Connected and Automated Vehicle Digital and Physical Infrastructure Needs

Texas CAV Task Force
Subcommittee on Safety, Liability, and Responsibility

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Table of Contents

List of Figures

List of Tables

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Disclaimer

The contents of this white paper reflect the views of the Texas CAV Task Force members, who are responsible for the information presented herein. The contents do not necessarily reflect the official views or policies of the State of Texas or any Texas state agencies. The white paper does not constitute a standard, specification, or regulation, nor does it endorse standards, specifications, or regulations. This white paper does not endorse practices, products, or procedures from any private-sector entity and is presented as a consensus broad opinion document for supporting and enhancing the CAV ecosystem within Texas.

Texas CAV Task Force Charter

The Texas CAV Task Force was created at the request of Texas Governor Greg Abbott in January 2019. The task force is responsible for preparing Texas for the safe and efficient rollout of CAVs on all forms of transportation infrastructure.

The primary functions are:

1. Coordinating and providing information on CAV technology use and testing in Texas.
2. Informing the public and leaders on current and future CAV advancements and what they mean in Texas. This process includes reporting on the current status, future concerns, and how these technologies are changing future quality of life and well-being.
3. Making Texas a leader in understanding how to best prepare and wisely integrate CAV technologies in a positive, safe way, as well as promoting positive development and experiences for the state.

The CAV Task Force is composed of a voting group of no more than 25 members and represents the full spectrum of CAV stakeholders.

Terminology Note

The Texas CAV Task Force addresses the full spectrum of connected, automated, and autonomous vehicles. An automated vehicle refers to a vehicle that may perform a subset of driving tasks and requires a driver to perform the remainder of the driving tasks and supervise each feature's performance while engaged. The performance capabilities of automated and autonomous vehicles consist of levels 0–5 with level 0 having no driving automation and level 5 having full automation, with automation increasing at each progressive level. A fully autonomous vehicle can perform all driving tasks on a sustained basis without the need for a driver to intervene.

These definitions are still blurred in common discussions and language. Currently, the industry is developing automated vehicle capability while pursuing fully autonomous vehicles. The white papers generally use the term autonomous to refer to vehicles with fully autonomous capabilities and the term CAV to refer to the grouping of connected, automated, and autonomous vehicles. Please see the 2021 terminology white paper for a full listing of terms and definitions used in this developing technology ecosystem.

List of Terms and Acronyms

AI	artificial intelligence
APNT	positioning, navigation, and timing
ATSC	adaptive traffic signal control
AV	autonomous vehicle
CAV	connected and autonomous vehicle
CPS	cyber-physical system
CSMS	cybersecurity management system
CV	connected vehicle
C-V2X	cellular vehicle to everything
DSRC	dedicated short-range communication
DT	digital twin
DTCD	digital traffic control device
ECU	electronic control unit
GNSS	global navigation satellite system
GPS	global positioning system
HD	high definition
IOO	infrastructure owner and operator
IoT	internet of things
IT	information technology
ITS	intelligent transportation system
LAN	local area network
LE	law enforcement
MUTCD	*Manual on Uniform Traffic Control Devices*
NHTSA	National Highway Traffic Safety Administration
OBD	onboard diagnostic
ODD	operational design domain
OEM	original equipment manufacturer
P3	public-private partnership

PINN	public infrastructure network node
SUMS	software update management system
TB	terabytes
V2I	vehicle to infrastructure
V2V	vehicle to vehicle
V2X	vehicle to other users

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Executive Summary

This paper discusses connected and autonomous vehicle (CAV) digital and physical infrastructure needs, challenges, and opportunities for future development. While connected vehicles (CVs) and autonomous vehicles (AVs) currently share many of the same technologies, their operational parameters and needs may differ. The evolution of the CAV industry aims to provide a greater safety benefit than previous technologies. Advanced driver assistance system (ADAS) technologies already in use have demonstrated their potential to reduce crashes, prevent injuries, and save lives. As the surrounding digital and physical infrastructure continues to improve and better meet the needs of CAVs, human error will be increasingly erased from the driving equation. There is however, a dichotomy of thought in the direction of research and development within the CAV industry. For some, improving vehicle performance focuses on the physical infrastructure consisting of the ODD, pavements, markings, signage, sensors, and other various infrastructure components so the vehicles can read the roadway. However, the other research and development direction focuses on digital infrastructure and the CAV's ability to safely perform within a surrounding operational domain by relying on precise digital communication.

Overall, both approaches have issues that need to be addressed to realize the goals. Some of the numerous challenges include interaction with law enforcement, work zones, extreme weather events, differing maintenance needs, standardization of physical infrastructure, cybersecurity, rural connectivity, and roadway conditions. These challenges all play a part in CAVs with respect to the direction of development. They may require a concerted effort on data sharing/exchange and may present possibilities for more investment through public-private partnerships for further development of the CAV industry. Within the context of this paper, the follow attributes of digital and physical infrastructure are discussed as they relate to Safety, Liability, and Responsibility.

The digital infrastructure areas are:

- Digital twinning,
- Data sharing/exchange,
- Geospatial data,
- Cybersecurity, and
- Data processing.

The physical infrastructure areas are:

- Operational design domain (ODD),
- Pavements,
- Pavement markings,
- Signage,
- Off-pavement,
- Maintenance,
- Drop-off/pickup lanes, and
- Work zones.

Regardless of the specific functions or attributes of digital or physical infrastructure discussed in this paper, a common theme is that in the future, roadways must be covered by a comprehensive communication infrastructure of some type. Pros and cons exist for numerous technologies, but the

prevailing thought is that private sector telecommunications companies will deploy, operate, and own, the roadside digital infrastructure and offer paid services to users, be they agencies, companies, or individual drivers. Even if some autonomous vehicles would not use this infrastructure and rely solely on the physical components, the mixed-use environment which will potentially continue for decades will be a user of this communications infrastructure, helping to support advanced traveler information, emergency response, and numerous other critical safety needs before the advent of fully autonomous vehicles.

Introduction

This paper provides a briefing on key digital and physical infrastructure considerations that may aid connected and autonomous vehicle (CAV) operations and provide a cooperative/supportive role for highway infrastructure owners and operators. As the development efforts in this arena continue, many different pathways to operations are being explored, each with its own set of challenges, opportunities, and issues. The goal of this paper is to provide awareness of the potential assistive technologies that could play a role in CAV development and safety. This paper is not stating that these infrastructure elements are specifically required for any individual vehicle. Additionally, the paper discusses the significant potential for public-private partnerships (P3s) related to data sharing and CAV infrastructure.

Background

According to the National Highway Traffic Safety Administration (NHTSA), the types of automated technologies, such as advanced driver assistance system technologies already in use on the roads and future automated driving systems at their mature state, have the potential to reduce crashes, prevent injuries, and save lives. These include safety features such as:

- Rearview video systems,
- Automatic emergency braking,
- Pedestrian automatic emergency braking,
- Rear automatic emergency braking,
- Rear cross-traffic alert,
- Lane-centering assist,
- Lane-keeping assist,
- Adaptive cruise control,
- Traffic jam assist, and
- Self-park.

In some circumstances, automated technologies may be able to detect the threat of a crash and act faster than drivers. These technologies could greatly support drivers and reduce human errors and the resulting crashes, injuries, and economic toll on society (*1*). Over 3.7 million miles were AV tested by various manufacturers from 2014 to 2018. Results showed 128 accidents with approximately 63 percent in AV mode. The AVs are frequently manually taken over by human operators, and the disengagement frequency varies based on different manufacturers. However, less than 6 percent of the reported accidents were due directly to the AV mode. Of the total, 94 percent of the accidents are passively initiated by the other parties, including pedestrians, cyclists, motorcycles, and conventional vehicles (2). As future technologies become more sophisticated and the digital and physical infrastructure becomes as one with the AV, safety is expected to become a prime motivator for the use of CAVs. Figure 1 shows the potential progression of CAV technologies and their safety potential.

As the transportation industry moves forward with the implementation of CAVs, industry research and manufacturing can provide vital information on the direction, preferences, and requirements for digital and physical infrastructure that may still need to be addressed to ensure optimal and safe performance and reliability of CAVs on roadways. Digital infrastructure has the potential to collect and transmit enormous amounts of data to and from numerous sources, that is, data sharing and exchange. The operational design domain (ODD) consists of the physical infrastructure, pavement markings, signage, etc., that allow the vehicle to “read the road.” Both the digital and physical infrastructures perform vital roles in the current operation of CAVs.

