TECH**BRIEF**

Impacts of Automated Vehicles on Highway Infrastructure

FHWA Publication No.: FHWA-HRT-21-051

FHWA Contact: Morgan L. Kessler, HRDI-20, 202-493-3187, Morgan.Kessler@dot.gov

This document is a technical summary of the Federal Highway Administration Report *Impacts of Automated Vehicles on Highway Infrastructure* (FHWA-HRT-21-015) (Gopalakrishna et al. 2020).

BACKGROUND

Vehicles with advanced driver assistance systems (ADASs) (SAE J3016 Level 1 and Level 2) are quickly becoming common along the U.S. highway network as automated vehicle (AV) development and deployment slowly progresses toward using automated driving systems (ADSs) (SAE J3016 Level 3 through Level 5) (SAE International 2018). By 2022, the transportation industry expects nearly all vehicles sold in the United States will include a forward-looking camera. This expectation is partially a result of the National Highway Traffic Safety Administration's (NHTSA's) and Insurance Institute for Highway Safety's automatic emergency braking (AEB) commitment, in which automotive manufacturers agreed to voluntarily equip all new passenger vehicles with AEB—which requires a forward-looking camera in addition to other sensors, depending on the specific manufacturer—by September 2022 (NHTSA 2019). Technologies that provide driver support features (i.e., ADASs) are the building blocks for ADSs. Understanding today's technology needs and future technology timelines can help infrastructure owners and operators (IOOs) plan and design their networks to maximize AV safety potential.

This document provides an overview of a multiphase research effort that involved a comprehensive literature review, engagement with highway IOOs, and interviews with industry experts and key stakeholders to document the potential impact of AVs on highway infrastructure. The research team identified the state of the practice among IOOs, knowledge gaps, and agency preparedness levels for the impact of AV use on highway infrastructure. This document does not cover the operations or policy aspects of AV infrastructure impacts because its goal is to provide information to IOOs as they prepare for the eventual infrastructure evolution driven by AV deployment.

OBJECTIVE

The primary objectives of this research project were to assess and understand the demands and potential impacts of AVs on current infrastructure assets as well as future infrastructure. Some of the important research questions considered for the project included the following:

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and
Technology
Turner-Fairbank Highway
Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

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- What should departments of transportation (DOTs) be doing right now with existing infrastructure to prepare for the needs of increasing AV use?
- What will the impacts of AV use be on the existing highway infrastructure, and how does the concept of state of good repair play into these impacts?
- What will the design and maintenance needs of future highways be, based on input from the AV sector?
- How should DOTs be preparing their physical infrastructure for the future needs of potentially high levels of AV use on the national highway network?
- How should a DOT determine its readiness for AV use on its highways?

INTRODUCTION

Until now, roads in the United States have been built with one driver in mind—the human—but there is much promise that AVs will become a reality in the not-so-distant future. However, AVs see and sense the road differently than humans. As such, IOOs are interested in understanding how road features will evolve to enhance AV safety and operability while maintaining the high level of service the traditional road user has come to expect.

In this document, AV is a broad term encompassing all vehicles with assisted or automated features, but SAE International has more formally established six levels of AVs commonly referenced in research—five of which are discussed in this document (SAE International 2018).

ADASs

SAE J3016 Level 1 and Level 2 make up ADASs, also referred to as partial automation because a human is always responsible for performing the driving task (SAE International 2018). ADAS features are designed to help the driver remain alert and engaged in the driving task. A variety of vehicles providing ADAS features (operating at Level 1 or Level 2) are currently available. The most common sensor in ADASs for longitudinal control (i.e., braking and acceleration) is radar, which constantly scans the path ahead of the vehicle to detect objects in the vehicle's path. The most common sensor for lateral control (i.e., steering) is a forward-looking camera that detects pavement markings to keep the vehicle in the intended lane.

ADSs

In contrast with ADASs, ADSs allow the driver to disengage under certain or all circumstances—encompassing SAE J3016 Level 3 through Level 5 (SAE International 2018). ADS specifics are still developing and, as such, various approaches are designed differently depending on which part of the driving task the AV industry automated (i.e., the use case).

The following are two emerging results of ADS advancement:

- Incremental progress toward automated highway driving, as refined Level 2 vehicles are available for personal ownership and continually provide more robust automation for highway driving.
- Automated rideshare fleets consisting of Level 4 vehicles owned, operated, and maintained by private companies in city and residential areas.

