FOUNDATION FOR TRAFFIC SAFETY

RESEARCH BRIEF

User Interactions with Vehicle Automation Technologies:

A Review of Previous Research and a Proposed Framework

January 2023

INTRODUCTION

There has been growing interest and continuous investment during the past two decades to advance transportation technologies with the vision that automated vehicles (AVs) will be deployed widely and transform the future of transportation. A report published by the U.S. federal government (2020) stated that a key benefit of automated vehicle technology is to improve safety and reduce roadway fatalities.

This perspective and, indeed, much of the enthusiasm regarding AV technologies is often grounded in perceptions of the relative safety of AVs compared with human drivers. Several reports by the National Highway Traffic Safety Administration (NHTSA) have cited actions or inactions by drivers as the critical reason for the critical pre-crash event in more than 90% of crashes examined in special studies designed to identify the key factors leading to the occurrence of crashes (Singh, 2015; Singh, 2018). Consequently, some transportation stakeholders have argued that if AVs can replace humans to operate future vehicles, then a majority of crashes will be eliminated. While it is implausible that all crashes previously attributable to driver errors could be eliminated by AVs, researchers have estimated that a substantial proportion of crashes, injuries, and deaths that occur on our roads today could be prevented by large-scale deployment of select advanced driver assistance systems (ADAS) (e.g., Benson et al., 2018); yet, numerous vehicle crashes still occur on a daily basis and there are too many lives lost on the roadways. It seems multiple areas still need to be improved before projected safety benefits of vehicle automation can be fully realized.

During the past several years, ADAS have become available in an increasing proportion of new vehicles sold, and are becoming more common in the vehicle fleet overall in the United States and other highly motorized countries. Multiple entities have entered the field to develop and test automated technologies. Such technology has been characterized by SAE J3016 (SAE International, 2021) as belonging to one of following levels of driving automation:

- Level 0 – no driving automation
- Level 1 – driver assistance
- Level 2 – partial driving automation
- Level 3 – conditional driving automation
- Level 4 – high driving automation
- Level 5 – full driving automation

Although information presented in this document focuses primarily on research related to Level 1 and Level 2 automation (i.e., ADAS or “driver support systems”), various aspects of the relationship examined here, between users and vehicle technologies, are also applicable to higher automation levels.

For AVs to reach their intended safety benefit potentials, users will have a critical role. This role is integral on two major fronts. First, public perception and acceptance of technologies will impact the rate at which these vehicles penetrate the market as well as the frequency with which the technologies are utilized. Second, correct understanding on the capabilities and limitations of technologies will help users calibrate their expectations and behaviors, leading to safe and appropriate interactions with the technology. It stands that education and training play an integral role on both fronts as they can help shape perceptions of technology while also ameliorating knowledge and understanding of how it works. For example, education and training should help drivers establish correct understanding of AV functionalities, capabilities, and limitations.

These three elements (user perceptions, user understanding, and education and training) provide the backdrop for this document, which presents a high-level review of recent research in these areas. Additionally, a framework is proposed that depicts the relationships between the topics listed above to help enable proper interactions between users and technologies. Ultimately, this document should contribute to the objective of utilizing vehicle automation technologies to reduce crashes and save lives on our roads.

Users' Perception of Vehicle Technologies

As mentioned in the introduction, experts in the transportation field anticipate vehicle automation will offer safety benefits to society. In order to maximize these benefits, large-scale market penetration of vehicles equipped with automation technologies, as well as infrastructure changes, are critical. Expected benefits and availability of AV in a market, however, do not ensure public trust and prompt adoption of these technologies. Many studies examining public perceptions and attitudes towards AVs reported that a majority are not in favor of these technologies. For example, in an early survey by Schoettle and Sivak (2014), most respondents were interested in having fully automated vehicles; however, the majority reported that they would not be willing to pay extra for such technology. Another survey showed that nearly half of respondents preferred conventional vehicles without automation features as their personal vehicles, while 16% of respondents preferred a fully automated vehicle (Schoettle & Sivak, 2016). A more recent survey administered in the U.S. just before the COVID-19 pandemic showed that nearly half of respondents reported that they would "never" get in an autonomous taxi or ride-sharing vehicle (Partners for Automated Vehicle Education, 2020).