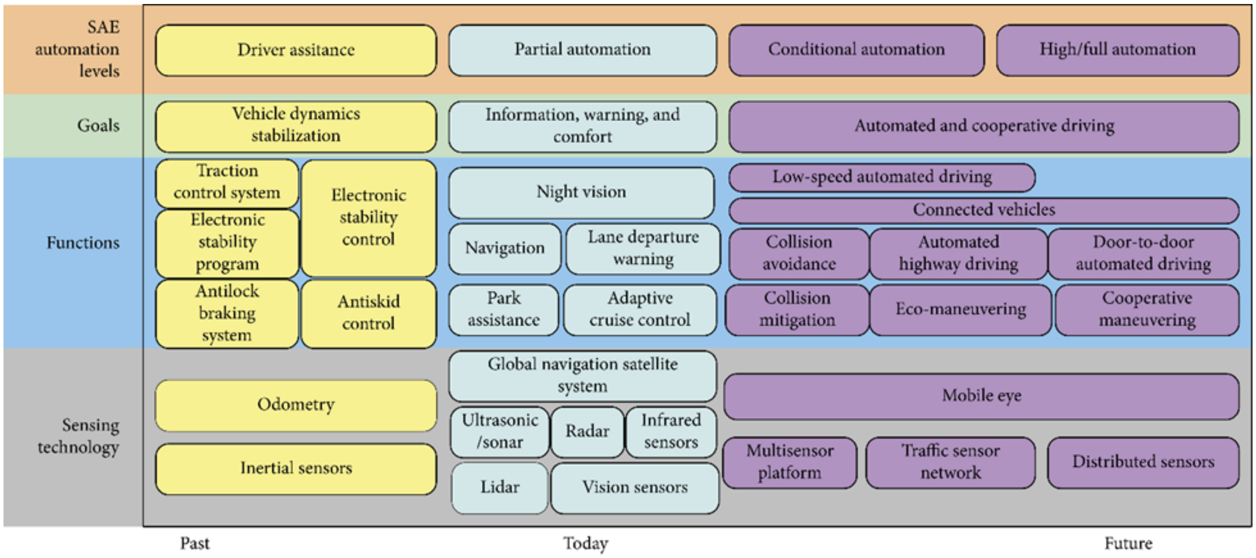

Figure 1: Past and Potential Future Evolution of Autonomous Vehicle Technology (2)

Digital Infrastructure

Autonomous vehicles (AVs) collect inputs, use image and pattern recognition to compare results with preloaded maps, plot a path, and send instructions to powertrain and control systems for managing acceleration, braking, and steering. These functions can be supported by enabling intelligent infrastructure; however, not all CAVs depend on it. A *cooperative intelligent transport system* refers to wireless communications between vehicles (V2V), vehicles and infrastructure (V2I), vehicles and other users (V2X), among infrastructure (I2I), and the use of dedicated digital infrastructure like fiber-optic cables and sensor networks (*3*). Digital infrastructure consists of a combination of several applications working together to enable CAV operations. These may include cloud, fog, and edge architectures. These types of applications are supported by a variety of different communications formats such as satellite, Wi-Fi, G4 LTE, G5, LTE cellular vehicle to everything (C-V2X), dual-mode dedicated short-range communication (DSRC)/C-V2X, and 5G, all of which could be used to support V2X in different implementations (*1, 3, 4*). These systems are designed and operated to support the CAV driving platforms needed for recognition, prediction, planning, situational awareness, and control. The systems also support the needs of a mixed traffic flow, which includes connected and non-connected vehicles and AVs with different levels of automation. According to Monsó (*4*), this infrastructure needs to offer hardware and software integrity, data security (security credential management systems will become a key asset), universal coverage, and wide interoperability. Infrastructure must be flexible enough to be adapted to urban and interurban use cases, congestion, and different traffic composition. Infrastructure also needs to accommodate different levels of penetration of CVs and AVs and associated technologies such as truck platooning (*4*).

A significant challenge in autonomous driving is developing a comprehensive real-time ability to receive, aggregate, analyze, and distribute the data that are collected by the vehicle, as well as integrate with data from other sources such as traffic and weather information. This must also be completed with all the necessary security and privacy controls in place. Various CAV levels differ in the amount of data necessary for operations. The amount of data collected, analyzed, and stored is huge—in the range of 20 to 30 terabytes (TB) of data per day as seen from tests conducted on level 2 autonomy vehicles, with estimates of up to 100 TB/day for level 4 vehicles. This volume of data presents challenges in terms of data access and distribution. Thus, some manufacturers may need to find a way to minimize data transfer latency by establishing proximity between datasets and accessing sufficient computer resources to manage the data on a global scale. Hybrid infrastructure at well-connected locations can deliver high-speed, secure access to edge devices, multiple clouds, private data centers, on-premises data, data brokers, and partners. These needs are driving the development of CV ecosystems based on third-party partnerships and hyper-converged infrastructures, as shown in Figure 2.

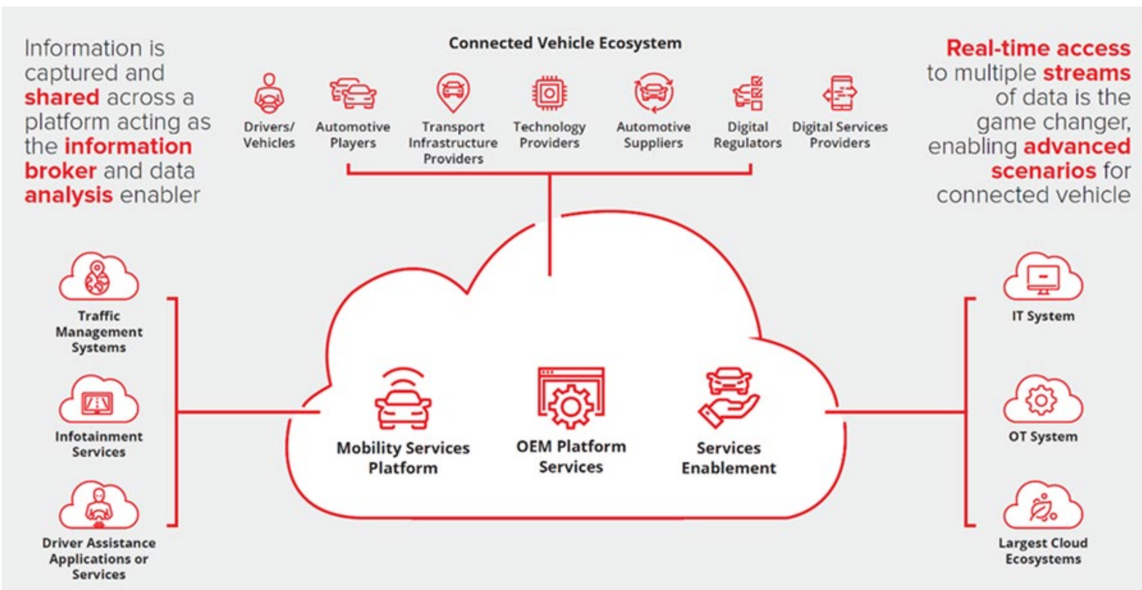

Figure 2: Connected Vehicle Ecosystem (5)

According to Steele and Hendel (5), the four key control points include sensors, high-definition (HD) mapping, processors, and software, as shown in Figure 3.

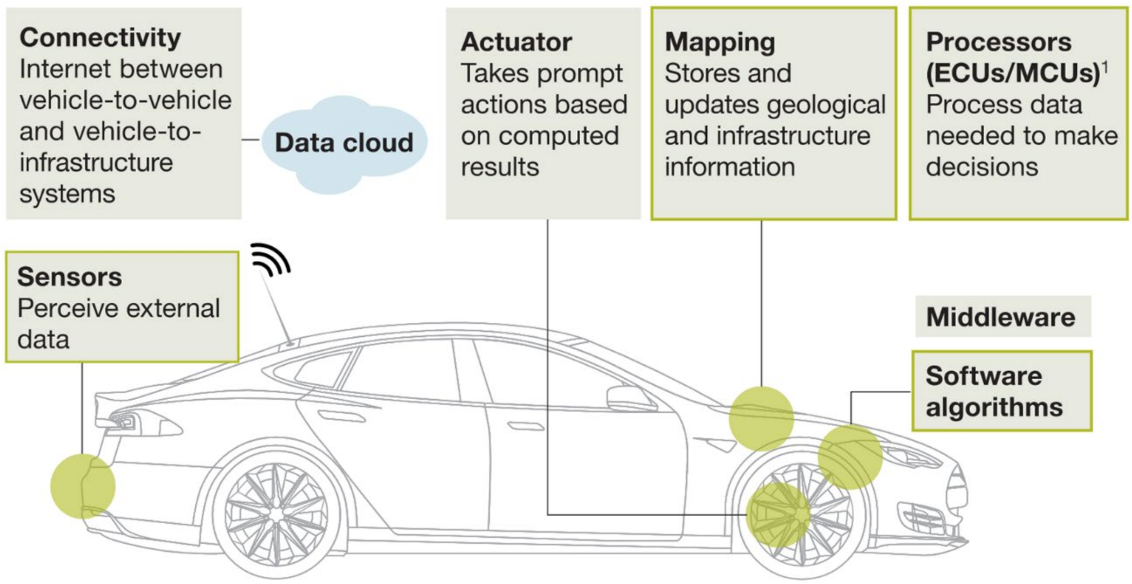

Figure 3: Key Components of Advanced Driver Assistance Systems (5)

