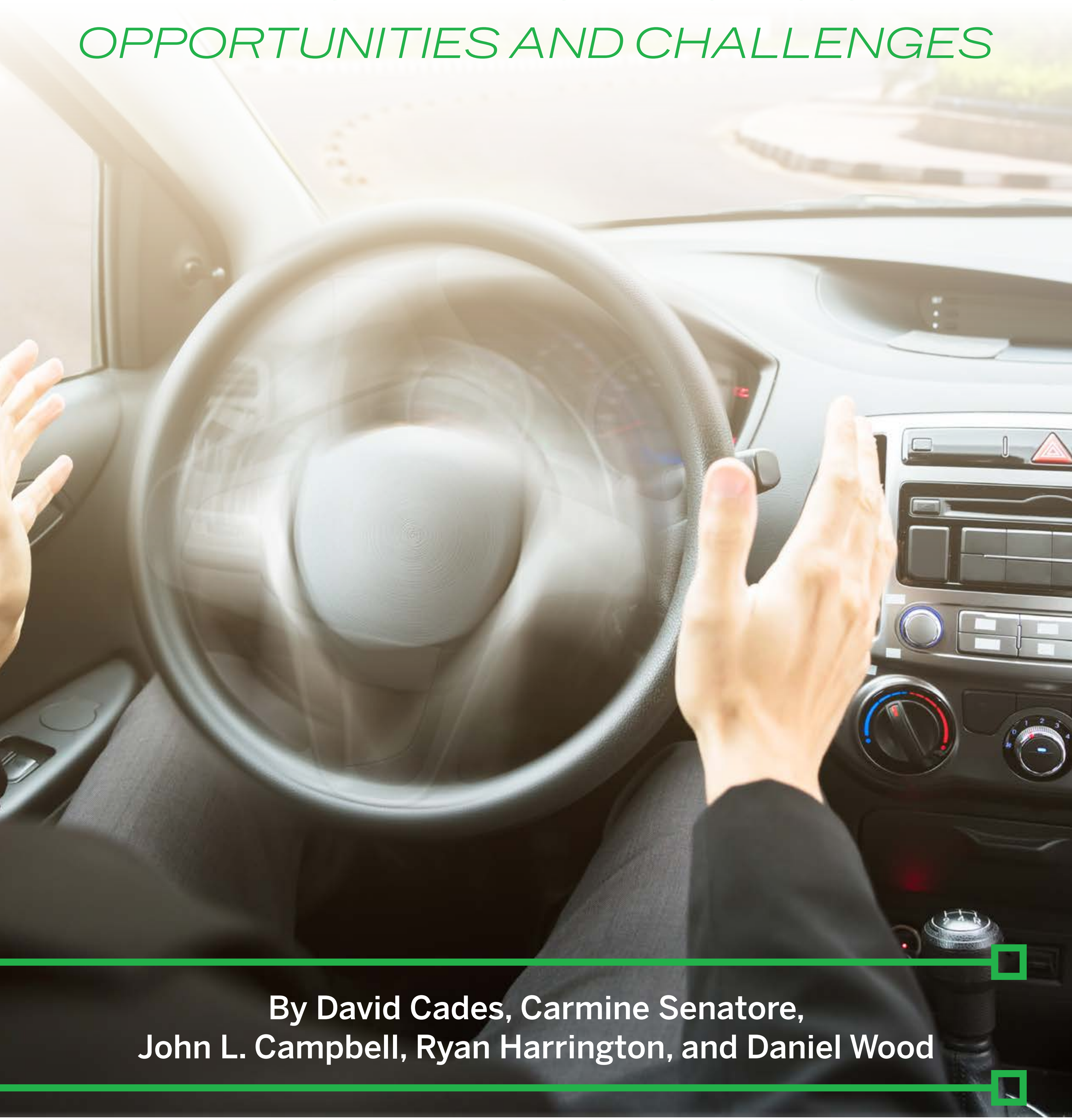
AUTOMATED AND ASSISTIVE VEHICLE TECHNOLOGY

OPPORTUNITIES AND CHALLENGES



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In the past two decades, there has been a sharp increase in the development and availability of technology related to automated vehicles and advanced driver-assistance systems (ADAS), generally aimed at improving safety and mobility for users of the transportation system. With the advent of increasingly automated driver-assistance features, the industry has been presented with new challenges as these innovative technologies are deployed and consumers are exposed to technologies with varying capabilities and limitations.

LEVELS OF DRIVING AUTOMATION

SAE International (formerly the Society of Automotive Engineers) has provided a framework to discuss advanced and automated vehicle technology and facilitate understanding of this technology in its J3016 standard, *Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems*. This standard describes six levels of automation, ranging from level 0 (momentary assistance) to level 5 (full automation). As the levels increase from 0 to 5, the amount of automation increases, and the role and control of the driver decrease. The levels are further grouped such that levels 0–2 are considered driver-support features, whereby the driver must be attentive and engaged in driving at all times even though the vehicle's automated features may intervene or support the driving task; and levels 3–5 specify various conditions under which the vehicle is automated, and the driver does not have a role in the driving task when these features are engaged.

Features of levels. Specifically, as can be seen in Figure 1, level 0 includes features like automatic emergency braking (AEB) and blind spot detection (BSD), while lane centering assist (LCA) and adaptive cruise control (ACC) can be ascribed (individually) to level 1.

The most advanced technologies currently on the general market are level 2; an example is the concurrent operation of LCA and ACC, which, together, maintain the vehicle's position on the roadway and relative to other vehicles, under certain circumstances. However, to ensure the safe operation of the vehicle, the driver must continue to monitor the driving environment.

Level 3 systems, which are described as full automation under specific conditions, are not available on the mainstream market yet; however, several systems have been announced for upcoming market deployment. One of the key considerations in a level 3 system is that the system and the driver have to hand off control of the vehicle to each other at particular times. Therefore, even when the vehicle automation is enabled, a driver must remain attentive to be able to promptly regain awareness of the environment and take control of the driving task.

Moving up the scale, levels 4 and 5 represent full automation of the driving task and do not require the driver to take over the driving task. In practical terms, the primary difference in these upper levels lies in the fact that the vehicle occupant does not have to remain engaged in the driving task. Level 4 provides for full automation only under certain driving conditions or in certain specified geographic areas, and level 5 provides for full automation under all driving conditions. Levels 4 and 5 systems currently are being tested, some on public roadways, but time to market for these systems is still uncertain. See Figure 1 on page 19, which is a graphic depicting the six levels of driving automation.

Incident investigations: technology concerns. Most of the automated technology at issue in current incident investigations of equipped (or nonequipped) vehicles would be categorized as ADAS (i.e., SAE levels 0–2). In considering incidents involving these technologies, a few technology-specific questions become immediately relevant:

1. Should the vehicle at issue have been equipped with a given advanced driver-assistance system?
2. Was a better technology available?
3. Did the technology function as intended?
4. How did the design and specific parameters of the technology effectively interact with the user?
5. What information was provided to the user with respect to the capabilities and limitations of the technology?

The technical and scientific concepts related to these questions highlight opportunities and challenges for incident investigators, regulators, and insurers, as well as system designers as they work on the development and deployment of these technologies while protecting consumers.