Regardless of the intended AV use case, the sensors and software in development for reading and sensing the roadway behave differently than human senses. For example, the cameras and machine-vision technologies are different than the human vision system, radar and light detection and ranging (LiDAR) technologies are different than any of the human senses, and AV behavior can be different from human-driven vehicles.

METHODOLOGY

Literature Review

The research team implemented a multifaceted research approach to satisfy the objectives of this research. The team conducted a traditional literature review, but since this is an emerging topic, there are few completed studies. Therefore, the research team also liaised with teams leading pertinent ongoing research projects (e.g., Federal Highway Administration (FHWA) and National Cooperative Highway Research Program projects as well as international sources).

The team considered several aspects of highway infrastructure, including the quality and uniformity of traffic control devices (TCDs); changing demands of intelligent transportation system (ITS) devices; structural requirements for pavements and bridges; impacts on multimodal infrastructure (e.g., bike lanes and Complete Streets designs); and the need for other roadside infrastructure like guardrails, enhancements to roadway digital infrastructure, and so forth. Throughout the project, the team divided highway infrastructure into four areas: physical infrastructure (e.g., pavements, bridges, and culverts), TCDs and other roadside infrastructure, transportation system management and operation (TSMO) and ITS infrastructure, and urban multimodal infrastructure.

Stakeholder Engagement

Gaining insight and feedback from the AV industry was important to the research team. As such, the team leveraged relationships within the automotive industry to conduct indepth interviews with AV industry stakeholders to capture a range of potential AV impacts on highway infrastructure design, maintenance, and operation. The research team also solicited technology-neutral input from and collaborated with associations representing the automotive industry.

AV Industry Interviews

The research team conducted interviews with AV industry stakeholders to better understand the interaction between AVs and highway infrastructure, preparedness among transportation agencies, and collaboration across various industry domains.

The purpose of these interviews was to capture a range of potential AV impacts on highway infrastructure design, maintenance, and operation—particularly the impacts associated with the more highly automated echelon of AVs with ADSs (i.e., those that correspond to SAE J3016 Level 3 through Level 5) (SAE International 2018). The final report provides all the relevant details, but some key takeaways are as follows:

- Automotive stakeholders interviewed for this project expressed a pragmatic understanding of the funding limitations and lengthy project delivery timelines associated with physical infrastructure improvements. Interviewees agreed rapid changes in the design and capabilities of ADS sensors, as well as changes to the mix of sensor types (e.g., camera, radar, and LiDAR), cause difficulty in predicting infrastructure needs over a 10-year-or-greater horizon. Given such rapid ADS technology and architecture changes, one subject noted, "There is no silver bullet in infrastructure engineering to dramatically advance AVs." However, most interviewees felt that infrastructure quality and consistency—especially for lane markings—support ADSs.
- Interviews revealed that the SAE J3016 vehicle automation levels are built into most subjects' thinking (SAE International 2018). In the original equipment manufacturers' (OEMs') view, Level 2 systems represent "AV 1.0," which removed the pain points from common driving scenarios and allow drivers to be more relaxed through technologies like traffic jam assist. Such products are expected to scale quickly, eventually reaching steady-state penetration. However, OEMs view Level 4 vehicles—which are currently equipped with dozens of sensors—as high-cost vehicles intended for use in small commercial fleets representing "AV 2.0."
- Subjects envisioned fleet deployments initially operating in constrained environments before extending more broadly. In the beginning stages of deployment, industry stakeholders believed mobility-on-demand (MOD) fleets will operate in predefined and geofenced areas utilizing ADSs at Level 4. The transportation industry expected fleet densities to be highest in cities and controlled environments before extending to include multiple operating environments and provide service to less developed areas. MOD fleet operations will also likely impact the transportation infrastructure design in urban areas over the long term, both eliminating the need for drivers to park vehicles and increasing the importance of curb management.
- Industry stakeholders asserted that an important aspect of safe AV operation is high-quality and consistent lane markings, traffic signs, and lighting. They also felt pothole and other structural deficiency repairs across pavements were important. IOOs' ability to provide high-quality, consistent TCD and surface-condition infrastructure is a fundamental safety contribution to AVs.
- Industry stakeholders reiterated that IOOs are responsible for ensuring quality and consistency across physical infrastructures, which are essential for smooth AV operation. Additionally, with the rapid rate of development and technological change in ADSs, the industry is looking to IOOs to collectively "hold the hoop steady."

