhem, Hedin, & Skarin, 2012). HMIs in these vehicles may need to communicate different information and allow for different driver control inputs based on the position of the vehicle in the platoon (e.g., the leader, a follower behind an exiting vehicle, etc.) and the planned path (e.g., entering or exiting). A general consideration for heavy vehicle HMIs is to minimize the information units communicated to the driver due to the already dense control and display layouts in these vehicle interiors (Campbell et al., 2016).

15.3.1.2 HMI Principles for Presenting Warnings in CVs

Warnings about immediate hazards should be given priority over other information displayed on the CV HMI. Designers have a choice of providing staged warnings in these situations; however, single stage warnings may be preferred in manually controlled CVs to alert the driver of sudden path incursions and to minimize the incidence of false or nuisance alarms. A cautionary alert followed by an imminent collision alert can be useful for drivers of heavy vehicles to decrease the need for sudden hard braking or steering. Here, we present parameters and principles to consider when designing warnings in CVs (summarized in Campbell et al., 2016). Note that many of these principles apply to AVs (see also Section 15.3).

- Consider staged warnings based on the purpose of the warning and the criticality of the situation (Campbell et al., 2016, pp. 4–6 & 4–7). Single-stage warnings are useful in alerting drivers of imminent threats and minimizing the likelihood of false or nuisance alarms. Multi-stage warnings are useful when providing continuous information (e.g., visual display of decreasing proximity to a lead vehicle in a forward collision warning system).

- Choose warning timings based on driver and situation factors, including driver response times, types of driver responses relative to the movement and projected states of the hazards, and hazard visibility (ISO 15623, 2013; Campbell et al., 2016, pp. 4–9).
- In multi-stage warnings, provide meaningful timing between stages (Kiefer et al., 1999; Lee et al., 2004). The driver should not receive cautionary information so early that they perceive it to be a false alarm. Similarly, they should not receive the imminent collision warning too late to select and execute a suitable response. When it is not possible to provide sufficient time between warning stages, a single-stage imminent collision warning should be used.
- For every stage of a multi-stage warning, the modality for providing information can be varied, as long as it is selected to ensure perception, extraction, and comprehension of the information by the driver (Campbell et al., 2016, pp. 4–6 & 4–7). For example, a short visual message (“Stop signal ahead”) can be provided as cautionary information when the driver approaches a traffic light hidden by a roadway curve. In the event that the driver does not slow down, imminent safety warnings can be provided using auditory alerts and/or haptic brake pedal pulses.
- Consider the complementary issues of rapid information perception vs. distraction when locating the CV HMI. Safety critical visual warnings are easily perceived if they are located near the central field of view of the driver. This might, for example, be implemented in an HUD located within ±5° relative to the driver’s central line of sight (ISO, 1984; 2005). The instrument panel is also a popular choice, particularly for information that is minimally safety-critical. Care should be taken to not obscure the roadway view of the driver when mounting visual displays; this may be particularly relevant in information-dense heavy vehicle CV HMIs (Campbell et al., 2016, pp. 11–9). Visual warnings can be distracting in situations which require immediate speed or heading changes or difficult to perceive in conditions of high glare. Auditory warnings are generally preferred for collision avoidance information. Auditory and haptic warnings can also be localized to indicate the direction of the hazard (Campbell et al., 2016, pp. 7–12).

15.3.2 VEHICLE-TO-“X” (V2X) AND “X”-TO-VEHICLE (X2V) INFORMATION

Options for CV configurations also include communication between vehicles (V) and other roadway users and infrastructure elements (X). Vehicle-to-“X” (V2X) HMIs can provide other road users with information about vehicles in the surrounding environment. “X”-to-Vehicle (X2V) HMIs give drivers access to information that has been transmitted from other non-vehicle data sources (e.g., pedestrians and cyclists, roadside equipment). From a broad systems implementation perspective, the source of V2X and X2V information is critical (e.g., where are the sensors located, is the data transfer time from the information source fast enough and sufficiently reliable to support the type of message being sent to the driver or other road user?). In this regard, Hartman (2015) provides resources on V2X and X2V implementations and system specifications. However, from the perspective of the HMI user (e.g., the driver or pedestrian) it often does not matter whether this information is collected via the roadway infrastructure, a pedestrian's mobile phone, or hardware in a bicycle, motorcycle, or other personal transportation device. Thus, many of the principles presented above for V2V guidance are relevant to a range of X2V scenarios using in-vehicle displays, but less relevant to HMI designs that involve displays that are not located within a vehicle.

