Impacts of Automated Vehicles on Highway Infrastructure

PUBLICATION NO. FHWA-HRT-21-015 MARCH 2021

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
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FOREWORD

The goal of this study was to collect input from stakeholders regarding how automated driving technologies might interact with highway infrastructure assets—which technologies interact with which assets and how the design, operation, and maintenance of those assets might evolve to increase the performance of the technologies without sacrificing the needs of human drivers. The Federal Highway Administration (FHWA) sought input on how infrastructure might evolve in a cost-effective manner based on the limited resources and vastly different paces of development within the infrastructure, automotive, and technology industries. This study covers current concerns and thoughts on the potential impacts of automated vehicles (AVs) on highway infrastructure while providing FHWA with information to stakeholders as they prepare for the eventual infrastructure evolution determined by AVs.

The target audience of this report is AV-related infrastructure stakeholders and highway construction and maintenance stakeholders. Several aspects of highway infrastructure are considered for this study, including quality and uniformity of traffic control devices, changing demands of intelligent transportation systems, structural requirements for pavements and bridges, impacts to multimodal infrastructure (e.g., bike lanes and Complete Streets designs), and the need for other roadside infrastructure. This report presents the results of a multiphase research effort that involved a comprehensive literature review, engagement with highway infrastructure owners and operators, and interviews with industry experts and key stakeholders. This document is supplemented with a TechBrief and webinars to educate and inform department of transportation stakeholders about AV-related infrastructure needs, ultimately assisting in their immediate and future infrastructure planning and design efforts.

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Director, Office of Infrastructure
Research and Development

TECHNICAL REPORT DOCUMENTATION PAGE

<table>
<tr><td>1. Report No.
FHWA-HRT-21-015</td><td colspan="2">2. Government Accession No.</td><td colspan="2">3. Recipient’s Catalog No.</td></tr>
<tr><td colspan="3" rowspan="2">4. Title and Subtitle
Impacts of Automated Vehicles on Highway Infrastructure</td><td colspan="2">5. Report Date
March 2021</td></tr>
<tr><td colspan="2">6. Performing Organization Code</td></tr>
<tr><td colspan="3">7. Author(s)
Deepak Gopalakrishna, Paul Carlson (ORCID 0000-0003-0859-9305), Peter Sweatman, Deepak Raghunathan, Les Brown, Nayel Urena Serulle</td><td colspan="2">8. Performing Organization Report No.</td></tr>
<tr><td colspan="3" rowspan="2">9. Performing Organization Name and Address
ICF Incorporated, LLC
9300 Lee Highway
Fairfax, VA 22031</td><td colspan="2">10. Work Unit No.</td></tr>
<tr><td colspan="2">11. Contract or Grant No.
GS00Q14OADU119/693JJ318F000403</td></tr>
<tr><td colspan="3" rowspan="2">12. Sponsoring Agency Name and Address
U.S. Department of Transportation
Federal Highway Administration
1200 New Jersey Avenue, SE
Washington, DC 20590</td><td colspan="2">13. Type of Report and Period Covered
Final Report; October 2018–October 2020</td></tr>
<tr><td colspan="2">14. Sponsoring Agency Code
HRDI-20</td></tr>
<tr><td colspan="5">15. Supplementary Notes
The Contracting Officer’s Representatives were Morgan Kessler (HRDI-20) and Abdul Zineddin (HRDS-10).</td></tr>
<tr><td colspan="5">16. Abstract
This report presents the results of a multiphase research effort, which involved a comprehensive literature review, engagement with highway infrastructure owners and operators (IOOs), and interviews with industry experts and key stakeholders to document the potential impact of automated vehicles (AVs) on highway infrastructure. The study attempts to identify the state of the practice among IOOs, gaps in knowledge, and agency-preparedness levels regarding the impacts of AV use on highway infrastructure. Operations or policy aspects of AV–infrastructure impacts are not covered. Several aspects of roadway infrastructure are considered for this study, including the quality and uniformity of traffic control devices, the changing demands of intelligent transportation systems, structural requirements for pavements and bridges, effects on multimodal infrastructure (e.g., bike lanes and Complete Streets designs), and the potential need for other roadside infrastructure (e.g., guardrails and communications systems for roadway digital infrastructure).</td></tr>
<tr><td colspan="2">17. Key Words
Automated vehicles, pavements, bridges, traffic control devices, pavement markings, barriers, traffic management, operations, pedestrians, bicyclists, curb space</td><td colspan="3">18. Distribution Statement
No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.
http://www.ntis.gov</td></tr>
<tr><td>19. Security Classif. (of this report)
Unclassified</td><td colspan="2">20. Security Classif. (of this page)
Unclassified</td><td>21. No. of Pages
107</td><td>22. Price
N/A</td></tr>
</table>

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized.

SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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LIST OF ABBREVIATIONS

5G	fifth-generation wireless
AASHTO	American Association of State Highway and Transportation Officials
ADA	Americans with Disabilities Act
ADAS	advanced driver assistance systems
ADS	automated driving systems
AI	artificial intelligence
ASC	Automotive Safety Council
ATSSA	American Traffic Safety Services Association
AV	automated vehicle
BRT	bus rapid transit
CAVs	connected and automated vehicles
CV	connected vehicle
DDT	dynamic driving task
DMS	dynamic message signs
DOT	department of transportation
DSRC	dedicated short-range communication
FHWA	Federal Highway Administration
HAR	Highway Advisory Radio
HOV	high-occupancy vehicle
I2V	infrastructure-to-vehicle
IOO	infrastructure owner–operator
IT	information technology
ITS	intelligent transportation system
LDP	lane-departure prevention
LDW	lane-departure warning
LED	light-emitting diode
LiDAR	light detection and ranging
LKA	lane-keeping assist
MOD	mobility on demand
MUTCD	*Manual on Uniform Traffic Control Devices*
NACTO	National Association of City Transportation Officials
NCHRP	National Cooperative Highway Research Program
NCUTCD	National Committee on Uniform Traffic Control Devices
NHTSA	National Highway Traffic Safety Administration
ODD	operational design domain
OEM	original equipment manufacturer
RSA	road safety audits
SPaT	signal phase and timing
TCD	traffic control device
TI	traction index
TIM	Traffic Incident Management
TMC	transportation management center
TRB	Transportation Research Board
TSMO	transportation systems management and operations

USDOT	United States Department of Transportation
V2I	vehicle-to-infrastructure
V2P	vehicle-to-pedestrian
V2V	vehicle-to-vehicle
V2X	vehicle-to-everything

EXECUTIVE SUMMARY

This project specifically covers the reported impacts of automated vehicles (AVs) on highway infrastructure. The goal is to provide information to stakeholders as they prepare for the eventual infrastructure evolution driven by the deployment of AVs. This project does not delve into operations or provide policy recommendations, although infrastructure impacts outlined in this report are contingent upon policy and operations decisions. This report attempts to provide infrastructure owner–operators (IOOs)[1] with a list of possible impacts of initial AV deployment on roadway infrastructure and identifies research opportunities based on AV-industry and State and local agency feedback.

AV development and deployment can be characterized based on the level of automation (SAE Levels) and the operational design domains (ODDs) under which the vehicles can provide automation features. ODDs include roadway type, speed, traffic, and weather conditions. AVs are often described as one generic type of vehicle, but it becomes more complicated when the SAE Levels of Driving Automation are included, as well as specific AV use cases, which are designed for different ODDs interacting with different highway-infrastructure elements. Understanding the layers of complexity provides clarity for understanding how AVs will begin to impact IOOs. Furthermore, acknowledging that certain elements of ODDs are dynamic in nature adds to the complexity and demonstrates the importance of the design and maintenance of specific highway-infrastructure elements. For this research, possible impacts of AVs are based on information for both advanced driver assistance systems (ADAS) currently available and operating on roadways (including SAE Level 1 and Level 2), and discussions with automated driving systems (ADS) developers about possible ADS technologies (SAE Levels 3 through Level 5). ADS are still under development and not at a level of maturity to understand fully how the highway infrastructure can support such deployment.

INFRASTRUCTURE CATEGORIES

Several aspects of roadway infrastructure were considered for this study, 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 potential need for other roadside infrastructure, such as guardrails and communications systems for digital infrastructure.

This report documents the impact of AVs on the following infrastructure categories:

- Physical infrastructure (e.g., pavements, bridges, culverts).
- TCDs and other roadside infrastructure.
- Transportation systems management and operations (TSMO) and ITS infrastructure.
- Urban multimodal infrastructure.

[1]IOOs include agencies, such as State and local departments of transportation, toll operators, and transit authorities, that own and operate infrastructure used for transportation.

SYNTHESIS OF THE LITERATURE

This is a developing topic; therefore, published research related specifically to AV impacts on roadway infrastructure is minimal. The following provides the current state of knowledge for each of the four areas of infrastructure review:

- **Pavement and bridges:** Wheel wander and distribution patterns, lane capacity, and traffic speed affect pavement-rutting performance, pavement fatigue, and hydroplaning potential, which can have positive and negative impacts on pavement service life. Depending on the implementation of AV technologies, platooning and positioning (particularly of autonomous trucks) may impact the condition and long-term performance of pavements. Limited data are available to adequately assess the current actual impacts of AVs on highway infrastructure, including how AV implementation and operation will affect pavement and bridge designs, maintenance, and asset-management strategies.

- **TCDs:** Discussions have increased in recent years regarding how roadway infrastructure might enhance the performance of ADAS and ADS-equipped vehicles. The Automotive Safety Council (ASC) and the American Traffic Safety Services Association (ATSSA) conducted a workshop in August 2018 designed to share information and educate representatives from the highway and automotive industries on the interactions between vehicle sensors and highway infrastructure. The National Committee on Uniform Traffic Control Devices (NCUTCD) works with several automotive industry associations to better understand what is needed from a TCD perspective that can be addressed in the *Manual on Uniform Traffic Control Devices* (MUTCD) (FHWA 2009). The NCUTCD has approved recommendations for the MUTCD to tighten national pavement-marking uniformity designed to increase safety for human-driven vehicles while also potentially supporting AV technologies. SAE has formed a task force aimed specifically at addressing hard roadway infrastructure aspects related to all levels of automation.

- **TSMO and ITS infrastructure:** The need for and role of TSMO strategies may be greater even in the near term to maintain reliability and overall system efficiency. Demand-management strategies may become more critical for managing reliability (e.g., pricing) and new performance measures for ADS use cases. There was stakeholder interest in the availability of signal phase and timing (SPaT) and intersection map (MAP) data as early use cases, as well as information on temporary and dynamic road-condition data. From an ITS standpoint, there are still significant challenges for ADSs in reading light-emitting diode (LED) signs (including variable speed limit and variable message signs) and barrier road crossings (e.g., tolls), which can impede ADSs from providing continuous eyes-off/hands-off travel.

- **Multimodal infrastructure:** The state of knowledge for multimodal infrastructure focuses largely on policy and planning implications within a normative framework. Literature that addresses design adaptations of the multimodal infrastructure to support AV operations and minimize ADS disengagements is limited. However, the importance of mode separation and the quality and consistency of TCDs in multimodal environments emerged as notable themes. Moreover, connected infrastructure that can communicate the presence and intent of vulnerable road users to vehicles was considered important.

Likewise, the importance of effective curbside design and management is likely to increase as a greater percentage of the vehicle fleet transitions to AVs and demand for curbside access grows.

STAKEHOLDER FEEDBACK

As part of this study, AV industry stakeholders were interviewed to gather input on the interaction between AVs and highway infrastructure, preparedness among transportation agencies, and collaboration across various industry domains. These interviews sought to capture a wide range of potential impacts of AVs on the design, maintenance, and operations of roadway infrastructure, particularly those impacts associated with ADS technologies.

AV industry stakeholders demonstrated a complex and deep understanding of roadway infrastructure, including the interaction of machine vision—the technology and methods used to provide imaging-based automatic detection and analysis for applications such as object detection, lane tracking, and sign detection—and various infrastructure elements. While specific questions were used during the interviews, there was also flexibility to allow the conversation to wander depending on the expertise and priority of the information that the interviewee conveyed. The following key observations emerged from stakeholder interviews:

- **Implications of sensor evolution:** The rapid evolution and regular maintenance needs of sensors for highly automated vehicles favor fleet operations in the near term and create challenges to future proofing infrastructure.
- **Influence of business models on early AV deployment paths and public perception:** Commercial fleets will be an important early application of SAE Level 4 AVs and will offer near-term and nontraditional partnership opportunities between fleet operators and IOOs, while early consumer AVs will build incrementally on SAE Level 2.
- **Quality and uniformity of physical infrastructure:** Physical infrastructure should be consistent and well maintained, especially regarding road markings and signage.
- **Digital information standards:** Digital information relayed to AVs should be standardized, secure, and specific to AV operational challenges, such as work zones.
- **ODDs:** Original equipment manufacturers (OEMs) are responsible for defining vehicle ODDs and assuming responsibility for safe operations within the ODD regardless of IOO actions.
- **Connectivity between the vehicle and infrastructure:** Connected vehicle applications, such as vehicle-to-infrastructure (V2I), can alert AVs to the presence of humans; however, industry does not rely on IOO support and is skeptical that V2I deployments will occur widely.
- **Role of transportation systems management and operations:** AVs may exacerbate congestion in the short term, making it important that IOOs implement advanced TSMO strategies.
- **Freight deployment:** Freight is an early and incremental adopter of AV technologies, starting with available ADAS and having its own path to deployment.
- **Governmental and institutional issues:** Clear guidance and policies are needed at the Federal level, while interagency and intergovernmental coordination are needed at State and local levels.

Assembling the project findings, the research team conducted national stakeholder engagement workshops to gather feedback from IOOs and automotive stakeholders as both industries prepare for the eventual infrastructure evolution driven by the increased presence of AV technologies. These workshops were conducted in conjunction with the following related national events:

- American Association of State Highway and Transportation Officials (AASHTO) Committee on Maintenance Workshop, Grand Rapids, MI, July 17, 2019.
- Transportation Research Board (TRB) Automated Vehicle Symposium, Orlando, FL, July 18, 2019.

The most often cited comments in both workshops focused on the need for continued highway–AV industry engagements, development of national guidance describing how to prepare the infrastructure for AVs, and funding concerns related to additional activities above and beyond current IOO responsibilities. Highway-agency preparedness was also a concern. Most participants acknowledged that roadway infrastructure will evolve, and while some agencies noted the value of proactive leadership supporting new AV-focused positions and cross-functional teams, other agencies reported to be in more of a standby mode with an understanding that certain policies and practices will likely need to be updated. Pavement markings was the roadway infrastructure element most often acknowledged as important for supporting the deployment of AVs. Participants were mostly aware of the value of uniform pavement-markings practices, as well as having well-maintained pavement markings. They also seemed mostly aware of the growing disillusionment regarding widespread ADS deployment, although the question of when widespread ADS deployment would occur was common. Participants requested more information for dealing with pavement markings in snow and ice regions and the pavement-marking maintenance criteria needed for lane-departure prevention (LDP) technologies. For this report, LDP includes both lane-departure warning (LDW) systems, and lane-keeping assist (LKA) systems.

Findings

Based on this research, including the literature review, AV industry interviews, and national stakeholder workshops, pavement markings currently appear to be the foremost infrastructure priority in terms of how IOOs can support AV deployment. For ADAS technologies, pavement markings provide technology-neutral information. For ADS developers, the stated reliance on pavement markings was not consistent. Some ADS developers indicate they are focused on what is currently available and will not count on changes to roadway infrastructure.

Improving Pavement Marking Characteristics for AVs

Uniformity, design, and maintenance were identified as three pavement-marking areas that should be considered when optimizing LDP effectiveness for current ADAS-equipped vehicles. The following areas may also potentially impact ADS functionality to perceive roads.

- **Uniformity.** The most often cited issue from the AV industry regarding roadway-infrastructure opportunities to support AV deployment is the lack of uniformity across the United States (and throughout the world). While U.S. highway agencies are generally in compliance with the national MUTCD, there is flexibility in the MUTCD that allows for varying practices. In some areas, the MUTCD does not address topics, such as contrast-marking patterns, that can have an impact on LDP effectiveness. The NCUTCD has recently approved some recommended changes to the MUTCD that were specifically designed to tighten pavement-marking uniformity throughout the Nation.

- **Design.** Pavement markings need to be designed to be visible and detectable under daytime and nighttime conditions and dry and wet conditions. Under ideal conditions, such as clear and dry conditions, pavement-marking visibility is generally considered adequate if the marking is present. However, LDP detection of pavement markings under sunny daytime conditions—dry and wet—can be particularly challenging depending on glare and pavement-marking contrast compared to the pavement surface adjacent to the pavement marking.
- **Maintenance.** Minimum retroreflectivity standards for pavement markings are currently under development. Standards are intended to provide minimum visibility standards for human-driven vehicles, but they are not specifically designed to address ADAS LDP technology or future ADS road-perception technology needs. The European Union Road Federation has recommended minimum maintenance standards for pavement markings for LDP detection. Standards include maintaining dry retroreflectivity to a minimum level of 150 millicandelas per square meter per lux (mcd/m^2/lx), maintaining wet-recovery retroreflectivity to a minimum level of 35 mcd/m^2/lx, maintaining contrast to a minimum level of 3 to 1 with a preferred level of 4 to 1, and using a minimum of 6-inch-wide longitudinal markings.

Potential Early Strategies

Stakeholder feedback identified a number of strategies believed to benefit ADS, ADAS, and human drivers; they considered potential early strategies (table 1). These strategies are based on consensus inputs of research participants and can be broadly considered as measures that could be implemented in the near term to maximize benefits and minimize consequences, regardless of prevailing uncertainties. Data are not available to support rigorous cost–benefit analyses of these strategies.

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

Functional Class	TCDs	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/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, including pothole repairs, 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 infrastructure-to-vehicle (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.

Functional Class	TCDs	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.

Identified Research Needs

Due to significant uncertainties regarding AV deployment, especially the transition from human-driven (including ADAS-equipped) vehicles to ADS-equipped vehicles, the following research needs were identified during this project (additional details for each of these research needs are included in the body of the report):

- **Research need one: tightening TCD uniformity for AVs.** One of the most common challenges cited by AV developers is the lack of uniformity across the United States regarding TCDs. The main objective of this research would be to evaluate how the MUTCD might evolve to continue to meet the needs of human road users while also evolving to meet the needs of a new-design driver (i.e., sensors that read the road to provide AV features).

- **Research need two: machine-vision standards for TCDs.** TCD standards regarding size, color, daytime appearance, and nighttime appearance have been developed based on human capabilities, including those of older drivers. The objective of this work is to conduct research on TCD standards that support sensor perception and recognition to support various sensor technologies used for current ADAS and future ADS systems.

- **Research need three: developing MUTCD material to support AV deployment.** The MUTCD is codified in the Code of Federal Regulations (CFR), which makes it difficult to keep current in a rapidly changing technological environment due to the required rulemaking process. The objectives of this research are to investigate if there are processes that would allow for more rapid updates to the MUTCD than the current method allows.

- **Research need four: developing a strategic approach to updating and maintaining pavement markings.** Based on the current state of knowledge, including the research documented in this report, pavement markings are one of the most important infrastructure elements for today's ADAS as well as for the more capable ADS of the future. The objective of this research would be to quantify the return-on-investment of making national changes (in design and/or maintenance) to any physical infrastructure element but particularly pavement markings.

- **Research need five: developing a safe-systems approach to AV deployment.** While the safe-systems approach to road safety has been adopted by various countries (e.g., Australia, Sweden, Netherlands), it is still a relatively new concept in the United States. The objective of this research is to apply a safe-systems approach to roadway safety from the perspective that there will be a mixed fleet of human-driven vehicles, including those with ADAS and ADSs using the roadways for decades.

- **Research need six: establishing AV test scenarios with representative infrastructure conditions.** Current testing of existing AV technologies, such as LDP systems, is conducted under ideal conditions with high-contrast markings in pristine condition. In addition, the current testing is conducted under ideal conditions with uniform and dry pavement and clear and dry weather. The objectives of this research are to define testing conditions for AV technologies representative of the existing roadway network that those AV technologies are expected to be used. For instance, if the AV technology is meant to work on interstate highways, then the testing of those technologies should be performed with conditions that represent the existing state of repair of interstates.

- **Research need seven: investigating a national traffic-control AV readiness assessment.** The role of TCDs is being reevaluated with the arrival of AV technologies. Historically, TCDs have been designed and maintained for the human road user but may need to be revised to support ADAS and ADS. The objective of this research is to investigate the potential benefits of developing a national traffic-control inventory and condition-assessment protocol that serves the highway agency and AV industry.

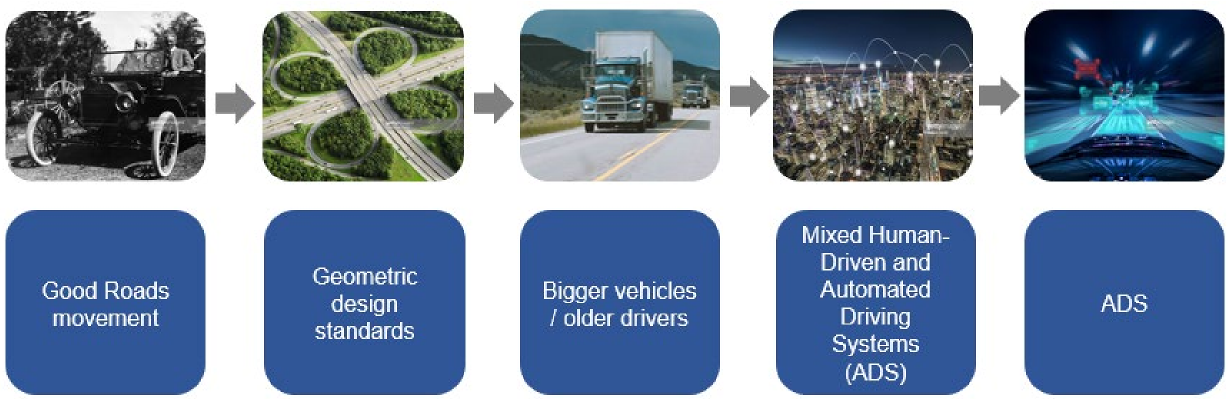
- **Research need eight: developing road safety audit materials that consider AV needs.** Road safety audits (RSAs) have been proven to be an effective proactive tool used on existing or planned facilities to identify opportunities for improvements in safety for all road users. However, current RSA support material does not yet consider how the needs of AVs might be considered. The research is envisioned to provide updated RSA material that includes the needs of AVs. In doing so, the research should consider how the needs of AVs differ and how to accommodate those needs in the training and support material for RSAs.

CHAPTER 1. INTRODUCTION

BACKGROUND

Since the advent of the automobile, emerging technologies and driving behaviors have repeatedly demanded highway infrastructure adaptations. While the roadway-infrastructure industry operates at a significantly slower functional product pace than the automotive and technology industries, they have historically coevolved. For example, the development of good roads and the improvement of geometric design to adapt to higher driving speeds and an increasingly older population of drivers were responses to the needs of users and driving tasks.

Figure 1 depicts the process by which evolving vehicle technologies and road-user demands encourage infrastructure adaptions. In turn, changing infrastructure enables evolving road-user behavior and vehicle classes, sparks new technical innovations, and catalyzes further infrastructure adaptations.



Source: FHWA.

Figure 1. Graphic. Coevolution of road users and roadway infrastructure.

The emergence of connected vehicle (CV) technology and AV technologies have placed new demands on roadway infrastructure, representing a shifting paradigm regarding the nexus of capabilities between vehicles and roadways that support navigational needs of humans and AV, especially over the next several decades. This anticipated transition will eventually evolve roadway infrastructure from its current state, which is designed for the needs of human drivers, to include AV technologies (while continuing to support the needs of human drivers).