Meanwhile, Acharya and Humagain (2022) showed a gradual increase of the AV adoption interest from 2015 to 2019 despite the increase of public concerns about AV as well. The onset of the COVID-19 pandemic in 2020 affected public perceptions and attitudes towards AV technologies to some degree. A U.S. study using a survey administered in June 2020 reported that the pandemic had a significant positive impact on people's willingness to use AV (Said et al., 2022). Another survey administered in July 2020 showed that one in five respondents were more interested in AVs compared with before the pandemic (Motional, 2020).

Multiple studies suggest that one of the biggest impediments to AV adoption comes from low public acceptance (Liu et al., 2018; Xu et al., 2018; Zhang et al., 2019). Towards increasing the public's acceptance, much research focused on factors such as age, gender, where people live, personality, and knowledge level, among others. Although Cho and Jung (2018) suggested people's perceptions towards AV vary by country owing to differences in culture, technological awareness, and social interactions between people, there are outcomes that have been consistently reported: males, high-income earners, those with higher educational levels, or those with tech-savvy personalities were more likely to be interested in AV than their counterparts (Kyriakidis et al., 2015; Bansal et al., 2016; Nielsen & Haustein, 2018; Asmussen et al., 2020). Experts have also noted that when measuring public interest in or acceptance of AVs, it is important to account for exposure to and experience with vehicle automation technologies among the study population (e.g., AAAFTS, 2022a). Several studies have suggested that people's perceived concerns and benefits, trust, and prior experience with AV affected their acceptance (Piao et al., 2016; Adnan et al., 2018; Asmussen et al., 2020).

Research by AAA Foundation for Traffic Safety

In 2018, AAA Foundation for Traffic Safety launched a national online survey to examine public understanding and expectations of emerging transportation technologies (Kim et al., 2019). This survey has been administered annually to collect data regarding people's perceptions, attitudes, and adoption behaviors towards each SAE level of automation. Analyses using data from 2018 to 2020 showed that in general, people were more likely to trust lower levels of vehicle automation (Levels 2 and 3) than higher levels to prevent crashes, and there were only marginal changes over time in this measure (Kim & Kelley-Baker, 2021). For each of several potential AV issues examined in this study (e.g., drivers' over-reliance on technology, no/lack of driving control), respondents' level of concern tended to increase as the level of automation increased. For example, when asked to consider a Level 5 vehicle, nearly three-quarters of respondents were extremely or very concerned about technology malfunction. Further, when asked what level of automation they would prefer in their own vehicle if cost were not a barrier, about half of respondents indicated that

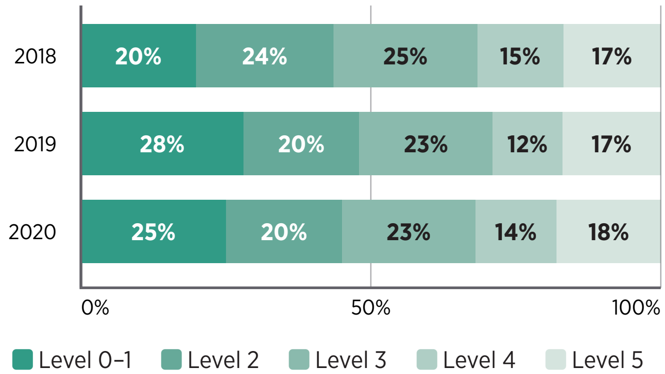

Figure 1. Level of automation drivers prefer to have in their vehicles, 2018–2020

they preferred Levels 1 or 2, and this propensity remained constant over time (Figure 1).