TECHNOLOGY DEVELOPMENT AND DEPLOYMENT

ADAS. While levels 4 and 5 vehicles are still in the development phase when it comes to direct consumer access, ADAS technologies (levels 0–2) have been present and growing in the U.S. fleet since the early 2000s (SAE level 3 systems are in the process of being introduced on select vehicles and are available in limited numbers in certain international markets).

ADAS include a variety of systems, which range from providing collision warnings to drivers to actively assisting drivers in the driving task through, for example, LCA or AEB. Individual ADAS generally are designed to support one specific aspect of the driving task and in general cannot (1) completely substitute for the driver, (2) operate in all

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TIP
Consider the entire landscape of vehicle technology rollout, deployment, and use when investigating incidents involving advanced vehicle technology.

environmental conditions, or (3) be 100 percent effective 100 percent of the time.

In 2006, Acura's Collision Mitigation Braking System (CMBS) and Mercedes-Benz's Brake Assist BAS Plus on its flagship S-Class model were the first radar-based systems capable of providing automatic braking. In the 2006–2008 time frame, other vehicle manufacturers followed suit with similar systems on their higher-end vehicles.

S curve. While more and more vehicles are being equipped with ADAS, such technology has not been deployed yet on every vehicle being produced and sold. This is not surprising as new technology deployment typically follows an S curve of market penetration, as seen in Figure 2 below. Historically, the first 10 to 15 years after a technology's introduction are characterized by a low-volume deployment rate (the flat part of the curve), followed by an increase in the deployment rate as the technology matures, and often taking another five to 10 years to reach the high-volume deployment rate on the top, or right, end of the S.

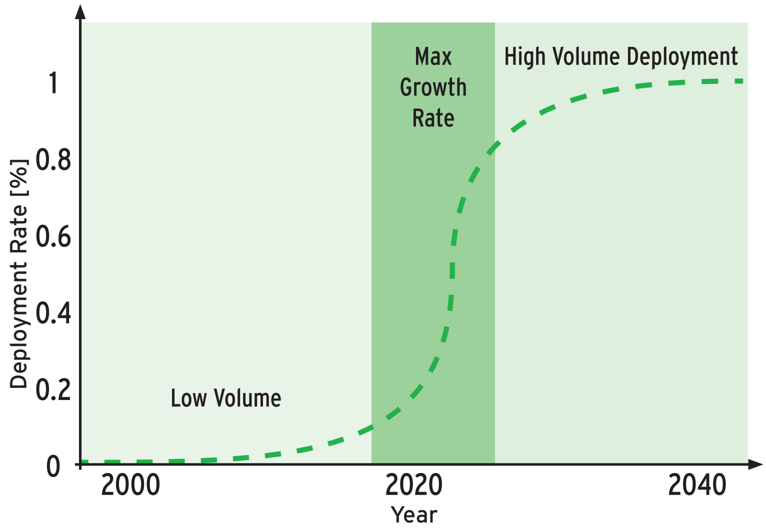

Figure 2. Deployment characterized by the S curve.

The shape of the S curve is defined by, among other things, the following:

- Capital investment and engineering resources,
- Technological breakthroughs and intellectual property (IP) considerations,
- Maturity of manufacturing processes,
- Design, production, and durability validation testing,
- Vehicle refresh and redesign cycles,
- Supplier capacity,
- Consumer acceptance and affordability, and
- Voluntary or mandatory standards.

NHTSA and deployment rates. When the National Highway Traffic Safety Administration (NHTSA) promulgates rulemakings (e.g., Corporate Average Fuel Economy (CAFE) standards), it expends considerable effort understanding and accounting for the deployment rate of a technology in its analyses.

For the CAFE rulemakings, emerging technologies are assumed to penetrate the market only in the single-digit percentage growth rate range per year; and even mature technologies, which are in the maximum growth rate regime of the S curve, are assumed to penetrate the market at growth rates of only 10 percent to 20 percent per year. The time horizon for the entire process of a technology becoming standard equipment on all vehicles produced can be 15 to 30 years. Furthermore, when considering the entire fleet, historical data suggests that it can, and does, take many decades for a technology to be present on nearly every vehicle on the road.

The 2017 announcement between the NHTSA, the Insurance Institute for Highway Safety (IIHS), and 20 vehicle manufacturers regarding those manufacturers' voluntary

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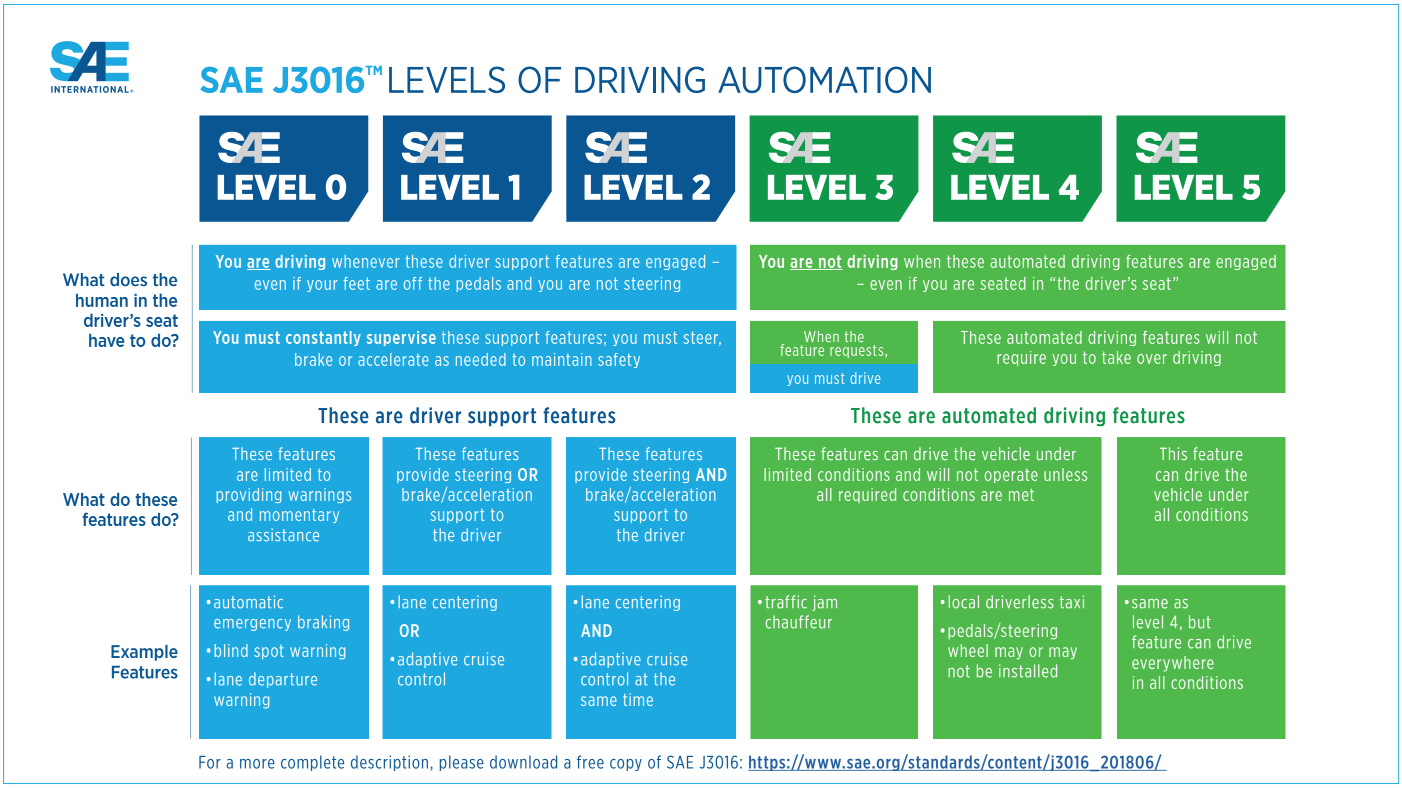