Messages from X2V-supported HMIs are often intended to augment tasks already performed by the driver in order to make them easier, and to convey information that a driver may not be able to obtain—or obtain as promptly as the vehicle can—within the network. Not all information may be relevant or desired by the driver depending on the criticality of the information and the situation. For example, heavy vehicle drivers and bus drivers may have different information requirements than commuters, and a driver stopped at an intersection may have more information bandwidth available than they will once they initiate a turn through the intersection. Many X2V-specific issues and interface elements that have been evaluated within the literature address the task of managing this influx of information. Although the potential applications of X2V and V2X technologies are vast, the ecosystem is still developing, and there are a limited number of studies that have evaluated these HMIs (Lerner et al., 2014). The following sub-sections provide guidelines that apply to V2X/X2V systems and reflect issues unique to HMIs within the CV environment.

15.3.2.1 V2X Information

Much of the currently available V2X literature reflects technical demonstrations rather than formal HMI evaluations. An example of the demonstrations is proof-of-concept studies[7] for mobile phone applications that provide pedestrians or bicyclists with supplementary traffic information to use while crossing the street (e.g., the status of approaching vehicles). Another example is the design of warnings for motorcyclists. Song, McLaughlin, and Doerzaph (2017) evaluated rider acceptance of multi-modal CV collision warning applications for motorcycles in an on-road study. They found that haptic, auditory, and visual modalities were all viable for the collision warning message displays (as measured by rider acceptance), but that haptic and auditory messages were preferred because they do not represent visual distractions. Single-channel auditory messages were not recommended, since hearing tests are not required to legally operate a motorcycle, and loud engine noise can mask auditory messages. Beyond this evaluation, there has yet to be sufficient research on V2X HMI evaluation to support definitive guidance.

15.3.2.2 X2V Information: Prioritizing, Filtering, and Scheduling

In high workload scenarios, drivers may have trouble accessing relevant information in the driving environment if the HMI is burdening them with excessive or

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[7] See for example: https://www.its.dot.gov/factsheets/pdf/CV_V2Pcomms.pdf

competing information. Messages may be managed through prioritizing, filtering, and scheduling (Campbell et al., 2016). Prioritization may be performed by only showing drivers the information that is most relevant to them. The existing X2V guidelines recommend using message urgency or criticality to derive relative priorities. Filtering can be performed by minimizing the dashboard complexity or creating lockouts for system notifications that may be irrelevant while the car is in motion. Scheduling system messages harnesses functionality afforded by CV capabilities to help pace the presentation of information to the driver and reduce the frequency of multiple warning scenarios (e.g., providing notifications in advance of conflict situations; Lerner et al., 2014)

15.3.2.2.1 Priority

Safety-critical warnings should be coded with sufficient urgency to prioritize the response (Ward et al., 2013). When managing simultaneous alerts, inferior messages may be suppressed based on this value system (Olaverri-Monreal & Jizba, 2016). Urgency of the driver response time is suggested as a way of categorizing alerts in X2V systems, and the highest levels of urgency may be reserved for situations where time-to-event is 5 seconds or less (Lerner et al., 2014). Lerner et al. (2014) also recommends limiting the number of warning categories so that drivers may easily discriminate the salience levels reserved for the highest stages of warning (e.g., "high threat, act now," "caution, measured action," and "no urgency, no action required"). Olaverri-Monreal and Jizba (2016) suggest using a standard priority index (ISO/TS 16951, 2004) to rank warning messages. This index derives the priority value from the response time for the driver to take an action and the potential resulting injuries or damages that may occur if no action is taken (see ISO/TS 16951, 2004 for the equation and categorization process).

When designing messages in an X2V context it is important to distinguish the format of non-safety-critical information from safety-critical information, and not design low-priority messages in a way that implies the driver is required to give an urgent response (Ward et al., 2013; Olaverri-Monreal & Jizba, 2016). This design may be approached in different ways (see Campbell et al., 2016), but consistency across X2V message design based on actual and perceived priority can facilitate fewer instances of perceived false/nuisance alarms, distraction, unnecessary workload, and distrust (Lerner et al., 2014).