Another study conducted by the AAA Foundation for Traffic Safety and SAFER-SIM University Transportation Center found differences across different road users (i.e., drivers, pedestrians, and bicyclists) in terms of their perceptions, understanding, and expectations related to ADAS (e.g., adaptive cruise control (ACC) and lane keeping assist (LKA)) and more highly automated vehicle technologies (Horrey et al., 2021). Even though in general, all road-user groups were less likely to trust AV than human drivers, non-drivers demonstrated lower trust in the vehicle technologies compared to drivers. Interestingly, despite these lower trust levels, in some instances, non-drivers reported riskier behavioral intentions than drivers when interacting with vehicles equipped with the technology (e.g., lower willingness to give more space to the vehicle or wait until the vehicle passed before crossing the road). These results underscore concerns about the mismatch between user expectations of the technologies and their behaviors in different use cases.

Collectively, these results stress the need for more studies to better understand all road users' expectations of and their behaviors towards new vehicle technologies, as well as to explore how information from different sources affects their understanding of technologies. Further, continued efforts are necessary to raise public awareness regarding the availability and potential benefits of new technologies and to educate on capabilities and limitations of AV. These issues are explored further in the following sections of this document.

Mental Models of Users on Vehicle Technologies

As technology progresses and becomes more available in personal vehicles, user perceptions of the technology will continue to evolve. Given that these technologies will change the fundamental nature of the driving task, people's understanding of the technology is of critical importance moving forward. Technologies categorized as ADAS, Driver Support Features (DSF), or active driver assistance systems (e.g., SAE, 2021) can take on more of the driving responsibilities and, in doing so, control the lateral and longitudinal position of the vehicle for extended periods, relegating drivers to a monitoring or supervisory role. Misunderstanding of system function and limitations, or confusion over what the driver is responsible for in a given situation, can lead to errors and increased risk of safety conflicts. Thus, driver knowledge and understanding of vehicle automation, sometimes referred to as a driver's mental model, are important considerations in the safe and proper use of these systems.

Mental Models

Mental models are not specific to vehicle automation, but are often implicated in human interactions with systems or technology, more broadly. A mental model is a reflection of a user's knowledge of a system's purpose, its form and function, and its observed and future system states (e.g., Johnson-Laird, 1983; Rouse & Morris, 1986; Seppelt & Victor, 2020). In other words, a mental model can, for example, help a user understand what a system is for, how to use the system, when a system can be used, why a system is behaving in a particular way, and how the system will behave in the future given the current situation.

It follows that a user's mental model of a system has important implications in determining how they interact with it. An incorrect mental model can lead to errors and can also detract from potential safety benefits that a system could deliver if used appropriately. For example, Dickie and Boyle (2009) showed that drivers who were aware of limitations of ACC used the system in a more appropriate manner than drivers who were unaware or unsure about the system. Thus, the overall quality of the driver's mental model of the technology in a vehicle plays an important role in the safe, efficient, and appropriate use of these systems.

Mental Models and Vehicle Automation

There are two important elements related to mental models of vehicle automation. First, the driver needs to understand the functions and limitations of the system, along with the conditions or situations that the systems was or was not designed for. Inaccuracies can lead drivers to overestimate the capabilities of the system (e.g., believing it can operate in situations that it cannot).

Second, drivers need to correctly recognize the current mode or status of the system. If the system is not transparent or employs confusing human-machine interfaces (HMI), the driver might act incorrectly—even if they otherwise have a good understanding of the system. This can be further confounded by the complexity inherent to some of these systems (including those systems that integrate direct driver monitoring, geofencing, cooperative or noncooperative steering, etc.). For example, Pradhan and colleagues (2021) documented how even a relatively simpler form of automation (ACC) can be characterized by very complex relationships between possible states or modes and transitions between them (see sample, Figure 2). Such mode confusion has been widely documented in other complex domains (e.g., Sarter & Woods, 1995; Cummings & Thornburg, 2011). However, recent work in vehicle automation has largely focused on driver's understanding of functions and limitations.

