Humans and Intelligent Vehicles: The Hope, the Help, and the Harm

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***Abstract*—Intelligent vehicles offer hope for a world in which crashes are rare, congestion is reduced, carbon emissions are decreased, and mobility is extended to a wider population. As long as humans are in the loop, over a half century of research in human factors suggests that this hope is unlikely to become a reality unless careful attention is paid to human behavior and, conversely, the potential for harm is real if little attention is given to said behavior. Different challenges lie with each of the two middle levels of automation which are the primary focus of this article. With Level 2 automation (National Highway Traffic Safety Administration; NHTSA), the driver is removed from always having to control the position and speed of the vehicle, but is still required to *monitor* both position and speed. Humans are notoriously bad at vigilance tasks, and can quickly lose situation awareness. Moreover, even if vigilant, the driver needs to interact with the vehicle. But voice-activated systems which let the driver continue to glance at the forward roadway are proving to be a potential source of cognitive distraction. With Level 3 automation (NHTSA), the driver is out of the loop most of the time, but will still need to interact with the vehicle. Critical skills can be lost over time. Unexpected transfers of control need to be considered. The surface transportation and aviation human factors communities have proposed ways to solve the problems that will inevitably arise, either through careful experimentation or extensions of existing research.**

***Index Terms*—Automation Levels 1–4, distraction, driver-vehicle interfaces, human factors, intelligent vehicles, situation awareness, supervisory control and, transfer of control, vigilance.**

I. Introduction

Three significant advances in intelligent vehicle technologies are influencing our relation as humans with the automobile. They include advances that bear on our understanding of how to design technologies that can help drivers avoid a crash, how to warn the driver of an imminent crash, and how to take actions which substitute for those the driver himself or herself would initiate. There has been a corresponding evolution in the role that human factors research plays in each of these advances. Although the focus of this paper is almost exclusively on the third advance in technology, and the role of human factors in maximizing the potential of that advance, it is instructive to take a bird's eye view of how we got where we are today to illustrate how human factors speaks broadly to the hope, the help and the harm that are associated with any advance in technology.

First, consider the advances in the active, crash avoidance technologies spurred on by research in vehicle dynamics. In just the last decade, there has been close to a 25% decrease in fatality rates per 100 million vehicle miles traveled [1]. The advances in crash avoidance technologies that have led to this decrease include anti-lock braking systems (ABS) and electronic stability control, just to name a few [2]. Vehicles with an ABS are examples of automation at the lowest level (Level 1 automation) [3]. But, interestingly, vehicles with an ABS were shown early in their adoption actually to be associated with an increase in crashes [4]. Why? It was hypothesized that drivers computed the cost and benefits associated with a given technology and kept constant the level of risk [5], [6]. This has come to be known as risk homeostasis theory [7]. It has since been shown that this cannot explain the fact that ABS systems were not having the initial predicted benefits [8]. Rather, it appears to be that early in the adoption of ABS drivers did not know how to operate a car equipped with such systems [9]. Exactly which explanation of why drivers did not reap the initial benefits from ABS that were predicted is not the issue here. Rather, what the ABS experience demonstrates rather vividly is that when the human is in the loop with any technology, as is the case with ABS, one cannot predict *a priori* how the human will behave. This is arguably the first and most fundamental law of human factors: intuition is not a reliable guide for ergonomic design. There is great hope for advanced technologies, but hope is not enough when the human is in the loop.

Second, at the same time as the above advances in automotive technologies were being made, advances were also being made in the systems that can warn the driver of a collision, including the broad class of longitudinal and lateral warning systems. Unfortunately, the early forward collision warning systems were often unreliable, falsely warning a driver when there was no reason to do so and, worse still, failing to warn a driver when there was a potential crash scenario [10]. Lane departure warning systems still suffer from these problems and actually appear to increase crashes [11]. It has been suggested that drivers learned to disregard such systems, a result hardly surprising in itself [11]. But, that does not mean that the baby had to be thrown out with the bathwater. Rather, what was needed was research

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to define the envelope within which the various different types of warning systems would work for the drivers of the vehicles in which they were installed. For example, it has been found that if false alarms with imminent crash warning systems are limited to less than 0.5 per 100 miles, then they are not considered a nuisance [12]. Systems exist which operate within this envelope and they reduce insurance claims [11]. This illustrates well what is arguably the second law of human factors and the necessary complement of the first law if human factors research is going to have a role to play: Human behavior is largely predictable (in the aggregate) but the prediction depends on careful, well controlled research. Intelligent vehicle technologies can truly be life-saving, but most require an intimate knowledge of human behavior when the human is in the loop. The human factors community can provide this help, whether it is simply comparing two or more technologies or, instead, developing and evaluating what is predicted to be the optimal design of a driver-vehicle interface (DVI) using computer and mathematical models of driver behavior [13]. This experimentation increases what the automation community refers to as the correct use of technology and decreases what this community refers to as the misuse (overreliance) and disuse (underutilization) of technology [14].