15.3.2.2.2 Filtering

While it may be possible to present multiple non-speech auditory and visual X2V alerts concurrently without overloading the driver or negatively impacting performance, more effective driver responses will be elicited if the warning display interrupts and overrides all other messages (Lerner et al., 2014). Information lockouts may also be managed by the driver. In a test-track study where messages of varying relevance to the driving task could be presented, drivers tended to request that the system suppresses messages that aligned with content that the National Highway Traffic Safety Administration' s (NHTSA) visual manual distraction guidelines advise omitting (Holmes, Song, Neurauter, Doerzaph, & Britten, 2016; Olaverri-Monreal & Jizba, 2016).

15.3.2.2.3 Scheduling

To avoid simultaneous safety critical alerts, messages should be paced, if possible. If the X2V system has predictive capabilities, the preferred approach is to suppress non-safety-critical information within a time window preceding the onset of safety-critical messages (Ward et al., 2013). A safety-critical warning should continue until the driver responds appropriately, without provoking driver annoyance or suppressing consecutive safety-critical warnings. Non-safety-critical warnings should endure (unobtrusively) over a period of time that allows drivers to execute a self-paced response (Ward et al., 2013).

15.3.2.3 X2V Information: Multiple Displays

CV X2V technology allows for information that is directly relevant to a particular driver to be displayed in multiple ways within the vehicle as well as outside of the vehicle. Generally, the position of X2V displays (including displays inside and outside of the vehicle) should correspond directionally with key task-related external elements to cue rapid information extraction (Hoekstra-Atwood, Richard, & Venkatraman, 2019a; b; Richard, Philips, Divekar, Bacon-Abdelmoteleb, & Jerome, 2015a).

For messages within the vehicle, visual warnings conveyed simultaneously should only be presented on one physical display (Olaverri-Monreal & Jizba, 2016). Driver responses may be better if messages (even separate messages from separate devices) are presented on a single display rather than separate displays (Lerner & Boyd, 2005).

Driver's visual attention should not be directed towards in-vehicle displays when they need to be looking outside (Stevens, 2016; Svenson, Stevens, & Guglielmi, 2013; Richard et al., 2015a). In-vehicle displays that present warnings should be within the driver's visual field (see earlier sections for location considerations). When non-safety-critical information is presented inside the vehicle, it should be positioned near the periphery of the driver's field of view to be unobtrusive to the demands of the immediate driving task (Olaverri-Monreal & Jizba, 2016). Detailed guidance on HMI display location is provided in Campbell et al. (2016).

A display on roadway infrastructure, or a Driver-Infrastructure Interface (DII), may be part of the X2V system if this type of display provides context and facilitates simplified messaging along with reduced visual workload. See Richard et al. (2015b) for specific guidance on when DIIs may be appropriate. When positioning a DII, designers should consider the driving task, situation, and the proximal roadway environment (Hoekstra-Atwood, Richard, & Venkatraman, 2019a).

If a DVI and DII assess the same hazard, the information or instruction should be consistent and coordinated (Hoekstra-Atwood et al., 2019a; Richard et al., 2015a). However, safety-critical warning messages are not suitable for DIIs because they can be readily seen by road users that are not the intended recipient of the message. The ubiquitous visibility of infrastructure-based messages could have the unintended consequence of warning the wrong drivers and eliciting unnecessary evasive responses (Richard et al., 2015b). In this case, supplementing a cautionary DII message with an imminent collision warning on the in-vehicle HMI may facilitate the appropriate driver's crash-avoidance responses (Hoekstra-Atwood, Richard, & Venkatraman, 2019b).

15.3.2.4 X2V Information: Message Content

Even though X2V technologies afford an abundance of information to drivers, designers should seek to provide drivers with sufficient, but not excessive information and evaluate the levels of distraction and workload imposed by system displays (Olaverri-Monreal & Jizba, 2016). Olaverri-Monreal and Jizba (2016) recommend that while the car is moving, no more than 4 information units[8] should be presented in visual text messages by X2V systems (but no more than 2 information units for safety-relevant messages). Messages should elicit a binary response (single reaction) rather than a choice of responses to avoid imposing additional cognitive processing load (Ward et al., 2013). Greater amounts of information may not translate to greater trust in the information, and drivers could end up spending more time with eyes off the road to take in information with no added safety benefit (Inman, Jackson, & Chou, 2018). Designers must consider both the driving task and how drivers may interpret information differently on an X2V interface versus a road sign. A change in message context (e.g., transferring road sign message content directly to an in-vehicle interface) may change the accuracy of message interpretation by the driver (Chrysler, Finley, & Trout, 2018).