ADAS enable partial automation and are already present to some degree in many vehicle models. ADS can perform sustained dynamic driving tasks (DDTs) in their entirety and their use in consumer and commercial vehicle markets is expected to increase. ADAS and ADS are constituents of AV and rely on continued coordination of roadway infrastructure for safe and reliable driving performance. Current ADAS technologies and their dependence on certain roadway infrastructure elements provide opportunities to develop an initial understanding of the possible impacts of AV deployment.

Increased adoption of AV transportation might introduce uncertainties related to AV interactions with roadway infrastructure. These uncertainties, combined with limited data and clarity on the actual use and scale of AV implementation, are expected to challenge transportation agencies and practitioners on how to adapt roadway infrastructure to meet AV needs and vice versa. The magnitude of this shift and the challenge of accommodating human and machine drivers during the progressive transition from human driver to fully ADS fleet of vehicles present an important opportunity and a significant challenge for infrastructure owner/operators (IOOs).[1]

AV technology is advancing quickly, but it is difficult to establish a timeline for market penetration of AVs that includes a mixed-fleet environment and full ADS penetration scenarios. Furthermore, short- and long-term impacts of AVs on highway infrastructure may differ for IOOs dependent on each IOO's transportation assets and knowledge and experience with ADS technology. As ADS are introduced, IOOs will need to consider many issues, such as agency policies and legislation, priorities, organizational and technological maturity levels, maintenance and operations levels, and risk capacity. There is also pressure for highway agencies and IOOs to move quickly to keep up with ever-changing technology and an already-present mixed fleet to recognize the possibility of increased safety, congestion relief, alleviated environmental impact, and other potential benefits of AVs.

PROJECT SCOPE

This project specifically covers current concepts and expert opinions on the potential impact of AVs on highway infrastructure. The goal is to provide information to stakeholders as they prepare for the future infrastructure evolution advanced by AVs.

This report does not delve into operations or policy, although infrastructure impacts outlined in this report are contingent upon operations and policy decisions. Rather, this report identifies possible impacts that IOOs and ADS developers have identified for consideration and represent research opportunities for the Federal Highway Administration (FHWA) and industry.

Several aspects of roadway infrastructure are considered for this study, including the quality and uniformity of traffic control devices (TCDs); the changing demands of intelligent transportation system (ITS) devices; structural requirements for pavements and bridges; impacts on multimodal infrastructure (bike lanes and Complete Streets designs); and the potential need for other roadside infrastructure, such as guardrails and communications systems for digital infrastructure. This report documents the impact of AVs on the following infrastructure categories:

- Physical infrastructure (e.g., pavements, bridges, culverts).
- Traffic control devices and other roadside infrastructure.
- Transportation systems management and operations (TSMO) and intelligent transportation systems (ITS) infrastructure.
- Urban multimodal infrastructure.

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[1]IOOs include agencies, such as State and local departments of transportation, bridge and toll operators, and transit authorities, that own and operate infrastructure used for transportation.

This list of infrastructure categories is not meant to be exhaustive; it attempts to capture highway infrastructure elements that may be directly impacted by implementation and operationalization of AVs in the future.

This report presents the results of a multiphase research effort, which involved a comprehensive literature review, engagement with highway IOOs, and interviews with industry experts and key stakeholders. Through this process, this study considered the findings of the available information in the literature, obtained additional automotive industry input and feedback, and identified the state of the practice among IOOs, any gaps in knowledge, and agency preparedness levels regarding the impacts of AV use on highway infrastructure.

REPORT STRUCTURE

The report is organized into the following chapters:

- Chapter 1 provides an introduction and background information on the development of ADAS and AVs.
- Chapter 2 discusses the interactions of AVs with roadway infrastructure.
- Chapter 3 details the perspectives of automotive industry stakeholders on AV impacts to roadway infrastructure.
- Chapter 4 summarizes feedback from two stakeholder events conducted as part of this research.
- Chapter 5 provides a summary of the impacts of AV operations on roadway infrastructure in the near term and in the future.
- Chapter 6 describes stakeholder recommendations for an AV-readiness roadmap for transportation agencies.
- The appendix lists additional information collected in this study.

CHAPTER 2. AVS AND THEIR INTERACTIONS WITH HIGHWAY INFRASTRUCTURE

LEVELS OF AUTOMATION

SAE International has established six levels of AVs that are commonly referenced today (table 2).

- Level 0 vehicles have no automation; a fully engaged driver is always required.
- Level 1 vehicles assist the driver by automating one of the following primary control functions: longitudinal control (speed, braking, and acceleration) or lateral control (steering).
- Level 2 vehicles can automate both longitudinal and lateral control.
- Level 3 vehicles can operate in an automated manner in a specific area with a driver being ready to take control if needed.
- Level 4 vehicles expand on Level 3 and can perform all driving tasks under certain conditions.
- Level 5 vehicles can operate in an automated manner in all areas, at all times, without the need for a driver to be available to take control.

Table 2. SAE levels of vehicle automation.

	Partial Automation of DDT*			Complete Automation of DDT		
No Automation	**SAE Level 0: No Driving Automation (Human Does All Driving)**	**SAE Level 1: Driver Assistance (Longitudinal or Lateral Vehicle Motion Control)**	**SAE Level 2: Partial Driving Automation (Longitudinal and Lateral Vehicle Motion Control)**	**SAE Level 3: Conditional Driving Automation**	**SAE Level 4: High Driving Automation**	**SAE Level 5: Full Driving Automation**
No Cooperative Automation	E.g., signage, TCD	Relies on driver to complete the DDT and to supervise feature performance in real time		Relies on ADS to perform complete DDT under defined conditions (fallback condition performance varies between levels)		
SAE Class A: Status Sharing—Here I am and this is what I see.	E.g., brake lights, traffic signal	Improved object and event detection**		Improved object and event detection		
SAE Class B: Intent Sharing—This is what I plan to do.	E.g., turn signal, merge	Improved object and event prediction		Improved object and event prediction		
SAE Class C: Agreement Sharing—Let us do this together.	E.g., hand signals, merge	—		Attain mutual goals through coordinated actions		
SAE Class D: Prescriptive Sharing—I will do as directed.	E.g., hand signals, lane assignment by officials	—		C-ADS designed to accept and adhere to a command		

*Driving automation predictability is limited by potential human override (versus C-ADS), and vehicle motion control is limited to longitudinal or lateral for Level 1.
**Driving automation sensing capabilities may be limited compared to C-ADS.
—Not applicable.
C-ADS = cooperative automated driving systems; DDT = dynamic driving task; N/A = not applicable; TCD = traffic control device.

GROUPING LEVELS OF AUTOMATION

Level 1 and Level 2 make up ADAS, also referred to as partial automation because a human is still responsible for performing the driving task at all times. Many vehicles available today provide ADAS features (operating at SAE Level 1 or Level 2). For longitudinal control (i.e., braking and acceleration), the most common sensor is radar, which constantly scans the path ahead of the vehicle to detect objects in the vehicle's path. For lateral control (i.e., steering), the most common sensor is a passive camera used for a variety of purposes; however, in this case, the main purpose is to detect pavement markings to keep the vehicle in the intended lane. ADAS features are generally designed for the driver to be constantly alert and engaged in the driving task.

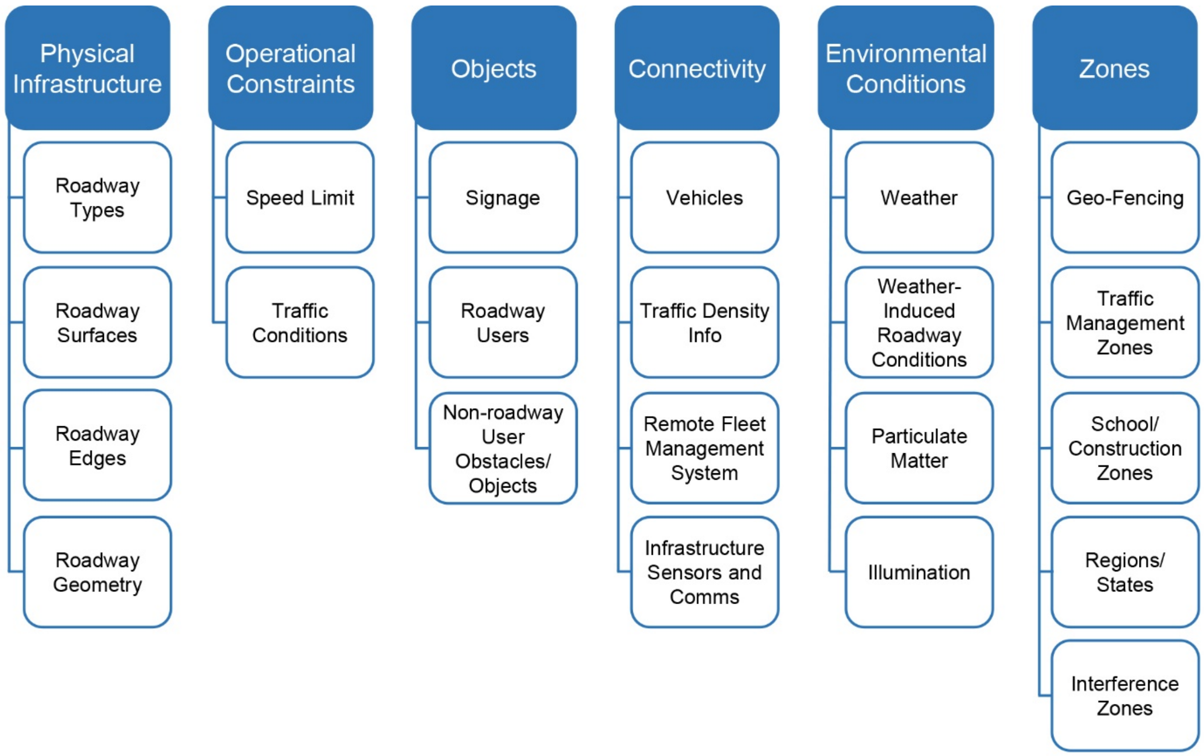
In contrast with ADASs, ADSs allows the driver to disengage under certain or all circumstances—encompassing Level 3 through Level 5. The specifics of ADSs are still developing, and in many ways, the various approaches are designed much differently depending on the specific part of the driving task where automation is intended (i.e., the use case).

For example, a recent National Highway Traffic Safety Administration (NHTSA) study identified 24 ADS concepts and placed them in the following 7 categories (described further in NHTSA Report No. DOT HS 812 623 (Thorn, Kimmel, and Chaka 2018)):

- **L3 conditional automated traffic jam drive.** This ADS feature uses automated travel for stop-and-go traffic following the preceding car.
- **L3 conditional automated highway drive.** This ADS feature uses automated travel for highway driving, including on interstate highways and other full-access controlled facilities.
- **L4 highly automated low-speed shuttle.** This ADS feature includes highly automated low-speed shuttles that only drive along predetermined routes.
- **L4 highly automated valet parking.** This ADS feature includes vehicles that can find an available parking spot and park by themselves (with no human driver in the vehicle).
- **L4 highly automated emergency takeover.** This ADS feature operates when a driver is in imminent danger. If this occurs, the Emergency Takeover assumes control of the vehicle and guides it to a safe stop.
- **L4 highly automated highway drive.** This ADS feature handles the entire DDT on a highway route, allowing the passenger to engage in other tasks. The system is responsible for the fallback performance of DDT.
- **L4 highly automated vehicle/transportation network company.** This ADS feature enables the vehicle to pick up passengers or goods and drive to a destination without the need for an onboard driver.

OPERATIONAL DESIGN DOMAINS

Both ADAS and ADS are constituents of AV, a term that encompass all of SAE's tiers of vehicle automation. All levels of automation, however, are being designed under operational design domains (ODDs) that define the specific operating conditions under which an ADS feature is designed to function, detailing elements such as roadway types, speeds, connectivity, and environmental conditions. For example, L3 conditional automated traffic jam drive reportedly works on freeways and at speeds less than 38 miles per hour (mi/h). However, defining ODDs is a complex task that is not yet well established. Figure 2 shows an example of an ODD framework that illustrates the elements that can be considered when specifying an ODD.

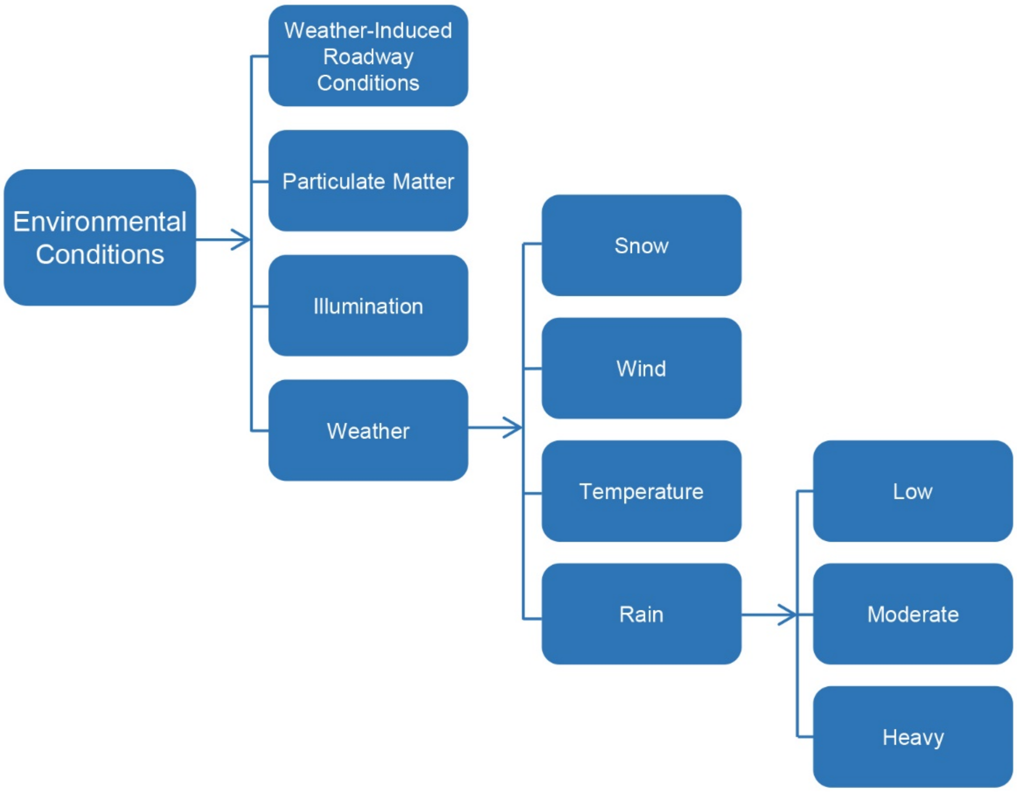


Source: NHTSA.

Figure 2. Graphic. Conceptual ODD elements (Thorn et al. 2018).

The ODD could also change based on the time of day or weather condition. For example, some ADS developers rely on the detection of pavement markings for lane-keeping. Pavement markings can degrade over time, and traffic and other activities, such as snow removal, can damage the markings and reduce the detection systems' ability to detect the markings. Similarly, pavement markings are not detectable under snow. Road markings often perform differently under various weather conditions. It is not uncommon for adequately performing pavement markings to be difficult to see in wet nighttime conditions. In addition to the nighttime performance of pavement markings that might limit lane-keeping performance, daytime performance (i.e., contrast) of pavement markings might also limit when and where an ADS will perform as designed, depending on the type of marking and the position of the sun.

Figure 3 shows an example of the environmental conditions that might be included when considering an ODD.



Source: NHTSA.

Figure 3. Graphic. Example of the environmental conditions of an ODD (Thorn et al. 2018).

For some ADAS and ADS features, the relative performance of TCDs, physical infrastructure, such as pavements and bridges, and other categories of infrastructure included in this review will likely have an impact on how an ADS developer defines an ODD. An ADS developer can think about the transition from ADAS to ADS by considering how the infrastructure elements of an ODD support the technologies that provide ADAS and ADS features. An ADS developer should examine what is needed from an ODD's infrastructure elements to make ADAS and ADS more reliable within the intended ODD. Another view is to consider the infrastructure elements that could be addressed to improve the performance of ADAS and ADS features. With this line of thinking, the key question becomes, "What role can infrastructure play to prepare/expand an ODD from transitioning from human-controlled vehicles to higher degrees of automation?"

As the transition from human-driven to ADS takes shape, additional infrastructure areas may be affected. For example, there is a developing concern over the accelerated rutting that could occur if ADS vehicles maintain a more-consistent lane position relative to human-driven vehicles, which have natural lane wander. These concerns have led to an acknowledgment of needed coordination of IOOs and ADS developers to better understand how ADS performance may impact the total transportation system, including infrastructure.

CHAPTER 3. AUTOMOTIVE INDUSTRY STAKEHOLDER PERSPECTIVES ON INFRASTRUCTURE-RELATED NEEDS

The research team conducted interviews with eight AV industry stakeholders to further the understanding of interaction between AVs and highway infrastructure, increase preparedness among transportation agencies, and promote collaboration across various industry domains.

These interviews sought to capture a wide range of potential impacts of AVs on the design, maintenance, and operations of highway infrastructure, particularly those associated with the more highly automated levels of AVs with ADS (i.e., those that correspond to SAE Level 3 through Level 5).

Table 3 indicates the sectors from which subjects were drawn and the number of representatives from each sector.

Table 3. Sectors and number of representatives for AV-industry interviews.

Sectors	Number of Representatives
Automotive OEM	3
Heavy truck industry	1
Automotive tier 1 supplier	1
ADS sensors	2
ADS computation software	1

The interviews sought pertinent information on topics including, but not limited to, the following:

- Roadway infrastructure and other related elements impacted by using ADS.
- Roadway users impacted by using ADS, including people with mobility challenges, pedestrians, and cyclists.
- Existing roadway infrastructure needs and the impact of ADS.
- Future roadway infrastructure needs and the anticipated impact of ADS.
- Infrastructure readiness as it relates to the impact of ADS.
- The role played by stakeholders outside departments of transportation (DOTs), such as the ADS/AV industry.
- Challenges related to operating ADS and conventionally driven vehicles within the same infrastructure space.

Researchers conducted anonymous interviews in a confidential manner to maximize the information obtained and to avoid any potential for undue influence by companies. The interviews focused on several key topics concerning the significance of AVs for infrastructure owners, managers, designers, and operators. The questions for interviewees included, but were not limited to, the following:

- What new demands will be made on the infrastructure (short and long term)?
- How different are AVs from the infrastructure perspective? What are the main differences to note?
- How does ADS see the infrastructure relative to the human? How may ADS reactions differ from human reactions?
- What new vehicle behaviors/impacts may occur? How may infrastructure provisions affect users' satisfaction with AVs?
- How different does the infrastructure need to be in the long term when potentially significant numbers of AVs are in operation?
- How could cyber-infrastructure, such as connectivity (vehicle-to-everything (V2X)), make AVs more attractive and robust in their operation?
- How do ITS and advanced traffic management technologies interact with AVs?
- What role could infrastructure play in maintaining and improving safety during the transition period of AV introduction?
- How can the infrastructure handle AV malfunctions and mishaps as well as the normal operations of AVs?
- What role could infrastructure play in limiting potential AV impacts on traffic flow, average speeds, etc.?
- What are the priority infrastructure needs (or sticking points) to support commercial use of AVs?
- What cooperation would be beneficial for the testing and safety evaluation of ADS? What types of information could be exchanged?
- How could IOOs contribute to defining and expanding the ODDs of ADS?
- What should DOTs be doing now with existing infrastructure to prepare for increasing AV use?
- What will the impacts of AV use be on existing infrastructure?

Industry stakeholders demonstrated a complex and deep understanding of infrastructure, including the interaction of machine vision and driving with infrastructure elements (e.g., lane markings, signage, signals). The following nine key observations emerged from the stakeholder interviews:

1. Implications of sensor evolution.
2. Influence of business models on early AV deployment paths and public perception.
3. Quality and uniformity of physical infrastructure.
4. Digital information standards.
5. Operational design domains.
6. Connectivity between vehicle and infrastructure.
7. Role of transportation systems management and operations.
8. Freight deployment.
9. Governmental and institutional issues.

The following subsections provide additional insights into each observation and include selected quotes and key takeaways from the interviews. The subsequent material in this chapter describe the opinions of individuals within the AV developer community and do not necessarily represent the view of USDOT or FHWA.

IMPLICATIONS OF SENSOR EVOLUTION

The rapid evolution and regular maintenance needs of sensors favor fleet operations in the near term and create challenges to infrastructure future proofing (i.e., provisioning for future needs or impacts on infrastructure assets).

There are several industry sectors that are essential to the creation of ADS in addition to original equipment manufacturers (OEMs). These industry sectors include sensors, maps, data processing, artificial intelligence (AI), and software. Of these, sensors, maps, and data processing all have direct connections with infrastructure engineering and operations.

Industry stakeholders interviewed for this report expressed a pragmatic understanding of the funding limitations and lengthy project delivery timelines associated with physical infrastructure improvements. They were generally optimistic about the ability of sensors and algorithms to solve the challenges presented to ADS by the existing physical infrastructure. Furthermore, interviewees agreed that rapid changes in the design and capabilities of sensors, as well as changes to the mix of sensor types (camera, radar, and light detection and ranging [LiDAR]), make it difficult to predict infrastructure needs over a 10-year-or-greater horizon. Given such rapid changes to ADS technology and architecture, one subject noted, “There is no silver bullet in infrastructure engineering to dramatically advance AVs.” However, most interviewees felt that the quality and consistency of the infrastructure—especially lane markings—support ADS.

Interview Highlights

- There seems to be no silver bullet in infrastructure engineering to dramatically advance AVs.
- Industry stakeholders are extensively exploring all modalities pertaining to AV implementation.
- There is a massive difference in sensor complexities with greater speeds.

Sensors are a critical but costly component of ADS. Minor impacts, however, can damage or destroy sensors, leading to diminished sensor performance and high sensor turnover rates. Interviewees noted that efforts are underway to use lower cost, higher value alternatives to reduce the cost of the sensor suite. Industry is also employing a variety of means to protect sensors from damage. Still, subjects tended to envision high sensor turnover rates prevailing in the near term. They also viewed the cost and maintenance issues associated with the sensors to be determinants of AV deployment paths. ADS sensors are costly and must be changed relatively frequently; therefore, industry stakeholders stressed the importance of professionally managed fleets—whether in the freight industry or with mobility on demand (MOD) applications, an approach that uses emerging mobility services, integrated transit networks and operations, real-time data, connected travelers, and cooperative ITS—as early adopters of AVs. (Sheehan and Torng 2011) Industry is developing modular sensor suites (or “backpacks”) that can be changed on a regular basis. Such developments favor scalable fleet applications.

Stakeholders also are considering certain well-defined and well-maintained operating environments and use cases where it might be possible to trim the sensor suite, which would greatly reduce the production costs of AVs. Conversely, subjects stated that there is a "massive difference in sensor complexities with greater speeds." Given these observations, industry stakeholders viewed highly automated vehicle operations in constrained environments, such as urban areas, as more feasible in the short term than conventional highways.

The following key takeaways were developed from the interviews:

- Sensors are a critical but costly component of ADS.
- Industry is optimistic about the ability of sensors to handle infrastructure challenges and is realistic about the funding constraints and project delivery lifecycles associated with capital improvements.
- The design, capabilities, and fusion of sensor packages are changing rapidly and will continue to change.
- Sensor modalities will not change; however, their mix is changing.
- Sensor protection and maintenance, or lack of it, can drastically affect sensor performance.
- There is no silver bullet in infrastructure engineering to dramatically advance AVs, but the consistency and quality of infrastructure are needed to support ADS.
- Sensor costs and maintenance issues favor professionally managed fleets in constrained operating environments in the near term.

INFLUENCE OF BUSINESS MODELS ON EARLY AV DEPLOYMENT PATHS AND PUBLIC PERCEPTION

Commercial fleets will be an important early application of SAE Level 4 AVs and offer near-term and nontraditional partnership opportunities between fleet operators and IOOs, while early consumer AVs will build incrementally on Level 2.