Third, we now have advances in technologies which can be used to take over the functions normally reserved for the driver, including those where the lateral and longitudinal control of the vehicle is managed by the automated driving suite (ADS). In some systems the driver is still supposed to be fully engaged in supervising the actions of the vehicle under all circumstances (Levels 1 and 2) [3]. In other cases, the driver is freed from supervision, either in limited situations or during the entire trip (Levels 3 and 4, respectively). Problems arise at these levels, not so much because of faults with the automation per se, but because the driver is in-the-loop and not always aware of what is happening (or supposed to be happening)—Levels 1 and 2—or is out of the loop and needs quickly to be brought back into the loop for some unexpected reason—Levels 3 and 4. In general, the National Highway Traffic Safety Administration (NHTSA) estimates that the critical reason for crashes can be assigned to the driver some 93% of the time [15]. While automation is predicted greatly to decrease crashes, if anything it will arguably be the case that the extent to which humans contribute to the crashes that do occur will only increase.

Consider three hypothetical systems, one each at Levels 1, 2 and 3, which can serve as examples of the above general point—that harm can potentially arise when the behavior of the human is not considered. In the first hypothetical system (Level 1), imagine that the host driver has adaptive cruise control set for 80 mph on a highway and is following a lead vehicle traveling at 60 mph in the right most travel lane. The host driver decides suddenly to exit the highway. Since the lead vehicle is no longer ahead of the host driver, as soon as the host driver exits the lane, his or her vehicle starts accelerating. At the same time as the host driver changes into the exit lane he or she notices that there is a crash in the travel lane ahead which requires some attention. The host driver's vehicle continues accelerating towards the exit. The driver's risk is potentially increased because of the use of cruise control [16]. In the second hypothetical system (Level 2), again imagine that the driver is on the highway. In this example, the ADS takes over both lateral and longitudinal control. The sensors lose track of the lane markings. The car starts to drift off the road, but does not warn the driver in time. The driver is actively focused on reading a variable message sign as the car drifts out of the lane. While warnings will be a critical part of Level 2 systems, the expectation is that the driver will always be in the loop: "The system can relinquish control with no advance warning and the driver must be ready to control the vehicle safely [3]." In the third system (Level 3), by definition the driver does not need to monitor the roadway ahead. The ADS has full control of the lateral and longitudinal position of the host vehicle. An intersection is ahead and so the ADS transfers control to the driver. The driver glances up and finds that a vehicle with its turn signal on is not turning, but there is little time to make the gentle avoidance maneuvers that would have been possible had the transfer occurred at an earlier period in time. All of these scenarios could occur (and some do now occur). Would you want to be the driver in any one of these scenarios? These examples illustrate well the third law of human factors: Failing to take into account human factors considerations in design can result in systems that are suboptimal or worse [14]. This is what the general automation community often refers to as abuse of technology [14].

Time is not on our side. Autonomous vehicles are coming to the United States. In a recent speech, the Secretary of the Department of Transportation (DOT) charged NHTSA with developing guidelines in the next six months for best practices for the safe operation of autonomous vehicles [17]. Fortunately, the surface transportation human factors community of researchers has been preparing for this day. An entire issue of *Transportation Research Part F* was recently devoted to just this topic [18]. NHTSA has also been actively preparing for this day, not only in defining standards of automation [3] but forging ahead in addressing human factors issues specific to Levels 2 and 3 [19]. A special issue on Holistic Approaches for Human-Vehicle Systems: Combining Models, Interactions and Control will soon be appearing in the *IEEE Transaction on Human-Machine Systems*. And more broadly, the human factors community has been concerned with issues in aviation human factors [20] and more general automation [21], [14], [22], [23] for over half a century with clear application to the design of human in the loop systems with intelligent vehicles.

So, what are the hopes for autonomous vehicles and, more generally, intelligent vehicles? For the general population they are to increase safety, decrease congestion, and reduce greenhouse gases [17]. But autonomous and intelligent vehicles can prove of particular benefit to special populations (older drivers, younger drivers, mobility impaired drivers), can dramatically increase the detection of driver state (fatigue, alcohol, THC), can be the backbone of smart cities, and can reduce, perhaps radically, the horrific crash rates in low- and middle-income countries [24]. What help can the human factors community provide to realize all of these many hopes? And where can harm come if that help is not provided? Below we discuss the hopes, the help, and the harm.

II. The Hope

The long term hopes for autonomous vehicles and the related intelligent vehicle technologies (e.g., vehicle-to-vehicle and vehicle-to-infrastructure communications) are broader still than the hopes for the automated highway systems of the 1990s [25]. These hopes can be more precisely articulated by referring to the different levels of automation. Both NHTSA and the Society of Automotive Engineers have developed a hierarchy of levels of automation.

Although there are criticisms of both classification hierarchies, we are using the system proposed by NHTSA for this article. Briefly, NHTSA defines four levels of automation [3]: (1) individual vehicle controls are automated (e.g., adaptive cruise control), but only one is active at any moment in time; (2) at least two controls are automated simultaneously (e.g., adaptive cruise control and lane keeping); (3) all controls are fully automated for certain portions of a trip; and (4) the ADS is in control for the entire trip. The real human factors distinctions may not be apparent in the above classification, so they need to be clarified here. In Level 1, the driver must keep his or her hands on the wheel or feet on the pedals, but one or the other (hands or feet) must be in the control loop. In Level 2, the driver can remove *both* hands and feet from the controls, but must maintain attention to the driving task at all times. In Level 3, the driver can literally do most anything but take a nap (the driver must be available for the occasional transfer of control) while in certain defined areas, but will need to be ready to resume full control of the vehicle when the ADS is operating outside of its envelope. In Level 4, the driver has no expectation that at any point along the trip will he or she need to take over the controls.