Digital Twinning

A digital twin (DT) is a digital version of a physical object or process based on two-way data exchange between digital and physical entities in real time designed to help improve decision-making. Basically, it is the integration of the internet of things (IoT) and cyber-physical systems (CPS) (*6*). The transportation DT can be conceptualized as traffic data being collected from different physical systems, such as sensors, CVs, traffic signals, and traffic-monitoring cameras in real time to create a cyber-copy of the systems. Although the concept of a DT replicates the idea of CPS, transportation DTs are expected to leverage the embedded sensor systems of physical transportation systems to provide real-time and time-sensitive transportation services instead of focusing only on the applications of the CPS domain. The primary challenge to achieve this is combining and linking data from heterogeneous sources of the physical systems to create a cyber-copy of the real-world traffic operations for real-time traffic management (*7*).

Dasgupta et al. (*8*) examined the use of the DT approach for adaptive traffic signal control (ATSC) to improve a traveler's driving experience by reducing and redistributing waiting time at an intersection. Researchers developed a DT-based ATSC that considers the waiting time of vehicles approaching a subject intersection along with the waiting time of those vehicles at the immediate upstream intersection. Using a microscopic traffic simulation package, Simulation of Urban Mobility (SUMO), Dasgupta et al. developed a digital replica of a roadway network with signalized intersections in an urban setting where vehicle and traffic signal data were collected in real time. Analysis of the results showed that the DT-based ATSC outperforms the CV-based baseline ATSC in terms of average cumulative waiting time, distribution of drivers' waiting time, and level of services for each approach for different traffic demands (*8*).

The University of Stuttgart is working with Audi AG and a consortium focused on detailing the benefits for society and the ecological impact by performing simulations using a DT of the urban traffic of Ingolstadt, Germany. Static elements such as roads, buildings, traffic infrastructure, various road situations, traffic volumes, traffic lights, and similar things were integrated as well as dynamic variables such as road users, rush hour, and the weather. Another project goal is to find solutions to issues of transport efficiency, ecology, and social acceptance (*9*).

Data Sharing/Exchange

Local governments, states, transportation-focused organizations, and the federal government are all working to better understand the opportunities and challenges around the sharing, analysis, and use of data collected as part of on-demand and shared mobility services. According to Stantec and ARA (*10*), numerous issues surround data sharing, including the following:

- The discussion around data sharing and AVs needs to be narrowed down to anticipated use cases.
- Regulations being implemented for new mobility are being developed in isolation from data standards.
- New privacy laws may affect government's ability to collect data for safe operations.
- Considering consumer interests around privacy and data security will likely play a role in the public adoption of AVs and continued use of shared mobility through digital applications.
- Consistent frameworks are needed for navigating open records requests and law enforcement requests for data.

A report by the Connecting Europe Facility of the European Union (*11*) discusses the emerging and existing types of data sharing and exchange. Communication among V2V, V2I, and V2X is enabled by technologies such as DSRC and cellular networks (4G LTE and 5G) that allow for exchange between all vehicle types and infrastructure (see Table 1 and Figure 4).

Table 1: CV Communication Technologies (11)

Attributes	DSRC/Intelligent Transportation Systems (ITS) G5	Cellular
Description	A Wi-Fi-based protocol for high-speed wireless communication between vehicles and infrastructure. It has two operating modes, V2V or V2I, and can provide communication in the presence of obstructions, fast-changing environments, and extreme weather conditions.	Cellular communication technology used for V2X communication is currently using 4G LTE. Original equipment manufacturers (OEMs) and governments arguing for the use of cellular networks are, however, relying on the development and rollout of 5G networks to ensure an efficient network for V2X communication.
Benefits	The main benefits of this communication technology are the maturity and readiness for deployment and adoption, which will allow possible use cases to be deployed near term. It has also proven to be superior in the ability to communicate directly because it does not rely on a network, which has advantages in rural areas, and proven low latency, which is important for safety messages and driver warnings.	The benefits of using cellular networks are the continuous development and improvement of the technology, combined with the ability to be backward and forward compatible (2G, 3G, 4G, and 5G). Cellular networks are already available throughout the developed world and will be deployed regardless of V2X communication systems. Therefore, no additional investments are necessary.

Attributes	DSRC/Intelligent Transportation Systems (ITS) G5	Cellular
Challenges	The adoption of DSRC will require an investment related to roadside units to support the adoption of V2X communication solely, and up to now the adoption has not been as broad as earlier expected. In addition, there is not any further development on the roadmap to meet future demands, and it cannot meet the higher bandwidth demands from AVs.	Currently, there are some limitations using cellular networks, the main one being the limited-ability bandwidth. The adoption of 5G will, however, eliminate this by enabling a dedicated bandwidth for V2X communication. Latency is another limitation together with the dependency on being connected to the network, which is no guarantee in rural areas.
Example usage	Companies like Volkswagen and Volvo have been using this technology in their cars.	Ford has stated that it will aim for cellular connectivity in its new cars.

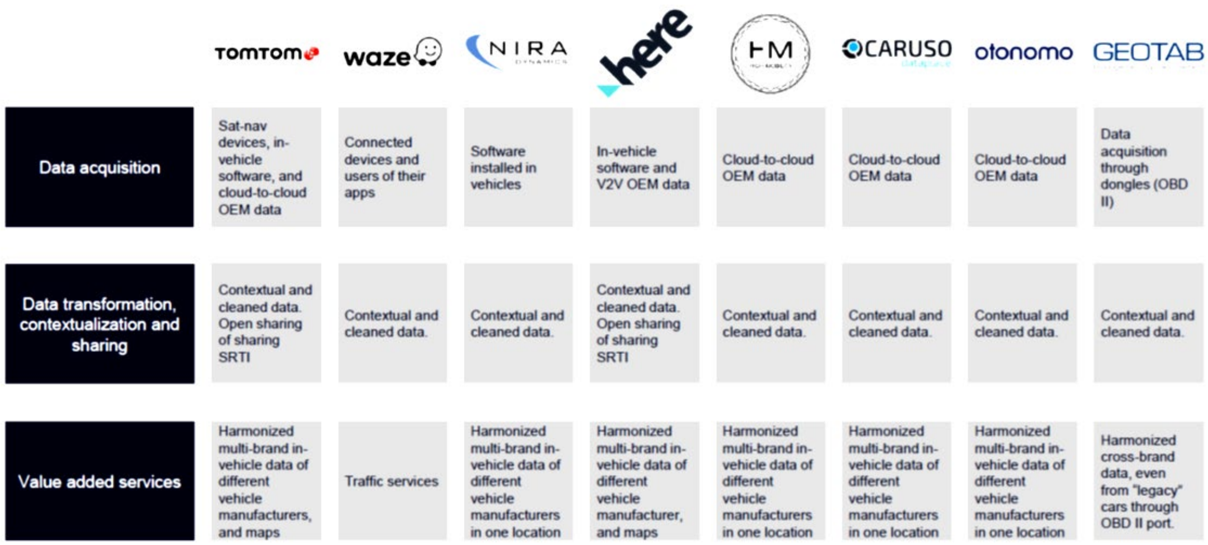

Figure 4: Examples of Data Services (11)

As has been stated, a key use case for CAV data is data sharing. Aptiv, Cruise (part of GM), Ford, and Waymo have all shared some of their AV data to further research. Ford documented various scenarios that include complicated freeways, built-up urban areas, tunnels, work zones, airport drop-offs, pedestrian activities, and various weather conditions. Ford used multiple AV platforms to collect these data simultaneously. That means data were collected about each car's performance from the outside as cars passed on the road, as well as internally. Ford used its driverless fleet to collect performance in favorable and adverse weather conditions using Detroit's cold winter, wet spring and autumn, and warm summer to collect data across a variety of weather types. Making these performance data available will help researchers design algorithms robust enough to cope with dynamic environments in the future.

Waymo released a motion dataset that includes over 100,000 segments, each around 20 seconds long, of objects like cars and people and their trajectories, as captured by Waymo's sensor-laden vehicles. The company has included corresponding three-dimensional maps and geographic details in each segment to provide researchers with context for their prediction modeling. In total, Waymo says it is releasing 570 hours of "unique data" (*12, 13*).