Stakeholder Engagement Events

The research team gathered feedback from IOOs and automotive stakeholders during two workshops held at the American Association of State Highway and Transportation Officials (AASHTO) Committee on Maintenance Meeting (Grand Rapids, MI, July 17, 2019) and the TRB Automated Vehicle Symposium (Orlando, FL, July 18, 2019). The team used a real-time audience polling application to collect information at each event. The workshop held by the research team during the AASHTO Committee on Maintenance Meeting provided feedback from State DOT maintenance leaders and managers. The workshop session had over 100 attendees, including representatives from Federal, State, and local transportation agencies; universities and research institutions; and private contractors and consultants.

Approximately 75 percent of participants were from State DOTs, and many participants reported that their agency had already started identifying and taking actions to prepare for AVs. The workshop held by the research team during the TRB Automated Vehicle Symposium included almost 50 participants. The attendees at this workshop were more diverse, including highway stakeholders like DOTs, experts, consultants, and manufacturers, as well as automotive industry representatives like OEMs, suppliers, and consultants.

RESULTS AND SUMMARY OF FINDINGS

Near-Term Impacts of AVs on Highway Infrastructure

This section provides a summary of the current state of knowledge and expert opinions on potential near-term impacts of interactions between AVs and the four roadway infrastructure categories (i.e., physical infrastructure, TCDs, TSMO and ITS infrastructure, and multimodal infrastructure).

Physical Infrastructure

Wheel wander and distribution patterns, lane capacity, and traffic speed all affect pavement-rutting performance, pavement fatigue, and hydroplaning potential, thus causing either a positive or negative impact on pavement service life. Depending on AV technology implementation, platooning and positioning (particularly of automated trucks) may impact pavement condition and long-term performance. However, there are limited data available to adequately assess the current impacts of AVs on highway infrastructure, including how AV implementation and operation will affect pavement and bridge design, maintenance, and asset-management strategies.

TCDs

Efforts for coordinating roadway infrastructure to enhance ADAS and ADS performance have increased in recent years. The Automotive Safety Council and the American Traffic Safety Services Association began a series of workshops in August 2018 to share information and educate the highway and automotive industries on vehicle sensor–highway infrastructure interactions. The National Committee on Uniform Traffic Control Devices (NCUTCD) collaborated with several automotive industry associations to better understand what the industry needs from TCDs for NUTCD to address in the *Manual on Uniform Traffic Control Devices* (MUTCD) (FHWA 2009). The NCUTCD approved specific recommendations for the MUTCD designed to improve national pavement-marking uniformity to increase safety for human-driven vehicles while also supporting AV technologies. SAE International has formed a task force to address physical roadway infrastructure aspects related to all automation levels.

TSMO and ITS Infrastructure

TSMO strategies may play a greater near-term role in maintaining reliability and overall system efficiency. For example, demand-management strategies may become more critical for reliability (e.g., pricing), and ADS use cases may need to consider new performance measures. Stakeholders expressed interest in employing signal phase and timing (SPaT) and intersection map data as early use cases, as well as information on temporary and dynamic road-condition data. From an ITS standpoint, AVs still face significant challenges in reading LED signs, including variable speed limit and variable message signs, and barrier road crossings (e.g., tolls) can impede AVs from providing continuous eyes-off/hands-off travel.

Multimodal Infrastructure

The current state of knowledge for multimodal infrastructure focuses largely on policy and planning implications within a normative framework. Literature addressing multimodal infrastructure design adaptations supporting AV operation and minimizing AV disengagement is limited. However, the importance of mode separation and TCD quality and consistency in multimodal environments have emerged as notable themes. Moreover, the industry stakeholders who were interviewed as a part of this research effort viewed connected infrastructure capable of communicating the presence and intent of vulnerable road users to vehicles as important. The importance of effective curbside design and management is also likely to increase as a greater percentage of the vehicle fleet transitions to AVs, causing demand for curbside access to grow.

Long-Term Impacts of AVs on Highway Infrastructure

Currently, automation's role within the transportation sector heavily depends upon the vehicle and telecommunications industries. In the future, the infrastructure industry will likely share more of the responsibility. Infrastructure-enabled automation is particularly promising in specific applications like strategically positioned infrastructure-mounted sensors in intersections with nonoccluded views of all approaches to the intersection, as well as sight lines to all other intersection-related activity like pedestrians, bicyclists, and others who might be approaching the intersection. Merging data from the infrastructure-mounted sensors in intersections with vehicle data under real-time conditions can improve intersection flow and safety.