Interviews revealed that SAE Levels of Driving Automation are built into the thinking of most designers. In the OEM view, Level 2 systems represent AV 1.0, which take the pain points, such as driver fatigue and blind spots, out of common driving scenarios and allow drivers to be more relaxed through technologies, such as traffic jam assist, which are expected to scale relatively quickly, with eventual penetration to a steady state. Level 4 vehicles, which currently include dozens of sensors, are positioned as high-cost vehicles for use in small commercial fleets and represent AV 2.0. Interview subjects did not provide much feedback regarding markets for Level 3 because of the requirement that drivers be prepared to take control at all times. Interviewees viewed Level 5 as hypothetical at this stage.

Interview Highlights

- The urban fleet case seems to have immediate feasibility.
- IOOs should give utmost importance to AV fleet operations. This will help refine AV technology and its use of infrastructure, prove its longevity, and facilitate exchange of valuable data.

Subjects consistently viewed fleet operations and urban MOD applications, such as robotaxi fleets, as a major path for ADS development and deployment. Interviewees identified professionally managed fleet operations as critical for addressing sensor maintenance issues, while economies of scale were noted as important for offsetting the high costs associated with these maintenance efforts. Fleet operations were also viewed to be in the most familiar with sensor development, high-level automation, operational learnings, and infrastructure-based data. Interviewees noted uncertainties around where the first significant economic effects of AVs will be felt, and where the public perception of AVs will be forged. One subject noted that the "urban fleet case has immediate feasibility," yet this view was tempered by the belief that such systems will still require "human–AV interaction or flexibility," for which drivers would be needed in certain scenarios, such as driving at night during inclement weather. One subject mentioned that ADS are currently used to move vehicles around factories, dealerships, and ports.

Subjects envisioned that fleet deployments would initially operate in controlled environments before increasing more broadly. In the beginning stages, industry stakeholders believed that MOD fleets will operate in predefined and geofenced areas using ADS at Level 4. Fleet densities are expected to be highest in cities and controlled environments before expanding to include multiple operating environments and service to less densely developed areas. One subject observed that MOD fleet operations are likely to impact the design of transportation infrastructure in urban areas over the long term, eliminating the need for drivers to park vehicles and increasing the importance of curb management.

Subjects viewed fleets of AVs coming to market as important partnership opportunities between fleet operators (such as rideshare companies) and State and local governments. "The importance of AV fleet operations should not be underestimated by IOOs," stated one interviewee. "This is where the AV technology and its use of the infrastructure will be refined, its longevity will be proven, and valuable data should be exchanged." Partnerships between fleet operators and State and local governments will offer IOOs essential opportunities for data and learning because of the central control of fleet systems. Subjects viewed information sharing and best practices development as critical to expanding collective action between cities and States around common goals regarding fleet operations. This view favored breaking agency silos to ensure that States could provide consistent technical expertise and guidance to cities. Furthermore, subjects stressed the importance of IOO infrastructure strategists interacting directly with fleets to better understand the infrastructure needs of these fleets and possible infrastructure impacts of their operations. Policy actions, such as mileage-based user fees for AV fleets, were viewed by some as leverage for opt-in features, such as programmed lateral wander, to reduce wear on pavements.

The following key takeaways were developed from the interviews:

- OEMs are focused on two paths of AV deployment: consumer AVs that will build incrementally on Level 2 to eliminate driver pain points, and professionally managed Level 4 AV fleets operating in constrained environments (often within cities).
- Urban MOD fleets are viewed as feasible in the short term, although operating environments are expected to be constrained and such systems may still require human drivers in certain scenarios.
- ADS are currently being employed by OEMs at scale to handle vehicle fleet logistics at production facilities.
- Urban MOD fleets are expected to cause changes to the infrastructure, especially regarding parking and curbside management.

- IOO infrastructure strategists will need to work closely with fleet operators to understand infrastructure needs and impacts.
- State and local policy actions, such as mileage-based user fees, will offer leverage between governments and fleet operators that can further IOO objectives, such as reduced pavement wear.
- IOOs have a role in providing consistent technical expertise and guidance to cities regarding fleet operations but this will require overcoming jurisdictional and agency silos.

QUALITY AND UNIFORMITY OF PHYSICAL INFRASTRUCTURE

Physical infrastructure should be well maintained and consistent, especially regarding road markings and signage.

Industry stakeholders noted that IOOs should not treat AVs as a single class of vehicle with specific, new demands on infrastructure because AVs cut across many applications and present high rates of change driven by data and computing. Stakeholders emphasized that AVs are in their infancy and there is no new normal. AVs are not a new vehicle class from an infrastructure perspective, although manufacturers develop AVs that look and act like human-driven vehicles. Manufacturers define and prescribe AV functions, areas, and routes of operation, envisioning that AV operations within its prescribed environment will be like any other vehicle. Trying to define a new vehicle class for infrastructure considerations, therefore, makes little sense.

Industry stakeholders observed that an important aspect of safe AV operations is uniform applications for lane markings and traffic signs. Repairs of potholes and other structural deficiencies across pavements were also important. Stakeholders mentioned that the ability of IOOs to provide high-quality, consistent infrastructure regarding traffic controls and surface conditions also contributes to AV safety. For example, lane narrowing could depend on the quality of the lane markings, and well-defined, well-maintained operating environments could lead to a simpler and less costly ADS sensor suite. Despite a significant desire for consistent and high-quality physical infrastructure, the stakeholders were pragmatic about their expectations because of the budget realities of State and local agencies. IOOs hold a position of authority on infrastructure, the

Interview Highlights

- Clear lane markings, lighting, and signage are critical.
- Increased reflections from signs are needed.
- Lack of pavement markings is an issue, and the quality of markings is critical.
- IOOs need to follow MUTCD guidelines consistently to enable efficient AV operations.
- Safety precautions need to be considered in conjunction with MUTCD guidelines.
- Issues hindering AV implementation include stripe maintenance, potholes, and tree maintenance.
- Road construction and signals could change, and there could be narrower lanes if markings are better.
- High-level AVs are acceptable in a city with V2X, clear markings, and clear signage.

operation of vehicles on the infrastructure, and technological advancements in traffic control, ITS, and connectivity. Industry stakeholders reiterated that IOOs are responsible for ensuring quality and consistency across physical infrastructure, which are essential for smooth AV operations. With the rapid rate of development and technological changes in ADS, industry will look to IOOs to provide tested and reliable guidance to make infrastructure safe for AV implementation.

The following key takeaways were developed from the interviews:

- AV developers are striving to design AV operations similar to human-led vehicle operations; therefore, AVs should not be treated as a new vehicle class from an infrastructure perspective.
- AV industry stakeholders recognize the increasing need for high-quality and consistent lane markings, lighting, and signage in order to support machine vision reliability.
- IOOs are responsible for ensuring quality and consistency across physical infrastructure.

DIGITAL INFORMATION STANDARDS

Digital information relayed to AVs should be standardized, secure, and specific to AV operational challenges, such as work zones.

OEMs expressed a desire for standardized data from IOOs to detect pedestrians, cyclists, and road workers. In a broader sense, interviewees expressed a need for a new level of traffic sensing affecting AVs and conventional vehicles alike, especially in and around urban intersections. Researchers are testing the same sensor mode used in AVs (i.e., LiDAR) to detect pedestrians and cyclists as well as vehicular traffic. IOOs will need to standardize infrastructure-related data in collaboration with ITS and traffic control companies.

Interview Highlights

- Consistent road and traffic standards and enforcement on AVs across the Nation is needed.
- A broad range of AV technologies will be introduced, and road owners and operators will need to standardize the related information. Services will be provided by ITS and traffic control companies.
- ITS will become more necessary and with greater demands placed on it.

A major new area for IOOs to assist with the rollout of AVs is the provision of data that could be added to base maps or made available to vehicles from the cloud. These data could include information on lane assignment, road work, and road conditions. In these cases, the IOO may not deal directly with the OEM; other parts of the AV ecosystem, such as maps, will be involved.

Industry stakeholders indicated that cybersecurity for infrastructure connectivity must be commensurate with cybersecurity practices of the automotive industry. Using information sharing and analysis centers (ISACs) is an important step, and the Auto-ISAC provides collaborators with a domain where scenarios of security breaches may be shared and analyzed.

Information-sharing strategies also include increased use of open-source software, which OEMs have started to embrace lately.

The following key takeaways were developed from the interviews:

- In collaboration with ITS and traffic control companies, IOOs will need to provide OEMs with standardized data related to the detection of pedestrians, cyclists, and road workers.
- IOOs can potentially assist with AV rollout by providing slow moving data via base maps or using data on lane assignment, road work, and road conditions, hosted on cloud platforms.
- Cybersecurity for infrastructure connectivity should be commensurate with the cybersecurity practices of the automotive industry.
- OEMs will increasingly use open-source software and related technologies for information-sharing purposes.

ODDs

OEMs are responsible for defining their ODD and assume responsibility for safe operations within the ODD regardless of IOO actions.

The operating environment of AVs is a topic of considerable interest for infrastructure. However, stakeholders view the operating environment as being firmly in the domain of the AV manufacturer, who defines the ODD, and/or the mobility service operator, who may geofence AV operations. Manufacturers will initially select controlled environments, in which case it should be possible to simplify the physical design of AV lanes, making them narrower and removing elements such as rumble strips. Per industry stakeholders, AV zones could eventually look very different.

Interview Highlights

- ODDs and responsible entities need to be properly defined.
- ODDs can have many definitions. An ODD could include a geofenced area or specific roads. For instance, a scenario that involves no unprotected left turns and no bike lanes indicates a very specific ODD.

The safe design of the AV is a fundamental task, and OEMs design AVs to be much safer than conventionally driven vehicles. Safety is the manufacturer's responsibility. Safety checkers are an integral part of the ADS architecture, in addition to perception and planning. AV manufacturers are responsible for safety assessment and establishing ODDs. The ability of IOOs to assist in defining ODDs is limited because ODDs are extremely complex and difficult and are proprietary to a company's AV product and its ADS.

The following key takeaways were developed from the interviews:

- AV manufacturers are responsible for safety assessment and nomination of ODDs.
- IOOs have a limited role in assisting with ODD definitions and nominations.

CONNECTIVITY BETWEEN THE VEHICLE AND INFRASTRUCTURE

Connectivity, such as vehicle-to-infrastructure (V2I), can alert AVs to the presence of humans; however, industry does not rely on IOO support and is skeptical that V2I deployments will occur widely.

Industry stakeholders noted that V2I technologies will be needed to reassign lanes and restrict turns at peak hours. AVs will need to know this type of traffic and lane data in a highly reliable manner. Standards will be needed for the content and timing of this data. Stakeholders noted that it will be necessary to instruct the AV to change lanes. Base maps will be provided by the vendor; however, the local agency needs to provide the vendor with information, such as road work, human presence, and other items that change by the hour or day.

Industry stakeholders expressed a lack of reliance on the Government for the deployment, operation, or maintenance of roadside equipment regarding the application of connectivity as an additional sensor for AVs. The lack of progress with the Federal vehicle-to-vehicle (V2V) legislation, despite lingering enthusiasm for V2V and V2I, has led industry to consider other wireless technologies and business models as viable alternatives. Industry leaders believe that integrated, multimode communication systems will be needed in vehicles.

Interview Highlights

- There is a need for signals with SPaT to assist AV operations.
- The private sector will need to play a key role in getting 5G for vehicle connectivity across the board.
- Agencies need to create AV-specific data and make sure it goes to the Cloud. The Cloud then provides the connectivity. This data should include SPaT, signal timing information, and work zones.
- AV-to-AV communications is expected in future. Even a few vehicles with V2V will help traffic flow.

Stakeholders saw a definite role for non-line-of-sight information and an AV-specific need for vehicle communications, either dedicated short-range communication (DSRC) or cellular vehicle-to-everything. Data also are needed concerning infrastructure status items, such as signal timing, lane assignment, road work, and human presence. Safety messaging, in general, is important, starting with signal phase and timing (SPaT). Speed advisories, SPaT data, and CV data are all areas for advancements by IOOs, and subjects felt that these data could reside in the cloud or in extensions to maps.

The following key takeaways were developed from the interviews:

- V2I will be needed for reassigning lanes and restricted turns at peak hours.
- Industry holds a high level of skepticism on the availability of roadside equipment to provide additional data for ADS functions.
- There is an AV-specific need for vehicle communications.

ROLE OF TRANSPORTATION SYSTEMS MANAGEMENT AND OPERATIONS

AVs may exacerbate congestion in the short term, making it increasingly important that IOOs implement advanced TSMO strategies.

Stakeholders identified that an important goal for ADS is that they must closely emulate human driving, and ADS-equipped vehicles need to integrate seamlessly into the mix of human and machine driving, which stakeholders believed to be largely within the domain of manufacturers. Stakeholders acknowledged that smooth integration with conventional vehicles is a major early challenge. ADS are conservative in driving style because manufacturers must adhere to traffic laws to minimize risks to all other road users and vehicle equipment. Manufacturers must also understand that AV crashes might be treated like airline crashes, which could have major repercussions for the industry.

In the long term, managed lanes may be an important component of the IOO's role in TSMO once ADS-equipped vehicles constitute a greater share of the traffic stream. As one observer noted, "In an ideal world, we would have automated zones with their own speed limits, platoons of cars as well as trucks, and two lanes instead of three." The scope for narrowing managed lanes, reflecting ADS capabilities, depended on the quality of lane markings.

Interview Highlights

- Current laws are structured for median human drivers. Stakeholders will need to examine opportunities in an AV environment to optimize speed for traffic throughput and manage safety.
- Sporting and entertainment venues cause a change in how traffic flows. To facilitate AV operations, stakeholders will need to develop a model to account for changes in signal timing for an influx of several hundred thousand people.
- Changes in infrastructure will need to support AV technologies.
- Automated zones with their own speed limits, car and truck platoons, and the use of two lanes instead of three will be needed.

The following key takeaways were developed from the interviews:

- Smooth integration of ADS vehicles in the traffic stream is a major early challenge for OEMs.
- IOOs should be concerned about the perceptions of more vehicles and greater traffic delays as more ADS vehicles are deployed and disengagements are initially high.
- With greater levels of ADS vehicles in the traffic stream, industry stakeholders are confident that mobility can improve, yet industry looks to IOOs to implement operational strategies to improve mobility and safety for ADS and conventional vehicles.

With greater ADS penetration, managed lanes for ADS vehicles will become important and can improve and reduce lane width given quality lane markings.

Freight Deployment

The freight industry is an early and incremental adopter of low-level AV with its own path to deployment.

Interview Highlights

- Fully evolved infrastructure will have dedicated lanes, including lanes for heavy trucks, which could pave the way for purpose-built powertrains with no cabs operating at higher speeds on high-volume freight routes.
- The truck is a commercial transaction in which the safety features are paid. It is, therefore, easier for IOOs to regulate.

Across AV industry sectors, subjects commented on the importance of freight for AV development and deployment. Like consumer applications, industry expects AV systems for freight to build incrementally on Level 1 and Level 2 driver assistive and safety applications, such as automatic braking and collision avoidance, rather than leapfrogging to driverless capabilities as urban ride-hailing fleets are expected to do. AV industry views these assistive and safety applications as welcome by the public and vehicle operators. One subject commented that this would be "good for the trucker's health." This incremental approach is expected to be true for owner-operated heavy trucks and motor carrier fleets. Trucks on highways, and platooning trucks especially, are seen by stakeholders as demanding of an incremental approach, because, as one participant noted, "any mistake will put a stop to it." From this perspective, slight automation to support mobility and drivers is favorable to full automation and presents less risk. However, as public perception and infrastructure evolves with greater penetration of ADS vehicles, freight-industry stakeholders envision that fully automated driverless commercial motor vehicles may one day be adopted widely.

Industry stakeholders noted several near-term opportunities for IOOs to deploy technologies to assist freight vehicles equipped with low-level automated capabilities. Many of these short-term actions focus on operational support rather than sweeping changes to the physical infrastructure and include broadcasting of operational conditions in the transportation system to provide situational awareness to freight operators by using sensing, data, and predictive analytics. Furthermore, instrumented interchanges that broadcast upcoming hazards or congestion on ramps and interchanges through DSRC channels were also perceived to support freight operations. Stakeholders considered signal priority for heavy trucks as another step that IOOs could take to improve traffic flow for both heavy trucks and cars. Over the long term, industry stakeholders viewed managed and dedicated lanes for freight as important steps for safety and mobility. Stakeholders also viewed freight as being within the purview of IOOs because of the current regulatory relationships with motor carriers and other freight operators.

The following key takeaways were developed from the interviews:

- Freight is viewed as an important business model for AVs across industry sectors.
- In the near term, the freight industry is expected to adopt driver assistive and safety features, while full automation is considerably further out.

- IOOs can implement operational strategies in the short term to support freight vehicles with low-level automated capabilities.
- Industry stakeholders view freight as being within the purview of IOOs because of the current regulatory relationships with motor carriers and other freight operators.

GOVERNMENTAL AND INSTITUTIONAL ISSUES

Clear guidance and policies are needed at the Federal level, while interagency and intergovernmental coordination are needed at State and local levels.

Industry stakeholders noted that NHTSA has so far applied a light touch to safety evaluation of AVs. The NHTSA safety assessment is a step forward; however, AVs will require assessment over a much broader range. OEMs and other AV stakeholders will need to share safety data and experiences. The sharing should occur via a Federal agency or a global association that could include interaction with IOOs. Furthermore, roles are emerging roles for IOOs to interact with the AV industry in a cooperative manner, particularly in relation to traffic, data, connectivity, fleets, and operations in cities. Currently, however, it is difficult to assess how significant investments can be made in intelligent infrastructure without a substantive, technically oriented exchange among OEMs, IOOs, and other AV stakeholders.

Interview Highlights

- Safety is of paramount importance, and the NHTSA safety assessment is moving forward rapidly.
- AVs require assessment over a much broader range. To meet the NHTSA vision of avoiding more than 90 percent of crashes, AVs need to be properly designed.
- The case of mobility for blind users represents a large financial investment.
- Risk management of the AVs is required, but demands on the human element should not increase.

The stakeholders also noted a need for clear guidance regarding fleet deployment situations and uniformity across local jurisdictions with potential leadership and coordination roles for IOOs. Another topic of discussion included risk management for AVs, with industry stakeholders indicating that IOOs bear a responsibility for creating and implementing a risk management plan at a system level in collaboration with OEMs and others.

The following key takeaways were developed from the interviews:

- Stakeholders indicated that the Federal Government should provide guidance on safety issues pertaining to AV deployment.
- IOOs will need to interact with the AV industry in a cooperative manner, primarily on traffic, data, connectivity, fleets, and operations in cities.
- Clear guidance regarding fleet deployment situations and uniformity across local jurisdictions is desired.
- IOOs are responsible for creating and implementing a risk-management plan at a system level to facilitate AV deployment.

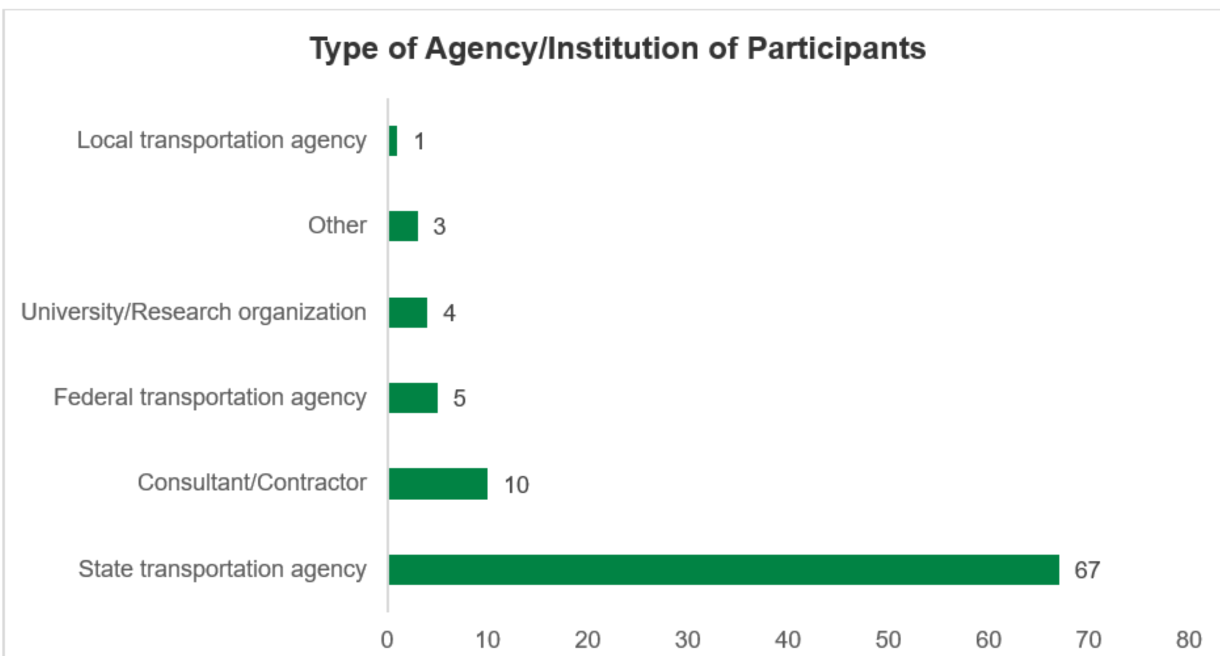
CHAPTER 4. FEEDBACK FROM STAKEHOLDER ENGAGEMENT EVENTS

STAKEHOLDER ENGAGEMENT EVENTS

Feedback from IOOs and other stakeholders was gathered through two events held at the American Association of State Highway and Transportation Officials (AASHTO) Committee on Maintenance Workshop in Grand Rapids, MI, on July 17, 2019, and the Automated Vehicle Symposium in Orlando, FL, on July 18, 2019. The following sections provide a summary of feedback from the events. A real-time audience polling application was used to gather feedback at each event. Subsequent material in this chapter describes the feedback from a broad group of roadway infrastructure and AV-developer community stakeholders and do not necessarily represent the view of USDOT or FHWA.

AASHTO COMMITTEE ON MAINTENANCE WORKSHOP

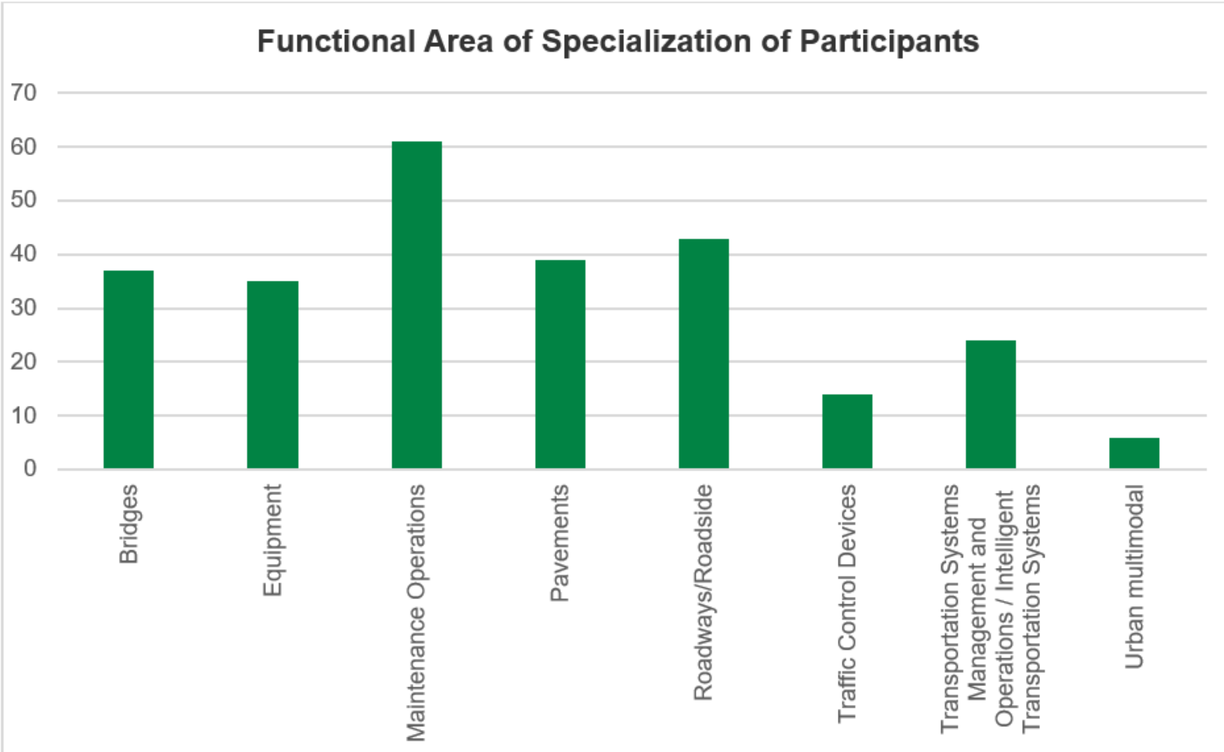
The AASHTO Committee on Maintenance Workshop provided feedback from State DOT maintenance leaders and managers. More than 100 attendees participated in the workshop and included representatives from Federal, State, and local transportation agencies, universities and research institutions, and private contractors and consultants. As seen in figure 4, the majority of workshop attendees were from State DOTs.