SAE J3016™ LEVELS OF DRIVING AUTOMATION

	SAE LEVEL 0	SAE LEVEL 1	SAE LEVEL 2	SAE LEVEL 3	SAE LEVEL 4	SAE LEVEL 5
What does the human in the driver's seat have to do?	**You are driving** whenever these driver support features are engaged – even if your feet are off the pedals and you are not steering			**You are not driving** when these automated driving features are engaged – even if you are seated in "the driver's seat"		
	You must constantly supervise these support features; you must steer, brake or accelerate as needed to maintain safety			When the feature requests, you must drive	These automated driving features will not require you to take over driving	
	These are driver support features			These are automated driving features		
What do these features do?	These features are limited to providing warnings and momentary assistance	These features provide steering **OR** brake/acceleration support to the driver	These features provide steering **AND** brake/acceleration support to the driver	These features can drive the vehicle under limited conditions and will not operate unless all required conditions are met		This feature can drive the vehicle under all conditions
Example Features	•automatic emergency braking •blind spot warning •lane departure warning	•lane centering **OR** •adaptive cruise control	•lane centering **AND** •adaptive cruise control at the same time	•traffic jam chauffeur	•local driverless taxi •pedals/steering wheel may or may not be installed	•same as level 4, but feature can drive everywhere in all conditions

For a more complete description, please download a free copy of SAE J3016: https://www.sae.org/standards/content/j3016_201806/

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Figure 1. SAE J3016 graphic depicting the six levels of driving automation (as discussed on page 17).

commitment to introduce AEB as standard equipment on most vehicles by model year 2022 seems to acknowledge the NHTSA's understanding of the current state of AEB (i.e., still an evolving, not yet fully mature technology) and the time required to achieve widespread deployment of the emerging AEB technology.[1] Even with this voluntary commitment to equip new vehicles with AEB, and with the impending transition into the max growth rate phase of the S curve, it still will take decades past 2022 before a substantial portion of the entire U.S. fleet of vehicles on the road will be AEB-equipped. Higher levels of automated vehicles, on the other hand, are still in the lower left corner of the S curve (in the low-volume deployment region) and will require more time to enter the max growth rate phase.

USER TRUST AND ACCEPTANCE

As vehicle manufacturers, suppliers, and technology developers bring ADAS and automated technologies to market, in addition to working within the frameworks provided by federal, state, and local authorities, care must be taken to consider how consumers will accept and use these systems. Regardless of how the technology functions, for any of these systems to have the desired effects that they often advertise, the ADAS-equipped vehicles must get into the hands of drivers, and the systems must be used by the drivers. For this to occur, consumers must be able to afford, perceive the benefits of, and ultimately use ADAS technologies.

Affordability. Affordability is one of the forces that drives newer technologies' debut in higher-end luxury makes and models because these vehicles and their prospective owners are more likely to bear the cost of new and expensive technology. Referring to the S curve mentioned above, an increase in market penetration of ADAS technology typically occurs as the technology enters a mature stage with associated lower production costs.

Trust. As these vehicles get into the hands of more users and the technology continues to mature and proliferate, the success of these systems' emergence also will be influenced by how the users trust the technology. Research on trust in automation has shown that an unreliable system can cause the user to lose trust and will be underutilized—and, thus, not effective due to nonuse.[2] At worst, the user will disable the system entirely.[3] Conversely, when a system performs reliably and is accepted by the user, trust (and use) can be facilitated. One study comparing drivers' reactions to adaptive cruise control systems with varying levels of reliability showed that trust grew over time for drivers exposed to a 100 percent reliable system.[4] With the knowledge that trust of the technology is integral, and that even infrequent violations of that trust can have a lasting effect on users' feelings toward automated

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systems,[5] consideration of these issues will go a long way to ensuring that ADAS will be integrated successfully into the automotive marketplace and become common equipment on larger portions of the automotive fleet.

If higher reliability fosters more trust among users, then a key challenge for ADAS development is the accuracy—and perceived accuracy—of hazard alerts that are provided by the system. False alarms or alerts are those provided by the ADAS device that are triggered in the absence of an actual hazard. A false alarm occurs, for example, when the system provides a forward collision alert in the absence of cars or other obstacles in front of the driver's vehicle or when the alert references an out-of-path vehicle or roadside object such as a guardrail or a sign that is not a hazard to the vehicle or the vehicle's intended path. Even a small number of false alarms can turn into a nuisance for the operator. Nuisance alerts include a subjective component; they can be triggered by an actual hazard but viewed as inappropriate or unnecessary due to the manner in which they are delivered, e.g., frequency, timing, intensity, or modality.[6] Whether or not the nuisance stems from false alarms or alerts that are deemed inappropriate by the user, the achievement of nuisance status will lead to higher rates of disuse and mistrust.

The "truth table" (Table 1) on this page summarizes performance outcomes from alerts provided by ADAS devices.

	Situation Warrants Alerting the Driver	Situation Does NOT Warrant Alerting the Driver
Alert Provided to the Driver	True Positive (hit)	False Positive (either a false alert or nuisance alert)
No Alert Provided to the Driver	False Negative (miss)	True Negative

Table 1. Performance outcomes from ADAS alerts.

Source: Adapted from Raymond J. Kiefer, David LeBlanc, Melvin D. Palmer, Jeremy Salinger, Richard K. Deering & Michael A. Shulman, Nat'l Highway Traffic Safety Admin., DOT HT 808 964, Development and Validation of Functional Definitions and Evaluation Procedures for Collision Warning/Avoidance Systems (1999).

Usage. Though the literature shows mixed driver responses to false alarms and nuisance alerts, either of these can affect driver behavior, performance, and acceptance of ADAS. For example, one study showed that false alerts resulted in longer brake reaction times immediately following a previous false or missing alert, and that drivers tended to brake for false alarms when they were timed to provide a relatively longer time-to-collision.[7] False alerts or alarms therefore can induce carryover effects from previous experiences such that experience with an alert can change behaviors and responses to subsequent alerts.

A field operational test of vehicles equipped with multiple collision-warning technologies (e.g., forward collision, curve speed warning, lane departure warning, and blind spot warning) found a nuisance alarm rate of 0.83 per 100 miles of driving across all warning types.[8] Despite this rate of nuisance alarms, 72 percent of all drivers were still interested in having the integrated system in their cars, versus 25 percent who were not interested. However, although many drivers found the nuisance rate to be tolerable, several drivers reported that the false alarms caused them to distrust the system and begin to ignore alerts.[9] While ignoring false alarms is appropriate, the danger is that drivers may ignore true positive alerts and not initiate an appropriate response in a hazardous situation that requires a response.