If future roadways permit even a small number of traditional human-driven vehicles, the appearance and quantities of TCDs and roadside infrastructure (not including AV-exclusive facilities) will remain nearly the same, though the infrastructure may have more capability through embedded technology. One such example is embedding traffic signs with QR barcodes only detected through vehicle-mounted active infrared vision systems. The Virginia Department of Transportation (VDOT) also tested sensor-embedded pavement markings that could extend today's sensor suites' operational design domain when detecting and tracking pavement markings. In the experiment, VDOT installed sensor-embedded pavement markings on Virginia Tech Transportation Institute's Smart Road and tested their effectiveness over a 6-month period, including during the winter. The results demonstrated the sensors' capabilities to detect and track pavement markings in heavy rain as well as under snow.

Furthermore, a full AV-penetration scenario should be complemented by automated surface-condition monitoring technologies that will enable a near real-time transmittal of data to and from AVs. These technologies could include newer sensor-based technologies capable of being embedded into pavement or bridge surfaces and better informing AVs of the physical infrastructure's surface condition. In addition, the technologies will provide detailed information on AV characteristics (e.g., vehicle class distribution, axle-load spectra, representative traffic volumes), which will help transportation agencies better characterize AV traffic impacts on long-term pavement and bridge performance. Dedicated AV infrastructure may necessitate adopting differing pavement and bridge design, maintenance, and asset management strategies (Huggins et al. 2017). As such, existing design standards and tools as well as agency asset maintenance and management programs will need to be updated to address AV needs.

THE PATH FORWARD

Based on the research, literature review, AV industry interviews, and national stakeholder workshops, pavement markings are the foremost physical infrastructure priority for IOOs in supporting AV deployment. This finding is in line with industry advancements, as automated robust pavement-marking detection is perhaps the most useful and promising AV safety benefit.

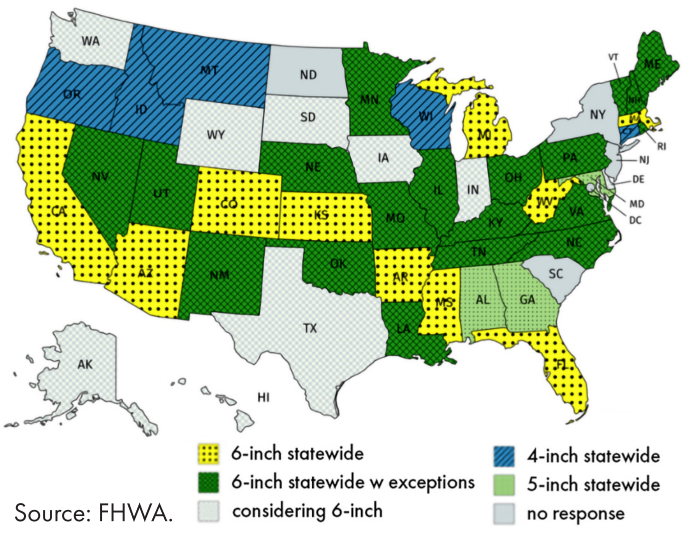
Improving Pavement Marking Characteristics for AVs

The following subsections detail three key pavement-marking areas to consider for optimizing lane departure prevention (LDP) effectiveness and thereby achieving the highest safety potential possible.

Uniformity

The lack of uniform applications across the United States (and throughout the world) is the AV industry's most often cited issue with highway infrastructure opportunities for supporting AV deployment. While U.S. highway agencies are generally in compliance with the MUTCD, the manual is flexible, which allows for varying practices. The MUTCD is silent on topics in some areas, such as contrast marking patterns, that might impact LDP effectiveness. These examples provide flexibility for agencies, but they also lead to nationally nonuniform pavement-marking practices. Figure 1 depicts a U.S. map showing national practices for longitudinal pavement-marking width, which is a pavement-marking characteristic demonstrated to provide support for AV deployment while improving highway safety. The NCUTCD has made some progress in this area and in January 2020 approved recommended changes to the MUTCD specifically designed to enforce pavement-marking uniformity throughout the Nation. Some of the recommendations more clearly defined where 6-inch-wide markings should be used, how long lane lines should be, and how to use dotted edgeline extensions along exit ramps. However, pavement-marking uniformity needs further vetting and research in some areas.

Figure 1. Map. Longitudinal pavement-marking widths across States.



Source: FHWA.