And what is the hope for each level with respect to the driver? With Level 1, the hope is a very basic one: that the driver can understand and trust the technology enough to engage with it. With Level 2 the hope is that the driver can remain alert, ready to take over at any moment, even when he or she is not involved in the control of both the speed and position of the vehicle. With Level 3, the hope is that the driver can gain control in a relatively short period of time when not being involved at all in monitoring the progress of the vehicle. And with Level 4, the hope is that the driver will never need to take over control.

III. The Help and the Harm

Below we focus on human factors issues germane to Levels 2, 3 and 4. As noted above, at Level 1 the driver still has either his or her hands on the wheel or foot on the accelerator or brake. Although automation is defined for all four levels, the primary focus of the research targeted by this journal will be on Levels 2–4, levels where the ADS is in control of both the lateral and longitudinal position. Thus, we confine our discussion to those levels.

In order to make these hopes a reality, help is needed. The primary areas where human factors help will be needed and the type of help that can be provided will be identified below. Three critical human factors questions must be answered at each level of automation. First, how can one ensure that the functions designed to save lives at the given level will actually be used? Second, what are the major problems at each level (major areas where disuse, misuse or abuse could occur)? And third, what can be done to design automation at a given level that will reduce the risk of a crash (reduce the risk of disuse, misuse or abuse)?

A. Level 2

At Level 2, the design of the DVI associated with a specific automation feature along with the trust in the feature [26] determines whether the specific type of automation will be used. We first speak to the design of the DVI and the two problems that can arise when the DVI does not support the automation. First, one needs to question very seriously whether drivers can realistically function as supervisor of an automated system in which the driver is controlling neither the longitudinal nor latitudinal position of the vehicle, especially when the DVI diverts attention away from the monitoring task. Second, one needs to take just as seriously the question of whether drivers can read the mode of their system any better than they can read the mind of another person (i.e., not well at all). We next speak to issues of trust and the two problems that arise around the issue. First, one needs to ask whether there is a real danger of level creep, in which a driver assumes that the level of automation has capabilities which have exceeded its envelope (overtrust or misuse). Second, as a complement to the above, there is the danger that the driver will assume that he or she needs to take control when such is not the case. In fact, the automation would perform better than the driver (mistrust or disuse).

1) Driver-Vehicle Interface: For reasons which will soon become clear, we begin this discussion of DVIs for Level 2 with what is known about DVIs for Level 1. There have literally been hundreds of refereed journal articles focusing on how to design a DVI for Level 1 that is both effective and user friendly, including interfaces designed simply to deliver warning information and those designed to control the status of the vehicle (e.g., windshield wipers, heat and air-conditioning, headlights). With this literature in hand, NHTSA has pushed forward with experiments targeting human factors considerations in the design of effective warning interfaces [27]. And they are in the process of developing principles and guidelines for single and multiple DVIs (integrated interfaces) that will populate the cars of the future [28]. These guidelines run into the 100s of pages and can help ensure that an interface will be used.

The human factors issues central to the design of effective warnings and interfaces used for vehicle control at Level 1 are arguably the same as those that will be needed for Level 2. For example at Level 2, drivers will need to be warned when a given automatic feature (e.g., lane keeping assistance) is not able to control the vehicle for whatever reason and will need to be able to set the particular features of Level 2 automation which they want to see active. Questions about what mode to use for a warning (auditory, visual, tactile) and what method to communicate with the controls (manual, voice) will be answered with Level 2 just as they are with Level 1. The myriad other decisions that need to be made about the design of warnings and controls are similar as well.

2) Driver as Supervisor: The major problem with Level 2 systems is that they put the driver in the role of a supervisor or monitor of systems in which the driver is potentially receiving no tactile feedback—the automation is controlling the speed and position of the vehicle [22]. A good supervisor needs both to notice changes to the system (remain vigilant) and keep track of the changing roadway environment (remain situationally aware). From laboratory studies, it is known that humans are particularly poor at vigilance [29] and that their ability to detect a failure is inversely related to the likelihood that that failure will occur [23].

This directly relates to the problems that may arise with Level 2 autonomous vehicles. In particular, a vehicle equipped with Level 2 automation allows the driver to take both hands off the wheel *and* feet off the pedals, at least for brief periods of time (that time depending on the manufacturer). As the level of automation which takes over control of the vehicle increases, the chance for monitoring failures also increases [30]. But this does not seem to be true of increases in automation which support information acquisition. In particular, in one of the first meta-analyses of the relation between the degree of automation and human behavior, the automation was found to be beneficial when it was used primarily to support information analysis (typical of most warnings). But there were negative consequences when the automation was used to support action selection (typical of Level 2).

Not only does the ability to remain vigilant decrease as the frequency of alerts decreases (in this case, the request to transfer control from the ADS to the driver), but so too does a human operator's situation awareness [31]. Basically, in order to be situationally aware a driver needs to perceive an event, comprehend what the event means for the driver, and then predict what actions the driver should take. A driver is necessarily in the loop if he or she is operating both the steering wheel and foot pedals. But such is not the case if control over both of these is relinquished. Thus, despite instructions to monitor the roadway, there is every likelihood that the driver will fail to monitor adequately and all three necessary ingredients of situation awareness will suffer [30], thereby increasing the likelihood of a crash.