Geospatial Data

Geospatial data are similar to the satellite navigation systems in many vehicles. However, geospatial data for AVs use a much higher resolution to describe the absolute or relative positions of the surrounding environment and are used to locate elements within a defined space or geography. Onboard sensors, geospatial data, and base mapping will likely be essential. Geospatial data apply to the vehicles themselves and to the environment and infrastructure those vehicles are connected to. Almost all data shared between vehicles, infrastructure, and systems need to reference relative or absolute positioning so that they have context and meaning to the user. Geospatial data are critical for CAV technologies because they provide the foundations for sharing data. The need to share data depends on understanding what the data mean and having a common reference point or set of standards (*14*, *15*).

According to Atkins (*14*), the geospatial data required consist of all data with a geographic component. This means that the records in a dataset have locational information tied to them such as coordinates, address, city, or postal area code. The four location types include:

- Point location (e.g., the position of roadside infrastructure),
- Segment location (e.g., the position and extent of a traffic jam),
- Area location (e.g., a weather situation), and
- Volume (e.g., the position and shape of an obstacle).

The potential sources for these data include:

- In-car sensor data;
- Base map data for navigation (also referred as static mapping);
- Additional map data with traffic signs, works, or other layers;
- Connected V2V or V2I data;
- Social network (e.g., Twitter) or commercial traffic data (e.g., INRIX); and
- Open-source data (e.g., Waze) (*14*).

Monsó (*4*) outlined several digital initiatives in the forefront for CAVs:

- **Lidar**: Despite lidar's obvious advantages, it is too large, complex, and expensive for mass market use. Additionally, lidar has a high susceptibility to vibration and shock, and features limited resolution and range. This is about to change. Solid state lidar fixes some of these constraints, providing both range and angular resolution, and is close to mass production. Several of lidar systems can be mounted in a vehicle to provide the appropriate geometry to serve AVs' needs well.
- **Radar**: Although still targeting levels 2 and 3, automotive-grade high-resolution radar chipsets that can receive data from multiple antennas and improved algorithms to handle interference are entering the marketplace.

- **Location**: On top of more conventional global navigation satellite systems (GNSS)/inertial measurement units, Qualcomm's visual odometry is promising trajectory drift below 1 percent, and the 3rd Generation Partnership Project's Release 17 features location accuracy.
- **HD maps**: The deployment of low-orbit constellations of satellites offering global coverage of HD images, up to 10-inch accuracy, and 24-hour refreshment ratios is an intriguing initiative. Key players are already emerging in this industry. Numerous providers are either planning or currently launching tens of thousands of satellites. While much of the current launches focus on achieving broadband connectivity, the outgrowth of services into areas such as HD maps is anticipated.
- **Teleoperation**: The University of Michigan Transportation Research Institute is investigating combining onboard artificial intelligence (AI) and machine learning capable of predicting the likelihood of a disengagement in the coming 10 to 30 seconds, and a remote center able to take control if necessary (*4*).

Some of the most important issues that researchers, automakers, and tech firms are currently grappling with include:

- Equipping vehicles to travel on rural roads that offer few visual cues, especially in low visibility;
- Efficiently storing and sharing the terabytes of data collected by vehicle sensors;
- Checking the accuracy of all the labels that AI generates for objects detected by the sensors;
- Adapting to variations in driving rules for different cities and countries; and
- Preparing to comply with anticipated new regulations governing the operation of self-driving cars (*16*).

Cybersecurity

As with any other system that is fully connected to the cyber-world, CAVs face some of the same security issues. The three key elements potentially vulnerable to cyberattacks identified by Kim et al. (*17*) are automotive control systems, autonomous driving system components, and V2X. An automotive control system consists of an in-vehicle network that connects the main device and the other devices. These are classified as units and networks. The most important units are electronic control units (ECUs) that manage all the systems within the vehicle from powertrains to door locks. The autonomous driving system consists of the components that "read" the roadway and surrounding areas. These are technologies such as global positioning systems (GPS), Bluetooth, lidar, radar, cameras, central computers, and ultrasonic sensors. The V2X communication technologies communicate with all the other technologies including vehicle ad-hoc networks. Attack methods and defenses are being vigorously studied by the CAV industry and information technology (IT) companies.

NHTSA suggests a multi-layered approach to cybersecurity by focusing on a vehicle's entry points, both wireless and wired, which could be potentially vulnerable to a cyberattack. Working with research and industry leaders, NHTSA aims to reduce the possibility of a successful vehicle cyberattack and mitigate the potential consequences of a successful intrusion. NHTSA promotes a comprehensive and systematic approach to developing layered cybersecurity protections for vehicles, including the following:

- A risk-based prioritized identification and protection process for safety-critical vehicle control systems;
- Timely detection and rapid response to potential vehicle cybersecurity incidents on America's roads;
- Architectures, methods, and measures that include cyber-resiliency and facilitate rapid recovery from incidents when they occur; and
- Methods for effective intelligence and information sharing across the industry to facilitate quick adoption of industry-wide lessons learned.

NHTSA encouraged the formation of the Automotive Information Sharing and Analysis Center, an industry environment emphasizing cybersecurity awareness and collaboration across the automotive industry (*18*).

Data security is a critical concern for CAV development to ensure data are from secure, reliable, and accurate sources. Vehicle-related security attacks are an ever-changing threat. Juliussen (*19*) describes the attack vectors that hackers use for automotive exploits, as shown in Table 2. The percentages are based on the cumulative attacks from 2010 to the latest year, 2021.

Table 2: Automotive Attack Vectors (19)

Hardware or Software	Share: 2010–2018	Share: 2010–2019	Share 2010–2020	Share: 2010–2021
Cloud servers	21.4%	27.2%	32.9%	41.1%
Keyless entry—key fob	18.8%	29.6%	25.3%	26.3%
Engine control unit and transmission control unit gateway	2.6%	5.0%	4.3%	12.2%
Mobile app	7.4%	12.7%	9.9%	7.3%
Infotainment system	7.4%	7.7%	7.0%	5.7%
Onboard diagnostic (OBD) port	10.4%	10.4%	8.4%	5.4%
IT system/network	N/A	N/A	7.0%	5.1%
Sensors	3.5%	5.3%	4.8%	3.3%
In-vehicle network	N/A	3.3%	3.8%	2.9%
Wi-Fi network	4.4%	5.3%	3.8%	2.9%
Bluetooth	3.1%	4.4%	3.6%	2.7%
OBD dongle	1.8%	3.6%	3.1%	N/A
Cellular network	4.8%	4.1%	2.4%	N/A
USB or SD port	3.1%	N/A	2.1%	N/A

Source: Upstream Security: 2019, 2020, 2021, and 2022 Cybersecurity Reports

According to Juliussen (*19*), there are several clear signals from these trends:

- Cloud server attacks have become the leading category with over 41 percent of the total for 2010 to 2021. A new issue, the Log4Shell vulnerability, has the potential to further increase server attacks in 2022 and beyond.

- The keyless entry method was the favorite in 2019 and remains a strong second favorite for hackers. It is increasingly used to steal and break into vehicles.
- ECU attacks have grown recently and are now in third place with over 12 percent of all attacks. Domain ECUs are expected to have better cybersecurity, which may help protect this category.
- Mobile app attacks seem to have both peaked and declined since 2019. With Apple and Google becoming dominant in interfacing apps and infotainment systems, there will be more standardization. This could increase the impact of hacks because many more vehicles could be attacked with a single vulnerability.
- Attacks via the OBD port have also declined since physical attacks are becoming a small portion of all hacks.
- Sensors have remained a secondary issue. With the growing number of sensors in advanced driver assistance systems and future AVs, however, it is worth keeping an eye on this category.
- A key requirement of these cybersecurity standards and regulations is that each vehicle must be secured throughout its entire life cycle—from development and production through all vehicle customer use phases. This means that OEMs and their supply chains must include multi-layered cybersecurity solutions to protect against current and future cyberattacks.
- WP.29 consists of two components: the R155 cybersecurity management system (CSMS) and R156 software update management system (SUMS). The CSMS is focused on implementing a high level of cybersecurity analysis, while the SUMS is dedicated to safeguarding software updates during the vehicle life cycle.
- ISO/SAE 21434 is focused on implementing WP.29 CSMS requirements at the beginning of the system design process and enabling OEMs and suppliers to demonstrate due diligence in implementing cybersecurity engineering.
- These two cybersecurity regulations have set the stage for what OEMs must do to protect against cybersecurity vulnerabilities. Even with solutions based on these standards, cybersecurity will remain one of the toughest problems in the auto industry—and maybe the hardest long-term problem (*19*).