For specific application guidelines and information needs, see Richard et al. (2015b) and Hoekstra-Atwood et al. (2019a). These documents cover the following systems: stop sign assist, signalized left turn assist, red light violator warning, curve speed warning, spot-weather information warning–reduced speed, and pedestrian in crosswalk systems.

15.4 INTELLIGENT VEHICLE HMI CONSIDERATIONS

Intelligent vehicles (IVs) are described as being able to monitor driver behavior and state, and then reconfigure the HMI and vehicle control to improve safety (e.g., Cadillac Super Cruise[9] or "driver attention guard" in Tawari, Sivaraman, Trivedi, Shannon, & Tippelhofer, 2014). Thus, the "intelligent" part of IVs could support improved system performance in an AV or a CV. Configurable features may vary across automation capabilities, driver states, and the purpose of HMI reconfiguration. For example, an IV could communicate messages such as "Do Not Disturb While Driving" to prevent the driver from receiving messages while driving, or it could activate lane-keeping assistance and adaptive cruise control (ACC) when the system detects driver distraction. A central purpose of such intelligent systems is to optimize driver behaviors to improve safety.

There is very little published research in the area, and it is certainly not enough to support strong guidance. However, there are a number of general design principles that could serve as initial considerations. Drivers may be given control over at least parts of these reconfigurations, unless driver choices could result in safety deficits.

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[8] Information units are a measure of information load. An information unit refers to key nouns and adjectives in the message that provide unique or clarifying information. For example, the phrase "Vehicle ahead. Merge to the right." contains the four information units underlined (Campbell et al., 2016).

[9] https://www.cadillac.com/world-of-cadillac/innovation/super-cruise

For example, L2 vehicles with intelligent features (e.g., Super Cruise) may monitor driver engagement levels, and slow down and eventually stop the vehicle if the driver remains disengaged or unresponsive. In this case, the IV's reconfiguration of safety maneuvers should not be disabled by drivers. At other times, the driver may have access to additional safety-relevant information that invalidates the need for system reconfiguration and should be able to provide control inputs.

IV HMIs are similar to proactive HMIs (discussed in the AV HMI design section), except that they may also reflect changes made to the function or level of automation as well as HMI based on estimations of driver state. Information that could be presented to the driver includes descriptive information about the current driver state (e.g., eyes are off the road, hand are off the wheel) and prescriptive information to help the driver maintain the desired level of automation (e.g., maintain eyes on the road, place hands on the wheel).

15.5 CONCLUSIONS

It should be clear from this chapter that there is much yet to learn about driver information needs and subsequent HMI design requirements for ACIVs. The rapid pace and changing nature of ACIV—combined with the relatively slow pace of research to support design—only adds to the challenges. The guidance that is available (e.g., guidance published by the National Highway Transportation Safety Administration (Campbell et al., 2016; 2018), plus various SAE and ISO documents, generally reflects pre-2015 research conducted on driver information/safety systems that provided little or no automated driving capability or connectivity. Perhaps the best that can be said about such guidance documents is that they provide provisionally useful design principles for ACIV supported by high-quality research. Basic driver information needs, HMI considerations for transitions of control alerts and warnings, and high-level principles of message management are well understood and have been documented in a variety of sources. The existing guidance can also serve as a roadmap for future research; i.e., holes or gaps in the topics covered by the available guidance may reflect areas where more research is needed.

The development of more comprehensive and effective HMI guidelines will require a better understanding of the changing nature of driving and of the implications of these changes for HMI design. Specifically, how will the range of ACIV functionality impact driver information needs, given the concurrent requirements to maintain driver trust, functional mental models, and SA? What new challenges are introduced through automation for which the HMI could serve as a solution? How could a broader focus on information management support driver engagement and SA? Could a proactive, flexible, and dynamic HMI address some of these challenges and, if so, how?

We are highly optimistic that answers to these and similar questions will be answered by the ACIV industry and broader research community. Even at this relatively early stage in the conceptualization and development of ACIV, many recent studies and analyses are serving to shed light on these and related topics and, we hope, will serve as a foundation for future HMI guidance; these include the changing role of the driver in AVs (Noy, Shinar, & Horrey, 2018); the definition and measurement of the "out-of-the-loop" concept (Merat et al., 2018; Biondi et al., 2018; this Handbook, Chapters 7, 21); driver engagement and conflict intervention performance (Victor et al., 2018); the challenges of partial automation (Endsley, 2017); and strategies for attention management in AVs (Llaneras, Cannon, & Green, 2017).

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