Driver acceptance data obtained from an independent evaluation of this same field operational test was similarly nuanced. One study reported that while false/nuisance alerts were the system characteristic liked least by 50 percent of the drivers, 81 percent still found the warnings helpful, and 82 percent were satisfied with the system overall.[10] These findings suggest, in general, that drivers find many of these systems useful but that the specific user experience and design of any individual advanced driver-assistance system will necessarily affect its utility and adoption.

Drivers also may respond differently to false alarms as compared to nuisance alerts. One study found that nuisance alerts were associated with greater compliance to the alert in critical situations, while false alarms were associated with less compliance.[11] Overall, false alarms and nuisance alerts can influence drivers' perception of the reliability of the ADAS device and change their degree of trust in the system;[12] impact their responses to alerts; reduce system effectiveness if "true" alerts are ignored; and, finally, as mentioned above, affect the overall efficacy of ADAS technology.

CONSUMER EDUCATION

Another aspect of the driver-ADAS interaction that will be critical to evaluate in order to understand the potential effectiveness of a given technology is the information available with respect to the systems' capabilities and limitations and how that information is communicated to the driver. Specifically, consumers' understanding of what the technology can do, and what it cannot do, will directly affect proper use and potential misuse. For example, certain forward collision mitigation

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systems are programmed to identify stopped cars in the vehicle's path of travel but may not alert drivers to a different object or shape in their path. Similarly, systems that rely on video processing to identify objects, roadway features, and hazards may not function as well in situations with limited optical ability (e.g., darkness, fog, rain, snow, etc.).

Lack of understanding. That users have difficulty understanding the capabilities and limitations of new technology is not new. In fact, in the early years of anti-lock braking systems (ABS), nearly 50 percent of complaints about ABS were related to occurrences in which the system was functioning as intended. The complaints were due to the users not understanding how the system worked.[13]

Similar trends have been observed with respect to ADAS and autonomous vehicle technologies. Specifically, one study revealed that less than 80 percent of respondents believed that a vehicle marketed as "Fully Autonomous" would be able to turn corners.[14] The study also showed that only about 50 percent of respondents believed that a vehicle marketed with "Driver Assistance" would notify the driver when the driver was needed.[15] When investigating a specific incident, it will be important to assess what the driver knew and understood, or could have known and understood, with respect to the available technology and how that may have influenced the driver's behavior.

Even if a driver is (1) operating a vehicle with a properly functioning ADAS technology and (2) encounters a hazard scenario within the system's capabilities and operational envelope, it is still possible that the driver will not comprehend or effectively respond to an evolving hazard or a system-generated alert. In order to understand either a situation as it unfolds or a hazard alert and then respond in an appropriate and timely fashion, drivers must develop and maintain a functionally accurate understanding of how the ADAS technology operates. This includes the user's knowledge of the technology's purpose, how it works, and how it is likely to work in the future.[16] While drivers generally have a good understanding of how common vehicle features operate (such as cruise control), their understanding will likely be weaker, incorrect, or nonexistent for early implementations of vehicles with ADAS technology. Given the many ways in which drivers can interact with such technologies, a challenge faced by ADAS developers is how to support the formation of a functionally accurate understanding of these vehicles.

A key challenge for ADAS development is the accuracy—and perceived accuracy—of hazard alerts that are provided by the system.

Greater automation: higher stakes. This issue becomes even more critical with higher levels of vehicle automation, as the human driver's role shifts toward having less responsibility for monitoring the external environment and actively controlling the vehicle and more responsibility for supervising the automation. In such situations, a lack of understanding of how the system operates can lead to incorrect assumptions about the system's abilities, confuse the driver, and even contribute to crashes. For example, suppose a vehicle equipped with both ACC and LCA systems is operating on a two-lane highway (i.e., both longitudinal and lateral control is being accomplished by the vehicle). The vehicle approaches a work zone in which the highway quickly narrows to one lane. Without a clear understanding of how the vehicle will behave in such a situation, the driver might (1) assume that the system can properly sense the situation and handle the lane shift—and face the possibility of a crash if it does not; or (2) seize control of the vehicle and initiate a manual lane shift without having the time to check and see if any vehicles are nearby. In both situations, a mismatch between the system's capabilities and the driver's understanding of those capabilities creates a potentially unsafe situation.[17]

Expectations-operation match. In general, greater levels of understanding of what the system can do and how it will operate in different situations are achieved when the driver's expectations of and experience with the technology are aligned with its actual operation and capabilities. Such operational consistency is crucial in the development of an accurate understanding of how advanced vehicle technology works. In the case of ACC technology, one study notes that the utility of the automation is a function of not only the driver's understanding of the vehicle-environment interaction but also the driver's understanding of the automation.[18] When the ACC system behaves in a manner consistent with that of a reasonable driver, the driver's understanding of the system will be supported, and the driver will be more likely to intervene when needed.[19]

Benefits of education. There are many benefits associated with helping drivers develop an accurate understanding of how ADAS

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technologies operate. For example, research in a variety of domains has identified that having a functionally accurate understanding of an automated system is a central aspect in reaching a desired level of expertise with the system,[20] improving users' level of trust in the system,[21] and improving users' ability to identify errors in the system's operation.[22] As detailed above, all of these traits generally lead to more use, more proper use, and better performance with automated technology and would do the same for ADAS.

INCIDENT INVESTIGATIONS AND ADVANCED VEHICLE TECHNOLOGIES

In the context of the issues and scientific principles mentioned above, it is clear that the investigation into (and corresponding evaluation of) the potential effectiveness of an ADAS-equipped or ADAS-nonequipped vehicle with respect to an individual incident (or series of incidents) is not as simple as a binary presence-or-absence discussion. This section discusses some of the aspects that will be critical for investigators to consider when dealing with incidents either involving ADAS and automated vehicle technology or involving claims that involved vehicles should have had ADAS or automated vehicle technology.

Data. Higher levels of automation not only will provide crash investigators with novel and nuanced situations to evaluate but also will provide new forms of data to assist in understanding an incident. For example, traditional accident-reconstruction methodologies will benefit from an enriched data set coming from the various sensor suites and data recorders that feed the ADAS and automated technologies.

With respect to available postincident data, the evolution of event data recorders (EDRs) and data loggers will provide useful information to accident-reconstruction specialists in determining precrash and postcrash maneuvers and movements even in the absence of physical evidence left on the roadway. The Code of Federal Regulations specifies current EDR requirements (if a vehicle is so equipped), including the data elements that have to be recorded before the triggering event (i.e., the crash).[23] Currently, vehicles equipped with an EDR are required to record indicated vehicle speed, accelerator pedal position, and service brake application up to five seconds before the triggering event. SAE International's J1698/1_201805 standard provides a recommended practice, detailing common data output formats and definitions for additional data elements that may be useful for analyzing vehicle crash and crash-like events that meet specified trigger criteria.[24] These additional data elements include information on ADAS status and activation that can support the reconstruction of precrash events. Furthermore, SAE International's EDR committee currently is working on a recommended practice for an ADS (automated driving systems) Data Logger. The draft recommended practice specifies that

> [t]he data elements defined in this document are unique to ADS and provide additional background of the events leading up to a collision in the absence of an eye-witness account. The camera(s), LiDAR(s), and other sensor data will provide this eye-witness record.[25]

The data stored in the ADS Data Logger, in conjunction with the data stored in the EDR, will help accident-reconstruction experts in painting a picture of what happened in the moments leading to a crash (or near-crash), even in the absence of eyewitness and physical evidence.