Data Processing—Edge, Fog, Cloud, etc.

Edge computing enables data processing relatively close to the data source. This means that instead of sending data to the cloud for processing, it is handled nearby. Due to high volumes of data, edge AI computing addresses latency-sensitive monitoring such as object tracking and detection, location awareness, and privacy protection challenges with cloud computing. The real value of edge computing can only be realized if the collected data can be processed locally, and decisions and predictions can be made in real time with no reliance on remote resources. Edge computing reduces the strain on clogged cloud networks and provides better reliability by reducing the lag between data processing and the vehicle. Vehicular edge computing systems are mobile and need to process an enormous amount of data in real time (*20*).

Both edge and fog computing are technologies aimed at resolving cloud-computing-associated challenges. Fog computing and edge computing appear similar since they both involve bringing intelligence and processing closer to the data source. A fog environment places intelligence at the local area network (LAN). This architecture transmits data from end points to a gateway, where the data are then transmitted to sources for processing and return transmission. Edge computing places intelligence and processing power in devices, as shown in Figure 5.

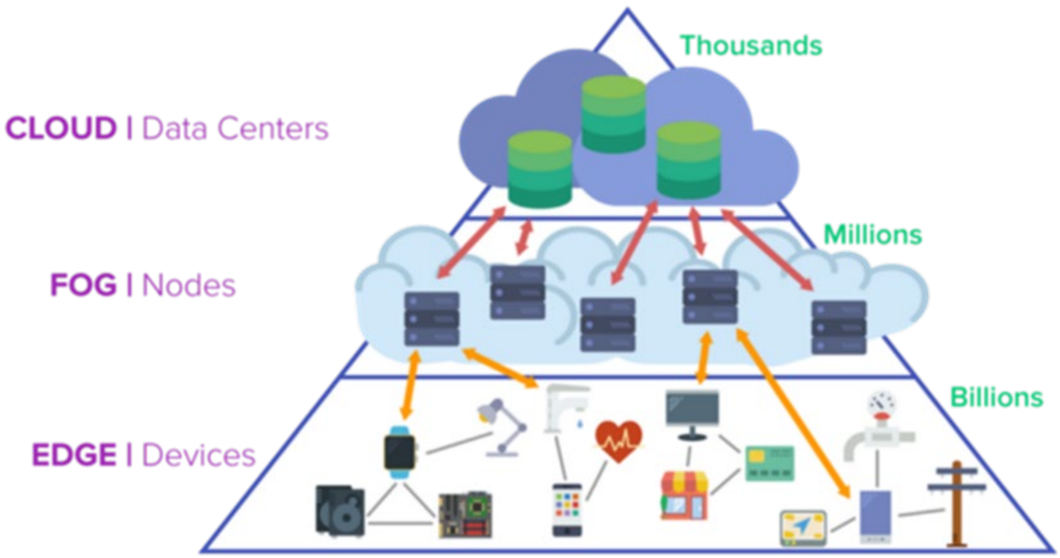

Figure 5: Data-Processing Examples (21)

Physical Infrastructure

Throughout the literature for physical infrastructure needs, there is one issue that emerges as dominant: the need for standardization, uniformity, and consistency. Infrastructure, whether digital or physical, should be standardized (for requirements and certification tests), and road signs/markings should be consistent nationwide to ensure messages between vehicles and infrastructure are seamlessly exchanged and easily understood (*3, 22*).

AV America (*3*) discusses the path forward for implementation of CAVs. The functions of AVs require the ability to read the roads through intelligent infrastructure that consists of a hybrid digital infrastructure combining digital components and physical infrastructure, that is, roadways embedded with sensors to detect and send information. Upgrades to existing assets and physical infrastructure include pavement markings, signage, traffic signals, and maintenance and how these all function within the ODD.

Operational Design Domain

Gopalakrishna et al. (*22*) identify many of the issues facing the development of CAVs through 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 AVs on highway infrastructure. These issues concern the following areas:

- Physical infrastructure:
    - Roadway types
    - Roadway surfaces

    - Roadway edges
    - Roadway geometry

- Operational constraints:

    - Speed limit
    - Traffic conditions

- Objects:

    - Signage
    - Roadway users
    - Non-roadway user obstacles/objects
    - Toll booths
    - Water-filled potholes
    - Overhanging vegetation
    - Downed power lines
    - Uncooperative people
    - Common human rule breaking
    - Falling objects
    - Delivery robots

- Connectivity:

    - Vehicles
    - Traffic density information
    - Remote fleet management system
    - Infrastructure sensors and communications
    - Outdated mapping details

- Environmental conditions:

    - Weather
    - Weather-induced roadway conditions
    - Particulate water
    - Illumination
    - Time of day
    - Glare
    - Ice/snow

- Zones:

    - Geo-fencing
    - Traffic management zones/school/construction zones
    - Regions/states
    - Interference zones (*22, 23*)

Gopalakrishna et al. (*22*) identify many of the issues facing the development of CAVs through a comprehensive literature review, engagement with highway IOOs, and interviews with industry experts and key stakeholders to document the potential impact of AVs on highway infrastructure, as shown in Table 3.

Table 3: Potential Early Strategies Identified by Stakeholders for AV Readiness (22)

Functional Class	Traffic Control Devices	Physical Infrastructure	ITS and Transportation Systems Management and Operations	Multimodal
Interstates, freeways, expressways, and principal arterials	• Standardize pavement markings to be 6 inches wide for all longitudinal markings • Use dotted edge line 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, and work zone management) across the country	• Prioritize treatments for transit operations, truck platooning, and managed lanes to benefit future AV operations

Functional Class	Traffic Control Devices	Physical Infrastructure	ITS and Transportation Systems Management and Operations	Multimodal
Minor arterials, and major and minor collectors	• Standardize edge line 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, and work zone management across the country) • Equip signal-controlled intersections with I2V hardware, including technology capable of signal phase and timing and hardware capable of communicating the presence of vulnerable road users • Equip parking systems with I2V capabilities	• Manage curb space and conduct safety audits

Pavement

Researchers are trying to resolve the issues relating to how CAVs drive and the effects this has on pavement longevity. CAVs drive like machines, not humans. This means they follow a designated path with little deviation (e.g., a certain distance from pavement markings), and pavement fatigue continually occurs in a precise location, creating ruts. There is a need to adapt the physical infrastructure to changes in traffic-load patterns. Zhou et al. (*24*) found that CAVs are less tolerant of pavement rut depth due to greater risk of hydroplaning. Researchers modeled human versus CAV pavement fatigue using the Texas Mechanistic-Empirical Flexible Pavement Design System. Results showed that an optimal AV wandering pattern with a uniform distribution could prolong pavement life and decrease hydroplaning potential.

Noorvand et al. (*25*) found similar concerns when researching the effects of truck platoons on pavement life and performance with respect to rutting, fatigue cracking, and overall pavement smoothness. The results showed that if controlled appropriately, autonomous trucks could be highly beneficial for the pavement infrastructure design, and they would be specifically most effective when they represent more than 50 percent of the total truck traffic. However, autonomous truck volumes as low as 10 percent repeatedly positioned in the same location can be highly detrimental.

Table 4 shows some of the pavement-related issues identified by Gopalakrishna et al.

Table 4: Pavement-Related Issues for CAVs (22)

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

Pavement Markings

Based on the research conducted by Gopalakrishna et al. (*22*), the three pavement marking areas that should be considered when optimizing lane departure prevention technologies' effectiveness are uniformity, design, and maintenance. Pavement markings or lane marking recognition systems are designed to recognize the markings through their color (white and yellow), shape (solid and dashed), and type (center, edge, lane, channelizing, merge, diverge, single, double, work zone, and permanent lines) so that lane-keeping assist systems fully understand the information that lane markings are intended to provide. Sensors for lane departure applications can be passive (e.g., a video camera with a machine-vision system) or active (e.g., lidar). Both are useful for vehicle distance and speed estimation and are functional in more conditions (*26*).

The National Committee on Uniform Traffic Control Devices CAV Task Force—through engagements with the American Association of Highway and Transportation Officials, Auto Alliance, the American Traffic Safety Services Association, and the Accredited Standards Committee—compiled the following list of the most recent recommendations for pavement markings as of June 15, 2019 (*22*):

- Use 6-inch-wide longitudinal markings on freeways and interstate highways.
- Use 6-inch-wide edge lines on roadways with posted speeds under 40 mph.
- Use dotted edge line 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-foot-long lane lines with 25-foot gaps.
- Use only arrow shapes approved in the *Manual on Uniform Traffic Control Devices* (MUTCD).