Using survey-based approaches, a number of recent studies have demonstrated that people do not have a good understanding of the function and limitations of current ADAS features, such as ACC and LKA. For example, in a survey of 370 drivers who have vehicles equipped with ACC, about 72% were unaware of the system functionality and limitations (Jenness et al., 2008). In a more recent AAA Foundation survey of over 1,200 owners of ADAS-equipped vehicles, McDonald et al. (2018) found that although there was wide variability across the

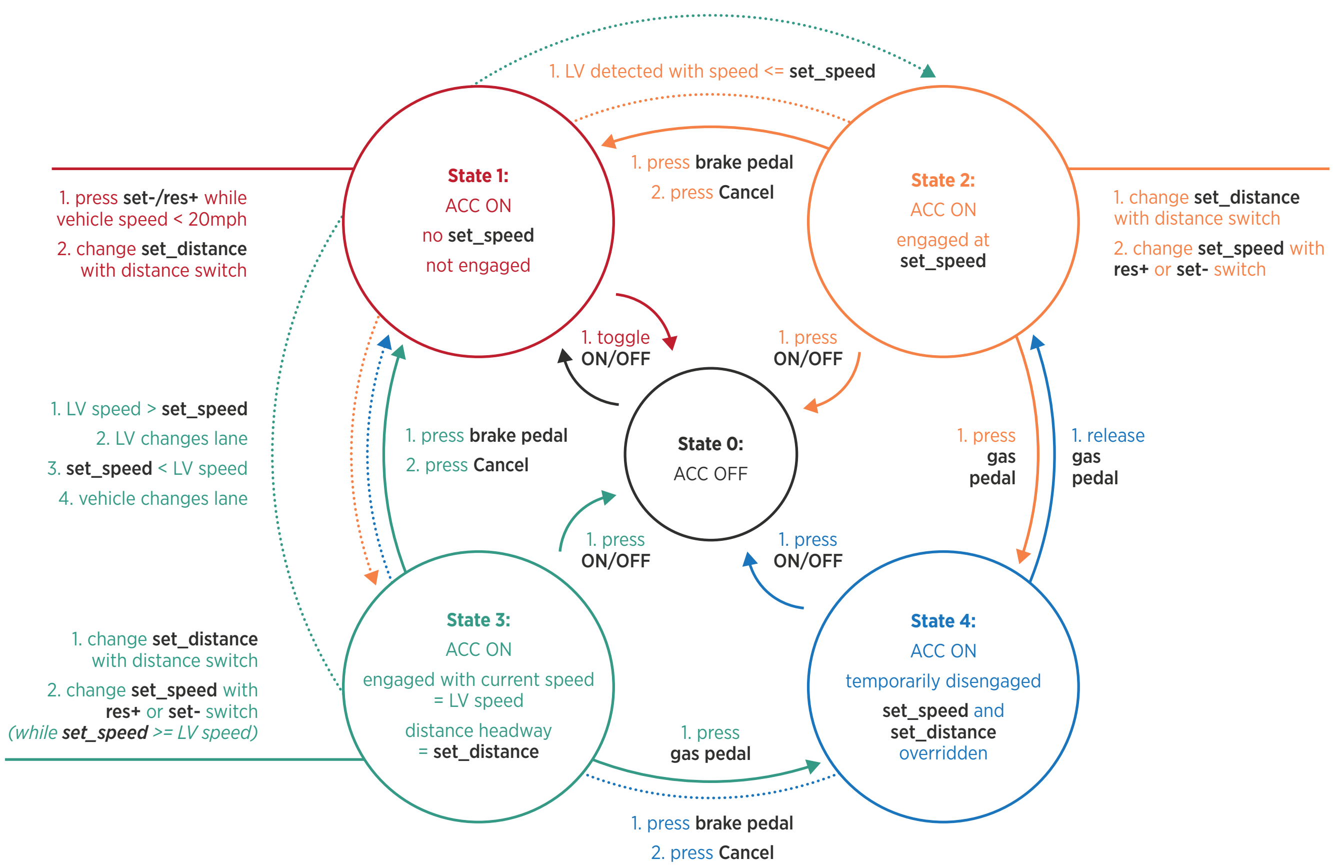

Figure 2. State diagram for a generic adaptive cruise control system (adapted from Pradhan et al., 2021)

different technologies examined, many drivers failed to understand the limitations of the technology as well as the driver's role and responsibility. Moreover, they found that owners expressed willingness to engage in a number of non-driving related tasks, which were incompatible with the driver's role, while using the systems.