Precollision information gleaned from data in ADAS-equipped vehicles will provide insight into driver behavior.

Human factors. From the perspective of a human factors investigator, the precollision information gleaned from all of the new sources of data in ADAS-equipped vehicles will provide insight into driver behavior that all too often is elusive in current incident investigations. However, for all of the reasons detailed in this article (e.g., consumer understanding, trust in automation, expectation of system performance, false and nuisance alarms, etc.), crashes involving ADAS-equipped vehicles will necessitate an expanded focus on the driver-vehicle interaction. The complex interaction between the driver and level 0–3 systems and the performance of the vehicle for level 0–5 systems will require an expansion and evolution of existing methodologies that examine the role of the perceptual, cognitive, and motor functions of the humans involved in crashes.

In vehicle incidents, a current human factors analysis might include evaluating driver perception-reaction time (PRT)—i.e., the time it takes a driver to perceive an obstacle and produce an appropriate response.[26] As ADAS and vehicle automation take over more tasks for the human driver,

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however, understanding what the driver may need to perceive and react to becomes slightly more complicated. For example, for many level 0–2 technologies, a driver who should still be attending to the roadway may react to the presence of a roadway hazard but may also react to an in-vehicle warning from an ADAS. The investigator must consider carefully how these perceptions and reactions may influence one another.

What cannot be lost to the investigator looking at driver behavior in the presence of ADAS and vehicle automation is how and to what a driver could have responded in the absence of the technology. For example, was the hazard available to be seen by the driver? As mentioned above, the general appearance, size, shape, and type of object may affect the ability of ADAS to detect it due to limitations of the technology's sensor suite—and the same is true of the human driver. Features such as object size, uniqueness, contrast, conspicuity, and expectation will factor into the likelihood of detection by a human driver[27] and can influence PRT.[28]

These features are the primary characteristics of the visual information available to a sensor, whether that sensor is an eye or a camera. While the human eye has certain advantages over camera sensors (e.g., dynamic range), the human eye can perceive only what is in the observer's field of view and also can be affected by goal-directed attention.[29] Camera sensors, on the other hand, can expand the field of view available for detection and do not necessarily lose acuity in the periphery. Understanding the capabilities and limitations of the various available perceptual systems (i.e., human or technological sensor) will be essential when looking at human factors aspects of incidents involving ADAS and automated vehicle technology.

As noted above, ADAS technology is effective when it behaves in line with how a human would be expected to behave.[30] This provides important constraints for individuals who design, implement, and use ADAS. And in terms of vehicle accident investigations, human factors practitioners will play a critical role by evaluating whether the behavior of an automated or driver-assistance system did, in fact, act in line with the expectations of human drivers.

In addition to looking at the general behavior of the driver in investigations of incidents involving ADAS-equipped vehicles, human factors investigators also must consider the aspects of the technology and its interaction with the driver. ADAS technologies rely on core human factors principles but necessarily create novel driver-vehicle interactions. As an example, imagine a scenario where a forward collision warning occurs, followed by possible activation of AEB without driver intervention. First, the driver will need to identify and understand the warning signal and then decide how or if to respond to it. Possible responses include beginning to search for what set off the warning (i.e., look for the hazard) or to brake or steer. Each of these responses will take time. Our research suggests that many drivers are able to use a forward collision warning to react to a conspicuous hazard (i.e., vehicle target) in their path and avoid a collision.[31] Other studies have shown that for inattentive or distracted drivers, it can take a minimum of two to three seconds to acknowledge that action needs to be taken in response to a warning.[32] There are many other variables, such as driver expectations, that may affect the takeover time. When a driver has lost situational awareness or is "out of the loop," it can be quite difficult for that individual to respond to sudden emergencies or warnings.[33] While the specific interaction between a human and ADAS is nuanced and situation dependent, one aspect that is clear is that the argument about the effectiveness of these technologies is far more complicated than simply their presence or absence.

CONCLUSION

Although still in small numbers, ADAS and automated vehicle technologies are here, and all predictions indicate that they will increase in proliferation and complexity in the upcoming years. However, it still will be some time before most vehicles on the road will be equipped with some form of an advanced automated technology. Until a point where all (or at least most) vehicles are automated, the safety and mobility benefits of these systems will not be realized fully. With time, though, a reduction in crashes and incidents is expected.

Regardless, with the increasing complexity of vehicle technology and the corresponding driver-vehicle interactions, multidisciplinary teams of experts from fields including, but not limited to, vehicle accident reconstruction, automotive engineering, human factors, biomechanics, and computer science will be needed to investigate incidents involving ADAS and automated vehicles. In performing these investigations, it is inappropriate simply to assume that the presence of a given technology could have avoided (or even significantly mitigated) a collision (or, conversely, that its presence negatively influenced the outcome). For all of the reasons discussed in this article, careful and detailed investigation must be used to understand

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what technologies reasonably could have been expected to be available (or not available), the capabilities and limitations of the advanced technologies, and how the driver may have interacted with the technologies. The rapidly changing landscape of vehicle technology and automation and consumers' understanding of the technologies also mean that each incident and each technology must be evaluated and investigated independently. ■

NOTES

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Understanding overdriving: Human factors considerations in heavy vehicle headlight visibility and stopping distance

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Abstract

Nighttime road fatalities are a significant safety concern in the U.S., especially those involving commercial vehicles. Often an explanation offered involves overdriving headlights, or driving at a speed that does not allow for safe response within the range of the headlights' visibility. The scientific literature was reviewed to assess the real-world applicability of guidance commonly provided in Commercial Driver's License (CDL) manuals that advises heavy vehicle drivers to drive at a speed that allows them to be able to stop within the range of the vehicle's headlights. We conclude that this guidance provided by CDL does not account for the variety of roadway types, driver expectations, and travel speeds, nor a scientific understanding about visual perception and hazard avoidance. It is recommended that further work be conducted to examine real-world application of commercial vehicle driver capabilities and variable roadway types to better inform guidance and recommendations.

Keywords

Driver behavior, Safety, Visual search/scanning

Introduction

Approximately 46% of traffic fatalities in the United States occur at night between the hours of 7:00 PM and 6:00 AM, yet only an estimated 22% of vehicle travel occurs during those hours – in other words, the crash fatality rate is three times higher for nighttime drivers than for daytime drivers (Brumbelow, 2022). Considerable scientific attention has been directed toward understanding the underlying reasons for this preponderance of nighttime crashes, and one area of inquiry involves the tendency for drivers to "overdrive" their headlights at night – that is, drivers do not drive at a sufficiently low speed to effectively use and respond to hazard information within the illumination range of their headlights under otherwise dark lighting conditions (e.g., Olson & Sivak, 1983; Owens, Francis, & Leibowitz, 1989).