We are not aware of any studies that have attempted to determine whether drivers can be trained to be better monitors and maintain their situation awareness at high levels of automation. However, researchers have suggested steps that can be taken to increase awareness and vigilance in automated systems. These include changes to the display (make salient alerts of automation failures; make the displays easy to understand), to the procedures (impose periodic times when the automation is disengaged), and to the training (impose unexpected automation failures during training; [32]) [33]. And, if there is a significant risk associated with automation, avoid the highest levels of automation altogether.

But perhaps most pernicious here is the law of unintended consequences [34]. Monitoring automation is supposed to reduce the load on the driver. This is done in part by integrating the many warning and control functions in an integrated DVI. But the consequence of doing such is that monitoring can actually become more difficult. In particular, at the same time as drivers are being asked to serve as monitors during Level 2 operation, the DVI is actually becoming ever more complex, assuming many control and display functions unrelated to automation. After all, if the driver has more free time, then it is only natural to populate the DVI with content. But at Level 2 the driver is being asked to serve as a monitor and therefore the DVI needs to have less content, not more (or at least be less distracting). To quote a leading human factors researcher in the field of automation: "... even though automation seems to relieve people of tasks, automation requires more, not less, attention to training, interface design, and interaction design." [23].

What can be done to the DVI to decrease the cognitive load required both to control the vehicle and to obtain status information that will help the driver remain in the loop as a monitor at Level 2? It has been clear for some time that interfaces used to control features of the vehicle which require drivers to look inside the vehicle increase crash risk [35], [36]. One obvious alternative to placing the display controls inside the vehicle where the eyes are off the forward roadway is to use voice-based interactive technologies to activate the controls. Guidelines will soon appear for audio DVIs [28].

While voice-based interactive technologies generally have a benefit over interfaces inside the vehicle, they do not come without their cost. In fact, it has been shown recently that certain auditory transactions place a high load on the driver, e.g., tasks such as speech-to-text conversion [37]. Attempts are now underway to provide measures of the cognitive workload of various speech tasks involved in the control of the vehicle that allow the driver to keep his or her eyes on the forward roadway. These measures will provide vehicle designers with much better indices of just how demanding a particular voice-based interaction can be. The research issues are much more subtle here, as there are clear benefits to speech-based interfaces over visual interfaces inside the vehicle, but there are costs as well depending on the load that the auditory display places on the driver.

Interfaces are also needed that provide the driver with information on the status of the vehicle. Visual interfaces, either head-up (HUD, e.g., the windshield) or a head-mounted (HMD, e.g., Google Glass), are one obvious alternative to visual in-vehicle displays. They do not require the driver to look down inside the vehicle and have been shown to provide advantages over head-down displays for certain classes of drivers [12]. The aviation human factors community has explored extensively the best way to display information on a HUD [38], [39]. And the aviation community has looked at the design of HMDs, first at largely technical issues [40] and then at issues more central to human factors, such as vision and perception [41].

The most critical problem with the visual displays, both head-up and head-mounted, is that they themselves can serve as a source of distraction, leading to both inattentional blindness and change blindness. Inattentional blindness [42] is best illustrated by the experiment made famous by the "Gorilla video" [43]. In this film, two teams of players, one wearing black jerseys and others wearing white jerseys, pass the ball to one another for some 15 seconds. Viewers of the film are asked to count the number of passes that the team with the white jerseys complete. In the middle of the team play, a person dressed as a gorilla walks across the stage, right between the black and white team, and then exits. Fully 70% of the individuals counting the passes between members of the white team fail to notice the gorilla. The connection to a HUD is immediate. A driver focused on the gauge displayed on the windshield would be much less likely to notice a pedestrian stepping out from the curb into his or her path. And the pedestrian is far less visible than the gorilla! Effects of HUDs on inattentional blindness have been shown both in the world of aviation [44] and that of surface transportation [45], [46]. There is no immediate antidote to inattentional blindness. But current research programs on the mitigation of inattentional blindness are showing real promise [45].

Change blindness refers to our inability to notice changes in the environment that occur as we shift attention from one location to another and back (the change occurs during the shift of attention) [47]. HMDs such as Google Glass create the potential for change blindness as the driver shifts his or her attention from the forward roadway to the display and back to the forward roadway. Specifically, we know that drivers are much less likely to detect changes which occur in their peripheral field of view than they are changes which occur centrally [48]. To go one step further, people tend to suffer from “change blindness blindness,” such that we routinely overestimate our ability to detect changes, thus making the phenomenon of change blindness that much more insidious [49]. As with inattentional blindness, experiments are in progress that suggest new ways of mitigating change blindness [45].

3) Driver as Mind (Mode) Reader: Even if the driver were to remain vigilant and situationally aware, there is the problem associated with Level 2 automation (and sometimes Level 1 automation) referred to as mode errors [50]. For example, in one fielded system the lane keeping assist system functions when the wipers are not on or when they are on only intermittently. But when they are on continuously, the lane keeping assist system turns off. This makes good sense from an engineering perspective. But what of the poor driver? With one fielded system, there are several icons on the dashboard that indicate that the system is off, but these can easily be obscured by the steering wheel (depending on the driver’s height and the position of the seat) [51]. And, the driver needs to remember constantly to monitor for the icons. Of course, all the other modes need the same level of attention. The driver can easily be overwhelmed. Experiments are needed to determine just where to mount and how to display the appropriate icons.