Source: FHWA.

Figure 4. Graph. Composition of the AASHTO workshop audience.

The audience was diverse in its infrastructure-related specializations. Experts in bridges, equipment, maintenance operations, TSMO, multimodal infrastructure, pavements, and roadside TCDs were in attendance (figure 5).



Source: FHWA.

Figure 5. Graph. Functional specializations of the AASHTO workshop audience.

The workshop session focused on achieving the following objectives:

- Share the information gathered from AV-industry interviews, engagements, and literature scan on near- to long-term impacts of AVs on roadway infrastructure.
- Gather feedback from public sector representatives regarding AV impacts on four functional areas of infrastructure, including:
  - Physical infrastructure (pavements, bridges, and culverts).
  - TCDs.
  - TSMO and ITS infrastructure.
  - Urban multimodal infrastructure.
- Discuss AV-readiness levels of agencies, including proactive strategies adopted to prepare for AV implementation and operations and anticipated challenges.

Researchers posed fourteen poll questions were posed to the workshop participants, primarily focused on the following themes:

- Potential AV issues and impacts on the four functional areas of infrastructure.
- Changes needed to agencies' existing infrastructure to facilitate AV implementation.
- Preparedness and readiness of agencies to address AV impacts on roadway infrastructure.
- Activities implemented by agencies to prepare for AVs.
- Participants will need support from government and industry stakeholders to prepare their region for AV impacts on roadway infrastructure.

Agencies noted the following high-level concerns about their current AV readiness (table 4).

Table 4. Current AV-readiness level of IOOs.

Area and Readiness Level	Types of Comments
Not ready; Inadequate funding	Many responses expressed a lack of funding for the preparation of AVs. Lack of resources. Inadequate funding to keep the existing assets in a state of good repair. Do not have the funding to address current issues. Current revenue source is based mostly on the gas tax, which will likely decline with AV adoption. Current pavement conditions are driving the funding priorities toward resurfacing and capacity projects; the ability to dedicate funding to this is not there yet.
Not ready; Maintenance plan for AV infrastructure is incomplete	Markings are difficult to maintain.
Ready; Agency already has begun preparations	Agency is in discussions about needs in this area. Early stages of preparation. When performing signal replacement, we include CV technology, slowly preparing with signs and striping.
Not ready; Technology needs	Technology keeps changing. Speed of technology is changing. Technology is not there, and our funding focus is on today and 5 yr from now.
Not ready; Need guidance and standards	Do not know what to do that will not be a waste. Needs are not well defined. Need to know where to begin. Limited expectations. No national standards. Needs are not developed or understood yet.
Not ready; Road conditions are inadequate	For many years, our infrastructure has been on the decline. Pavement conditions. Poor roads.
Not ready; Roadside signage and markings are inadequate	Agency needs significant improvement in lane markings. Pavement markings are not ready. Signage and pavement markings are probably not maintained well enough for AVs. Striping is inadequate.
Ready; Organizational structure includes AV-specific personnel	Agency has initiated an AV office. Agency is beginning to train staff.

Area and Readiness Level	Types of Comments
Ready; Leadership supports preparations	Adopting 6-inch-wide edge lines; State leadership supports the adaptation process.
Ready; Agency has a plan	ITS upgrade plan.
Not ready; External communication is insufficient	Public confidence is low. Lack of understanding. No proven confidence in AV.
Ready; AV collaboration	We are working with AV companies and doing trials, but there are many unknowns.

Participants noted the following regarding current actions that agencies are taking (table 5).

Table 5. ADS-roadway integration considerations by IOOs.

Area	Types of Comments
Changing approach to pavement markings	6-inch-wide markings. Beginning changing striping. Discussing putting a priority on the maintenance of traffic stripes and safety. Focus on striping and signs. Moving more toward epoxy markings and away from waterborne markings.
Initiating and starting task forces	Governor's Task Force on AVs. Have a connected and autonomous transportation group wrestling with this topic. Have an AV group within DOT initiating an AV office.
Engagement with OEMs	Talking to the CV and AV industries: What caused disengagement? Staying current with AV technology. Staying in communication regarding AVs. Coordinating with the automotive industry and internal coordination—maintenance, construction, and design.
Support/promote legislation	Promoting legislation.
Traffic control	Discussing whether to start placing chevrons again in gore areas; eliminated chevrons in gore areas not long ago.
Undertaking strategic planning	Identifying AV gaps. Incorporating the planning for AVs as part of our strategic plan.
Upgrading ITS equipment	Roadside units in signals. Signal controllers' AV capabilities. Updating ITS and Bluetooth systems. Increasing ITS staffing expertise.

Area	Types of Comments
Research	Estimating the additional cost to implement the recommended checklists. Working on a project demonstrating AV navigation in winter and in work zones. Working with a university to research impact. Developing test areas/tracks.
Nothing	Several agencies noted that they are in a waiting mode.

Similarly, when committee members asked what support State DOTs need, participants noted the following (table 6).

Table 6. Public- and private-sector support needed by IOOs.

Area	Types of Comments
Funding support	Many comments specified the need for funding to make appropriate preparations. Multiple comments indicated that AV funding should come from a separately identified source. AV pooled fund. Private investment share to fund transportation-related improvements.
Research and outreach	Education. More research. Consensus on methodology.
Organizational support	An AV organization involved with current planning processes. A checklist for the department to prepare for an AV guide.
Clear policy guidelines and expectations	Multiple comments requesting guidance on actions that should be taken. Clear and consistent requirements. Clearly defined goals. Knowing what to do. Quickly set standards. Clear vision. Reality-checked goals and objectives. Settle liability issues as they relate to timely maintenance and meeting standards.
State level	AV industry to become involved at a State DOT district level to understand current demands and available funding, let alone additional needs.
Standardized technology and data	Decision on DSRC versus 5G. Release standards. What are the standards and specifications? Transparency in data needs and sharing.
External communications	Public outreach. Stay engaged in the conversation.

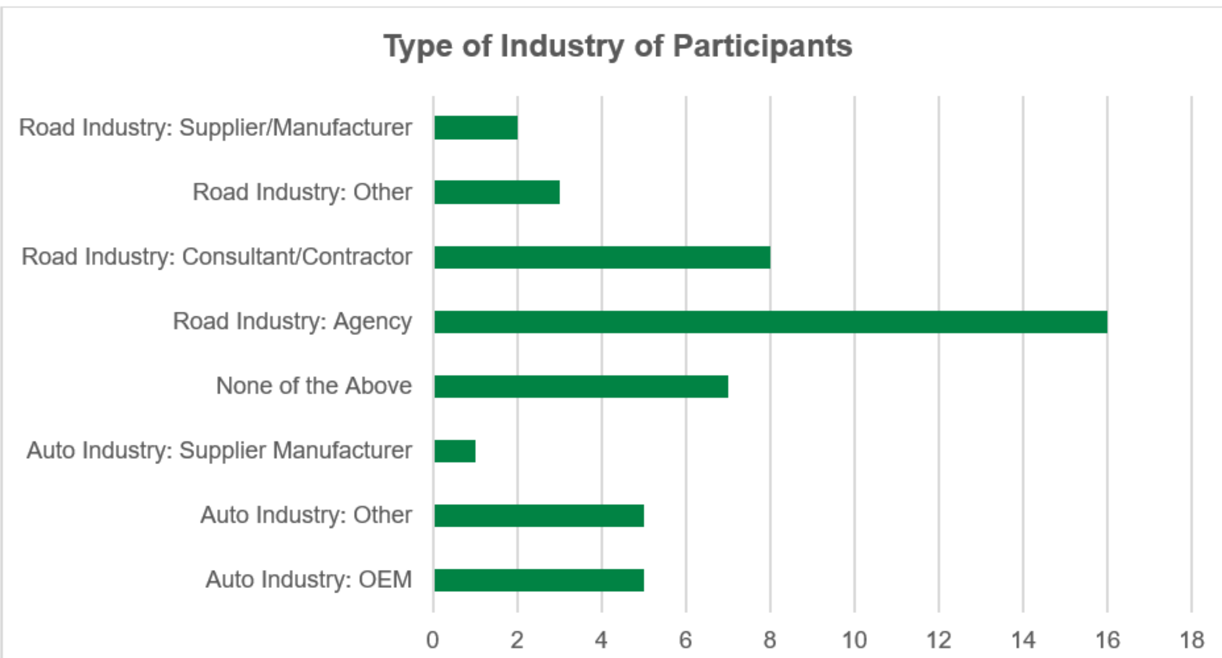
Area	Types of Comments
Prioritization of routes	Prioritized needs. Priority routes. Choose a few selected geographical areas in which to fully pilot this new technology.

5G = fifth-generation wireless.

The appendix contains detailed feedback on infrastructure categories.

AUTOMATED VEHICLE SYMPOSIUM

Nearly 50 participants attended the Automated Vehicle Symposium. Figure 6 shows that the composition of the participants was a mix of private and public stakeholders.



Source: FHWA.

Figure 6. Graph. Composition of the AV workshop audience.

Participants noted the following needs for IOOs as they prepare for AVs (table 7).

Table 7. Industry feedback on ADS needs for IOOs.

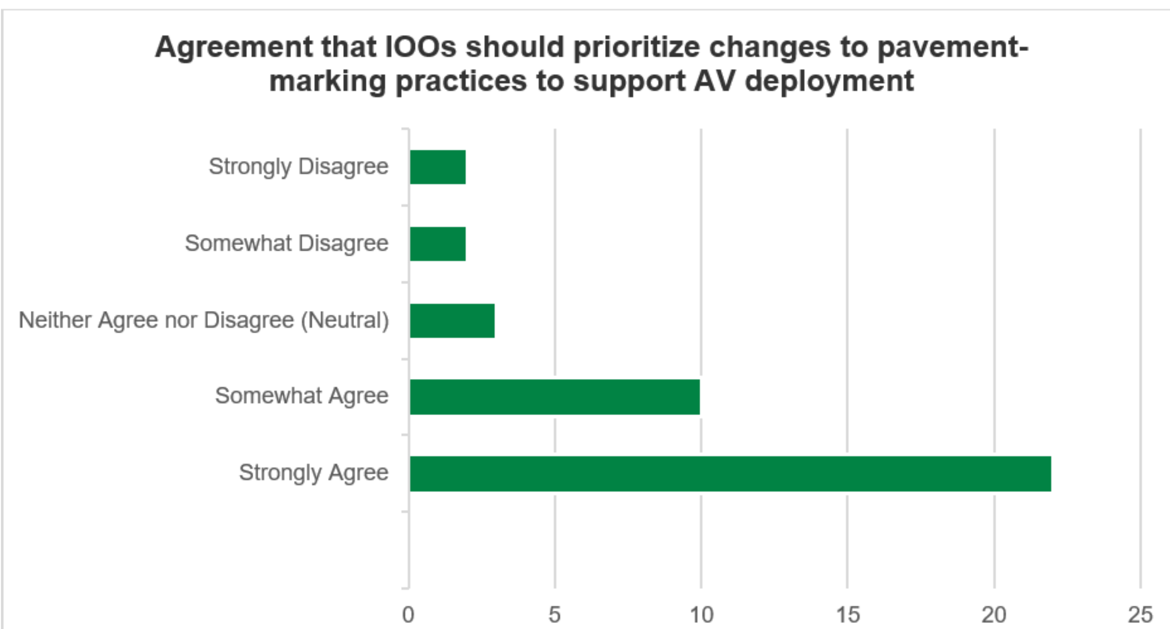
Area	Types of Comments
Organizational/ legislative support	Agency champion. Guiding policy framework.
Data collection	Classification of roadways based on support for ADS performance.
Staff capabilities	Multiple comments about work-force development and training. Aligned the skillsets of staff to orchestrate the transition, adoption, and maintenance of AV deployments. Dedicated staff. Retraining of existing personal. Technical expertise.
Defined standardization	Define standardization so that there are no wasted investments. Minimum levels of retroreflectivity of markings. Standards and policies.
Funding mechanisms	Shift the business model to support procuring, consuming, maintaining, and replacing technology. Rethink project delivery approaches.
Strategic adoption of technology	For requested changes to the infrastructure, adopters need defined benefit measures to justify costs. Pilot projects. Show AV benefits quantitatively. Understand which ADS systems will be broadly deployed.
Data asset management	Revised agency data governance.
Communication	Communications investment. State DOTs need to align messaging.
Shift agency operations to support AVs	Shift the business model to support procuring, consuming, maintaining, and replacing technology. Rethink project delivery approaches.

Participants noted the following for improving collaboration between public and private sectors (table 8):

Table 8. Collaboration opportunities between industry and IOOs.

Area	Types of Comments
Tie funding to collaboration efforts	Joint funding. Shared profits. Pilot project requirements.
In-person meetups	Job exchange. Shadowing: have OEMs spend a week in a maintenance garage, and vice versa. Work side-by-side daily. Joint workshops.
Include AV industries in the discussion of standardization	Involve automotive/AV vendors in updating the MUTCD and uniform infrastructure standards.
Use existing collaboration forums	Use the IOO/OEM Forum sponsored by the Cooperative Automated Transportation Coalition; they are already meeting today, and progress has been made. Involve ATSSA, ASC, and the American Road and Transportation Builders Association.

There was strong support for IOOs to look at pavement markings as an early readiness metric (figure 7).



Source: FHWA.

Figure 7. Graph. Agreement that IOOs should prioritize changes to pavement-marking practices.

CHAPTER 5. SYNTHESIS OF REPORTED IMPACTS OF AVs ON ROADWAY INFRASTRUCTURE

This chapter provides a summary of the literature on potential impacts of interactions between AVs and roadway infrastructure. This summary focuses on four sections that cover roadway infrastructure categories and their interactions with AVs (table 9). Each section contains detailed information that describes the current state of knowledge and expert opinion regarding the relationship among the specific roadway-infrastructure category, their respective infrastructure elements, and safe and robust AV deployment. Some sections may differ in the depth of content because these sections depend on the available literature, which is scarce for some of the elements discussed in this chapter.

Table 9. Roadway-infrastructure categories affected by AVs and their corresponding elements.

Infrastructure Category	Types of Infrastructure Considered
Physical Infrastructure	Pavements Bridges and culverts
Traffic Control Devices	Pavement markings Traffic signs Traffic signals Work-zone devices Vertical delineation devices Roadside barriers
TSMO and ITS Infrastructure	ITS roadway equipment TSMO strategies TSMO systems
Multimodal Infrastructure	Bicycle, pedestrian, and transit infrastructure Curb space

PHYSICAL INFRASTRUCTURE

AVs are expected to have an impact on the condition and long-term performance of roadway infrastructure and may necessitate a need for newer construction techniques and materials, in addition to an improvement in current design, maintenance, and asset-management strategies. Correspondingly, physical infrastructure is also expected to impact AV operations. This section highlights the impact of AVs on the following physical infrastructure elements:

- **Pavements**—structures that can be defined as a combination of subbase, base course, and surface course placed on a subgrade to support the traffic load and distribute it to the roadbed (Applied Research Associates, Inc. 2004). Typical pavement types are flexible (asphalt concrete), rigid (jointed plain or continuously reinforced concrete), composite, and other variations.
- **Bridges**—structures that include supports erected over a depression or an obstruction (e.g., water, highway, railway) and have a track or passageway to carry traffic or other moving loads and comprises an opening measured along the center of the roadway of

more than 20 feet between undercopings of abutments or spring lines of arches or extreme ends of openings for multiple boxes (Weseman 1995). Bridges can be single- or multispan in nature, and bridge types include slab, girder, beam, truss, arch, cantilever, and so forth.
- **Culverts**—structures designed hydraulically to take advantage of submergence to increase hydraulic capacity and typically covered with embankment and composed of structural material around the entire perimeter (Weseman 1995). Typical culvert types include pipe, box, and arch culverts.

The following key takeaways were developed from the interviews:

- **State of knowledge:** Changes in AV wheel wander and distribution patterns, lane capacity, and traffic speed can positively or negatively impact the pavement-service life by affecting a pavement's rutting performance, fatigue life, and hydroplaning potential. In addition, AV platooning and positioning (particularly of autonomous trucks) can impact the condition and long-term performance of pavements. However, limited data are available to adequately assess the current actual impacts of AVs on roadway infrastructure, including on how AV implementation and operation will affect pavement and bridge designs, maintenance, and asset-management strategies.
- **Agency readiness/maturity level:** Limited data are available on agency readiness regarding future AV impacts on pavements and structures. However, agencies are exploring emerging infrastructure technologies that interact with AVs. For example, the Missouri and Colorado DOTs are conducting pilot studies on smart-pavement technologies that can effectively communicate with CVs and AVs (Pape and Habtemichael 2018).
- **Uncertainty/knowledge gaps:** Uncertainties and gaps in literature pertaining to AV impacts on pavements, bridges, and culverts include:
    - Inability of AVs to effectively respond to the current roadway environment and visible pavement, bridge, and culvert defects.
    - Quantification and comparison of varying impacts of AVs on pavements, bridges, and culverts, including the impacts from increased traffic speeds of AVs.
    - Changes in vehicle class, axle-load distributions, and lateral wander resulting from AV deployment may have impacts on pavements, bridges, and culverts.
    - Impacts of AVs on pavement technologies that may already have a higher rutting susceptibility than traditional pavement mixtures.
    - Impacts of multiple AVs with varying lateral wander and distribution on pavement skid resistance.
    - Impacts of mixed traffic (e.g., AVs, manually driven vehicles, trucks) on long-term pavement and bridge/culvert performance.
    - Adequacy of current pavement and structure design standards and tools, maintenance strategies, and asset-management techniques to address the potential impacts of AVs on roadway infrastructure.

Pavements

The following issues were identified as potential impacts on pavements and are detailed in the subsequent sections (table 10).

Table 10. Pavement-related issues for AVs.

Surface Condition and Long-Term Pavement	Design and Asset Management	Emerging Infrastructure Technologies
Lower threshold for pavement distresses (e.g., pavement distresses, potholes, edge wear) for AVs.	Widespread platooning may increase dynamic loads.	Smart pavements.
Increased pavement-rutting potential (e.g., decreased wheel wander, increased lane capacity).	Changing traffic load patterns and vehicle characteristics.	Encoded asphalt materials/embedded sensors.
Potential for faster accumulation of pavement damage.	Changes to design and asset-management practices.	—

—No data.

Surface Condition and Long-Term Performance

Smoother pavements are critical for ensuring safe and durable roadway infrastructure and will help facilitate implementation of emerging intelligent technologies, such as AVs. Current surface conditions of pavements, however, could affect the introduction and operation of some AVs. These surface condition-related distresses or imperfections could include uneven pavement on which bitumen has been used to seal cracks, cuts, or drainage, the presence of potholes, edge wear, accident damage; and debris impact. Uncertainty exists on how an AV system will perform on a roadway environment with visible road defects. Examples of uncertainties include the unavailability of adequate information for AVs to change speed or direction to avoid debris on the road and enhanced sensors to provide last-minute information to AVs to help avoid minor collisions. Pavement distresses or imperfections, such as potholes, edge wear, and accident damage, will require monitoring and maintenance once pavement degradation is greater than the federally acceptable threshold levels for an AV (Huggins et al. 2017).

Changes in AV wheel wander and distribution patterns, lane capacity, and traffic speed can impact pavement-rutting performance, pavement fatigue, and hydroplaning potential, thus causing a positive or negative impact on the pavement service life. As such, large-scale implementation of AVs; impacts of changes related to the structural optimization of physical road infrastructure; and use of innovative road materials, conventional construction, and pavement-maintenance strategies should be considered. Chen et al. (2016) evaluated the potential consequences of large-scale AV implementation on the long-term service performance of practical physical road infrastructure. Researchers used a finite element modeling approach to investigate pavement performance based on pavement rutting and changing traffic characteristics, such as the vehicle’s wheel wander, lane capacity, and traffic speed of automated vehicles. The analysis considered a typical flexible pavement structure (with two asphalt-bound layers, a base layer, a subbase layer, and a subgrade layer), which was subjected to the loading of a single axle with dual tires. Rut-depth results indicated that the decreased wheel wander and increased lane capacity with AV use would accelerate the rutting potential (higher rut depth);

however, an increase in traffic speed would compensate for the rutting effect (lower rut depth). Thus, the rutting potential of the pavement would primarily depend on the practical road and traffic conditions.

Another study by Zhou et al. (2019) measured AV lateral-wandering patterns versus those of manually driven vehicles. The results indicated that while wandering patterns for both scenarios could be modeled as a normal distribution, their standard deviations varied considerably. The AVs' lateral wander was at least three times lower than regular vehicle traffic. Using the Texas Mechanistic–Empirical Flexible Pavement Design system, the study modeled the influence of smaller lateral wandering traffic on pavement rutting and fatigue life for two scenarios, including 100 percent manually driven truck traffic and 100 percent AV truck traffic. The study did not consider a mixed-traffic scenario (i.e., human drivers and AVs present on the roadway simultaneously.) The pavement structure used for the analysis was assumed to be located in Austin, TX, carrying 30-million equivalent single axle loads within a 20-year design period. The simulation results indicated that AVs were expected to reduce pavement life by 20 percent and increase pavement rut depth by 30 percent, which could potentially result in a higher risk of AV hydroplaning. Researchers computed maximum tolerable rut depths at different hydroplaning speeds, which indicated that AVs had much smaller tolerable rut depths than non-AV traffic because of the presence of a thicker water film in the rutted wheel path caused by hydroplaning. The study recommended an optimal AV-wandering pattern and a uniform distribution to reduce the negative impact of AVs and prolong pavement fatigue life, reduce rutting, and decrease hydroplaning potential.

Lane-centering technologies used by ADAS- and ADS-equipped trucks may lead to accelerated pavement damage because of reduced lane wandering. Noorvand et al. (2017) conducted a study to evaluate the impact of the lane choice and positioning of ADAS- and ADS-equipped trucks on long-term pavement performance. The study involved performance simulations of pavement structures for varying scenarios, considering both full and partial use by autonomous trucks. Researchers characterized the pavement performance based on pavement distresses (e.g., rutting, fatigue cracking) and overall pavement smoothness (International Roughness Index) Results were tabulated in terms of the reduction in pavement thickness. Results from the study indicated that with controlled lane choice and positioning, autonomous trucks could be highly beneficial for pavement-infrastructure design and most effective if constituting more than 50 percent of total truck traffic. The absence of appropriate control, specifically repeated positioning of trucks in the same location, resulted in higher amounts of damage with noticeable influences tending to occur at approximately 10 percent autonomous truck volumes.