While overdriving headlights is a safety-critical concern for all types of motor vehicles, it is especially so for heavy vehicles such as commercial trucks, which exhibit longer delays between a brake pedal input and subsequent deceleration, and generally require longer stopping distances than passenger vehicles do (e.g., Bayan et al., 2009; Fricke, 1990). Commercial Driver License (CDL) manuals advise heavy vehicle drivers to drive such that they can stop within the range of the vehicle's headlights (e.g., ADOT, 2022). Similarly, the "assured clear distance ahead" rule holds that a driver must maintain a speed low enough to enable stopping within their range of vision (Leibowitz et al., 1998). However, driver manuals also encourage conformity with traffic flow and adherence with posted speed limits, the latter of which can often be too high for drivers in nighttime visibility conditions to operate within their vehicle's headlight range unless they drive substantially slower than the posted speed limit (Leibowitz et al., 1998). Given the aforementioned criticality of this issue for commercial vehicles, in this paper the consistency of guidance provided by CDL manuals with scientific understanding of driver visual capabilities under nighttime conditions and heavy vehicle stopping distances is examined. Commercial or heavy vehicles are those that have a Gross Vehicle Weight Rating (GVWR) over 10,000 pounds and include, for example, single-unit trucks and tractor-trailers (National Center for Statistics and Analysis, 2022).

Visual Perception

Whether in the driver's seat, cooking a meal, or in any other day-to-day context, a person's perception of their environment emerges from the integration of sensory signals both between and within modalities such as vision, audition, and even the

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vestibular system in a bottom-up process that weights modality-specific cues according to reliability (Ernst & Banks, 2002; Fetsch, DeAngelis, & Angelaki, 2010; Toscano & McMurray, 2010). The utility of visual perception in the traffic environment is readily demonstrated by driving impairments that occur in reduced visibility conditions (e.g., fog or glare).

Not only must drivers process and integrate visual and environmental information, but they must also manage the cognitive and motor demands associated with safely operating a motor vehicle. The load placed on drivers is such that they cannot possibly process all of the visual stimuli available to them at any given moment - a person can focus on *some* things, but they cannot focus on *all* things. The process by which a person, such as a driver, allocates their cognitive capacity to focus on environmental features is known as *attention*, and the analogous process by which the person directs their ocular gaze to certain features within their field of view is referred to as *visual search*. Decades of research have demonstrated human visual search to be dependent on context, including task demands and situational factors (Rauschenberger, 2003; Rauschenberger et al., 2015). For drivers, gaze and attention allocation are heavily influenced by the salience of the environmental information's source, the driver's perceived likelihood that the source will provide useful and relevant information, the perceived costs in the hypothetical event relevant information is missed, and the perceived effort involved in attending to the source (Horrey et al., 2006; Land, 2006).

The effectiveness of visual signals as an indicator of potential hazards hinges on the driver's gaze and attention actually being directed to the location(s) or feature(s) in the roadway that provide information pertinent to roadway conditions – in other words, drivers should "look ahead" to better anticipate and respond to obstacles and hazards - and also on whether such hazards are available to be seen in the critical time frame (Falkmer & Gregersen, 2005; Krauss, 2015). Without such anticipatory visual behavior, the driver may lack the situational awareness necessary to detect hazards with enough time to safely respond (Tijerina et al., 2004; Krauss, 2015). Endsley (1988) defines situation awareness as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future." Drivers must also direct their gaze to a variety of other locations, including roadway boundaries, other vehicles, traffic signs or signals, mirrors, and in-vehicle displays or devices. Typically, drivers' glance durations to locations other than the roadway ahead do not exceed 2000 milliseconds (Dukic et al., 2005).

Vehicle Headlights

As one might expect, a driver's visual capabilities generally decrease at night due to the relative dearth of available visual information compared to daytime conditions (Krauss, 2015; Olson et al., 1989). At nighttime, drivers tend to look in the area illuminated by headlamps, ahead of the vehicle and in the vicinity of the centerline (Olson et al., 1989). Additionally, the durations of fixations are generally longer at nighttime compared to daytime (Olson et al., 1989), and drivers' vision is directed more to road edge lines and road surfaces at night (Rackoff & Rockwell, 1975). Research shows that exterior vehicle lights, such as flashers, are detectable in low light conditions for over 3,000 feet, but the ability to discern potential roadway obstacles such as pedestrians, animals, or other vehicles is significantly reduced in conditions with reduced luminance (e.g., Curry, 2007; Krauss, 2015; Owens & Sivak, 1993). Unless traversing roadways with ample environmental lighting sources, such as streetlights or business lights, drivers often rely on the illumination of their headlights to obtain visual information regarding upcoming roadway features or potential hazards. Thus, a driver's ability to detect hazards is generally limited by the illumination distance of their headlights. Drivers require approximately 1 - 2 lux of light to recognize a bright object, 3.2 - 5 lux to recognize a grayish object, and as much as 15 - 20 lux to recognize dark objects (e.g., Muttart et al., 2013; Neale et al., 2019). Muttart et al. (2013) observed that, for vehicles that were less than five years old at the time of testing, low-beam headlights provided 3.2 lux of light for an average of approximately 250 feet, whereas highbeam bulbs provided 3.2 lux of light for over 350 feet. Important considerations for headlight illumination distance include the age of the bulb, the height of the bulb, the cleanliness of the bulb, and the tendency of headlights to be aimed slightly downward and toward the passenger side of the vehicle to reduce glare effects for oncoming vehicles (e.g., Mace et al., 2001; Muttart et al. 2013; Schoettle et al., 2002). Thus, illumination for hazards approaching from the driver-side of the vehicle is typically lower than passenger-side hazards when using low-beam headlights.

One approach for conceptualizing the illumination afforded by headlights is based on determining the *twilight distance*, or the distance at which the illumination cast by headlights becomes equal to the illumination characteristic of the dark limit of civil twilight, or approximately 3.2 lux (Owens, Francis, & Leibowitz, 1989). Visibility in civil twilight ranges from relatively optimal daytime illumination to minimal illumination toward the dark limit. In other words, visibility of non-luminescent, non-retroreflective objects is significantly degraded as distance forward of the vehicle approaches the twilight distance. Andre and Owens (2001) refined this approach to describe headlight beams as creating a threedimensional area of useful illumination (i.e., useful illumination distance varies based on object height), defining the resultant *twilight envelope* as the distance beyond which foveal functions are severely impaired. Specifically, for low beam illumination, the authors found that the twilight distance at headlamp height of approximately 2 ft was 175 ft ahead of the vehicle and 260 ft at ground level. At the eye level of the driver at a height of approximately 3.6 ft the twilight envelope extended to 80 ft. The authors cautioned that the exact illumination level to be used as the threshold for useful visibility must be carefully considered – the twilight approach is based on the dark limit of civil twilight (3.2 lux), at which point visual acuity and contrast sensitivity degrade to below 20% of daytime levels, and some researchers suggest 33 lux (corresponding to the midpoint of civil twilight) to be a more appropriate threshold for providing a wider margin of safety (Andre & Owens, 2001; Sivak et al., 1992). Andre and Owens (2001) concluded that stopping distances at most speeds are longer than civil twilight distances – in other words, it is difficult *not* to overdrive one's headlights.