4) Trust: If drivers are going to use Level 2 automation, not only does the interface need to be informative (warnings) and navigable (controls), but of equal importance, if not more, is a driver’s trust in the automation. Study after study has shown that individuals are less willing to take on risks over which they have little or no control rather than risks over which they have control. This includes those making decisions on the floor of the stock market [52] and those making decisions in the flight deck of an airplane [53]. It is one of the factors that was thought to contribute to the failure of automated highway systems [25].

The human factors community knows a great deal about how a driver’s calibration of his or her own ability and of the ability of a particular feature of automation determines the driver’s trust in the automation [54]. The models could be used to predict for individual drivers how to modify, say, the driver’s calibration of his or her ability in order to increase trust in automation. However, only a small number of studies have empirically attempted to increase drivers’ trust in automation. For example, one study has looked at drivers’ trust in automation in a vehicle before and after use of the automation [55]. The participants were told that the automation would occasionally fail and that they would be warned prior to the failure. The warning always came seven seconds before a vehicle in their lane was stopped ahead. The study showed an increase in trust, but the warnings were sufficiently timely (and consistent) and the hazard was always the same, so it is hard to know what to make of the results.

5) Level Creep: Overtrust: A problem related to the above is what we are calling level creep where the driver trusts the capabilities of the automation more than he or she should, an example of a misuse of the automation [14]. How might this occur? Briefly, imagine a driver is using a Level 2 system which controls both speed and position, is supervising it, and never encounters over the many hours of operation anything that requires the ADS to transfer control to the driver. But, then, one day the driver enters a curve whose radius is too tight for the ADS. The driver may have assumed because of a long and successful experience with the ADS that it could handle most anything. Whether the driver is supervising the system or not, he or she will be surprised when control is transferred, with or without an alert depending on the system.

Human factors researchers have addressed broadly the problem of misuse (overtrust) such as described above and how this can be overcome in the design stage, perhaps requiring of drivers training as well. In particular, the ADS capability should be designed so that the driver understands well the operating range of the system and thereby changes his or her level of trust in the system dynamically over time as the capabilities of the ADS change [26]. There is much additional research that needs to be done here to detail just how to implement these design guidelines.

6) Mistrust: Just as a driver can place too much trust in automation, so too can the driver place too little trust in automation [26]. As a start, this can be dangerous. As noted above in our discussion of inattentional and change blindness, even when a driver is looking toward the forward roadway, he or she may not perceive potential hazards when cognitively distracted [56]. For this reason it is important that drivers trust the automation; otherwise, they may retake control when the automation would drive more safely. For example, the automation may take a different route or change speed for reasons that the driver does not understand because he or she receives insufficient input or is unable to process the input as well as the automation. The automated vehicle may act more intelligently than a driver who becomes cognitively distracted while attending to the forward roadway in response to unexpected vehicle actions. The solution to this problem is more complex than the solution to the problem of overtrust [26], since the driver now needs to be made aware of his or her own fallibility. The human factors community has found that error training works well in this context in a laboratory setting [57], but how it would be implemented broadly across all automated vehicles is not clear. So, the question is how to build trust between the driver and the ADS just as trust is built between two humans. In this regard, it has been found that when the ADS takes over control or generally performs maneuvers that are unexpected drivers trust it more if it provides continuous and transparent feedback to the driver than if it does not [58].

B. Level 3

In Level 3, it is assumed that the ADS will be controlling all driving functions for major portions of each trip, depending on the particulars of the trip. Again, as with Level 2, there are questions of whether the automation will be used—of usability and of trust—and of the problems which arise when either or both of these are compromised. Many of the problems will be similar to those of Level 2. But the problems of usability and of trust at Level 3 will also presumably be different ones. For example, the subpopulation of users here may be mobility impaired drivers. The usability questions relevant to the design of the DVI could be much broader ones. Or the users could be those caught in heavy traffic creeping along the highway. The trust issues here are much more specific ones—does the driver trust a Level 3 system at very low speeds. In addition, unlike Level 2, there are questions of what will happen to drivers' skills over time as they exercise those skills less and less often.

1) Driver-Vehicle Interface: For Level 3, assuming that drivers can monitor their driving, can read the mode correctly, and do not assume that the mode has functionality beyond—or short of—its actual capabilities, the major human factors problems that are likely to occur are during the transfer of control. In particular, one can ask just how much time the driver needs before transfer of control can be made safely from the ADS to the driver (preventing abuse). And one can ask what information one could provide the driver that might most facilitate this transfer of control.

The interface must be designed with this in mind. There are two likely scenarios where control must be transferred, one where it is expected by the driver and one where it is unexpected.

To begin, consider the question of how much time the driver should be given to take over control from the ADS in Level 3 systems when the transfer can be anticipated. There has long been concern in the human factors community about how to measure dynamically the elements of situation awareness [59]. Ideally, we want the automation to remain in the loop even after the driver has taken over control (ready to step in as lifeguard) long enough for the driver to regain full situation awareness. With respect to automobiles, there have been two basic approaches examining the minimum time required after control is transferred from the ADS to the driver for the driver to regain full situation awareness. One approach asks how long it takes after a transfer of control signal is issued for the driver to control the vehicle as smoothly as the driver does when glancing continuously at the forward roadway [60]. The other approach asks how long it takes after a transfer of control signal has been issued for the driver to anticipate hidden hazards as well as the driver does when glancing continuously at the forward roadway [61]. A hidden or latent hazard in this case might be a pedestrian stepping out into a marked midblock crosswalk in front of a vehicle stopped in the parking lane immediately adjacent to and upstream of the crosswalk.