According to Gopalakrishna et al. (*22*), tightening national uniformity in these areas should help provide more robust marking detection and fewer false positives, and prepare roadways for AV technologies. Other uniformity topics include:

- Durable markings,
- High-contrast markings,
- Markings that maintain their colorfastness,
- Markings visible under wet conditions,
- Markings visible under glare conditions (certain sun angles), and
- Markings compatible with lidar technologies.

The research conducted for the Virginia Department of Transportation by Boateng et al. (*27*) prioritized the approach to enhancing pavement marking and pavement messages to accommodate CAV technologies, as shown in Table 5 and Table 6.

Table 5: Example Prioritized List for Pavement Markings (27)

Types	Details	Digital Traffic Control Devices (DTCD) Inclusion		
		1st Priority	2nd Priority	Exclude
Pavement and curb markings	Yellow center line pavement markings	x		
	No passing zone pavement markings	x		
	Other yellow longitudinal pavement markings	x		
	White lane line pavement markings	x		
	Edge line pavement markings	x		
	Extensions through intersections or interchanges		x	
	Lane reduction transition markings		x	
	Approach markings for obstructions		x	
	Raised pavement markers		x	
	Stop and yield lines	x		
	Do not block intersection markings	x		
	Crosswalk markings	x		
	Parking space markings		x	
	Pavement word, symbol, and arrow markings		x	
	Speed measurement markings		x	
	Speed reduction markings		x	
	Curb markings	x		
	Chevron and diagonal crosshatch markings	x		
	Speed hump markings	x		
	Advance speed hump markings		x	
Roundabout markings	White lane line pavement markings for roundabouts		x	
	Edge line pavement markings for roundabout circulatory roadways		x	
	Yield lines for roundabouts		x	

Types	Details	Digital Traffic Control Devices (DTCD) Inclusion		
		1st Priority	2nd Priority	Exclude
	Crosswalk markings at roundabouts		x	
	Roundabout word, symbol, and arrow pavement markings		x	
	Markings for other circular intersections		x	
Markings for preferential lanes		x		
Markings for toll plazas				x
Delineators				x
Islands				x
Rumble strip markings				x
Bicycle lanes		x		
Shared lane markings		x		

Table 6: Example Prioritized List for Pavement Messages (27)

Types	Details	DTCD Inclusion		
		1st Priority	2nd Priority	Exclude
Regulatory	STOP	x		
	YIELD	x		
	RIGHT (LEFT) TURN ONLY	x		
	25 MPH	x		
	Lane-use and wrong-way arrows	x		
	Diamond symbol for high-occupancy vehicle lanes		x	
	Other preferential lane word markings		x	
Warning	STOP AHEAD	x		
	YIELD AHEAD	x		
	YIELD AHEAD triangle symbol	x		
	SCHOOL XING	x		
	SIGNAL AHEAD	x		
	PED XING	x		
	SCHOOL	x		
	R X R	x		
	BUMP	x		
	HUMP		x	
	Lane-reduction arrows		x	
Guide	Route numbers (route shield pavement marking symbols and/or words such as I-81, US 40, STATE 135, or ROUTE 10)			x
	Cardinal directions (NORTH, SOUTH, EAST, or WEST)			x
	TO			
	Destination names or abbreviations thereof			x

Signage

As with pavement markings and other physical infrastructure, the ability of CAVs to read signage is paramount in their safety and performance. The key issues identified by Gopalakrishna et al. (*22*) are:

- **National uniformity:** Many agencies have developed signs that are not in the MUTCD.
- **Speed limit signs:** A speed limit sign 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 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. No known effort has been made 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.

As with pavement markings, Boateng et al. (*27*) investigated the use of DTCDs for the Virginia Department of Transportation. To identify specific traffic control device information content that is recommended to transition from the current physical approach to a virtual system using wireless communications, the researchers reviewed the MUTCD, the Virginia Supplement to the MUTCD, and other relevant documents. Table 7 and Table 8 show the research results for prioritizing the transition to DTCD. One reason given for exclusion of some signs is that CAVs do not need to read these messages because the information is mapped into the vehicle, such as exit-only and supplemental guide signs.

Table 7: Example Prioritized List for Pavement Marking (27)

Type	Static/Dynamic Signs	DTCD Inclusion		
		1st Priority	2nd Priority	Exclude
Regulatory signs	STOP	x		
	ALL WAY sign	x		
	YIELD sign	x		
	YIELD sign:			
	- To pedestrian and stop here for pedestrians	x		
	- In-street and overhead pedestrian crossing	x		
	Speed limit	x		
	Variable speed limit*	x		
	Movement prohibition signs	x		
	Intersection lane control signs		x	
	Mandatory movement lane control signs	x		
	Optional movement lane control signs		x	
	DO NOT PASS sign		x	
	Selective exclusion signs:			
	- WRONG WAY	x		
	- DO NOT ENTER	x		
	Wrong-way traffic control at interchange ramps	x		
	ONE WAY signs	x		
	LOCATION signs		x	
	Parking, standing, and stopping signs (R7 and R8 series)		x	
	Emergency restriction signs		x	
	WALK ON LEFT FACING TRAFFIC and no hitchhiking signs			x
	Traffic signal signs	x		
	Headlight use signs			x
	Rest area directional sign		x	
	Commercial vehicle lane restriction signs		x	
Warning signs	BUMP and DIPS	x		
	Warning signs and plaques for motorcyclists			x
	Intersection warning signs		x	
	Non-vehicular warning signs		x	
	Playground sign		x	
	Watch for children		x	
Guide signs	Design of route signs			x
	Route sign assemblies			x
	Design of route sign auxiliaries			x
	Location of distance signs			x
	Street name signs			x
	Advance street name signs			x

* Dynamic signs.

Table 8: Example Prioritized List for Pavement Message (27)

Type	Static/Dynamic Signs	DTCD Inclusion		
		1st Priority	2nd Priority	Exclude
Regulatory	Speed limit and end XX mile speed signs	x		
	DO NOT PASS sign	x		
	Variable speed limit*	x		
	Dynamic message signs*	x		
Warning	*Horizontal alignment warning signs:*			
	- Truck rollover warning sign	x		
	- ONE LANE BRIDGE sign	x		
	Low clearance signs	x		
	BUMP and DIP signs	x		
	Warning signs and plaques for motorcyclists		x	
	Reduced speed limit ahead signs		x	
	Vehicular traffic warning signs		x	
	Merge signs		x	
	STEEP GRADE AHEAD plaque		x	
Guide signs	Overhead arrow per lane guide sign			x
	Guide sign spreading			x
	Pull-through signs			x
	Diagrammatic guide signs			x
	EXIT ONLY signs			x
	EXIT DIRECTION signs			x
	Route signs and trailblazer assemblies			x
	Interchange signs			x
	Advance guide signs			x
	Other supplemental guide signs			x
	Next exit guide signs			x
	EXIT DIRECTION signs			x
Toll roads	Electronic toll collection account only			x
	Auxiliary signs (M4-16 and M4-20)			x
	Toll payment regulatory signs		x	
	Preferential and managed lanes signs			x
	Preferential and managed lanes signs*			x
	Guide signs for priced lanes			x

* Dynamic signs.

Off-Pavement

There is a wide discrepancy regarding the direction of development for CAVs. One relies solely on digital technology, such as digital twinning, and the second uses physical infrastructure, such as lane striping and radar, to guide their vehicles. (*28*), Most AVs cannot navigate on gravel roads or roads without clear lane markings. Development of high-precision digital maps and GNSS technology (e.g., GPS) may provide an alternative although developing these maps in rural areas is a challenge due to the limitations of infrastructure and connectivity. That said, high-precision digital maps and GNSS alone are not enough for AVs to navigate on unpaved roads, and more research and industry changes will need to happen (*28*).

Maintenance

Table 3 shows some of the anticipated maintenance issues identified by Gopalakrishna et al. (*22*).

Drop-Off and Pickup Lanes

Curbside design and planning will become more important as AV demands for curb space increase for ridesharing pickup and drop-off, goods delivery, on-street parking, and transit stops. Urban areas have already seen increased demand for curb space due to ridesharing and e-commerce (*22*). Crute et al. (*29*) suggest retrofitting frontage roads and turn lanes for ridesharing pickup and drop-off. However, the authors caution not to fragment bicycle and pedestrian networks by changes to the curb.

The National Association of City Transportation Officials (*30*) discusses emerging technologies that can help cities dynamically shape and manage curbs because flexible, or flex, zones serve different uses and users at different times. Enhanced with sensors, the price and allowed use for the most in-demand curb space could fluctuate according to the time of day or shifting public priorities. Real-time curbside management systems could allow vehicles to automatically reserve time slots a few minutes in advance of arrival at a site. Armed with sufficient data, cities could actively manage curbsides, setting rates in real time, changing uses with demand, and automating enforcement to ensure turnover. Many cities are already using these emerging technologies and are repurposing static parking meters to enable dynamic pricing tools. Figure 6 shows how cities should expand on these investments by inventorying curbside uses and regulations, building smart partnerships with the private sector, and using new technologies like lidar to collect data (*31*).