Hazard Detection & Response

How conspicuous an object is within vehicle headlights is also dependent on the characteristics of the object, such as its size, brightness, or reflectiveness. Once a hazard becomes available for to a driver see, the driver undergoes a process known as perception-response time (PRT). PRT refers to the amount of time that it takes for a driver to perceive a stimulus ahead, identify whether the stimulus represents a hazard, decide an appropriate response (such as steering or braking), and then initiate the planned response (e.g., Krauss, 2015; Muttart, 2005). As discussed above, drivers that are traversing roadways at night typically have less visual information available to them, which may lead to delays in the detection and identification stages of PRT. Under nighttime conditions, drivers can require a PRT of 1.5 seconds to respond to conspicuous hazards, such as lit traffic signs or vehicle lights, with PRT durations increasing to 2.5 seconds or more for hazards that are low conspicuity or unexpected (e.g., Krauss, 2015; Muttart, 2005). Given that low-beam headlights tend to be aimed slightly downward, roadway hazards such as pedestrians may be difficult to detect as low-beam headlights typically illuminate lower portions of pedestrians more than upper portions at greater distances (Krauss et al., 2015). However, the ground and roadway surrounding the lower portions of pedestrians are similarly illuminated and, when pedestrians are wearing dark clothing, there is often insufficient contrast for drivers to detect the presence of a pedestrian (Krauss et al., 2015). In fact, research has shown that as much as 60% of drivers using low beam headlights fail to detect pedestrian targets at a distance of

300 feet (Krauss et al., 2015). Wood et al. (2005) found that drivers using low-beam headlights reacted to road-side pedestrians wearing black clothing from an average distance of 18.5 feet, pedestrians wearing white clothing from an average distance of 132 feet, and pedestrians wearing retro-reflective material from an average distance of 486 feet. Importantly, for pedestrians wearing black clothing, drivers recognized the pedestrian at a distance that was likely insufficient to avoid an incident (if they detected the pedestrian at all) even when the drivers were informed that a pedestrian would be positioned somewhere on the experimental driving course (Wood et al., 2005).

Table 1. FMVSS §571.121 maximum stopping distances in feet for 1.) loaded and unloaded buses, 2.) Loaded single-unit trucks, 3.) Loaded tractors with two axels; with three axels and a gross vehicle weight rating (GVWR) of 70,000 lbs. or less; or four or more axels and a GVWR of 85,000 lbs. or less, 4.) Loaded tractors with three axels and a GVWR greater than 70,000 lbs.; or four or more axels and a GVWR greater than 85,000 lbs., 5.) Unloaded single-unit trucks, 6.) Unloaded tractors (bobtail), 7.) All vehicles except tractors, loaded and unloaded, using emergency brake, and 8.) Unloaded tractors (bobtail) using emergency brake.

	Stopping Distance (ft) per vehicle type							
Vehicle Speed (mph)	*(1)*	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*
20	32	35	32	35	38	30	83	85
25	49	54	45	54	59	43	123	131
30	70	78	65	78	84	61	170	186
35	96	106	89	106	114	84	225	250
40	125	138	114	138	149	108	288	325
45	158	175	144	175	189	136	358	409
50	195	216	176	216	233	166	435	504
55	236	261	212	261	281	199	520	608
60	280	310	310	310	335	235	613	720

For commercial truck drivers, however, there are additional considerations for slowing or stopping in response to a hazard – even after the driver finishes PRT and the brake pedal is pressed. For example, tractor-trailer vehicles can experience a delay between when the driver presses the brake pedal and when full deceleration of the vehicle begins. Bayan et al. (2009) examined tractor-trailer braking for vehicles traveling either 30 mph or 60 mph and found that a steady rate of deceleration began, on average, 0.48 seconds after braking was applied. This means that, for a commercial vehicle traveling 65 mph (95.3 ft/s), the vehicle may travel approximately 46 feet after the brake pedal is pressed before steady deceleration begins. Once deceleration begins, the size and weight of commercial vehicles can further increase their stopping distance compared to passenger vehicles. According to the Federal Motor Carrier Safety Association (FMCSA), commercial trucks can require 20-40% longer stopping distance than passenger vehicles (FMCSA, 2015). Federal Motor Vehicle Safety Standards (FMVSS) §571.121 allows commercial trucks to have a maximum stopping distance 250 – 335 feet when stopping from 60 mph using the service brake, depending on the type and weight of the vehicle (see Table 1).

Overdriving Headlights

Given that low-beam headlights provide 3.2 lux of light for approximately 250 feet and high beam headlights provide

3.2 lux of light for approximately 350 feet (Muttart et al., 2013), many of the allowed stopping distances for commercial trucks are greater than the distance at which the vehicle's headlights would provide reliable illumination to detect relatively bright hazards. This is also before accounting for driver PRT, which may be over 2.5 seconds (approximately 238 feet at 65 mph) for inconspicuous or unexpected hazards as well as the halfsecond brake lag (approximately 46 feet) before steady deceleration begins. Assuming a PRT of 2.5 seconds or more for an unexpected and/or low conspicuity hazard, a half-second of brake lag, and the maximum permitted stopping distances set by the FMVSS, a commercial truck driver operating a standard tractor-trailer would begin to overdrive their low-beam headlights upon exceeding a speed of approximately 35 mph and begin to overdrive their high-beam headlights upon exceeding a speed of approximately 45 mph. Should commercial drivers travel at speeds as low as 35 mph on limited-access roadways, this would introduce slow-moving vehicles (i.e., potentially hazardous conditions) to the roadway, impede the flow of traffic, and reduce the bandwidth of the commerce implications supported by the trucking industry.

Some states have implemented minimum speed laws (e.g., ADOT 28-704) which prohibit drivers from traveling at speeds low enough to impede the flow of traffic unless that speed is necessary for the safe operation of the vehicle. This begs the question, then, of whether commercial drivers must drive at low speeds (i.e., speeds below the overdriving thresholds) to safely operate their vehicles under nighttime conditions. High-speed roadways have an expectation that nighttime hazards will be either highly visible (e.g., braking vehicles communicated through lights that are visible for over 3,000 feet) or will be made highly visible (e.g., disabled vehicles communicated through retroreflective triangles visible from 720 feet; Curry et al., 2007). These same roadways are also expected to be free of inconspicuous hazards, such as unlit vehicles or darkly clothed pedestrians in the lane of travel. Thus, commercial drivers are typically able to travel at speeds that conform to the flow of traffic without incident, making it reasonable for commercial drivers to travel at speeds that overdrive their headlights in most circumstances. Furthermore, lowering speed limits – and therefore slowing the flow of traffic – to accommodate overdriving thresholds would likely have negative economic consequences. Research has demonstrated an association between development of highway infrastructure and positive outcomes in economic productivity and output across several industries that rely on expedient transport of goods (Butler et al., 1984; Shatz et al., 2011), with commercial vehicles being essential to said expedient transport.