Chen et al. (2019) conducted a finite element analysis on a typical flexible pavement structure under specified environmental conditions to evaluate the effects of autonomous trucks' lateral distribution within the lane regarding rutting depth and fatigue damage. The research considered four lateral control modes on managing autonomous trucks' lateral distribution, including the zero-wander mode, uniform mode, double-peak Gaussian mode, and the two-section uniform mode. The ratio of autonomous trucks was also evaluated to account for the difference between autonomous trucks and human-driven trucks. The simulation results from the study indicated that, with appropriate control, autonomous trucks greatly benefit asphalt pavements, thus enabling wider use. Better lateral control can also help mitigate the negative effects of AVs because AVs are able to use a wider section of lanes and thereby prolong pavement-service life.

However, lack of appropriate lateral control of autonomous trucks will result in a repeated single point load caused by lane-centering and -keeping, thereby negatively impacting the typical flexible pavement life.

The uniform mode, double-peak Gaussian mode, and the two-section uniform mode had a positive effect on the pavement while the zero-wander mode led to increased rutting and fatigue damage. Specifically, under the zero-wander mode, a rutting depth of 15 millimeters advanced the maintenance year by 1.56 yr, and fatigue damage at the bottom of the asphalt layer increased by 146 percent. The best-performing control mode (i.e., the two-section uniform distribution of autonomous trucks) delayed the maintenance year by 2.3 yr. The two-section uniform mode also resulted in a more-uniform distribution curve of fatigue within the lane. With appropriate lateral control of autonomous trucks, the two-section uniform mode could reduce fatigue damage on the flexible pavement by up to 35 percent under repeated standard axle-load conditions.

Design and Asset Management

AV (particularly truck) platooning can have a significant impact on the condition and performance of pavements and other structures. Automated heavy-vehicle platoons are expected to increase dynamic loads on pavements and structures (including bridges and culverts), thus resulting in a need to adapt the physical infrastructure to changes in traffic-load patterns. Changing traffic-load patterns and vehicle characteristics (e.g., traffic volume, vehicle-class distribution), and increased road use may necessitate modification of present-day design standards for pavements and structures. However, the magnitude of the impacts of AV platooning, specifically from groupings of heavy vehicles (with small headways and little lateral offset), on design standards would need further evaluation. AV-platooning operations could potentially result in increased rutting and surface wear as AVs may follow the exact wheel path of other vehicles, and pavements with high proportions of AVs will require the use of improved design- and pavement-asset–management strategies. Nonetheless, AVs could potentially reduce the impact on pavements if vehicles within a platoon (or all AVs that use a given lane) were laterally offset from other vehicles, which, will improve the fuel efficiency of the platooning vehicles. Additional research to consider the tradeoffs between the design of pavements and the operation of AVs may be needed (Huggins et al. 2017). Furthermore, the impact of a broad spectrum of mixed traffic (e.g., AVs, manually driven vehicles, trucks) on pavement design and maintenance will need to be further evaluated (Zhou et al. 2019).

Improved vehicle-monitoring programs can be used to influence AV operations (primarily heavy-vehicle lane allocation and platooning) to ensure uniform loading on pavements. Examples include Australia’s Intelligent Access Program, which uses satellite tracking and wireless communications technology to monitor where, when, and how heavy vehicles are being operated on the road network, thus allowing for more access or an increase in allowable mass for road operators who adhere to compliance standards. Increased loads from vehicle platooning would also entail changes to agency pavement- and asset-maintenance programs. Real-time data from AVs could be used to evaluate pavement and structure condition (e.g., pavement smoothness/roughness, location of potholes), which will allow road operators to use more consistent and proactive asset-management techniques and help maintain AV infrastructure. Newer technologies, therefore, will be required to monitor the performance of key roadway infrastructure assets at frequent intervals, or even in real time, to ensure the longevity of assets and improve the safety and efficiency of the roadway network (Huggins et al. 2017).

Smart Infrastructure and Emerging Technologies

Using less-invasive construction procedures, encoded asphalt materials can be developed to inform AVs about pavement-surface condition and roadway characteristics. Moreno-Navarro et al. (2019) conducted a study to develop an innovative asphalt material, codified using magnetic particles, to facilitate the driving of AVs. Traditional asphalt concrete mixtures were collected using varying types and proportions of metallic particles, which could transmit different types of signals that could be detected by sensors. Each signal type acts as a code associated with pavement and roadway characteristics (e.g., pavement-surface condition, presence of tunnels), which can be read by sensors installed in the vehicles and linked to software with the ability to interpret the signal and provide travel directions (e.g., speed-reduction advice). The results from the study indicated that the encoded materials are sufficiently sensitive to provide information to AVs and can be developed by using less-invasive construction procedures.

Similarly, advanced warning information on hazardous road-surface conditions shared among vehicles through CV and AV technologies can help caution travelers on safety-related issues and assist with vehicle rerouting. A study by Druta et al. (2018) found that existing concepts, such as the tire microslip phenomenon, which occurs at the tire-pavement interface leading to over- or under-rotation of wheels corresponding to the distance traveled by the vehicle, can be used to inform connected and automated vehicles (CAVs) about road-surface conditions based on relative rotational displacements of driven and nondriven wheels. The study evaluated the use of the relative rotational rates of driven and nondriven wheels to further assess road-surface conditions under varying situations involving multiple vehicles, different constant speeds, acceleration and braking effects, and road inclines. Researchers used the Traction Index (TI)—a dimensionless tire-pavement interaction factor—to evaluate road-surface slipperiness and slope for various lengths of time. Lower TI values indicated the presence of slick surfaces and uphill directions. This approach, if integrated with onboard vehicle sensors, can be used to analyze road-surface conditions and is expected to inform travelers better about immediate road conditions or localized road hazards.

Smart pavement surfaces can also be used to communicate effectively with CVs and AVs. One smart-pavement surface concept involves using tempered safety glass that can harness solar energy. The glass panels support the weight of a commercial vehicle and have a traction equivalent to asphalt. Another concept involves interlocking, precast concrete slabs embedded with digital sensors that provide wireless connectivity to vehicles. The Missouri and Colorado DOTs are facilitating demonstration projects on smart pavements. The smart-pavement structure includes a digitizer layer to identify vehicle tire position, weight, and speed, and is capable of accurately identifying crash locations, determining vehicle departure from the roadway, and calling for assistance if needed (Pape and Habtemichael 2018). In addition, innovative pavement treatments, such as high-friction surface treatments and Safety Edge℠, can serve as effective pavement-safety countermeasures to increase pavement–tire friction and reduce pavement-edge dropoffs on roadways, respectively, which can help reduce the frequency and severity of roadway-departure crashes from CV and AV technologies (Pape and Habtemichael 2018).

Bridges and Culverts

The following issues were identified for bridges and culverts and are detailed in subsequent sections (table 11).

Table 11. Bridge-related issues for AVs.

Traffic-Loading Impacts	Design and Asset Management
Groupings of heavy vehicles (with small headways and little lateral offset).	Widespread platooning may increase dynamic loads.
I2V strategies (e.g., gap control) can help mitigate bridge loading.	Changing traffic-load patterns and vehicle characteristics.
—	Increased protection for barriers at critical physical infrastructure.

—No data.

Traffic-Loading Impacts

Reduced traffic loading on bridges helps prevent distresses and accelerated deterioration. Lipari et al. (2017) evaluated the use of infrastructure-to-vehicle (I2V) communication strategies to mitigate bridge loading. Researchers assessed potential benefits of an innovative gap-control device based on site-specific traffic features and structural conditions, which can warn a truck driver when the gap to the leading vehicle falls below a certain threshold. Using an ad hoc formulation of the car-following Intelligent Driver Model, the research team performed microsimulation to analyze the effects of the gap-control system on traffic characteristics. Results indicated that the use of the gap-control system does not significantly disrupt traffic during a congestion situation; however, gap-control values of approximately 160 feet or more may result in traffic disruption during uncongested conditions because road capacity is reduced by about 12 percent. The gap-control system, when used to mitigate loading on long-span bridges, indicated that a 10-percent traffic-load reduction over a 200-m bridge span can be achieved when only 10 percent of trucks respond to the device. If 90 percent of the trucks respond, however, then traffic loads could be reduced by as much as 47 percent. The study concluded that by regulating the distance between heavy vehicles, the gap-control system serves as an effective alternative to the traditional and occasionally inefficient practice of posting a truck weight limit. Mitigated bridge loading due to the gap-control system is expected to result in a savings in bridge maintenance costs.

Design and Asset Management

The Nation's current highway infrastructure systems, including bridges and other structures (e.g., tunnels, culverts), are not designed to accommodate traffic platoons. AV platooning enables small intervehicle distances, thus leading to an increase in traffic loading that can have detrimental impacts on aging road infrastructure (Bergenhem et al. 2012; Lipari et al 2017). Specifically, automated truck-platooning strategies help heavy vehicles travel at short intervehicle distances. While allowing for benefits related to traffic safety, operations, and fuel consumption, automated truck platoons will result in greater traffic loading, primarily because of their varying vehicle-load characteristics and increased road use.

Bridge-related structural impacts from automated truck platoons will depend on factors other than increases in static weights because closely spaced vehicles will travel at high speeds and dynamically interact with bridges, unlike during congestion events (Ramakers et al. 2009; Lu and Shladover 2011; Tsugawa 2014; Lipari et al. 2017). AV platooning impacts that arise from groupings of heavy vehicles (with small headways and little lateral offset) may necessitate special design considerations and standards for structural systems, such as bridges and culverts because contemporary bridge-design standards are based on assumptions pertaining to the number of vehicles likely to be on the bridge at a time, vehicle distribution, axle spacing, and load spectra; these assumptions will need to be revised based on platooning and mixed-fleet conditions. Any change to the design approach will likely result in a change in existing bridge-management and -maintenance strategies, making it imperative to monitor bridge conditions and performance at frequent intervals or in real time. AV platooning also may necessitate increased protection for barriers at critical physical infrastructure (e.g., protecting bridge piers on a high-speed road under a rail bridge). However, with the use of improved vehicle-monitoring programs (e.g., Intelligent Access Program), AV operations (specifically heavy-vehicle lane allocation and platooning) could be influenced to lessen the impacts on bridges (Huggins et al. 2017).

Future Impacts and Anticipated Changes

A full AV-penetration scenario is expected to be complemented with technologies that automatically monitor surface conditions that will enable a near real-time transmittal of data to and from AVs. These technologies could include newer sensor-based technologies that can be embedded into pavement or bridge surfaces and can better inform AVs about the surface condition of physical infrastructure. In addition, detailed information will be available on AV characteristics (e.g., vehicle-class distribution, axle-load spectra, representative traffic volumes), which will help better characterize AV traffic impacts on long-term pavement and bridge performance. Dedicated AV infrastructure may necessitate the adoption of differing pavement and bridge designs, maintenance, and asset management strategies (Huggins et al. 2017). As such, existing design standards, tools and agency-asset maintenance and management programs may need to be updated to address AV needs.

TCDs AND OTHER ROADSIDE INFRASTRUCTURE

TCDs and other physical infrastructure elements, such as roadside barriers, provide human-driven vehicles with critical information for safe vehicle operations. One of the earliest and most significant safety benefits that can be realized as vehicle automation features become more prevalent is a reduction in roadway-departure crashes (Jermakian 2011), which represent the largest portion of fatal and serious injury crashes in the United States. From 2016 to 2019, roadway-departure crashes represent 52 percent of all traffic fatalities in the United States (FHWA 2019). This section describes the elements of the TCD and roadside infrastructure areas that have been mentioned, described, or referenced as they relate to roadway-infrastructure elements that vehicle-automation technologies interact with to provide features, such as lane-departure warning (LDW), lane-keeping assist (LKA), and lane-centering control. In detail, these elements include the following:

- **Pavement markings**—used to convey messages to roadway users, these markings indicate which part of the road to use, provide information about the conditions ahead, and indicate where passing is allowed.
- **Traffic signs**—used to regulate, warn, or guide traffic. They are placed on, over, or adjacent to a street, highway, or private road open to public travel, a pedestrian facility, or shared-use path by the authority of a public agency or official having jurisdiction, or, in the case of a private road, open to public travel, by the authority of the private owner or private official having jurisdiction.
- **Traffic signals**—used to allow traffic to either stop or proceed.
- **Work-zone devices**—used to help orient traffic on areas of roadways where road-user conditions are changed because of a work zone or incident.
- **Vertical delineation devices**—installed on roadways and used to separate adjacent lanes of traffic. Many times, they are used to separate high-occupancy toll (HOT) or high-occupancy vehicle (HOV) lanes that would otherwise have pavement marking buffers only. They also are used to channelize and/or restrict certain turning movements.
- **Roadside barriers**—installed along the roadside to safely redirect and/or stop out-of-control vehicles.

Most of the work referenced below has been developed through several meetings with representatives from the ASC, Auto Alliance, ATSSA, and NCUTCD. These organizations have been collaborating in a formal manner since summer 2018 to bridge the automotive and highway industries with a goal of advancing highway safety by more thoroughly describing how roadway infrastructure can evolve to support AV technologies.

The available research, literature, and documentation from these meetings provide evidence of three key areas where TCDs play an important role in the deployment of AV technologies: uniformity, quality, and maintenance. The following sections provide insight into each of these key areas within the context of the identified element.

TAKEAWAYS FOR TCDs

While TCD uniformity and quality was frequently discussed during the AV industry stakeholder interviews, key takeaways have been categorized into the following three areas: state of knowledge, agency readiness/maturity level, and uncertainty/knowledge gaps.

- **State of knowledge.** The coordination of roadway infrastructure to enhance the performance of ADAS and ADS has increased in recent years. The Automotive Safety Council and ATSSA held a workshop in August 2018 to share information and educate the highway and automotive industries on interactions between vehicle sensors and roadway infrastructure. The NCUTCD and several automotive industry associations are collaborating to better understand what is needed from a TCD that can be addressed in the MUTCD. SAE formed a new task force aimed specifically at addressing the physical infrastructure aspects related to all levels of automation. SAE included AASHTO representative to participate on the task force, and the two groups are working on how to

manage ownership and maintenance of forthcoming documents that have yet to be fully defined. FHWA provided many methods for input and feedback through their ADS Request for Information and their national dialog meetings.
There are a variety of efforts to bring stakeholders together, and the result of these efforts is a rapid expansion of the state of knowledge.

- **Agency readiness/maturity level.** Agency readiness across the United States is not complete, but not from a lack of interest. Incomplete agency readiness results from a lack of understanding about what should be done to declare readiness. Many agencies are actively pursuing guidance to understand how they can prepare their infrastructure for ADAS and ADS, but other agencies believe that ADAS and ADS should conform to existing standards and practices. A common concern across all agencies is having access to adequate funding if changes to current standards and practices require additional resources. Through ongoing activities and liaison engagements, such as NCUTCD's efforts and SAE's On-Road Automated Driving Committee Infrastructure Task Force work, and the workshops planned as part of this project, researchers expect to have a better understanding of what readiness looks like.
- **Uncertainty/Knowledge Gaps.** Researchers are gaining clarity regarding the uniformity of TCDs. Growth-rate projections for ADAS-equipped vehicles are more reliable than for ADS vehicles, which have proven to be far too aggressive with missed milestones set by OEMs. For ADAS, researchers project that by 2020, LDW technologies will be standard on 40–80 percent of new-car sales, and that number increases to 70–99 percent by 2025. Currently, LKA technologies will be standard on 10–24 percent of new-car sales and 30–73 percent by 2025. LDW and LKA are intended to keep vehicles on the road and in their lane. LDW and LKA also address roadway-departure crashes, which account for the largest category of crashes involving highway fatalities (approximately half of all highway fatalities) (FHWA 2020). Roadway-departure crashes from distracted and/or impaired drivers are one of the most significant safety concerns that ADAS and ADS features can positively impact. Despite the limited vehicles on the roadway with ADAS and ADS technologies, data show their benefits (Cicchino 2018). Researchers anticipate that what works for ADAS will also work for ADS. The targeted ODD for ADS is more focused than ADAS because of the increased complexity of successfully deploying ADS. One of the most significant knowledge gaps is determining how TCDs can support ADAS and ADS in different ODDs (e.g., highway versus urban driving).

Pavement Markings

The AV community notes that pavement markings are the roadway infrastructure element that supports their efforts toward deployment, mobility, and safety. Pavement markings support automated driving technologies because camera and machine-vision systems can detect and track pavement markings for ADAS features, such as LDW, LKA, and lane-centering control. These ADAS features are the building blocks for higher levels of automation.

The NCUTCD CAV Task Force is identifying areas where tightened pavement-marking uniformity can be beneficial. Through engagements with AASHTO, Auto Alliance, ATSSA, and ASC, the following list represents the most recent recommendations as of June 15, 2019.

- Use 6-inch-wide longitudinal markings on freeways and interstate highways.
- Use 6-inch-wide edgelines on roadways with posted speeds under 40 mph.
- Use dotted edgeline extensions along entrance and exit ramps.
- Include chevron markings in gore areas.
- Use continuous markings at the beginning of work zones and in all tapers.
- Eliminate the use of Botts' dots (i.e., round, nonreflective raised pavement markers) as a substitute for markings.
- Use contrast markings on light-colored pavements.
- Use 15-ft-long lane lines with 25-ft gaps.
- Use only arrow shapes approved in the MUTCD.

Many States already use 6-inch-wide markings and other States are making similar changes. For example, California (in 2018) and Kentucky (in 2019) adopted 6-inch-wide pavement markings to prepare their roadways for AV deployment, among several reasons. In addition, California has terminated its policy of using Botts' dots as a replacement for markings. Many States already use dotted edgeline extensions and many also use chevron markings in gore areas. Tightening national uniformity in these areas will help provide more robust marking detection and fewer false positives and represent an initial step in preparing roadways for AV technologies. The following uniformity topics have been discussed but are not fully examined:

- **Develop uniform chevron markings for gore areas.** Consensus on a standard pattern for gore areas has not been reached. Some AV developers prefer the gore area to be entirely painted over but others prefer crosshatch or chevron patterns.
- **Develop uniform contrast marking patterns.** There are at least seven contrast marking patterns used in the United States (Carlson et al 2007). In a May 2019 survey of six machine-vision companies, respondents did not reach a consensus on a uniform pattern (Joint Automotive Safety Council and American Traffic Safety Services Associations Meeting 2019).
- **Tighten the delineation of special lanes.** There are many types of pavement-marking practices used in the United States to delineate special lanes (e.g., toll lanes, HOV, bike lanes). There is currently no consensus on how to tighten the delineation of these special lanes.

The AV community indicates that pavement-marking quality is also a topic of concern. The AV community has identified key quality topics. Some States are using more durable markings, but the other items in the following list are still being understood, researched, and debated.

- **Durable markings.** States, such as California, have begun using mostly thermoplastic, methyl methacrylate (MMA), and preformed tape markings and are moving away from using waterborne paint.
- **High-contrast markings.** The machine-vision system needs to detect the contrast between the markings and the road surface under all lighting conditions, weather conditions, and hours of the day. A standard method for defining how contrast is measured has not yet been developed.
- **Markings that maintain their colorfastness.** Colors used for new pavement markings are codified in the Code of Federal Regulations; however, there is no end-of-service

criterion for marking color (FHWA, MUTCD Color Specifications (23 CFR § 655)). Therefore, there is no standard to measure when a marking has faded to the point that maintenance is needed.

- **Markings visible under wet conditions.** Marking visibility can degrade during daytime and nighttime wet conditions depending on the wetting rate and other factors such as the sun position and pavement surface roughness. Markings with high refractive index optics and markings with vertical structure have been developed to address nighttime wet conditions; however, they are not yet widely adopted.
- **Markings visible under glare conditions (certain sun angles).** Some markings exhibit glare under certain sun conditions, which makes it difficult for humans and machine-vision systems to see the markings.
- **Markings compatible with LiDAR technologies.** The University of Michigan is testing pavement-marking detectability using LiDAR technology (Park, Reed, and Sayer 2019). Researchers have identified that pavement-marking maintenance is a problem for the AV community as well as human drivers. FHWA is in the final stages of completing the minimum pavement-marking retroreflectivity rulemaking; however, that rulemaking is designed for the needs of human vision, not machine vision. The first research to consider the minimum pavement-marking performance needed for machine-vision systems was conducted under NCHRP Project 20-102(6), *Road Markings for Machine Vision* (Pike and Barrette 2018). Findings of this study indicate that human vision needs higher retroreflectivity levels than machine-vision systems and that a daytime contrast-measurement standard needs to be developed so that daytime visibility (or contrast) can be designed, specified, and managed—not unlike the current efforts to provide and maintain nighttime visibility through retroreflectivity levels (Pike, Barrette, and Carlson, 2018). A leading manufacturer is conducting research in this area and has reported that at shorter distances, the luminance factor of a pavement-marking color, measured as Cap Y by a colorimeter, is more relevant to machine-vision detection than retroreflectivity (presentation made at ATTSA's Annual Convention and Traffic Expo 2019). The pace of research in this area has not kept up with the pace of interest and possibly the pace of machine-vision technology.

Traffic Signs

The AV community has indicated that the application, uniformity, and design of traffic signs are challenges for the industry, although not as much of a challenge as pavement markings. Many of the issues identified are also issues for human drivers. The following list details common traffic sign issues identified by the AV community:

- **National uniformity.** Many agencies have developed signs that are not in the MUTCD.
- **Speed-limit signs.** Speed-limit signs should be clearly associated with its specific lane/road (e.g., in the case of parallel roads with different speed limits).
- **Pictograms versus text.** The AV community has requested additional use of pictograms, where possible, as a preference over text.
- **Vegetation management.** If vegetation occludes a sign for a human driver, then it is also occludes the sign from detection by sensor technologies.

- **Retroreflection.** Having high levels of retroreflection is often cited as a need by the AV industry but not quantified. On the other hand, some AV industry stakeholders have reported situations where too much retroreflectivity blinded sensors. There has been no known effort to research how sign retroreflectivity might be addressed to support AV technologies.
- **Electronic signs.** The illuminated portion of electronic signs should have a standard refresh/flicker rate. The refresh rate of light-emitting diodes (LEDs) should be greater than 200 Hz to be easier for the vehicle's camera to detect. If the refresh rate is standardized for all electronic signs, then AV systems will be able to detect them much easier.
- **Digitizing.** Some AV developers have called for a digital database of sign types and placement. Virginia DOT conducted a research project with findings that support a national standard for a digital TCD protocol that supports AVs and CVs (Atta Boateng et al. 2019).

Traffic Signals

Traffic signals are a key roadway-infrastructure–element support for CV technologies, particularly because of their ability to communicate SPaT data to approaching vehicles. However, the AV community has identified traffic-signal issues related to automated driving technologies. The following list includes traffic-signal challenges and suggestions from the AV community:

- **Traffic-signal placement consistency:** The AV community has expressed challenges related to the consistency of traffic-signal placement regarding approach lanes and horizontally aligned traffic-signal heads.
- **Lane-direction uniformity:** The AV community noted that the lack of guidance on lane-direction uniformity is also a challenge. Some agencies use green and red arrows, some do not use arrows as often, and some use flashing arrows but others do not.
- **Frequency variation:** AV industry leaders noted that LED traffic signals create visibility challenges related to the frequency (in Hz) at which they operate (variability in the hertz of the displays).
- **Traffic-signal relevance:** The AV community indicated that identifying a lane to which the traffic signal is intended to provide traffic-control information can be a challenge. In some countries, a small arrow is placed above the traffic signal head to minimize confusion.

Work-Zone Devices

Work zones are designed with temporary TCDs to allow for safe and easy deployment, flexibility to accommodate needed traffic-pattern changes, and quick removal when the work is completed. Temporary TCDs tend to be less uniform than permanent TCDs. For connected vehicles, there has been progress related to work-zone messaging and providing work-zone information to approaching vehicles; USDOT's Work Zone Data Exchange initiative is one example of the progress. However, less work has been performed to understand how to accommodate work zones from the AV realm. The AV community has requested more uniformity and standardization, but there has not been as much effort to understand the specific challenges and priorities as there has been in the pavement-markings area. The following list includes specific work-zone challenges identified by the AV community:

- **Sign standardization**—standard signing at a standard distance approaching and exiting the work zone.
- **Clear lanes**—traffic lanes through work zones should be unambiguous.
- **Retroreflective devices**—vertical panels, tubes, and other channeling devices should be at least 8-inches wide with retroreflective material for reliable machine detection under all weather conditions.
- **Visible pavement markings**—markings entering the work zone and through lane shifts should be made with highly visible and continuous materials, not intermittent buttons and reflectors.
- **Orange markings**—orange markings should be used to delineate the vehicle path through a work zone. Orange markings have been tested by Wisconsin DOT and are currently under evaluation in Texas (DeDene and Dupont 2017).
- **Device spacing**—maximum spacing for vertical work-zone devices needs to be determined.