Briefly, consider the experiments designed to address the second index of situation awareness, i.e., hazard anticipation [62]. The driver is assumed to be glancing inside the vehicle in a Level 3 system. The forward roadway is not visible to the driver. At some point a signal is given that transfer is to occur. The driver can then take over control at any point. A latent hazard appears either 4, 6, 8 or 12 s after the signal is given. The driver's latent hazard perception skills are compared to a driver's latent hazard perception skills who is glancing continuously at the roadway. In general, it is found that it takes at least 8 s after the driver has been told that he or she can take control for the driver to recognize latent hazards as well as he or she did when driving and looking continuously at the forward roadway. This has immediate implications for automated vehicles. Specifically, control should only be transferred when at least 8 s separates the signal to transfer control from potential latent hazards (e.g., a marked midblock crosswalk into which a pedestrian might step). Moreover, the automation should remain in the loop as a lifeguard to take over control just in case something does happen before the 8 s elapses. Much remains to be done here, as these various measures have not considered older drivers, different roadway geometries, changes in traffic densities, and so on.

Second, consider scenarios where control must be transferred suddenly and unexpectedly. To the best of our knowledge, no one has reported any experiments which bear on this issue, at least in surface transportation. But, elements of the discussion described above suggest what needs to be done to the extent possible. The driver needs to be made as situationally aware of the driving context as quickly as possible. This would seem to require a combination of spoken commands (or auditory alerts) and visual displays. The spoken commands will get the drivers attention and potentially alert him or her to a possible hazard ahead more quickly than a visual alert [51]. The visual displays can then depict the critical spatial and other visual features of the roadway much more quickly than can a verbal description. The above information required for emergency auditory alerts and visual displays could come from having a black box continuously updated (maybe 10 Hz) with verbal instructions and visual displays of the roadway ahead that would be made available to the driver when the ADS failed. No one to the best of our knowledge in the human factors community has yet addressed this issue.

2) Trust: The major issues of trust with Level 3 systems are apt to be fundamentally different than those issues with Level 2 systems. With Level 3 systems, the driver is out of the loop for the most part. The driver does not need to be concerned about monitoring the environment, only about being warned sufficiently ahead of time in order for the transfer of control to be a smooth one. Assuming that the transfer of control can be made seamless, trust will presumably be high when the benefits of automation are substantial and the costs are low. Such should be the case, say, when the driver is stuck in traffic moving very slowly. But what about mobility impaired drivers? Will the benefits outweigh the potential costs? The complex models developed to predict the interaction between calibration and trust in automation may not apply here as well as they did above [54]. For mobility impaired drivers, calibration of their driving skills may not be part of the equation.

More generally, problems which cross the boundary between human factors and philosophy will need to be addressed if not solved [63]. In particular, at some point the driver will need to decide how the ADS should respond to life threatening situations when the driver's life or someone else's life is at stake. Should the ADS cede control immediately to the driver? But the driver will be out of the loop. These are not easy questions to answer.

3) Loss of Skills: As drivers pay less and less attention to the forward roadway, it is reasonable to hypothesize that they will lose critical hazard anticipation skills which let the driver determine where a latent or potential hazard might materialize. The level of a driver's hazard anticipation skills has been linked directly to the risk of a crash [64]. One study in surface transportation suggests that this can happen for drivers who have been using adaptive cruise control for extended periods of time during just a single drive [16]. However, there has been no evaluation of the long term loss of skills among drivers using automation.

Interesting and relevant work in aviation looked at what happens to pilots' cognitive skills after prolonged exposure to automation. In particular, it appears that when asked to perform the cognitive tasks needed for manual flight, significant problems arose [65]. The cognitive tasks needed for manual flight are not all that different from those needed for manual driving and loosely fall under the umbrella of hazard anticipation. It was found that there was a correlation between pilots' retention of the cognitive skills and the extent to which they focused on supervising the flight when the automatic pilot was engaged. This suggests, as mentioned above, that there need to be periodic time outs from the automation in order for a driver to maintain hazard anticipation skills. But periodic time outs may not be enough. In fact, because of the known erosion of the cognitive components of manual flying skills with increased automation, a top recommendation of the FAA Flight Deck Automation Working Group [66] is to "Develop and implement standards and guidance for maintaining and improving knowledge and skills for manual flight operations." Moreover, this document stresses that "manual flying skills ... involve more than stick and rudder skills. They also involve cognitive skills and knowledge on how to handle situations that arise and how to keep the pilot engaged with the [automation] and ready to take over manually."

Drivers may also lose critical hazard mitigation skills in addition to important hazard anticipation skills. For example, the above study [65] also looked at the retention of manual skills among the pilots. Those skills which had been well learned were still retained. At one level, this may suggest that drivers should maintain their critical hazard mitigations skills even with extensive automation. But this really begs two important questions. First, a driver cannot mitigate a hazard who does not anticipate it and so a loss in hazard anticipation skills cannot be overcome by a high level of hazard mitigation skills. Second, the drivers of the future will not be like the pilots of today. They will not have had years of training with cars in manual mode. Everyone will, at some level, be a novice driver. Again, training is most likely the only answer to the acquisition and maintenance of critical hazard mitigation skills that may never be acquired if Level 3 autonomous vehicles become a reality for the great majority of drivers from the moment that they first step foot into the car. The human factors community has a long history of success with training in aviation [67], some most recently with critical skills for novice drivers [68].