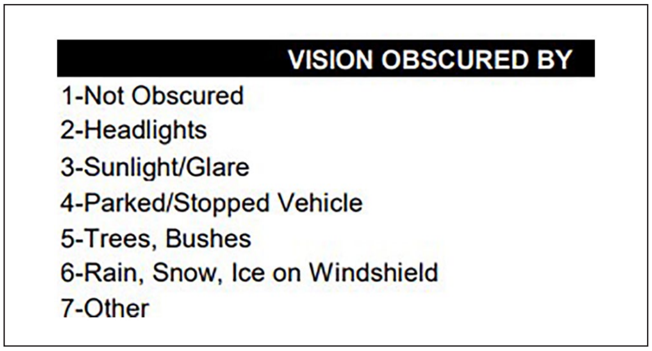
Regulations

The Commercial Driver's License (CDL) manuals for all 50 U.S. states provide the following guidance on driving within the range of the vehicle's headlights (page numbers based on ADOT, 2022):

1. "You should always be able to stop within the distance you can see ahead. Fog, rain, or other conditions may require that you [slow down] to be able to stop in the distance you can see. At night, you can't see as far with low beams as you can with high beams. When you must use low beams, slow down." (p. 2-15)
2. "Drive slower when lighting is poor or confusing. Drive slowly enough to be sure you can stop in the distance you can see ahead." (p. 2-26)
3. "With low beams you can see ahead about 250 feet and with high beams about 350-500 feet. You must adjust your speed to keep your stopping distance within your sight distance. This means going slowly enough to be able to stop within the range of your headlights. Otherwise, by the time you see a hazard, you will not have time to stop." (p. 2-26)
4. "At night, drive slowly enough to see obstacles with your headlights before it is too late to change lanes or stop gently." (p. 6-1)
5. "Most good drivers look at least 12 to 15 seconds ahead. [. . .] At lower speeds, that's about one block. At highway speeds it's about a quarter of a mile [1320 feet]." (p. 2-10)

The U.S. Department of Transportation's National Highway Traffic Safety Administration (NHTSA, n.d.) keeps a database of nationwide traffic crash fatalities. The NHTSA crash database was queried for data on accidents involving heavy trucks, both commercial and non-commercial. In 2020, heavy trucks were involved in 4.8% of crashes, and buses were involved in 0.3% of crashes (National Center for Statistics and Analysis, 2022). Of those crashes involving large trucks, 3.8% were injury crashes and 8.9% were fatal crashes (National Center for Statistics and Analysis, 2022). There were various factors listed for the drivers involved in those crashes including over speeding, impairments due to drug or alcohol use, driver fatigue, making improper turns, vision obscured, and other factors. None of the factors involved in these accidents were specifically related to a heavy truck driver overdriving their headlights. It is hard, therefore, to know and track how many accidents involving heavy trucks are attributed to overdriving headlights each year.

According to NHTSA, 2.8% of all fatal crashes are related to vision being obscured by rain, snow, glare, lights, building, or trees (National Center for Statistics and Analysis, 2022). It is unclear if 'vision obscured' by lights implies that one of the drivers involved in the crash was overdriving their headlights. Traffic crash reports sometimes also have a 'vision obscured' section. For example, the GA Traffic Crash Report has a section for 'VISION OBSCURED BY' (see



VISION OBSCURED BY

1-Not Obscured
2-Headlights
3-Sunlight/Glare
4-Parked/Stopped Vehicle
5-Trees, Bushes
6-Rain, Snow, Ice on Windshield
7-Other

Figure 1. “Vision obscured by” options found in the Georgia Traffic Crash Report (GDOT, 2023).

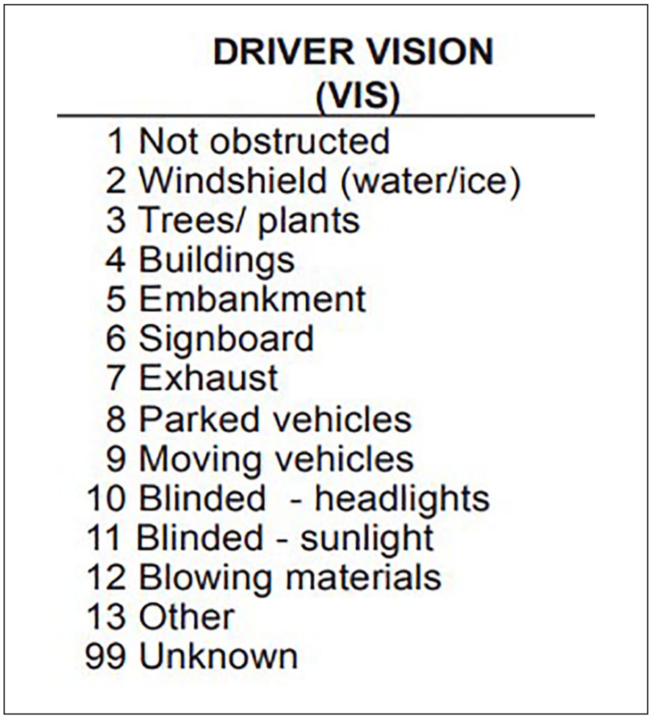
Figure 1). The IL Traffic crash report also has a section on ‘DRIVER VISION’ (see Figure 2). However, the relevance of this data point rests on assuming that selecting the ‘Headlights’ option means that overdriving headlights is the intended contributing factor.

Even then, this information does not translate to the NHTSA database to provide relevant information on traffic accidents involving large trucks that are caused by the driver overdriving his headlights.

Discussion and Conclusions

In this paper, motivated by the safety-critical issue of commercial vehicle operators overdriving their headlights, the scientific literature was reviewed to assess the real-world applicability of guidance commonly provided by CDL manuals that advises drivers to drive at a sufficiently low speed to be able to stop within the range of the vehicle’s headlights. Specifically, literature pertaining to the visual perception and hazard avoidance capabilities of commercial vehicle operators was applied to understand how these capabilities and limitations are negatively affected by low-illuminance (e.g., nighttime) conditions, and the utility of headlights in mitigating these negative effects. Finally, the guidance provided by CDL manuals from across the United States was examined, as well as the “assured clear distance ahead” rule, with regard to their consistency with scientific understanding and to contextualize such guidance with real world application.

Based on this literature review, several conclusions have been reached. First, attentive drivers briefly and sequentially direct their gaze, for up to 2 seconds at a time, to myriad locations including the road directly ahead, roadway boundaries, other vehicles, traffic signs or signals, mirrors, and in-vehicle displays or devices. Second, the illumination provided by low-beam headlights, described via the concept of the twilight envelope, is generally not sufficient to allow a driver to avoid overdriving their headlights at most typical roadway speeds, and especially at highway speeds. Third, heavy vehicles typically exhibit longer delays between brake pedal input and the onset of deceleration, as well as longer stopping distances overall compared to passenger vehicles. These conclusions are, on paper, inconsistent with guidance provided by CDL manuals, which advise commercial vehicle operators to drive at sufficiently low speeds to not overdrive their headlights – despite scientific literature on driver visual perception and performance demonstrating such a task to be unfeasible at highway speeds.



DRIVER VISION
(VIS)

1 Not obstructed
2 Windshield (water/ice)
3 Trees/ plants
4 Buildings
5 Embankment
6 Signboard
7 Exhaust
8 Parked vehicles
9 Moving vehicles
10 Blinded - headlights
11 Blinded - sunlight
12 Blowing materials
13 Other
99 Unknown

Figure 2. “Driver vision” options found in the Illinois Traffic Crash Report (IDOT, 2019).

A need exists for more research from a human factors perspective to better understand commercial vehicle driver capabilities. Such research can serve to inform policymaking and driver training efforts to ensure that traffic regulations and licensure procedures and materials are consistent with scientific understanding and therefore facilitate safer roadways. Presently, CDL manuals and common highway speed limits place expectations on drivers – especially those operating heavy vehicles – that are not consistent with what is known about human visual perception and reaction time.

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When Will The Cars Drive Us?

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