Recently, Gaspar et al. (2020; 2021) examined how the quality of a drivers' mental model of vehicle technology impacted their safety and performance in a variety of scenarios that represented situations that were outside of the technologies' capabilities. In their study, drivers were divided into two groups: one that received in-depth training regarding ACC and another that received only minimal training. The resulting groups exhibited very different levels of understanding of the technology as measured by a knowledge survey. More importantly, when exposed to different edge-case scenarios, drivers who exhibited a poorer understanding (i.e., a weaker mental model) were less likely to disengage the system in some scenarios when it was appropriate to do so and in other cases they were slower to deactivate the system compared to drivers with strong mental models (see Figure 3). These results underscore two important things: (1) there is a clear mapping of system understanding to safety and performance outcomes and (2) even a modest amount of training and information can elicit large differences in driver's understanding of technology.

In a follow up study, Carney and colleagues (2022) observed how the understanding of technology progressed in drivers who were new to ACC over their first 6 months of ownership. They found that drivers' mental models of technology did improve over the course of the study as drivers became increasingly exposed and familiar with the system. Importantly, however, this group of drivers did not achieve the level of system understanding that was exhibited by the strong mental model benchmark group from the earlier study, suggesting that exposure and practice, while beneficial, can only get drivers so far. Additionally, this study revealed the emergence of a sub-group of drivers that demonstrated relatively low understanding of the system yet were highly confident in their knowledge. This problematic combination has been