C. Level 4

If the issues of usability and trust are solved with Level 3, almost by definition there can be no problem with Level 4 since it is designed to operate under all conditions. Yet, technologies do fail. So, there will need to be research on what to do when the ADS suddenly fails. Presumably one could use here the same techniques for sudden failure that were developed for Level 3. Critical driving skills will also decay with time. Again, there will presumably be a need for training.

IV. Additional Considerations

For the most part, we have addressed the general driving population when it is otherwise not impaired (except by distraction) and when it is engaged in some level of control of a car. But there are a whole host of other considerations where human factors will intersect with intelligent vehicles. A few of these are touched on below.

A. Special Populations

The safety implications of intelligent vehicles will be most dramatic for older and younger drivers, those most at risk for crashing. And the ability to relinquish control to the vehicle will be most critical for mobility impaired drivers.

1) Older Drivers: Older drivers are at a greatly inflated risk of crashing, especially at intersections [69]. Although they are beset by declines in visual, physical and cognitive function, there is one behavior that appears to explain the increase in crashes at intersections. In particular, older drivers fail to glance towards areas where potential threats could emerge after they enter the intersection [70]. Vehicle-to-vehicle communications will mean that the older driver can now be warned ahead of time of threat vehicles that the previous collision warning systems could not handle. But, we have no knowledge at the moment of how older drivers will respond to these warnings. This is a case where we hope the older driver would transfer control to the ADS. But we know that older drivers are less likely to trust technology than middle-aged drivers [71]. Human factors researchers can help here given their expertise in how trust in automation is developed and used appropriately, rather than misused, disused or abused [26].

2) Younger Drivers: Novice drivers are another high risk group. During the first month after they get their license they can be at ten times the risk they are just six months later [72]. Despite literally half a century of attempts to reduce novice driver crashes during these first critical six months [73], there has been only one randomized control trial with any indication of a large effect, and then only among males [74]. It was hoped that Graduated Driver Licensing programs would change this initially risky period with the large increase in the number of hours of supervised driving. But there has been little if any change [75].

Intelligent vehicles offer real promise here. As a rule, novice drivers are not careless; rather they are clueless [76]. They are overinvolved in intersection, run-off-road and rear-end crashes, all of which can be reduced by intelligent vehicles [77]. There is great hope here as novice drivers generally accept technology and so are generally likely to keep all crash avoidance systems active. However, this comes at a cost. Younger drivers will not learn the hazard anticipation, hazard mitigation and attention maintenance skills that they need in order to operate a vehicle at Level 2, or to take over when automation fails at Levels 3 or 4. Human factors researchers can bridge this gap, recommending the training of novice drivers on those skills which typically they do not exercise when driving automated vehicles [78].

3) Mobility Impaired Drivers: Mobility impaired drivers probably stand the most to gain in terms of sheer advances in their freedom to access their environment. Research at Ohio State University is now ongoing which will make it easier for mobility impaired individuals to move between their initial and final points of travel by developing small, golf-cart like automated vehicles [98]. Here, not only will one need to be concerned about all of the human factors issues discussed above that are broadly classified under cognitive ergonomics, especially with the interface used to control the vehicle, but one will also need to be concerned about the equally broad field of physical ergonomics [79].

B. Detection of Driver State and Remediation

Although not yet a major factor in the reduction of crashes, intelligent vehicles of the future may soon have the capability to detect driver states, warn the driver of the problem, and take over control in situations that require it. The ability to detect different driver states greatly improves with the increase in the level of vehicle automation because the sensors required to advance the level of automation are also the ones that provide the output to the algorithms often used to detect driver state. Moreover, the possibility exists when drivers are operating at Levels 1 or 2 of remediating an undesirable state when the vehicle is equipped with higher levels of automation (Levels 3 or 4).

1) Sleepiness, Drowsiness and Fatigue: Currently, drowsy driving is estimated by NHTSA to be a causal factor in 2.6% of all crashes [80]. The AAA Foundation for Traffic Safety puts this estimate much closer to 20% [81]. Either figure is too high. A number of researchers, not just human factors researchers, have contributed to the efforts to detect sleepiness, drowsiness and fatigue in the driver. Perhaps most research has been done on detecting driver drowsiness [82]. Indices are typically based on vehicle behavior, driver behavior, and driver physiology [83]. While the accuracy of physiological measures to detect drowsiness is very good, they are too intrusive as currently designed to be used on a widespread basis. Efforts are going forward to develop non-intrusive measures of physiological state [84].

Automatic, connected and intelligent vehicles can greatly expand the opportunity to detect driver drowsiness at Levels 0, 1 and 2 and to do something to remedy the situation by transitioning to Level 3. For example, drivers operating a vehicle at, say Level 1, that has up to Level 3 functionality could keep track of vehicle (lateral and longitudinal position) and driver (hands and foot) behavior. If the signature of the behaviors was one that was indicative of a drowsy driver, the system could recommend a transition to Level 3. Automated systems that allow drowsy persons incapable of driving to "be driven" are being explored by the industry [85].