Vertical Delineation Devices

Vertical delineation devices, or pylons, are used to separate traffic or prevent weaving and/or turning movements, but they are sometimes difficult for machine-vision systems to detect. The AV community has suggested that when pylons are used, they should be supplemented with the appropriate color pavement markings and include retroreflective materials.

Roadside Barriers

The AV community has made several comments and suggestions regarding possible infrastructure enhancements to roadside barriers.

- **Concrete walls.** Concrete walls, such as dividers, should be marked with highly reflective markers, especially in the beginning section of the wall, to enhance visibility.
- **Barrier.** Barriers should provide high contrast from the adjacent road surface.
- **Steel-beam barriers.** Steel-rope barriers are less visible to computer vision than steel-beam barriers. Steel-beam barriers or concrete walls with reflective markings are preferred.

Future Impacts and Anticipated Changes

If just a few traditional human-driven vehicles are permitted on future roadways, TCDs and roadside infrastructure will remain similar in appearance and quantity (not including AV-exclusive facilities). However, the infrastructure may have more capability through embedded technology. For example, at least one technology solution has been demonstrated where traffic signs with embedded QR barcodes are only detected though vehicle-mounted active infrared vision systems. Similarly, Virginia DOT tested sensor-embedded pavement markings that would extend the ODD of today's sensor suites when detecting and tracking pavement markings. In the demonstration, embedded pavement markings were installed on Virginia Tech

Transportation Institute's Smart Roads research facility and tested over a 6-mo period. Testing was conducted year-round and demonstrated the capabilities of detecting and tracking pavement markings in heavy rain and snow.

Automation heavily depends on the vehicle industry. In the future, it is possible that the infrastructure industry will share more of the automation load. Infrastructure-enabled automation is particularly promising for specific applications, such as intersections in which strategically positioned infrastructure-mounted sensors may have nonoccluded views of all approaches to the intersection, as well as sight lines to all other intersection-related activity, such as pedestrians, bicyclists, and others who might be approaching the intersection. These data, along with vehicle data, can be merged under real-time conditions to improve intersection flow and safety.

TSMO AND ITS INFRASTRUCTURE

The TSMO and ITS infrastructure category includes technologies and equipment that enable traffic management and operations strategies. This category can be separated into three elements, described in table 12, and in more detail in the following sections.

- **ITS Roadway Equipment**—ITS equipment distributed on and along the roadway, which monitors and controls traffic and monitors and manages the roadway. The equipment also includes components of a toll-collection system and parking-management systems.
- **TSMO Strategies**—Current tactics used to manage the transportation systems for reliability, safety, and mobility.
- **TSMO Systems**—Back-office systems used to implement TSMO strategies and manage ITS roadside equipment.

Table 12. TSMO- and ITS-related issues for AVs.

ITS Roadside Equipment	TSMO Strategies	TSMO Systems
Need for SPaT and intersection map (MAP) data as early use cases.	Need for TSMO strategies may actually be greater in the near term.	Will require new or upgraded systems to ingest and manage large amounts of CAV data.
Significant challenges for AVs to read LED signs (including variable speed limit and variable message signs).	Demand-management strategies may become more critical to manage for reliability (e.g., pricing).	New data-management framework will require a clearly defined data governance structure.
Barrier road crossings (e.g., tolls) can impede AVs ability to provide continuous eyes-off/hands-off travel	New performance measures may be needed.	Agency's risks regarding data-sharing agreements, privacy policies, and IT/network security.

ITS ROADWAY EQUIPMENT

ITS equipment is distributed on and along the roadway and monitors and controls traffic; the equipment also monitors and manages the roadway itself. This equipment provides environmental monitoring and includes sensors that measure road conditions, surface weather, and vehicle emissions. Work-zone systems, such as work-zone surveillance, traffic control, driver warning, and work-crew safety systems, also are included in ITS roadside equipment (USDOT 2018a). Examples of this physical equipment include traffic detectors, environmental sensors, traffic signals, highway advisory radios (HARs), dynamic message signs, closed-circuit television cameras and video image-processing systems, grade-crossing warning systems, and ramp-metering systems. Lane-management and barrier systems that control access to transportation infrastructure, such as roadways, bridges, and tunnels, also are included.

In an operational AV scenario, accurate and timely information is of the utmost importance—even more so as penetration increases. Issues may arise when AVs cannot read signs or when they receive conflicting information (e.g., what the signs indicates versus what the AV system indicates).

For example, some AV manufacturers have noted significant challenges to AVs' ability to read LED signs (including variable speed limit and variable message signs). Some manufacturers have observed that the readability issue could be because of the refresh rate of the LEDs used in the signs and general legibility problems caused by luminance levels from LEDs, which can cause bleeding between characters, making the sign incomprehensible (Huggins et al. 2017).

Additionally, signage may be obscured by other vehicles, roadside infrastructure, or vegetation. This needs to be assessed from an AV technology perspective to ensure adequate detection is possible.

Data from ITS roadside equipment will likely not have a direct impact on ADS in all cases, but there is a potential for direct communication between signs and vehicles rather than through V2I connectivity. Direct communication will transfer data that can be combined with other data captured by the vehicle and will add to the redundancy of safety applications. This furthers the need for national consistency when provisioning data.

AV stakeholders have expressed skepticism about widespread roadside-connectivity deployment, but they have also identified several use cases of value, including SPaT information and situational awareness messages alerting AVs that a pedestrian or other object is in their intended path—especially when the path extends beyond the line of sight such as around the corner of an intersection. Such benefits are expected to require upgrades to signal controllers around the country.

ITS Roadway-Payment Equipment

ITS roadway-payment equipment represents the roadway components of a toll-collection system and provides the capability for vehicle operators to pay tolls without stopping their vehicles. It supports the use of locally determined pricing structures and includes the capability to implement variable pricing policies. Transactions are typically accompanied by a record of the transaction is provided to a back-office system (e.g., the payment administration center) (USDOT 2018b). Examples of this physical equipment include electronic tolling systems and parking-detection systems on the street and in garages.

Barrier road crossings, such as tolls, can present a significant challenge for AVs when providing continuous eyes-off/hands-off travel (England 2017). Vehicle connectivity can help bypass this challenge by enabling new virtual tolls that do not need barriers or infrastructure. While the impact of vehicle connectivity on the toll industry is uncertain, it could be disruptive (HNTB 2019). The continued push toward open-road tolling is expected to grow as AVs become prevalent within the fleet.

Increased use of AVs in both urban and rural settings will eventually affect parking-management systems. However, AVs will still rely on readily available instrumentation, signs, and other infrastructure to operate because it is unknown when a significant market penetration of AVs (e.g., 70 percent or higher) will occur; therefore, parking-management systems cannot completely rely on V2V and V2I communications to estimate occupancy.

Limitations from parking-management systems regarding AVs relate more to regulatory and policy aspects than to available management systems. Some reports provide recommendations on what actions can be taken to promote the use of AVs, such as ensuring interoperability between various charging infrastructure providers (Infrastructure Victoria 2018) and dedicated parking spaces for car-sharing companies or shared vehicles (Huggins et al. 2017).

TSMO Strategies

Early deployment of AVs may create new challenges for TSMO. Stakeholders noted that AVs' adherence to traffic rules will negatively impact traffic unless AVs are configured to "go with the flow." This clash of driving styles between AVs and human-driven vehicles is leading some to ask, "What do you do with the AVs that follow the law, such as traveling at free-flow operating speeds that tend to be higher than posted speeds?"

Others noted that IOOs should be concerned about more vehicles and greater traffic delays as additional AVs are deployed and disengagements are initially high. Stakeholders have also noted the need for places where AVs can stop safely if disabled and can provide emergency vehicle access as needed.

Some stakeholders, however, believe that a small number of vehicles that employ ADAS technologies, such as adaptive speed control and LKA, will lead to "more organized, regulated, and disciplined" traffic patterns over the next 5–10 years with "fewer crashes and less energy consumed." With vehicle fleet turnover, vehicles with ADAS and ADS are expected to eventually constitute most of the traffic stream.

For TSMO, active management of facilities, including dynamic lane assignments, congestion pricing, and other approaches used to manage demand and supply for system efficiency, may become critical for IOOs as competing fleets and AVs take up road space.

AV stakeholders considered event and incident management as important roles for IOOs in a mixed-traffic stream. Signal preemption and smart pathways for emergency responders were perceived as important steps in an AV operating environment. Stakeholders noted that ITS strategies, such as SPaT, are a means to smooth traffic flows in an AV operating environment and to enable "green waves" (i.e., synchronization of the green phase of traffic signals, for fleets).

TSMO Systems

Transportation Management Center

A transportation management center (TMC) is the hub, or nerve center, of most freeway management systems. The TMC is where data about the freeway system are collected and processed, fused with other operational and control data, synthesized to produce information, and distributed to stakeholders, such as media, agencies, and the traveling public. TMC staff uses the information to monitor freeway operations and initiate control strategies that change the operation of the freeway network. TMCs also allow agencies to coordinate their responses to traffic situations and incidents (FHWA 2017).

CAVs will produce a significant amount of raw data that cannot be processed by operators; therefore, TMCs will require new or upgraded systems to collect and manage raw data efficiently and securely. The availability of the data collected by AVs provides an opportunity to offer new data (e.g., traffic, driver behavior, weather) that could potentially lower infrastructure commitment by road authorities. However, data may be proprietary to third-party suppliers and may require a licensing fee to access it (Huggins et al. 2017).

This new level of data management will also need to define the data governance structure that expands the availability of open real-time information on government-owned transportation-system data and establish principles for data sharing between government and commercial transportation service providers (Infrastructure Victoria 2018). This new data-governance structure for TMCs could be even more important if CAVs rely on this information to operate and make decisions at the earliest stages of deployment. TMCs also will need to plan carefully for their operation, maintenance, and emergency response strategies to secure the funding needed to train existing personnel, add new personnel, and procure or upgrade systems and equipment.

Digital Infrastructure

As digital infrastructure becomes a mission-critical function, transportation authorities will need to enhance the capacities of their data-management and communications networks. AV piloting and eventual deployment will push forward the development of new, digital infrastructure, which could be a significant risk for many agencies that have yet to prepare for the accompanying requirements for AV deployment, such as data-sharing agreements, privacy policies, and information technology (IT)/network security (WSP 2016).

Future Impacts and Anticipated Changes

Like all predictions that relate to a scenario where AVs have significant or full market penetration, defining the changes to TSMO and ITS infrastructures is a challenge. The following summary details the expected impacts and changes to existing infrastructure discovered in the available literature:

- Toll barriers may become obsolete. AVs might open the market (and network) for toll agencies because they will not be bound by their physical infrastructure and can implement virtual tolling points (HNTB 2019). CAVs could also help expand the reach of traditional tolls by implementing advanced congestion-pricing strategies, such as link-, distance-, and travel-time-based pricing (Simoni et al. 2018). Consequently, payment equipment and systems will need to evolve to handle more information and transactions securely and efficiently.

- AVs will likely result in a substantial change in pickup and dropoff activities around parking infrastructure and high-demand central business areas, which will need to be carefully considered during planning, development, and operations.
- TMC operations will have changing roles as vehicle throughput is improved by reducing the separation between vehicles and platooning buses could help V2V communications (Lutin and Kornhauser 2014). As such, TMCs could shift their role from congestion/traffic managers to data managers and maintenance providers.

MULTIMODAL INFRASTRUCTURE

Multimodal infrastructure in this report largely refers to infrastructure elements that support nonautomobile modes of transportation, the connections among those modes, and the general transportation system. Multimodal ODDs can pose significant challenges for AVs. The safety of vulnerable road users is a critical concern for OEMs and IOOs. AV sensors often have difficulty detecting and predicting travel paths of nonmotorized roadway users, such as bicyclists and pedestrians, in a mixed human–vehicle operating environment (Crute 2018). Ensuring that AVs provide the expected safety and mobility gains in human–vehicle operating environment will require not just OEM-driven improvements to sensor technology and vehicle-to-pedestrian (V2P) interfaces, but that IOOs consider improving and standardizing multimodal infrastructure, including bicycle/pedestrian infrastructure, ADA-accessible infrastructure, TCDs, street design, curb design, parking, and more. This section will provide an overview of the literature on operational challenges to AVs and impacts on the multimodal infrastructure in a mixed environment that includes both human- and machine-driven vehicles. The following multimodal infrastructure groups emerged as primary areas of focus from a literature review:

- **Bicycle, pedestrian, and transit infrastructure**—represents portions of the transportation network designated for preferential or exclusive use of bicyclists, pedestrians, or transit and addresses the reallocation of space for each mode.
- **Curb space**—represents the design of curbside resources along roadways and sidewalks to provide reliable access to homes, work, commercial and public facilities, and amenities and addresses the reallocation of space to each activity.

TAKEAWAYS FOR MULTIMODAL INFRASTRUCTURE

Many transformative impacts on the multimodal urban environment depend on a complete transition to a fully automated vehicle fleet. However, given the current pace of AV development and deployment, fleet turnover rates, and a host of other variables that will affect the progress toward a fully automated vehicle fleet, this development is likely decades away. In the mixed-mode and mixed-technology environment that will prevail in the interim, the need for road-design standards and TCDs that accommodate human drivers will remain for the foreseeable future. However, adoption of uniform and quality TCDs, and design standards that provide dedicated infrastructure for each mode, can help future-proof infrastructure investments for AVs and provide positive transportation-system outcomes regardless of which trajectories of technological change unfold (Alta Planning and Design 2018).

The following summary details the state of knowledge and the gaps identified through a review of the literature on the impacts of AVs on multimodal infrastructure and the adaptation of this infrastructure for AV operations.

- **State of knowledge.** The state of knowledge for multimodal infrastructure focuses largely on policy and planning implications within a normative framework. Literature that addresses design adaptations of the multimodal infrastructure to support AV operations and minimize AV disengagements is limited. However, the importance of mode separation and the quality and consistency of TCDs in multimodal environments emerged as notable themes. Moreover, connected infrastructure that can communicate the presence and intent of vulnerable road users to vehicles was an important development. Likewise, the importance of effective curbside design and management is likely to increase as a greater percentage of the vehicle fleet transitions to AVs and demand for curbside access grows.
- **Agency readiness/maturity level.** The state of readiness for IOOs was not assessed systematically nor were any case study examples provided in the literature. However, the literature identified limited activities being undertaken by public agencies to support emerging transportation system needs that are likely to support future AV applications.
- **Uncertainty/knowledge gaps.** The National Association of City Transportation Officials (NACTO) (2017) identifies parking standards for AVs as an area requiring immediate attention. Knowledge of infrastructure best practices to support machine vision and V2I in a multimodal environment is limited, which could reflect the proprietary nature of ADS-technology development. A dialog with OEMs led by a neutral third party may help to identify common challenges and support a priority framework for multimodal infrastructure investments to support ADS operations and safety. Moreover, the review revealed a lack of research that addressed the impact of transit infrastructure on AV operations (and vice versa) and a lack of research that addressed the potential impacts of AVs on ADA accessibility-compliant infrastructure. Short-term research agendas could focus on filling these gaps.

Bicycle, Pedestrian, and Transit Infrastructure

Bicycle and pedestrian infrastructure includes portions of the roadway or sidewalk that have been designated by striping, signage, and pavement markings for the preferential or exclusive use of bicyclists or pedestrians (NACTO 2014). Pedestrians are defined in this report as individuals who travel on foot or who use assistive devices for mobility, such as wheelchairs. Examples of bicycle and pedestrian infrastructure include sidewalks, crosswalks, curb cuts, and bike lanes. The limited research on interactions of AVs with transit infrastructure (e.g., dedicated bus rapid transit (BRT) lanes) is also discussed in this section.

Behavioral Factors and Sensing Technologies

Rasouli and Tsotsos (2018) found that pedestrian behavior varies based on many factors, including pedestrian demographics, traffic dynamics, street configurations, and environmental conditions. The authors identified 38 factors that can potentially affect pedestrian behavior. Consequently, AV-detection algorithms in multimodal ODDs must be sufficiently robust to understand pedestrian and bicyclist intention in a full spectrum of traffic scenarios, roadway configurations, and environmental conditions. However, current sensor suites and algorithms might have difficulty detecting and responding to bicyclists and pedestrians in all scenarios because they are "small, unpredictable, and hard to see" (Crute et al. 2018).

Connected Infrastructure

Bicycling infrastructure, sidewalks, and other infrastructure elements, such as traffic signals, may be augmented with sensors or V2X technology to provide advance notification to AVs about the presence of a bicyclist or pedestrian. For example, Rasouli and Tsotsos (2018) contend that smart roads equipped with connected sensors and lighting can be used to transmit the intentions and locations of road users (e.g., a new interactive crossing in London equipped with LEDs flash warning lights to vehicles when pedestrians are crossing). Magnetic devices embedded in street infrastructure can also aid AV navigation under less-than-ideal environmental conditions where LiDAR systems may fail. Magnetic devices have been successfully tested on a BRT line in Eugene, OR (Crute 2018). Furthermore, dedicated BRT lanes can be retrofitted with AV technologies to test automated transit systems, which might aid in navigation and mitigate disengagements, but they alone will not solve the detection problems previously discussed.

TCDs for Bicyclists and Pedestrians

TCDs for bicyclists and pedestrians are wayfinding systems consisting of comprehensive signing and/or pavement markings to guide bicyclists and pedestrians to their destinations along preferred routes (NACTO 2014). Devices can include bollards, which provide a physical separation between motor vehicles and nonmotorized road users.

AVs have an increased reliance on TCDs, yet Crute et al. (2018) argue that AVs must include redundancies to allow for detection of pedestrians outside clearly demarcated areas. The National Association of City Transportation Officials (NACTO 2017) contend that intersection controls should have pedestrian- and bike-only phases where a flashing, audible beacon can indicate that vehicles are permitted to enter an intersection at a slow speed but still must yield to pedestrians and bicyclists. Before intersections are equipped with this technology, inexpensive design elements, such as regulatory signs and warning devices, could be retrofitted to replace nonconnected hardware in the street environment.

Safety Audits

Infrastructure Victoria (2018) suggests that surveys and audits of road infrastructure should be conducted prior to the introduction of AVs in a multimodal ODD to ensure that the pedestrian right-of-way is clear. Surveying and auditing can also help identify areas where AVs may present the greatest risks and benefits and help provide for an appropriately phased rollout. According to NACTO (2017), third-party data platforms that anonymize and aggregate data can also be used to pinpoint hotspots for vulnerable road users and inform street redesign to minimize conflicts with both AVs and conventional vehicles.

Mode Separation

It is unclear whether AVs will encourage or discourage active travel and transit use. The results of a stated-preference survey and random parameters logit model conducted by Blau et al. (2018) suggest that the presence of driverless vehicles in a variety of hypothetical scenarios more than doubles bicyclists' preference for separated facilities (e.g., buffered bicycle lanes and cycle tracks) when controlling for other factors, such as sociodemographics, street types, and facility preferences. Accordingly, the physical separation of modes will become increasingly important to avoid shifts away from active travel modes resulting from a perceived AV safety risk. Crute et al. (2018) indicate that AVs perform better on roads with formal rules and clear demarcations; therefore, mode separation can mitigate AV disengagements and boost the safety and confidence of vulnerable road users. Similarly, contemporary design and policy principles, such as Complete Streets, which seek to reduce vehicle speed and safely accommodate all road users (i.e., bicyclists, pedestrians, transit users, and motorists), can be applied to improvements in multimodal environments to advance safety outcomes and improve the efficiency of transit operations through the provision of dedicated facilities (Alta Planning and Design 2018).

ADA Infrastructure

A site, building, facility, or portion thereof is ADA accessible if it complies with the standards of the 2010 ADA Standards for Accessible Design (Caltrans 2017). ADA infrastructure, including curb ramps, curb cuts, and slip-resistant surfaces, references ADA-compliant components of the multimodal transportation network. The impacts of AVs on ADA-accessible infrastructure are largely unknown, which represents an important gap in the literature. Collaboration with disability-rights advocates becomes especially important when analyzing the impacts of AV on multimodal infrastructure (Alta Planning and Design 2018).

Design and Allocation of Curb Space

This element of the multimodal infrastructure refers to the design of curbside resources along roadways and sidewalks to provide reliable access to homes, work, commercial and public facilities and amenities, and the allocation of space to each activity (DDOT 2014). Examples of curbside design include designating curb space for ridesharing pickup and dropoff, goods delivery, onstreet parking, and transit stops.

Demand for curb space has increased significantly over the past decade with the introduction of ridesourcing companies and the growth of e-commerce. According to Crute et al. (2018), a dropoff revolution is expected to occur with shared and self-parking AVs leading pickup and dropoff areas to become an important component of site and street design and access-management standards. Frontage roads and turn lanes could potentially be retrofitted for ridesharing pickup and dropoff. Care must be taken, however, that bicycle and pedestrian networks are not fragmented by changes to the curb.

NACTO (2017) notes that third-party data platforms that anonymize and aggregate data can be used to pinpoint high-volume ridesourcing passenger pickup, dropoff, and urban goods delivery areas. These tools can then be used to inform the redesign and reallocation of curb space to accommodate the most productive uses and minimize conflicts with other modes. Separate parking standards for AVs were also considered an area requiring immediate attention.

Mobility hubs provide access to a variety of shared mobility options using clearly marked zones with dedicated curb space, signposts, or flexible medians. These spaces are likely to become increasingly important with the growing mix of shared mobility options and the introduction of automated ridesourcing fleets. In such a scenario, mobility hubs can support node-to-node travel (rather than door-to-door travel) to make more efficient use of curb space and encourage the use of shared modes (NACTO 2017).

Future Impacts and Anticipated Changes

Knowledge of infrastructure design to support a fully automated vehicle fleet in a multimodal environment is limited, and the impacts on multimodal infrastructure and its evolution in an AV environment will not occur in a vacuum. The rise of shared mobility, MOD, dynamic road/curb pricing, growth of goods delivery, ubiquitous travel data, and many other recent mobility trends and policy considerations are already placing new demands on multimodal infrastructure. Furthermore, sensor technology and ADS algorithms are likely to evolve considerably over the lengthy transition to a fully automated vehicle fleet. For these reasons and more, the nature of long-term infrastructure needs to support a fully automated vehicle fleet in a multimodal environment that is likely to remain uncertain for some time.

The following is a summary of the insight available in the literature for multimodal infrastructure elements in a scenario of full or near full AV penetration:

- **Bicycle, pedestrian, and transit infrastructure.** Removal of traffic signs and signals and the creation of free-flowing intersections in high AV-penetration scenarios could impede safe and efficient bicycle and pedestrian crossings (in this scenario, above- or below-grade crossings could be used in limited cases, where appropriate, to mitigate safety and accessibility issues created by these intersections). Remaining signs and signals would benefit pedestrians and bicyclists (e.g., creative wayfinding could replace street signs). Controlled lane guidance can lead to road diets that reduce pedestrian crossing distance (Crute 2018). NACTO (2017) envisions that frequent gaps in short vehicle platoons, along with miniroundabouts at minor intersections, could reduce or eliminate the need for long and complex signals and lead to midblock crossings becoming the new norm.
- **Curb space.** As lane widths narrow and lane throughputs increase in a high AV-penetration scenario, an opportunity arises to rebalance the right-of-way for alternate modes or purposes (e.g., extending the curb) (Infrastructure Victoria 2018). Furthermore, according to Crute et al. (2018), there is a strong likelihood that self-parking AVs will eliminate the need for onstreet parking with fully automated vehicle fleets. This elimination of onstreet parking and general reduction and relocation of parking demand may have a significant impact on the quality and configuration of multimodal infrastructure. Elements such as bollards, accessible textured pavers, and other cues can be used to demarcate uses in a flush curb space environment that would improve ADA accessibility. Furthermore, bicyclists and vehicles could interact seamlessly using

separated but flush lanes demarcated by differing street surfaces or other alternatives to conventional striping (NACTO 2017).