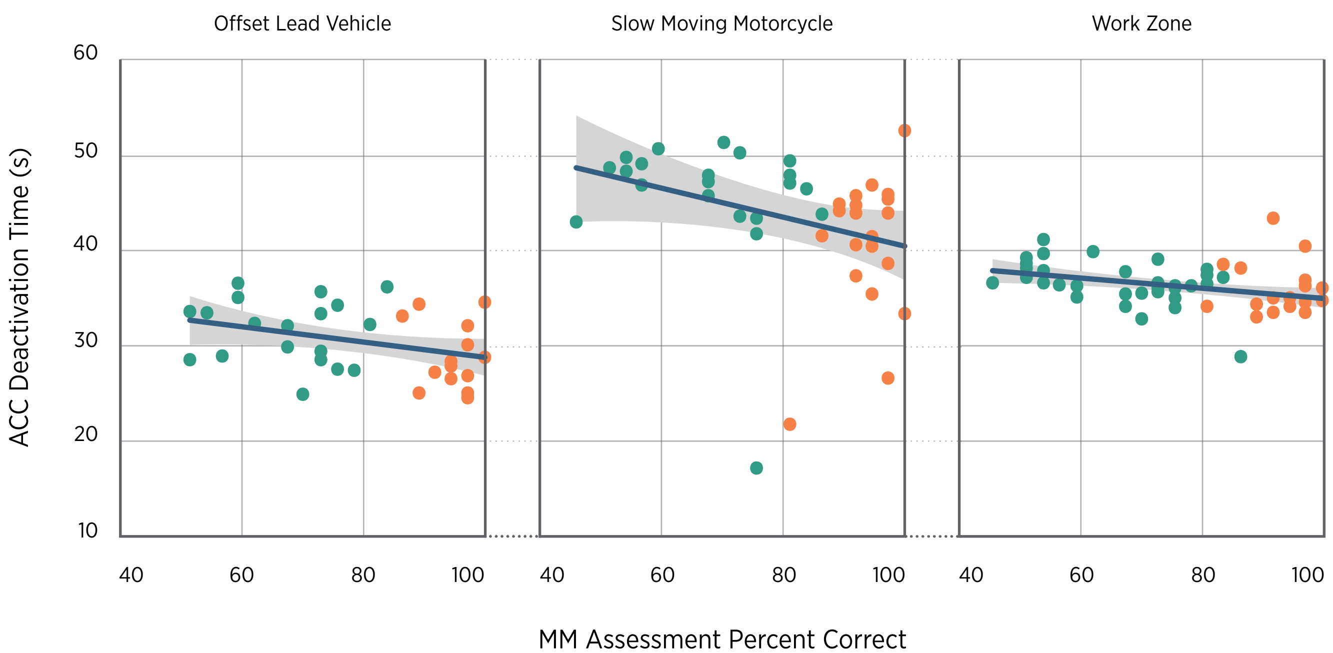

Figure 3. Plots showing time to deactivate as ACC (lower time is better) by mental model score (higher is better) for three different edge-case scenarios (adapted from Gaspar et al., 2020). Green dots represent drivers in the weak mental model group and red dots represent drivers in the strong mental model group.

observed by others (e.g., Lenneman et al., 2020) and could indicate the need to consider individual differences and other driver characteristics in various targeted remediation.

Educating and Training Drivers to Use Vehicle Technologies

The Need and Opportunity for Education and Training

As noted in the previous section, many drivers of vehicles equipped with ADAS or other driver support features are unaware of at least some of the capabilities and limitations of the technologies in their vehicle (e.g., Jenness et al., 2008, Braitman et al., 2010, McDonald et al., 2018). As illustrated in Figure 3, drivers with poor understanding of the technology in their vehicle often respond poorly when confronted with situations that exceed the capabilities of the technology (e.g., Gaspar et al., 2020). Thus, it is important to find ways to improve drivers' mental models of the technology in their vehicles.

It is clear from past research that there is opportunity for improvement in drivers' mental models of ADAS and driver support features through training and education, as many drivers receive little or no formal training. One survey of registered owners of ADAS-equipped vehicles found that roughly half were not offered or did not recall having been offered any training about the system at the dealership (McDonald et al., 2018). Although a more recent survey of owners found a substantially higher proportion received at least some training at the time of vehicle purchase, only about one in six reported having received formal, structured training (Lubkowski et al., 2021).

Moreover, some research suggests that informal sources of information have the potential to be detrimental to drivers' initial mental models. Abraham, McAnulty, et al. (2017) observed instances of automobile dealership staff explicitly providing incorrect information about safety critical systems to researchers posing as customers. Dixon (2020) noted that media and marketing materials often exaggerate the capabilities of partial vehicle automation technologies. Because these informal sources of information are often drivers' very first exposure to any information about a new vehicle technology, incomplete, incorrect, or misleading information has the potential to be particularly consequential. Numerous studies not specific to driving have found that people often give inordinate weight to the first information that they receive, and then have difficulty updating their initial judgments later upon exposure to new information (e.g., Tversky & Kahneman, 1974; Nickerson, 1998).

One obvious source of accurate initial information regarding the technology in a vehicle is the vehicle owner's manual; however, research suggests that providing drivers with a vehicle owner's manual alone is unlikely to suffice. At the most basic level, a substantial proportion of drivers do not typically read their vehicle owner's manual. For example, in a survey conducted before meaningful availability of ADAS, Mechlenbacher et al. (2002) found that while the majority of respondents reported having read at least part of their vehicle owner's manual, more than two in five did not. Abraham et al. (2018) reported a similar percentage in a more recent survey as well. McDonald et al. (2018) found that while the owner's manual the most frequently cited source of information drivers reported using to learn about various ADAS features in their vehicles, fewer than half of respondents reported using the owner's manual to learn about any given ADAS feature. Additionally, as Wright et al. (2019) note, vehicles are often driven by other people besides the owner, and non-owners' access to the manual may be limited.