Works Zones

Work zones continue to be challenging for the CAV community. The dynamic situations make it difficult to map. As a result, automakers and researchers cannot feed free cars any information to help the vehicles identify construction zones. A solution is to embed IoT communication technology into traffic cones and other devices to help autonomous cars know where potential dangers are while also allowing humans to see the dangers (*32*).

Figure 6: Curb Usage Examples (31)

As with other aspects of CAVs, uniformity and standardization of technology are important. The U.S. Department of Transportation's Work Zone Data Exchange initiative is one example of the progress regarding efforts to provide direction for the work zone, including

- **Sign standardization:** Standard signing should be 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 the Wisconsin Department of Transportation and are currently under evaluation in Texas (*33*).
- **Device spacing:** The maximum spacing for vertical work zone devices needs to be determined (*22*).

Interaction with Law Enforcement

The ability of CAVs to send and receive information, read the road, and communicate with surrounding infrastructure must include safe and effective interaction with law enforcement (LE). Many questions need to be answered regarding LE, not only from a safety perspective but also a legal standpoint. LE, industry developers, and stakeholders need to determine how interactions should occur and what behaviors can be expected of AVs. Goodison et al. (*34*) conducted a series of workshops with LE to discuss their most important concerns and needs. The discussion was divided into three general categories:

- Cybersecurity and means of communicating with AVs, their owners, or remote operators;
- Stakeholder communication and collaboration; and
- Standard procedures, guidelines, and training needs for LE interacting with AVs.

The most common types of LE interactions discussed included:

- Traffic stops,
- Collisions,
- Emergencies (e.g., detours and evacuations), and
- Tangential interactions (e.g., AVs as a source of evidence during an investigation and the creation of AV exclusion zones).

The results of the workshop produced the following list of needs and recommendations:

- Identify the costs and benefits of options to identify AV capabilities and authorization to run in automated mode.
- Conduct an assessment of AVs and design tools to detect cyberattacks and facilitate investigation for law enforcement.
- Conduct research to examine the costs and benefits of various options of communicating with AVs running in automated mode.
- Develop a system that allows LE to communicate their intentions to AVs.
- Develop the equivalent of license and documentation that allows LE to check the authorization to operate an AV.
- Conduct research to identify the most promising technological solutions that could be used in situations in which verbal communications are used.
- Conduct workshops and ride-alongs for LE and other agency staff (as well as for AV system developers) to raise knowledge levels.
- Conduct information-gathering exercises to develop ideal approaches for conveying information to first responders.

- Conduct a survey of LE and crash reconstruction experts to identify information that would be most useful in crashes.
- Develop web portals that could inform OEMs about the kinds of information from which LE would benefit.
- Identify best practices for cities and other entities that have information about upcoming closures.
- Develop model training and guides for LE for identifying and interacting with AVs running in automated mode.
- Develop guides and tools for potential LE responses to AV hacking.
- Develop a guide containing likely scenarios in which AVs are used illegally and the potential solutions.
- Develop a description of the kinds of behaviors that LE will expect AVs to be able to perform that is representative across the United States.

Interviews with CAV Industry Leaders

As transportation agencies move forward with the implementation of CAVs, industry leaders provide vital information on the direction, preferences, and requirements for digital and physical infrastructure that may still need to be addressed to ensure optimal and safe performance and reliability of CAVs on roadways. Information gathered found a wide discrepancy between the two companies interviewed regarding their direction for CAVs. One development direction will rely on digital technology, such as digital twinning, and the second development direction focuses on the physical infrastructure, such as lane striping and radar, to guide vehicles.

Digital Infrastructure Focus

For the AV research and development direction that focuses primarily on digital technology for vehicle communication and control, the DT is the basis for the digital universe of the AV functions. The DT is the mechanism by which a real-life vehicle is alerted to its surroundings, like how radar functions for airplanes. The DT consists of three main components:

- Imaging data,
- Physics, and
- Simulation/modeling.

Imaging data such as geographic information systems, lidar, and data shared by satellite companies are used to build something that looks like a Google Earth image but is specific to the region that it is serving. Physics comes into play by incorporating the physical attributes of an area into the system. This may consist of buildings, roads, and other physical entities. This all becomes the environment where simulations, modeling, and even operations take place.

Mapping is a necessary component. The data used to build roadways can be incorporated directly into the DT to include sharable work zone data. Data sharing is key to making AVs a workable reality. The P3 model may be a viable solution, such as finding a way to monetize data by providing an economic incentive for data sharing. Proprietary/permission issues will need resolution.

There is a correlation between how AVs and airplanes operate. Both rely on digital mapping for guidance. With the proper deployment of digital infrastructure, many of the problems associated with using physical infrastructure, such as paint, pavement markings, etc., will go away. Navigation will be able to be disseminated to the millimeter level using advanced assured positioning, navigation, and timing (APNT).

One of the remaining issues is how to get widespread digital coverage. A solution may involve investors, part of the P3 model, so departments of transportation will not have to bear the financial burden of digital infrastructure. Technology that will advance AV is the deployment of public infrastructure network nodes (PINNs) as part of the intelligent infrastructure that includes broadband, edge, ~~ITS~~, APNT, GRID, etc. PINNs allow the DT to morph and adjust in real time (see Figure 7) (*35*). The PINN and DT will also have meteorological input to allow for adjustments based on weather events. Public awareness and education will help the AV industry to advance.

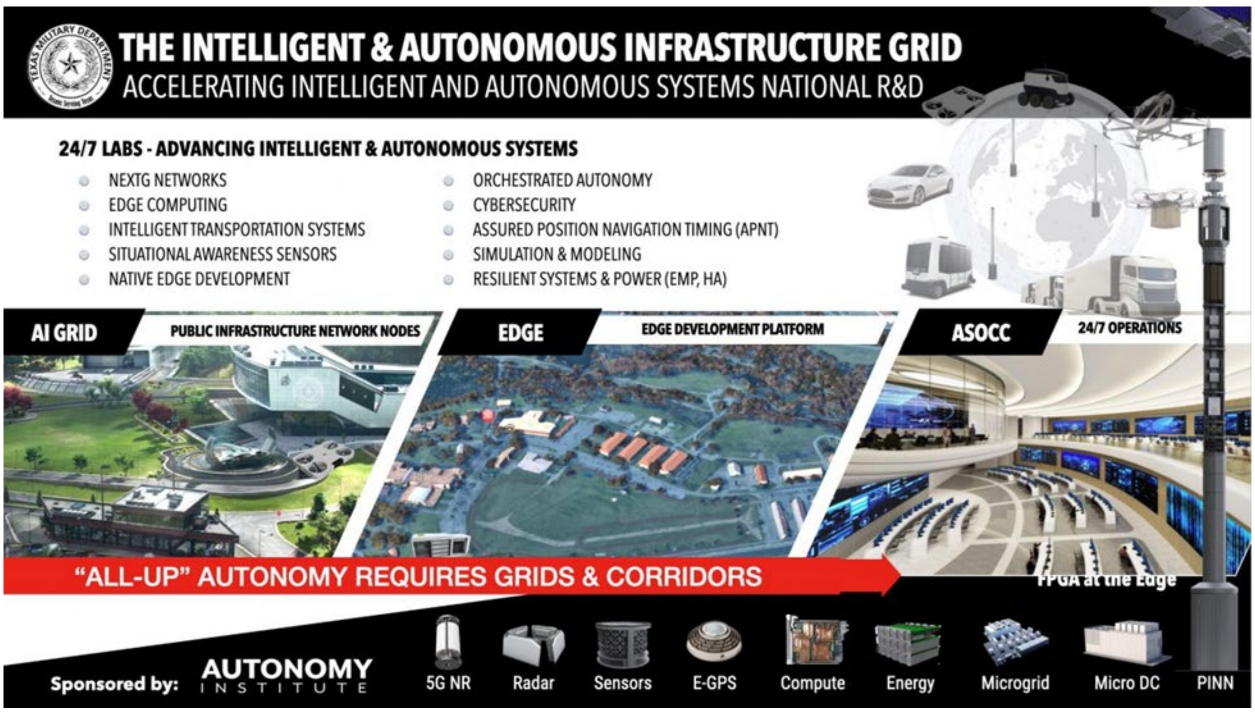

Figure 7: Data Exchange and PINN Clusters (35)

Physical Infrastructure Focus

Research and development focusing on physical infrastructure have a different perspective on the direction of CAVs. Some fleets rely on the physical infrastructure of the highway surroundings for guidance. Instead of relying on the HD mapping and DT, the fleets use a lightweight mapping approach. The fleet primarily moves within highway corridors, so the maps contain just enough information about the highway to make autonomy possible. Accordingly, the maps are easier to build and maintain and are small enough that entire fleets can receive updates over the air. This makes it easier to relay information when a construction zone pops up or a lane changes. The maps combine macro-level awareness of their surroundings by using sensors, cameras, lidar, radar, lane lines, edge line, etc., as shown in Figure 8.