In the future, researchers could work with OEMs to identify types of multimodal infrastructure investments that support all tiers of automation and help to ensure that design specifications are ready to support a fleet predominated by AVs. Furthermore, there is a lack of literature on how infrastructure can support connectivity between AVs and other modes (e.g., the ability of AVs to support trunk-line transit first-mile/last-mile connectivity in a MOD framework). Finally, research on ADA accessibility implications of changes to the highway network and pedestrian environment that result from ubiquitous AVs would better inform infrastructure stakeholders regarding potential needs and risks.

CHAPTER 6. RECOMMENDATIONS FOR ROADMAP TO AV READINESS

AV development and deployment can be characterized by the SAE Level of automation and the ODDs for which the vehicles can provide automation features. As noted in figure 2, the ODD includes roadway classification, speed, traffic, and weather conditions. When considering AV deployment, it is important to recognize the diversity of AV applications and operations and the significant differences regarding their availability to market. ADS vehicles have the potential to revolutionize the transportation system; however, there are significant uncertainties regarding how far in the future ADS vehicles will be available.

ADAS technologies and the market share of ADAS vehicles are expected to grow significantly in the coming years. Many technologies that support ADAS features are the building blocks for ADS. Transportation officials can apply their understanding of current roadway infrastructure elements so that they can prepare future roadways for ADAS technologies that will maximize the benefits of all AVs.

For now, the primary safety benefits from the use of connectivity and AV technology are likely to come from ADAS features. While ADAS vehicles do not perform DDTs on a sustained basis, they can warn drivers about hazards or even intervene for a brief time to avoid or mitigate an imminent crash (e.g., using automated emergency braking or lane departure prevention). These lower levels of automation provide convenience features for the driver; however, the driver must always be in control.

IOOs work with a complicated mix of industries: technology, vehicle, and infrastructure. These industries are radically different in their product lifecycles and investment horizons. Although consumer technology is on the fast track, with product functional lifetimes measured in months, vehicles are designed for functional lifetimes of years and civil infrastructure is designed to last decades. These differences play a significant role in AV-readiness criteria because it is not possible for vehicles and roadway infrastructure to change as rapidly as an individual technological component, such as a camera-based sensor. Decisions about changes to the roadway infrastructure need to be robust regarding the technology-change rate. Transportation decision makers must ensure that they make cost-effective choices and not lock themselves into a situation where they too heavily depend on any one specific outcome.

This chapter combines the findings of the research, including the literature review, AV industry interviews, and national stakeholder workshops, into recommendations for AV readiness that include current opportunities as well as identifying future needs. The subsequent material represents the opinions and interpretations of the authors and not necessarily the views of USDOT or FHWA.

AV FORECASTING RELATED TO KEY INFRASTRUCTURE ELEMENTS

This research was specifically focused on the roadway-infrastructure impacts of AVs and was not designed to address the impacts of CVs. As AVs enter the vehicle fleet and start to generate a mixed fleet, it becomes important from an IOO planning perspective to understand the timelines so that road authorities can evolve their policies and practices as they prioritize safety and support the national guiding principles as described in *Preparing for the Future of Transportation: Automated Vehicles 3.0* (USDOT 2018).

Forecasting timelines for the deployment of AV technology is complex and far from an exact science. However, understanding the expected forecast for AV deployment that depends on roadway infrastructure elements is an important consideration for highway agencies planning and preparing infrastructure to maximize the safety and operational benefits of AVs.

Based on this research, including the literature review, AV industry interviews, and national stakeholder workshops, pavement markings are the foremost infrastructure priority for IOOs to support AV deployment. The ability of an AV to detect robust pavement marking provides a useful automation feature that promises safety.

As described in chapter 2, fundamental AV technologies described as ADAS are already available in new car. Within the family of ADAS features, pavement markings are needed for the broad class of features termed as lane departure prevention (LDP), which can include LDW, LKA, and lane-centering assist, sometimes called auto steer. Future SAE Level 3 through Level 5 automated vehicles also are expected to include these core automation technologies, depending on the specific use case.

For example, Level 3 Traffic Jam Assist, which is available in Europe but not in the United States, relies on car-following technology combined with marking detection. NCHRP Project 17-91, *Assessing the Impacts of Automated Driving Systems (ADS) on the Future of Transportation Safety*, shows Level 3 Traffic Jam Assist available in new cars near 10 percent in 2025 and near 20 percent in 2030 (Transportation Research Board 2019). Some automotive OEMs are skipping Level 3 Conditional Automated Highway Drive, but some are indicating that it will be available in the next year to two. Both Level 3 and Level 4 Conditional Automated Highway Drive rely on markings and have been estimated to have similar penetration rates as Level 3 Traffic Jam Assist. AV industry interviews described in chapter 3 reveal that Level 5 availability is too far out to begin to estimate timelines.

For now, highly automated vehicle technology will increase slowly at first and will not likely be prevalent for another 10 years or so. In the meantime, ADAS technology is already available and gaining ground. ADAS technology provides convenience for the driver but is also expected to have positive impacts on crash reduction. Understanding the timing is important so that highway agencies can plan accordingly.

Forecasting the availability of ADAS features like LDP is complex and depends on many factors, including possible regulations. Høye, Hesjevoll, and Vaa (2005) estimate that LDP technologies are likely to be included in 70 percent of new-car sales by 2025 and 90 percent by 2030. In terms of market penetration, Bansal and Kockelman (2017) estimate that LDP technologies will appear in 19–33 percent of new cars by 2025 and 31–51 percent by 2030. These estimates depend on the pricing of the technology and willingness of the customer to pay.

The latest safety estimates show a range of effectiveness depending on the reliability of LDP technology, which is directly related to the detection of pavement marking, which is related to the condition of the pavement markings. In ideal cases, pavement-marking detection has been shown to be quite reliable, with detection rates of in situ markings near 99 percent. However, depending on the condition of the markings and environmental factors, such as sun position, rain, and shadowing, detection can also be as low as 50 percent (Lundkvist and Fors 2010). Using LDP effectiveness rates of 50 percent, research shows that the expected reduction in single-vehicle, run-off-road crashes is estimated to be 11.2 percent by 2025 and 17.8 percent by 2030. Assuming a higher but conservative LDP effectiveness rate of 80 percent, crash reductions are estimated to drop 19.9 percent by 2025 and 33.0 percent by 2030 (Penmetsa, Hudnall, and Nambisan 2019). From a safety perspective, LDP technologies provide a significant amount of promise for road authorities meeting their safety goals.

IMPROVING PAVEMENT-MARKING CHARACTERISTICS FOR AUTOMATED VEHICLES

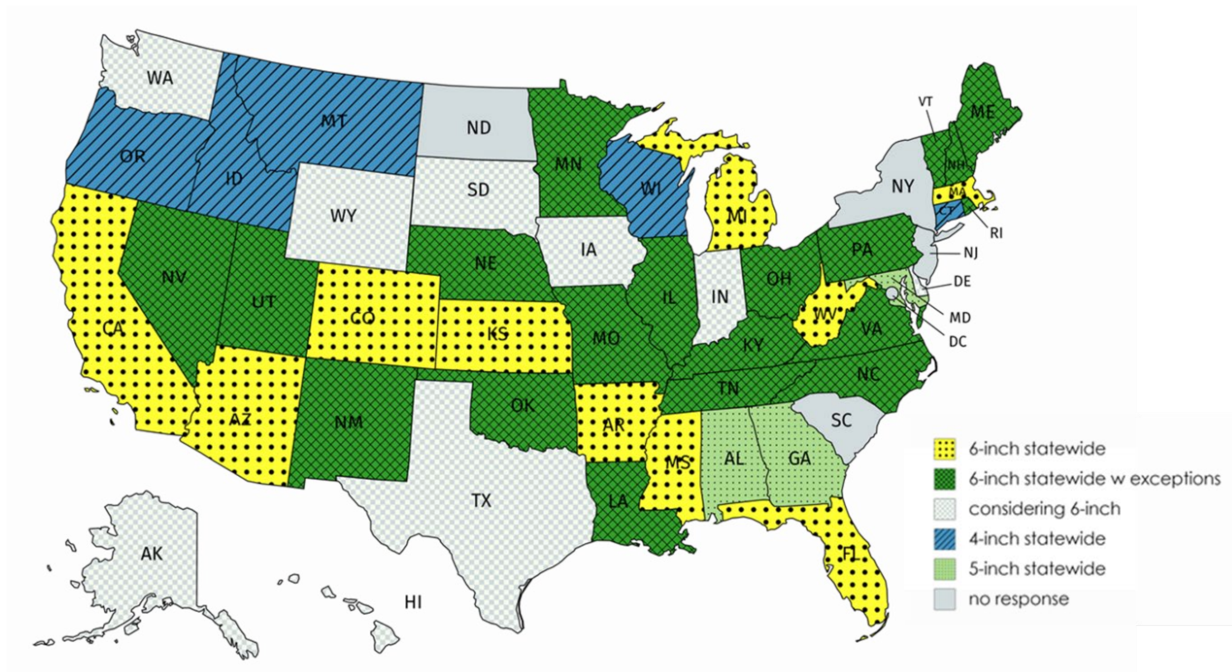
As described in the Executive Summary of this report, there are three pavement-marking areas to consider for optimizing LDP effectiveness and thereby achieving the highest safety potential. The areas are uniformity, design, and maintenance.

Uniformity

The most often-cited issue from the AV industry regarding roadway-infrastructure opportunities to support AV deployment is the lack of uniform applications across the United States (and throughout the world). While U.S. highway agencies are generally in compliance with the MUTCD, there is flexibility in the MUTCD that allows for varying degrees of practice. In some areas, the MUTCD does not address topics, such as contrast-marking patterns, that can have an impact on LDP effectiveness.

The MUTCD flexibility is preferred by the agencies but it can lead to pavement-marking practices that are not uniform nationally. The map of the United States in figure 8 displays national practices for longitudinal pavement-marking width, a pavement-marking characteristic demonstrated to provide support for AV deployment while improving highway safety. States labeled as “6-inch statewide with exceptions” implement 6-inch-wide markings statewide on interstates only and other States implement 6-inch-wide wide markings statewide on all interstates and roads meeting specific criteria, such as posted speed and functional classification.

Tightening national uniformity should be a top priority, and there is some discussion about updating part 3 of the MUTCD with some of the most critical needs of machine vision developers that provide LDP technologies to automotive OEMs.



Source: FHWA.

Figure 8. Map. Widths of longitudinal pavement markings across States.

Design

Pavement markings need to be visible and detectable under daytime and nighttime conditions and under dry and wet conditions. Under ideal conditions, such as clear and dry conditions, pavement-marking visibility is generally considered adequate if there is presence. However, LDP detection of pavement markings under sunny daytime conditions, dry and wet, can be particularly challenging depending on glare and pavement-marking contrast compared to the adjacent pavement surface.

Authors of *Road Markings for Machine Vision* (Pike and Barrette 2018) demonstrated how glare from the sun can wash out otherwise visible markings and the need to establish metrics to specify, measure, and maintain pavement markings for LDP technologies, specifically daytime performance metrics. Metrics included using daytime luminance to achieve contrast, standardizing contrast patterns on light-colored pavements to achieve contrast, and developing ways to assess the washout potential of certain marking materials and applications under glare conditions caused by the sun.

ODDs are used by AV developers to define where the vehicles are designed to operate safely. ODDs should include the dynamic nature of key infrastructure elements, such as markings. Visibility and detection of markings vary from day to night; however, they also vary in light rain versus heavy rain and wet roads with no rain (figure 9 through figure Figure 13). Figure 12 and figure Figure 13 show a nighttime scene in dry and wet conditions, respectively. Pavement markings labeled 1 and 3 are profiled markings that can provide added visibility in wet nighttime conditions. In contrast, pavement markings labeled 2 and 4 are flat or conventional markings that can typically lose visibility in wet nighttime conditions. The sun's angle on a sunny day can change marking performance so that a marking may not be detectable throughout portions of the day. The service life of pavement markings is one of the shortest of all physical roadway-infrastructure elements. Pavement markings are in a constant state of decay as soon as they are installed. In some areas of the country, such as Las Vegas, NV, with extreme heat and little rain, markings can lose their whiteness rather quickly because of asphalt oil tracking. In States with regular snowfall, winter-maintenance activities can severely damage pavement markings to the point that they need annual maintenance.

Source: FHWA.

Figure 9. Graphic. Glare in daytime wet conditions.

Source: FHWA.

Figure 10. Graphic. Glare in daytime dry conditions.

Source: FHWA.

Figure 11. Graphic. Contrast markings on a highway with faded asphalt.

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Figure 12. Graphic. Nighttime image of dry-pavement markings (Park et al. 2019).

Figure 13. Graphic. Nighttime image of wet-profiled and flat pavement markings (Park et al. 2019).

Maintenance

FHWA is finalizing minimum retroreflectivity standards for pavement markings. The standards are intended 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 has recommended minimum maintenance standards for pavement markings for LDP detection. The standards include maintaining dry retroreflectivity to a minimum level of 150 mcd/m^2/lx, maintaining wet-recovery retroreflectivity to a minimum level of 35 mcd/m^2/lx, maintaining contrast to a minimum level of 3 to 1 with a preferred level of 4 to 1, and using a minimum width of 6 inches for all longitudinal markings.

OTHER EARLY STRATEGIES FOR AV OPERATIONS

This section provides information based on stakeholder feedback that IOOs can use to assess and evolve their physical infrastructure policies and practices to support AV operations and deployment in the near term. Many of these strategies benefit ADS, ADAS, and human drivers and may be considered good practices regardless of the length of time for ADS development. The information in this section represents the most current information, which also received support at national workshops.

The information aligns with the findings from FHWA's reports on the National Dialogue on Highway Automation, (FHWA 2019, National Dialogue on Highway Automation) and meets the objectives of USDOT's *Preparing for the Future of Transportation: Automated Vehicles 3.0*; however, the information is based on expert opinion and limited data and is not Federal guidance (USDOT 2018).

Interstates, Freeways, Expressways, and Principal Arterials

AVs with Level 2 systems currently operate on interstates, freeways, expressways, and principal arterials. The AV industry is developing a variety of Level 3 and Level 4 use cases that also intend to operate on these facilities in future. While maintenance is lacking in some cases, roadways are generally uniform in design, operations, and maintenance. However, there are known areas where national policies and practices can be updated to support AV deployment. Some of the high-level reasons to evolve the interstate and like roadways relate to global economic competitiveness, including freight mobility, traffic congestion, and national security. AV levels and use cases expected to be deployed on these roadways include the following:

- **L3 conditional automated traffic jam drive—**Automated travel for stop-and-go traffic following the preceding car.
- **L3 conditional automated highway drive—**Automated travel for highway driving, including on interstate highways and other full-access controlled facilities.
- **L4 highly automated emergency takeover—**Emergency takeover assumes control of the vehicle and guides it to a safe stop if a driver is in impending danger.
- **L4 highly automated highway drive—**Handles the entire DDT on a highway route, allowing the passenger to engage in other tasks. The system is responsible for the fallback performance of the DDT.
- **Truck platooning applications—**Links two or more trucks in a convoy to maintain a close, set distance for some parts of the trip. In current applications, drivers in lead and following vehicles are still expected to be in control of the driving task during platooning behavior.

Table 13 presents strategies for agencies to consider in terms of AV readiness for their interstates, freeways, expressways, and principal arterials.

Table 13. Strategies for interstates, freeways, expressways, and principal arterials.

Functional Class	TCDs	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/eliminate confusing speed-limit signs on parallel routes.	Expand efforts in preventive maintenance, including pothole repairs, edge wear, and rutting.	Implement greater standardization of active traffic management and dynamic management signage across the country (e.g., variable-speed limits, lane controls, work-zone management).	Identify priority treatments for transit operations, truck platooning, and managed lane, which might benefit future AV operations.

Minor Arterials and Major and Minor Collectors

Minor arterials and major and minor collectors might experience significant gains in safety with increased presence of AVs equipped with LDP features. However, the readiness of these facilities and the traffic they carry is not as significant as the higher-class roadways addressed in the previous section. National policies and practices for these facilities are not as uniform as for the interstates. The number of miles for minor arterials and major and minor collectors and the maintenance funding could be significant. Table 14 presents strategies for agencies to consider in terms of AV readiness for minor arterials and major and minor collectors.

Table 14. Strategies for minor arterials and major and minor collectors.

Functional Class	TCDs	Physical Infrastructure	ITS – TSMO	Multimodal
Minor arterials and 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, including pothole repairs, edge wear, and rutting.	Implement greater standardization of active traffic management and dynamic management signage (e.g., variable speed limits, lane controls, work-zone management). 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.	Conduct curb-space management and safety audits.

Urban and Local Roads

This roadway classification serves different use cases that rely more on connectivity than physical infrastructure; however, issues still exist with complex intersections with dense multimodal interactions. Heavy rains impede smoother operations of AVs on urban and local roads, which can impact image quality for AV sensors. AV levels and use cases expected to be deployed on these roadways include the following:

- **L4 highly automated low-speed shuttle.** This ADS feature includes highly automated low-speed shuttles that only drive along predetermined routes.
- **L4 highly automated valet parking.** This ADS feature includes vehicles that can find an available parking spot and park independently with no human driver in the vehicle.

- **L4 highly automated vehicle/transportation network company.** This ADS feature enables the vehicle to pick up passengers or goods and drive to a destination without the need for an onboard driver.

Table 15 presents strategies for agencies to consider in terms of AV readiness for their urban and local roads.

Table 15. Strategies for urban and local roads.

Functional Class	TCDs	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, including pothole repairs, edge wear, and rutting.	Implement greater standardization of active traffic management and dynamic management signage (e.g., variable speed limits, lane controls, work-zone management). 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 BRT lanes with AV technologies to provide opportunities for automated transit-system testing.

IDENTIFIED RESEARCH NEEDS

Several research areas, described in the next sections, were identified over the course of this research.

Research Need One: Tightening TCD Uniformity for AVs

Background

AV developers often cite the lack of uniformity among TCDs across the United States as one of the most common challenges related to the infrastructure industry domain. While the MUTCD provides some uniformity, it has one fundamental objective—to meet the need of the road user, which until recently has been a human driver. The gradual deployment of AV technology has introduced a new design driver—sensors that read the road to provide AV features—to the roadways.

Objectives

The main objective of research need one would be to evaluate how the MUTCD might evolve to continue to meet the needs of human road users while also evolving to meet the needs of new design drivers. In January 2020, the NCUTCD recommended the benefits of increasing uniformity in the MUTCD on pavement-marking topics, such as more research in the pavement-marking area. Additionally, the research should address, at a minimum, the need for more uniformity in sign design, such as machine-readable traffic signs and opportunities to improve work-zone uniformity.

Potential Benefits

Defining road readiness has been of interest to agencies, researchers, and AV developers. While some initial work has started on the definition of road readiness as it applies to AVs, such as NCHRP 20-24(112), there has not been a focus on understanding how AV technologies interact with TCDs and how TCDs might be specified differently so that they meet the needs of human and machine road users. Recent research by Alabama Transportation Institute shows that AV lane-departure-prevention technologies can reduce roadway-departure crashes of single vehicles by 66 percent (Penmetsa et al. 2019).

Research Need Two: Machine-Vision Standards for TCDs

Background

TCD standards regarding size, color, and daytime and nighttime appearance have been developed based on human capabilities, including the capabilities of older drivers. Existing standards are scattered throughout various sources, such as the MUTCD, CFR, ASTM, National Electrical Manufacturers Association, Institute of Transportation Engineers, and AASHTO. Researchers developed NCHRP 20-102(6) to investigate how pavement-marking standards could be updated to support machine-vision systems. More work is needed. For example, TCDs with LEDs are becoming more popular across the country; however, some AV sensors cannot read them because the LEDs in the TCDs operate at a different hertz frequency than the equipment in the vehicle. Ongoing research in Europe is starting to demonstrate how sensitive AV sensors, such as passive cameras and LiDAR sensors, are to pavement-marking color.

Objectives

The objective of research need two is to determine if TCD standards need to be updated to accommodate AV sensors and if so, how. The research would include an inventory of the existing TCD standards across all National and Local policies, an assessment of the sensors used on AVs today, including their capabilities, and a thoughtful look at the future regarding timelines of existing sensors and their evolution as well as sensors likely to be included in technology suites for AVs.

Potential Benefits

Part of understanding road readiness is determining if the TCDs have been designed to accommodate both human and machine vision. While tightening uniformity is perhaps the first step (research need one), another step is synchronizing TCDs so that they are visible to both human- and machine-vision systems. LED-based TCDs are everywhere, from traffic signals to dynamic message signs, and they are critical for roadway safety.

Research Need Three: Developing MUTCD Material to Support AV Deployment

Background

The MUTCD is codified in the CFR; therefore, it can be difficult to keep current because of the required rulemaking process. As the AV industry makes technological advancements at a relatively fast pace, it will become even more difficult to update the MUTCD with information relevant to the AV industry. It has been 11 years since the last edition of the MUTCD was released. Research is needed to identify and describe methods to provide the necessary TCD-related support in efficient ways so that the material can be kept current.

Objectives

The objectives of research need three are to investigate ways to update the MUTCD in a more timely manner than the current method allows. The research should explore separating the MUTCD from the CFR, splitting the MUTCD in two parts that so that the fundamental material remains codified while other material is included in a document that might be easier to keep relevant (such as a supplement), and other options.

Potential Benefits

The MUTCD should continue to be the authoritative national reference document for TCDs, but the method for maintain it needs to be modernized. Developing a modern maintenance plan for the MUTCD will provide accelerated deployment of more efficient and lifesaving TCD principles and practices.

Research Need Four: Developing a Strategic Approach to Updating and Maintaining Pavement Markings

Background

Based on the current state of knowledge, including the research documented in this report, pavement markings are one of the most important infrastructure elements for today's partial AVs (SAE Level 2) as well as the more capable AVs of the future (SAE Level 3 through Level 5). However, if markings require a systemwide update and possibly higher maintenance standards, what is the best approach from a national perspective to optimize such investments?

Objectives

The objective of research need four is to quantify the return-on-investment of making national changes (in design and/or maintenance) to any element of physical infrastructure but particularly pavement markings. The research should consider the cost-effectiveness of making national changes in relation to pertinent AV-penetration rates. Finally, the research should also address funding opportunities. For instance, will there be any relief of current agency expenditures as

AVs become more prevalent (therefore, those funds can be reallocated to other areas, such as pavement markings).

Potential Benefits

From the national workshops completed as part of this research, two common agency concerns related to initial road-readiness recommendations have been funding and timing. These issues were not fully addressed in this research and more work is needed to help agencies understand their role in supporting AV deployment.

Research Need Five: Developing a Safe-Systems Approach to the Deployment of AVs

Background

While the safe-systems approach to road safety has been adopted by various countries (e.g., Australia, Sweden, Netherlands), it is still a relatively new concept in the United States. The safe-systems approach envisions a roadway system (including the built environment and policies that guide and support it) that sends practicable feedback to road users about safe and appropriate behaviors, improving safety despite human error.

Objectives

The objective of research need five is to apply a safe-systems approach to roadway safety considering there will be a mixed fleet of human-led and automated vehicles using roadways for decades into the future. The research should address AV-penetration rates so that recommendations different from current practices can be implemented to maximize research results.

Potential Benefits

Sweden's 1997 adoption of a Vision Zero strategy was one of the earliest applications of a safe-system approach to road safety. Since then, Vision Zero strategies have been adopted throughout the United States, including by many State and local agencies. As AVs become more prevalent in the vehicle fleet, Vision Zero strategies need to be updated to accommodate AVs and accelerate the potential safety benefits that their deployment provides.