AAA Foundation Research on Education and Training

Recent research illustrates the ease with which incorrect initial mental models form, and the difficulties of correcting them, in the context of partial driving automation. Singer & Jenness (2020) recruited a sample of drivers and gave them brief training on a real Level 2 system portrayed to the drivers as a prototype. Half of the drivers were given training emphasizing the system's capabilities and convenience; half were given training emphasizing its limitations and the driver's responsibilities. No false information was given nor safety-critical information withheld. However, those given training emphasizing system capabilities were significantly more likely to expect the system to successfully control vehicle speed and lane position, and avoid crashes, in a wide array of scenarios beyond its actual capabilities. Most of these differences persisted even after participants drove the vehicle and used the Level 2 system. These findings underscore the importance of ensuring that information provided to drivers about ADAS and vehicle automation features is not only accurate but also balanced. The findings also illustrate the rapidity of mental model formation and the difficulty of correcting faulty initial mental models.

Future Directions for Research and Practice in Education and Training

Fortunately, research has shown that providing drivers with training on ADAS and partial driving automation technologies can improve drivers' confidence, trust, mental models, and use of the technologies. McDonald et al. (2017) found that reading relevant portions of a vehicle owner's manual and experiencing a ride-along demonstration increased survey-based measures of knowledge about ADAS. A simulator-based study by Manser et al. (2019) found that training devised by the research team improved drivers' scanning and cognitive load when driving with simulated ADAS. Forster et al. (2019) found that both reading the owner's manual and completing an interactive tutorial improved questionnaire-based measures of mental models as well as interaction with a simulated partial automation system.

More work is needed, however, to determine how best to educate and train drivers to use ADAS and partial driving automation. One outstanding question is how or whether drivers can be motivated to consume information or complete training that is made available to them. Abraham et al. (2018) found that drivers have diverse preferences for how to learn about ADAS, and that those who learn about it through their preferred method have better understanding of the technology than those who learned through other methods. Research should investigate whether, or to what extent, the availability of training resources that align with an individuals' preferred method of learning increases their probability of completing the training, and ultimately, whether it improves their mental models and use of the system. Additionally, Beggiato et al. (2015) found that drivers quickly forget about system limitations that they do not actually experience while driving, suggesting a potential role for periodic refreshers or reminders regarding safety-critical system limitations experienced infrequently during normal driving. More research is needed to examine whether or how such reminders could be provided.

Framework for User Interaction with Vehicle Technologies

In the final section, a framework, presented in Figure 4, depicts the interrelationship between many of the concepts and outcomes discussed throughout this research brief. This proposed framework shows three major areas that will influence the safety benefits of vehicle technologies for drivers and other road users: (1) variables impacting drivers; (2) drivers; and (3) behavioral outcomes.

Variables Impacting Drivers

As presented previously in this document, there are a number of variables that will impact drivers, such as education and training, media, experience, and exposure, as well as the characteristics of the technology and user interface itself, which can affect or shape drivers' perceptions, understanding, acceptance, and trust of vehicle technologies. As an example, education and training can impact a driver's understanding of vehicle technology, which in turn can influence how they use the system and the subsequent safety benefits from the technology. Similarly, negative media surrounding a new vehicle technology could adversely impact an individual's acceptance or trust, which can limit their adoption or use, and result in little or no safety benefits.

Drivers

As shown throughout this document, there are various factors that will influence drivers' perceptions of vehicle technology and automation, their level of understanding (or mental models) and acceptance, and their trust in the technology. As an outcome, drivers will adopt certain behaviors and use systems according to their understanding and level of comfort. These behavioral outcomes may not result in the intended safety benefits of the technology.

Behavioral Outcomes

Behavioral outcomes of drivers, including adoption (i.e., uptake of new technology) and actual system use (including the manner in which technology is employed by drivers) play a key role on whether safety benefits of a vehicle technology can be fully realized. Positive behavioral outcomes lead to proper technology utilization and maximizing safety benefits while negative behavioral outcomes could yield opposite results.