Design

Pavement markings should be designed to be visible and detectable in dry and wet conditions during both daytime and nighttime. Under ideal—such as clear and dry—conditions, the industry considers pavement-marking visibility adequate if the marking is present. However, LDP pavement-marking detection under sunny daytime conditions, dry or wet, can be challenging depending on glare and contrast between pavement markings and the pavement. Further research will need to be conducted on how to design pavement markings for both human and machine vision.

Maintenance

FHWA is currently finalizing minimum retroreflectivity standards for pavement markings with the intention to provide minimum visibility standards for human-driven vehicles; however, the standards are not designed to address LDP technology needs. The European Union Road Federation created recommended minimum maintenance standards for pavement markings to enable LDP detection. The standards include maintaining dry retroreflectivity at a minimum level of 150 mcd/m2/lx, maintaining wet-recovery retroreflectivity at a minimum level of 35 mcd/m2/lx, maintaining contrast at a minimum level of three to one, with a preferred level of four to one, and using a minimum width of 6 inches for all longitudinal markings.

OTHER CONSIDERATIONS

Stakeholder feedback identified a large number of potential early strategies benefitting ADSs, ADASs, and human drivers for IOOs to consider (table 1). These considerations can be implemented in the near-term to maximize benefits and minimize consequences of implementing AVs, regardless of prevailing uncertainties.

Table 1. Potential early strategies identified by stakeholders for AV readiness.

Functional Class	TCD's	Physical Infrastructure	ITS—TSMO	Multimodal
Interstates, freeways, expressways, and principal arterials	Standardize pavement markings to be 6 inches wide for all longitudinal markings. Use dotted edgeline extensions along ramps. Include chevron markings in gore areas. Use continuous markings for all work-zone tapers. Eliminate Botts' dots as a substitute for markings. Use contrast markings on light-colored pavements. Minimize or eliminate confusing speed limit signs on parallel routes.	Expand efforts in preventive maintenance to address distresses like potholes, edge wear, and rutting.	Enforce more standardized active traffic management and dynamic management signage (e.g., variable speed limits, lane controls, work-zone management) across the country.	Priority treatments for transit operations, truck platooning, and managed lanes to benefit future AV operations.
Minor arterials, major and minor collectors	Standardize edgeline pavement-marking width to 6 inches for roadways with posted speeds less than 40 miles per hour. Use continuous markings for all work-zone tapers. Eliminate Botts' dots as a substitute for markings. Use contrast markings on light-colored pavements. Minimize confusing speed limit signs on parallel routes.	Expand efforts in preventive maintenance to address distresses like potholes, edge wear, and rutting.	Enforce more standardized active traffic management and dynamic management signage (e.g., variable speed limits, lane controls, work-zone management across the country). Equip signal-controlled intersections with I2V hardware, including SPaT-capable technology and hardware capable of communicating the presence of vulnerable road users. Equip parking systems with I2V capabilities.	Manage curb space and conduct safety audits.

I2V = infrastructure-to-vehicle.

Table 1. Potential early strategies identified by stakeholders for AV readiness. (continued)

Functional Class	TCD's	Physical Infrastructure	ITS—TSMO	Multimodal
Urban and local roads	Use continuous markings for all work-zone tapers. Eliminate Botts' dots as a substitute for markings.	Expand efforts in preventive maintenance to address distresses like potholes, edge wear, and rutting.	Enforce more standardized active traffic management and dynamic management signage (e.g., variable speed limits, lane controls, work-zone management across the country). Equip signal-controlled intersections with I2V hardware, including SPaT-capable technology and hardware capable of communicating the presence of vulnerable road users. Equip parking systems with I2V capabilities.	Adopt mode-separation policies (e.g., Complete Streets). Anticipate growing curbside demand in site design, street design, and access-management practices. Retrofit bus rapid transit lanes with AV technologies to provide opportunities for automated transit system testing.

I2V = infrastructure-to-vehicle.

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Researchers—This study was conducted by Deepak Gopalakrishna (ICF), Paul Carlson (ORCID: 0000-0003-0859-9305) (Road Infrastructure, Inc.), and Deepak Raghunathan (ICF). The study was conducted under contract number GS00Q14OADU119/693JJ318F000403.

Distribution—This TechBrief is being distributed according to a standard distribution.

Availability—This TechBrief may be obtained at https://highways.dot.gov/research.

Key Words—Automated vehicles, pavements, bridges, traffic control devices, pavement markings, barriers, traffic management, operations, pedestrians, bicyclists, curb space.

MAY 2021

FHWA-HRT-21-051
HRDI-20/05-21(WEB)E