Research Need Six: Establishing AV Test Scenarios with Representative Infrastructure Conditions

Background

Current testing of existing AV technologies, such as lane-departure prevention systems, are conducted under ideal conditions with high-contrast markings in pristine condition. In addition, current testing is conducted under ideal conditions with uniform and dry pavement as well as clear and dry weather. Unfortunately, many pavement markings and highway networks in the United States are in a condition much different than existing testing protocols.

Objectives

The objectives of research need six are to define testing conditions for AV technologies that are representative of the existing roadway network on which those AV technologies are expected to be used. For instance, if the AV technology is meant to work on interstate highways, then the testing of those technologies should be performed with conditions that represent the existing state of repair of interstates. This research should include testing factors (e.g., day/night and sunny/cloudy) and changing environmental factors, such as rain and fog.

Potential Benefits

Establishing realistic expectations of AV-technology performance may help the public in terms of understanding and accepting AVs. In addition, there is a growing need to develop robust expectations of how AV technologies will impact fatal and serious injury crashes. Conducting tests of these technologies with realistic scenarios will help researchers and agencies prioritize their focus in the most cost-effective ways.

Research Need Seven: Investigating a National Traffic Control AV-Readiness Assessment

Background

AV technologies are enhancing the role of TCDs. Until recently, TCDs have been exclusively designed and maintained for the human-road user but TCDs are beginning a new role for AVs. Pavement markings are considered the rails for AVs, which was confirmed by AV-industry interviews conducted as part of this research. In addition, for some AV technologies, traffic signs are also important for confirming AV geolocation in the digital world. Many AV developers are independently scanning roadways to develop their own TCD inventory and geolocation information. Some State and local agencies also scan their roadways to assimilate similar information, albeit for different purposes, such as bridge height clearances.

Objectives

The objective of research need seven is to investigate the potential benefits of developing a national traffic-control inventory and condition-assessment protocol that serve both highway-agency and AV-industry purposes. The research should consider the priorities of both industries to establish a common protocol for collecting and sharing appropriate data. The research should consider various functional classifications; existing data from State and local agencies; and methodologies, criteria, and technologies to develop a national road-readiness assessment.

Potential Benefits

The results of this project could lead to the development of something similar to American Society of Civil Engineers' Infrastructure Report Card but focused on TCDs for human-led vehicles as well as AVs. By coordinating the needs of both industries, the research has the potential to eliminate the redundancy of scanning roadways to collect similar information.

Research Need Eight: Developing Road Safety Audit Materials that Consider AV Needs

Background

Road safety audits (RSAs) have been proven to be an effective, proactive tool used on existing or planned facilities to identify opportunities for improvements of safety for all road users. FHWA provides many State and local agencies with comprehensive RSA support. However, current RSA support material does not yet consider how the needs of AVs might be considered.

Objectives

The research is envisioned to provide updated RSA materials that include the needs of AVs. The research should consider how the needs of AVs differ from human-led vehicles and how to accommodate those needs in RSA training and support materials. For example, one approach is to include an AV expert in the multidisciplinary RSA team. This research should include different use cases for AVs, (e.g., how highway AV needs are different from urban AV needs).

Potential Benefits

RSAs are designed to consider all road users; therefore, there is a developing need to enhance the RSA support and training material with the newest road user in mind: the AV. AVs will continue to become more prevalent on U.S. roadways and to achieve smooth integration as well as maximize their potential safety benefits, RSA programs need to be kept current.

APPENDIX. DETAILED FEEDBACK ON STAKEHOLDER ENGAGEMENT EVENTS

This appendix details the feedback obtained from IOOs and industry stakeholders during workshops organized at the AASHTO Committee on Maintenance and AV Symposium. Collectively, more than 100 workshop participants were polled on their agency practices pertaining to potential AV issues and impacts, constraints they encountered as a part of AV implementation, recommended changes needed to current infrastructure elements, and AV-readiness levels. Their feedback is compiled without further interpretation for the purpose of this report and presented in the following lists and in table 16 through table 25.

DETAILED FEEDBACK FOR THE AASHTO COMMITTEE ON MAINTENANCE WORKSHOP

Pavements, Bridges, Culverts

Question 1: Are there other potential AV issues and impacts that should be considered for pavements, bridges, and culverts? If yes, please describe briefly.

Table 16. Potential AV issues and impacts related to physical infrastructure.

Area	Types of Comments
Obstacles	Debris on roadway, roadway cleanliness.
Hazards	Animals, wildlife.
Maintenance	Maintenance treatments that may interfere with AV interpretation of lane limits, such as crack sealing, and pavement rutting from reduced vehicle wander.
Stress of platooning	Consideration of traffic signal operation and the impact of platooning. Effect of platoon loads on approach slab bumps. Platooning of AVs = increased volume = increased stress on all infrastructure. Platoons entering/exiting a route and interacting with other motorists. Stopping force of platoon on bridge. Truck platooning on bridges. Truck scales. Travel distance between trucks in platoons, bridge reliability, increased bridge postings, etc.
Funding mechanisms based on the AV traffic incurred on particular roadways	Funding of road maintenance with more electric vehicles on the roadways after adoption of AVs. If traffic is channelized, can design and maintenance be focused in that channel?
Interstate consistencies and differences	Change in pavement surface and markings. Differences in infrastructure when crossing State lines.

Area	Types of Comments
Weather, especially water, creating hazards for AVs	How will AVs react to sudden changes in weather conditions, such as a sudden downpour that leads to standing water over pavement markings? Pavement lines when snowing. Salt/brine build-up on sensors. Change in ice condition between road and bridge. Weather impacts. Winter conditions.
Work zones	How will AVs react to gravel roads, detours, mobile work zones, and incidents?
Insufficient data on some roads	Lack of data on roads other than National Highway System routes.
Communication needs	Infrastructure IT sensors and communication needs.
Technology and data availability	Bridge-load rating and vertical clearance information needs to be available for AV systems. Asset inventory databases need to be created.
Traffic-prioritization processes	Prioritization of traffic under emergency conditions.
Bridge-safety considerations	Potential for bridge collapse from achieving the natural frequency of a structure.

Question 2: Given the constraints and uncertainties regarding AV interactions with infrastructure, what existing practices for pavements, bridges, and culverts do you think should be prioritized?

Table 17. Constraints and uncertainties on AV interactions with physical infrastructure.

Area	Types of Comments
Reporting mechanism for missing/insufficient asset	Ability to indicate missing asset (i.e., sign knocked down).
Asset management	Comments emphasized that maintaining pavement conditions is vital to ensuring AV safety. Asset management. GIS tracking of alignment/features. GPS location data. Implementing full network definition and maintenance inventory. More and better data collection on existing system.
Assessment of design procedure	Adjust design loading for bridges; lane-loading component. Consider how treatment options will change based on an increased focus on pavement-marking integrity. Adjust design widths as needed. Examine the impact on bridge load-rating methodology.
Regular needs identification process	Correct local fatigued-pavement zones.

Area	Types of Comments
Research and expertise	Need for additional research and availability of subject-matter expertise.
Technology improvements	Improve longitudinal joint construction so that the joints hold stripes better.
Project prioritization process	Identify interstates where AVs will be introduced first. Identify ITS priorities.
Clear communication of infrastructure capabilities	Load rating and posting. Use detectable lane markings. Ensure that crack-seal material is not confused with stripes. Indicate risk zones where failure to sense markings accurately could cause a safety risk (e.g., no shoulder, fog area, cliff). Maintain traffic stripes and signs. Assess bridge approach condition.
Policies	Use minimum contrast and retroreflectivity for pavement markings.
Pavement-marking standardization	Standardize pavement-marking requirements and performance.
Maintenance	Improve conditions on deficient bridges. Maintain roadway striping and other markings. Ensure smooth pavements. Ensure signs are readable.

TCDs and Other Roadside Infrastructure

Question 3: Are there other potential AV issues or impacts that should be considered for TCDs and other roadside infrastructure? If yes, please describe briefly.

Table 18. Potential AV issues/impacts related to TCDs.

Area	Types of Comments
Bike-lane infrastructure	Bike lane is solid green over the location where a vehicle can cross.
Pedestrian signage	School crossing guards.
Obscured pavement markings	Debris or spills that obscure pavement markings. Sensors that rely on the line of sight could be easily obstructed. Snow and ice on pavement markings and signs.
Roadside signage, signals, or rumble strips	Road-closure gates and stop bars. Delineators. Rumble strips.
Balancing the benefits between AVs and human drivers	Focus should be on changes that also provide significant improvement for human drivers. Making large investments today for a relatively small percentage of vehicles may divert funding from other efforts that are needed for the fleet on the road today. Still need human-driver investments—what will happen during power outages?

Area	Types of Comments
Temporary emergencies, incidents, and work zones	Temporary work zones. Emergency law-enforcement lane closures. Emergency lanes/contraflow. Short-term closures (e.g., flag control, rolling closures with mobile attenuator vehicle) are typically different from routine work zones. Incident management.
Routine work zones	Mobile work zones. Moving work zones. Short-duration work zones. Temporary rumble strips.
Confusing markings	Identify difference between markings and sealant. Cracked sealant could look light/white in different light conditions and confuse AVs.
Impact of slight geolocation changes of TCDs	Impact of reinstallation of the sign in a location that is not in the exact location as previous location. Update load posting signs after inspection.
Lifecycle of markings	Merge areas and curves where cars drift over markings and cause more rapid wear. Snowplow damage. Snowplow wear on thermal plastic.
Winter weather impacts	Snow and ice cover on pavement markings and signs. Snow-covered signs. How long will agencies have to replace markings after winter?
Policies for managing TCDs/roadside infrastructure	Varying DOT standards for TCDs. Response time to fix/update markings Minimum pavement-marking retroreflectivity. Minimum sign reflectivity.
Cost of TCDs	High cost of pavement markings with wet-weather beads. More TCDs will require more funding.
Industry support	Striping industry cannot support current programs; need additional industry-support capability.
Reduced need for some sorts of signage	Should be able to eliminate some signage if geolocated.
Roadside infrastructure	Median curbs.
Alternative markings for AVs	Are nonvisual markings (e.g., magnetic) a better investment for machines? What about using recessed raised pavement markings instead of paint stripe?

Question 4: Given the constraints and uncertainties regarding AV interactions with infrastructure, what existing practices for TCDs and other roadside infrastructure do you think should be prioritized?

Table 19. Constraints and uncertainties regarding AV interactions with TCDs

Area	Types of Comments
Real-time information	Ability to quickly/immediately update asset inventory and location as work is done.
Data collection and sharing	Building and maintaining inventories. Geolocation. Communicating work-zone locations. Add features to vehicles that reduce agency's costs for floats collection.
Asset management	Prioritizing traffic signals and signs. V2I with signals. Maintenance support for enhanced devices. Vegetation removal around signs. Maintenance of pavement markings. Pavement-marking removal.
Research and expertise	Training for staff to maintain enhanced devices.
Technology improvements	I2V.
Clear communication of infrastructure capabilities	Sun glare during sunrise and sunset hours; it's harder to see pavement markings.
Policies	Compliance with AASHTO's *Manual for Assessing Safety Hardware*. Standardized devices. Sign-replacement strategies across States.
Work zones	Road barricades. Mobile traffic signal in work zones. Communicating work-zone locations.
Prioritize safety of human drivers	Only practices that improve the human driver's experience today.
Obstacles	Weather events, such as flooding and debris from high winds.

TSMO AND ITS INFRASTRUCTURE

Question 5: Are there other potential AV issues or impacts that should be considered for TSMO and ITS infrastructure? If yes, please describe briefly.

Table 20. Potential AV issues/impacts related to TSMO and ITS infrastructure.

Area	Types of Comments
Responsibility of data collection and reduction	Data collection and reduction must be by a third party. States cannot stay current with the evolving technology.
Technology compatibility	Will AV technologies be compatible with ITS architecture integrating existing active traffic management systems?
Consistent data-sharing practices	Data-sharing agreements. Communication frequency. short-term road closure for incident response short-term closure; response vehicles, fire, and rescue not using MUTCD. Quick response and incident reporting. Road closures and incident reports. Nonproprietary open data. Privacy issues.
AV communication with equipment	How will vehicles communicate with other equipment (e.g., agricultural equipment)?
Technology-maintenance requirements	Infrastructure optimization needs to consider maintenance ramifications. Will more maintenance be required if many roadside units are needed?

Question 6: Given the constraints and uncertainties regarding AV interactions with infrastructure, what existing practices for TSMO and ITS infrastructure do you think should be prioritized?

Table 21. Constraints and uncertainties regarding AV interactions with TSMO and ITS infrastructure.

Area	Types of Comments
Device communication	Interaction with DMS boards. Communication between all devices. Communication of vehicles with DOT assets. Communication protocols. Communication to vehicles, ensuring that the frequency is reserved. Communication with DOT vehicles. Standards for compatibility with cameras.
Asset management	Develop asset-management plans for ITS equipment.
Responsive reporting procedures	Fast incident reporting. AV awareness at incident-response training.
Data responsibility	Security. Should DOTs expand their systems or rely on the AV industry to provide good data? Nonproprietary open data. Privatize the data collection.
Real-time information	Real-time reporting of traffic conditions and closures.

Area	Types of Comments
External communication	Public outreach and education.
Standardized operating procedures	Concept of operations/system engineering.
Technology safety upgrades	Identifiers for individuals in roadway, chip in vest, for first-responder tow operators. ITS cameras.
Maintenance Responsibility	TSMO hardware maintenance—who maintains it, how it is staffed, and training in new technology.

DMS = dynamic message signs.

Multimodal Infrastructure

Question 7: Are there other potential AV issues and impacts that should be considered for multimodal infrastructure? If yes, please describe briefly.

Table 22. Potential AV issues and impacts related to urban multimodal infrastructure.

Area	Types of Comments
Separated signals	Bicycle signals versus traffic signals.
Right-of-way and intersections	Determining which vehicle has the right-of-way. Time restrictions for AVs to accommodate school hours, etc. Trains and train crossings.
Consistent signals	What is the minimum condition or consistent use of green bike lanes, symbols, etc.?
Multimodal infrastructure maintenance	Green bike lanes, which are difficult to maintain.
Micromobility	Scooters. Identification of motorcycles.
Communication mechanisms	Vehicle-to-worker communication.
Pedestrians	Consider first responders in pedestrian identification.
Nontypical equipment	Agricultural and construction equipment.
Non-AV user conflicts	Non-AV user complaints.

Question 8: Given the constraints and uncertainties regarding AV interactions with infrastructure, what existing practices for multimodal infrastructure do you think should be prioritized?

Responses from IOOs and industry stakeholders included the following:

- Agricultural equipment, trains
- Process for loading AVs onto ferries.
- Concentrate on limited-access facilities only and expand usage later as the technology advances.
- One-lane bridges.

- Oversized loads.
- Pedestrian-signal operations.
- Railroad crossings.
- Shared use of roadway by bikes.
- Wildlife crossings.

AV SYMPOSIUM DETAILED FEEDBACK

TCDs and Other Roadside Infrastructure

Question 9: What other near-term changes to the TCD infrastructure would best support AV deployment?

Responses from IOOs and industry stakeholders included the following:

- 5G small cells on light poles.
- Access to test beds for research and public education of city personnel.
- Adding I2V communication.
- AVs will work better if they are connected.
- Barcode signs.
- Better signs and signals.
- Bigger and more frequently used work-zone signage (e.g., for beginning and end of work zones).
- Bilingual text.
- A cable barrier is much more effective than a rigid barrier. We need to find a way for AVs to recognize cable barriers and not go back to something less safe.
- Decommission unneeded legacy equipment (i.e., HAR, Road Weather Information Systems, unneeded signs. No more loops in pavement for traffic-measurement monitoring.).
- Digitize work-zone and sign-location data.
- Dynamic message signs.
- Ensure that network connectivity (i.e., fiber or cell coverage) is available.
- Guidance on what is needed.
- High-contrast markings that benefit both human drivers and AVs. Avoid markings that have been shown to confuse L2+ systems. Standardize improved signaling well in advance of work zones. Managed and dedicated lanes that allow AVs to operate separately from human drivers will accelerate deployment of L4.
- I2V communications between signals and approaching vehicles (i.e., SPaT).
- Intelligent TCDs.
- IOOs should fix the simple stuff (e.g., vandalized and covered signs).
- Larger speed-limit signs, particularly in Canada.
- LED signage readability by onboard camera systems.
- Lighting.
- More detection.
- Anything that helps the human driver should help automation and vice versa.

- Open-source reference for machine-vision systems.
- Open roadways to fiber.
- Polarized lights.
- Proper maintenance. Technology will move faster than the infrastructure, so we cannot wait for some future development.
- Share mealtime work-zone data (e.g., mile post, taper).
- Traffic Incident Management (TIM) data on dynamic message signs (DMS) and HAR are sent to connected vehicles.
- Uniform signs.
- Uniform work-zone setups.
- Uniformity of paved versus gravel shoulders.
- Use of standard retroreflective patterns with specific meanings.
- V2I connectivity.
- Wet retroreflective markings.
- Who pays? Can tech companies pay?

Question 10: Do you agree or disagree with the recommended changes to pavement-marking practices? Please explain briefly.

Table 23. Recommended changes to pavement-marking practices to facilitate AV implementation.

Area	Types of Comments
Agree: Building for human drivers while being useful for AVs is common sense.	Many comments agreed that prioritizing markings will benefit both humans and AVs, but it is the improvement for humans that is the most important component.
Agree: Standardization should be defined.	Agree that uniformity is needed. Agree that the standard for pavement markings should be defined, but implementation should not be prioritized yet because there are other more immediate needs.
Disagree: Changes to enhance markings should not be prioritized because of current technology.	Funding is an issue and technology is advancing quickly. The technology might adapt to existing pavement markings. It is too soon to define which pavement markers will be prioritized based on defined AV technology. The life of pavement markings varies by geographic location based on climate. Increasing maintenance requirements should be accompanied by increased funding to support consistent markings.
Disagree: Proof of benefit is required.	No, not until we have a measurable benefit, such as an improvement in the percentage of pavement-marking detection.
Neutral: Quality and quantification of markings must also be specified.	They are a good start regarding uniformity of configuration, but need to move on to quality and quantification so that they can be specified.

Area	Types of Comments
Disagree: Suggested standardization is impractical with existing agency capabilities.	It is not practical with the number of IOO agencies and their varying capabilities. This is something we could implement within existing agency culture and capability with near- and long-term benefits.

TSMO and ITS Infrastructure

Question 11: What near-term changes to TSMO and ITS infrastructure would best support AV deployment?

Responses from IOOs and industry stakeholders included the following:

- A mutual data exchange; need AV data for more effective, real-time system management.
- Agreement on what useful data (e.g., weather) IOOs can expect to get from AVs.
- AV vendors' ability to share information with public agencies.
- Back-office IT infrastructure to handle data exchange and data sharing among roadside units, vehicles, and interagencies.
- Better understanding of cybersecurity risks.
- Better understanding of life-cycle costs.
- Compatibility with vehicle technology.
- Connectivity.
    - Creation of a Manual of Uniform Digital Traffic Control Devices.
    - Decommissioning legacy equipment to make funding available.
    - Development of open source.
    - Digital mapping: The public sector will share the information and format it has. Standards are not needed. The private sector will do the heavy lifting.
    - Ensure reliable work-zone data are available.
    - Improve real-time updates and details about construction zones; V2X deployment.
    - Improved detection technology.
    - Increased uniformity between message signs and construction-warning trailers.
    - More fiber deployment.
    - Optimized advanced traffic-management systems in urban areas.
    - Distributing HAR and DMS TIM information via CV with location data attached.
    - Security.
    - Sharing real-time advisories with AVs using V2I communications.
    - SPaT.
    - Uniformity.
    - V2I.
    - V2I connectivity.
    - V2V and V2I connectivity.
    - Data shared via I2V should also be shared to the cloud. AVs can download ahead to plan their trips.

Question 12: Are there other impacts on the TSMO/ITS infrastructure to note?

Table 24. Other AV related impacts to TSMO and ITS infrastructure.

Area	Types of Comments
Maintenance costs and considerations	Consideration of life-cycle costs. Long-term maintenance. Valuation of data infrastructure for future investments. Capabilities of staff.
Technology procurement	Contracting for technology-based equipment. Procurement strategies for these new technologies or software Where is the discussion of the transfer of the owner, operator, maintainer of select equipment from the public sector to the private sector (e.g., traffic signals, TMCs, data collection, monitoring equipment and analytics)?
Technology reliability	Cybersecurity. Frequency interference for wireless communications.
Multimodal	Multimodal users.
Adaptability to infrastructure conditions	Lane width. Emergency operations—mapping and detour routing after incident closures. New pavement. Recently paved roads might not have pavement markings and in some cases remained that way for several days. Machine-vision AVs would not be able to operate on new pavements with no markings.
General considerations	Support CAV deployment is not moving as fast as would be ideal for the TSMO/ITS infrastructure to be handled properly and at a comparable pace as technology shifts. Use of open-source standards. There is too much focus on AVs being a given (i.e., many policy goals work to reduce or guide the use of single-occupancy vehicles).
Research validation	Research institution engagement for validation and proof-of-concept new technology procurement with State DOTs.

Multimodal Infrastructure

Question 13: What near-term changes to urban multimodal infrastructure would best support AV deployment?

Responses from IOOs and industry stakeholders included the following:

- 5G.
- Apps for ride rideshare hailing.
- Automated buses operating on dedicated lanes: a rubber-tired light-rail system.
- Automated collision-avoidance systems on buses.

- Bike/pedestrian detection.
- Charging stations for electric scooters and bikes.
- Constraining pedestrians is very difficult. Pedestrian bridges and tunnels are often not used, partially for safety concerns. Roundabouts are safer for pedestrians. The maintenance committee is not the best for discussing safety.
- Curb-lane reservation systems.
- Dedicated modal lanes.
- Enhanced pedestrian-crossing sections.
- Equity issue (i.e., AVs must detect pedestrians without wearables or requiring a smartphone).
- Exclusive lanes for pooled rides and autonomous shuttles.
- Grade-separated lanes for bikes.
- I2V connectivity.
- Improved delineation for bike lanes.
- Improvements to AI technology to recognize and learn unique features.
- Inventory of existing curb space and uses.
- Low-speed curb lane.
- Mode separation.
- Personal delivery devices on sidewalks may need guiding regulations.
- Policies for land use that support AV operations.
- Rail crossings.
- Reduction of conflict multimodal points.
- Remove bike lanes in exchange for a wider, separated, shared-use path.
- "Roundabout first" policy—remove traffic signals.
- SPaT.
- Standards for using curb space.
- Transforming parking lots/structures into mobility centers (e.g., training, synchronizing, guidelines).
- Curb and crosswalk uniformity.
- Use of transit-first policy.
- V2I, V2V, and V2P.
- Video analytics and multi-access -edge computing at traffic signals to process and communicate.
- Focus on pedestrian/bike misses share with buses, vehicle using DSRC/4G/LTE and 5G.

Question 14: Are there other impacts on the urban multimodal infrastructure to note?

Table 25. Other AV-related impacts to urban multimodal infrastructure.

Area	Types of Comments
Nonstandard urban infrastructure use	Special event surges of different modes of traffic (i.e., large pedestrian flows or major transit alighting). Personal delivery devices. Enforcement of nonstandard uses, such as delivery-zone encroachments on travel lanes.
Micromobility	Electric scooters and bikes (i.e., charging locations). Impact of micromobility.
Pedestrian-signal technology	Pedestrian signal.
Changes to parking needs	Outdated pedestrian-signal technology.
Cost of empty vehicles on roads	Effects of deadheading or zero-passenger vehicles. Electric vehicles will be traveling empty to self-charge at charging stations. There may be fewer spaces needed between charging slots because of more accurate maneuvering.
Intersections of different modal uses	Rail crossings. Mode connection.

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