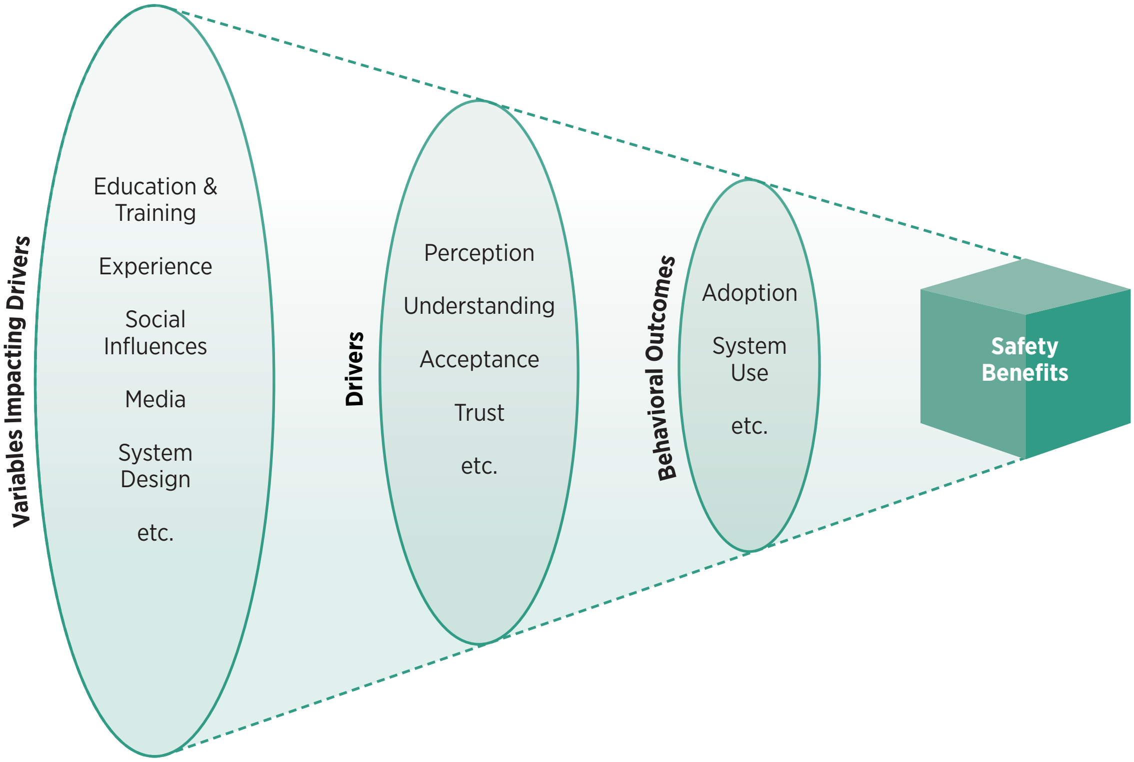

Figure 4. Conceptual framework highlighting critical elements that influence safety benefits of vehicle technologies

Realizing Safety Benefits

The framework presented in Figure 4 is intended to provide a context and visualization for many of the research themes undertaken by the AAA Foundation for Traffic Safety in recent years and is not intended to represent an exhaustive reflection of all related factors or interrelationships. For example, there are demographic variables, individual differences, driver states, and situational factors that could further interact with those factors illustrated in the framework. Nonetheless, this framework clearly illustrates three major areas that have direct influence on the safety benefits of vehicle automation technologies.

Started in 2017, the AAA Foundation for Traffic Safety has organized an annual forum and engaged hundreds of stakeholders in discussions concerning critical research needs related the implementation and safety of vehicle automation technologies (AAAFTS, 2018; 2019; 2020; 2022a; 2022b). Many of the elements captured in the proposed framework have been prominent and recurring topics in those discussions. Through the information and framework presented in this document as well as efforts such as the AAA Foundation forums, the momentum to further explore and find solutions to maximize safety benefits of vehicle automation technologies can grow stronger.

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