2) Distraction: The holy grail of human factors researchers interested in reducing crashes due to distraction and mind wandering would be to be able to detect these states in the driver and then warn the driver or, in extreme conditions, take over control. A recent review of the literature on distraction and mind wandering concludes that it is failures of interruption management that create these two related problems [86]. Now that we have a better sense of why distraction and mind wandering occur, it should be possible to develop nonintrusive measures that provide some estimate of the probability that a given driver at a particular point in time is not fully engaged [87]. The most likely such model would take the driver's behavior as indexed by eye movements, steering inputs and speed information to determine the driver state and then decide whether, based on the costs and benefits of providing a warning to the driver, that the driver was distracted. Partially observable Markov decision processes are one obvious place to start, assuming that one can model the underlying latent processes governing performance as a Markov process [88].

Again, automated, connected and intelligent vehicles are being equipped with these monitoring technologies. Drivers operating at Level 1 or 2 who are sufficiently distracted could be switched to Level 3, assuming that the vehicle in which they are riding is equipped with such technology. Clearly this would involve some sort of permission from the driver, but one can easily imagine situations in which such permission would be given.

3) Alcohol and THC: It is estimated that alcohol is involved in a quarter of all crashes among teens [89]. And the problems do not disappear for older drivers, though they lessen with each succeeding year. Ignition interlock devices can prevent the engine from starting based on BAC levels. They have proven effective for first time and repeat offenders in several different countries, so much so that NHTSA has developed model guidelines for their implementation at the state level [90]. From a human factors standpoint, the question to date has been whether the devices are both reliable and fast enough to be useful. The quality of the evaluation of breathalyzers was greatly enhanced recently and makes possible much more rigorous testing of them in the Alcohol Countermeasures Laboratory at the Volpe National Transportation Systems Center in Cambridge, MA. Current estimates are that they cost

$100 to install and $50–$100 per month to maintain. All the evidence suggests that these costs will come down.

Intelligent vehicles offer an entirely new level of opportunity, especially at the higher levels of automation. Vehicle interlock systems are only in place for repeat offenders in most states. But the vehicle and driver behaviors that are signature of drink driving [91] could be used for anyone, before he or she becomes a first offender, let alone a repeat offender. A Level 3 system could then take over control. How that permission would be given in this case is something that would need extended debate. Similar opportunites exist for THC impaired drivers.

C. Low- and Middle-Income Countries

Road traffic injuries are currently the 9th leading cause of death globally and they are predicted by 2030 to be the 7th leading cause of death [24]. A recent estimate indicates that road traffic injuries were the direct cause of more than 1.25 million deaths in 2012 [92]. This number is staggering. It is a no small part of what motivates many of us to push forward the research frontiers with intelligent vehicles, especially as this research will impact the safety of the transportation system. Many opportunities to reduce crashes have been held back by a safety culture that is not favorable to the advance in technology. The introduction of seat belts in the United States is just one example. The human factors community has been heavily involved in efforts to improve the safety culture across a broad spectrum of issues [93], [94]. However, with intelligent vehicles, the ADS itself may intervene. It may take a decade or so for the vehicle fleet to begin to reflect the new capabilities in the low- and middle-income countries. But, it may not take a shift in culture so much as a shift in technology. Thus, the human factors research community may be involved more peripherally in this change than they are in other changes mentioned above.

V. Conclusion

It is clear that autonomous and intelligent vehicles can provide tremendous gains in safety. There is true reason for hope. Much of the research on the usability of DVIs and the trust that drivers have in automation can help make this hope a reality. But, there is no pat or easy answer to all issues which might arise as long as humans are in the loop on how best to design a given level of automation or a given DVI. The technology is simply changing too rapidly. Experimentation will continue to be necessary, despite all that we know about how drivers perform with the various levels of automation or DVIs. The human factors community is particularly well positioned after years of related experience to design the carefully controlled experiments that are needed to evaluate the future advances in automation.

Of interest, many of the human factors issues arise because the car is the driver and the human is out of the loop (Levels 3 and 4) or too easily can forget to stay in the loop (Level 2). Instead, what if for many drivers the car became their lifeguard for most of the trip, rather than their driver. If the car were to become the lifeguard, then some of these problems may simply disappear. Instead of manufacturers putting forward a vision of autonomous vehicles where the car is the driver for everyone, such as Google's Driverless Car Program [95], it may be that manufacturers will change their message to one where the car is a lifeguard for those who would prefer this role, there to assist them whenever they need help, but not there to take over control when they are doing fine by themselves. For example, the vision for the Center for Autonomous Cars that Toyota recently funded at MIT is described in the following way: they plan "to start by exploring a new alternative approach, in which the human driver pays attention at all times with an autonomous system that is there to jump in to save the driver in the event of an unavoidable accident. This type of system could not only improve safety by reducing the number of accidents, but could also enhance the overall driving experience . . . [the system] could prevent collisions and also provide drivers with assistance navigating tricky situations; support a tired driver by watching for unexpected dangers and diversions; and even offer helpful tips such as letting the driver know she is out of milk at home and planning a new route home that allows the driver to swing by the grocery store" [96]. This change in the way drivers view the new advances in intelligent vehicles could reduce considerably the current skepticism [97] and thereby improve acceptance (trust). It would reduce the problems that occur with Level 2 systems and transfer of control since the driver is, for the most part, actively involved in maintaining the speed and direction of the vehicle (the Level 2 system is still there when needed or desired). And it would decrease problems with Level 3 systems due to loss of skills. Again, the Level 3 systems would be there when needed, just not there all of the time.

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