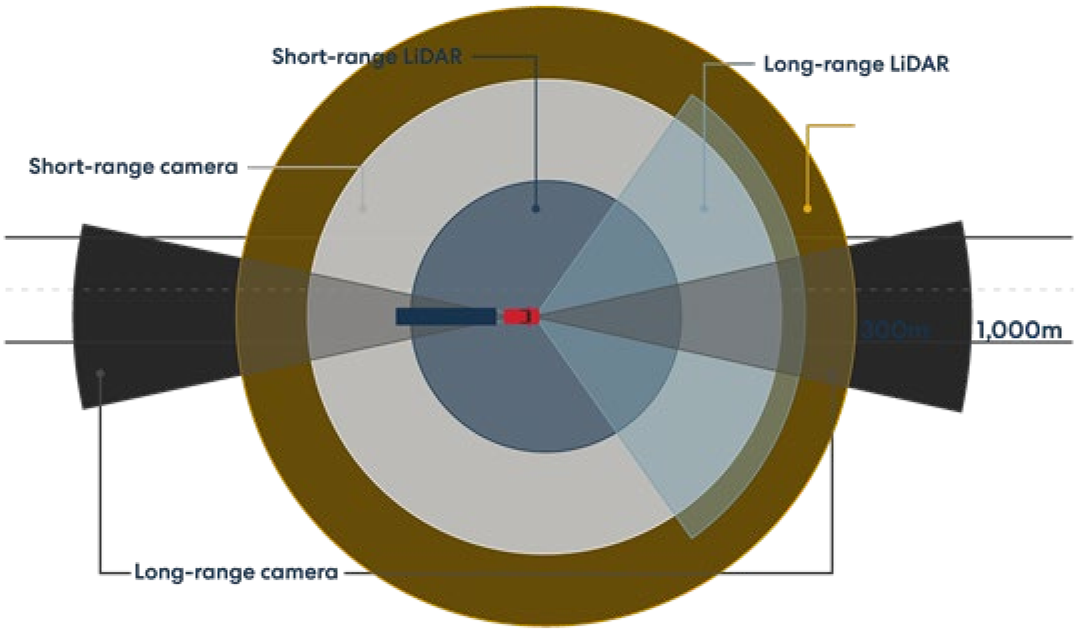

Figure 8: Physical Infrastructure for Surroundings Awareness (36)

This level of technology is robust enough to alert fleets to adjustments within work zones and other emergency situations to allow for lane shifts. Some fleets have sensors that report every 1/10 second. If a sensor fails to report, the vehicle can fall back to minimal risk position and then pull over. Their research is currently working on the next technology milestone for 4G radar systems. Reduced visibility from weather events such as fog, heavy rain, and snow are a continuing challenge. Transfer hubs are a complicated issue but critical to the strategy of both public and private sectors. Highway driving differs from urban street driving.

The company interviewed for the physical infrastructure focus does not currently have driverless vehicles on the road. The safety driver is with the vehicle to handle emergency situations and responses to LE vehicles. The company is working with LE to develop an appropriate interaction with the vehicles.

Three specific comments about how the department of transportation can provide for AV trucks include the need for:

- Wider right lanes for trucks,
- Clearly marked work zones, and
- Better and consistent striping/marking within work zones (*36*).

Conclusion

This paper discusses CAV digital and physical infrastructure issues and opportunities. While AVs and CVs currently share many of the same technologies, their operational parameters and needs differ. There is a dichotomy of thought in the direction of research and development within the CAV industry. For some, vehicle performance focuses on the physical infrastructure consisting of the ODD, pavements, markings, signage, sensors, and other various infrastructure components so the vehicles can read the roadway and communicate through digital infrastructure. However, the other research and development direction relies on digital infrastructure and the CAV's ability to safely perform regardless of the surrounding operational domain. The vehicle will rely on precise digital communication.

Interaction with LE, work zones, extreme weather events, differing maintenance needs, standardization of physical infrastructure, cybersecurity, and rural connectivity and roadway conditions are at the forefront of CAV development direction. These conditions and scenarios may require a concerted effort on data sharing/exchange and may present possibilities for more investment through P3s for further development of the CAV industry.

Opportunities

During the background research and interviews performed for the development of this white paper, a primary consideration that came to light was the need for data sharing. Most often, this was referenced in the form of data exchanges where a two-way street of data reception and disbursement could be used to provide entities within the CAV arena with enhanced information about the roadway characteristics and the vehicles driving on them.

To effectively move forward with data exchanges to support the increasing levels of CAV activity in the state, Texas should consider taking an ownership role in participating in and/or developing data exchanges. Specifically, Texas should consider the following:

- Develop a comprehensive list of data exchange use cases and which potential exchanges might serve those needs. This list would include an inventory of which private-sector companies would participate in data exchanges for any given use case.
- Identify the most useful data exchange use cases for the state and its jurisdictions by collaborating with current and future users to identify needs.
- Develop an action plan for using or creating a data exchange for a particular use case that enjoys strong support from both public- and private-sector participants.
- Identify potential failure points of data exchange collaboration and mechanisms to mitigate the concerns that could impact acceptance and usage.

References

1 National Highway Traffic Safety Administration. “Automated Vehicles for Safety.” https://www.nhtsa.gov/technology-innovation/automated-vehicles-safety.

2 Wang, J., Zhang, L., Huang, Y., and Zhao, J. “Safety of Autonomous Vehicles.” *Journal of Advanced Transportation,* Vol. 2020, Article ID 8867757, 2020. https://doi.org/10.1155/2020/8867757.

3 AV America. *Digital Infrastructure for Autonomous Vehicles—Requirements, Deployment and Plans.* 2020. https://www.globalmasstransit.net/report/report-sample-digital-infrastructure-for-autonomous-vehicles-2020.pdf.

4 Monsó, J. “Autonomous Vehicles: Making the Case for Digital Infrastructure.” Ferrovial. October 23, 2020. https://blog.ferrovial.com/en/2020/10/autonomous-vehicles-making-the-case-for-digital-infrastructure/#.

5 Steele, P., and Hendel, D. “How Digital Ecosystems Power Connected Vehicles.” Equinix, 2021. https://blog.equinix.com/blog/2021/02/17/how-digital-ecosystems-power-connected-vehicles/.

6 Veledar, O., Damjanovic-Behrendt, V., and Macher, G. “Digital Twins for Dependability Improvement of Autonomous Driving.” In: *Systems, Software and Services Process Improvement: 26th European Conference, EuropSPI 2019, Edinburgh, UK, September 18–20, 2019, Proceedings,* Walker, A., O’Connor, R., and Messnarz, R. (eds.), 2019. https://doi.org/10.1007/978-3-030-28005-5_32.

7 Watts, B. “Digital Twins in the Automotive Industry.” October 2018. https://www.challenge.org/insights/digital-twins-in-the-automotive-industry/.

8 Dasgupta, S., Rahman, M., Lidbe, A., Lu, W., and Jones, S. *A Transportation Digital-Twin Approach for Adaptive Traffic Control Systems.* 2021. https://arxiv.org/ftp/arxiv/papers/2109/2109.10863.pdf.

9 Remlinger, W. “Digital Twin for Autonomous Driving.” University of Stuttgart, January 21, 2021. https://www.uni-stuttgart.de/en/university/news/all/Digital-twin-for-autonomous-driving/.

10 Stantec and ARA. *Preparing for Automated Vehicles and Shared Mobility: State-of-the-Research Topical Paper #1 Models for Data Sharing and Governance for Automated Vehicles and Shared Mobility.* National Cooperative Highway Research Program Project 20-113F, 2020.

11 Connecting Europe Facility of the European Union. *Automotive Data Sharing.* 2020.

12 Salter, A. “Ford Going Further with Autonomous Data Sharing: 2025AD—Driven by Driverless.” 2020. https://www.2025ad.com/ford-going-further-with-autonomous-data-sharing.

13 Hawkins, A. "Waymo Is Disclosing More Autonomous Vehicle Data for Research Purposes." The Verge, March 10, 2021. https://www.theverge.com/2021/3/10/22322100/waymo-motion-dataset-autonomous-vehicles-research.

14 Atkins. *Analysis of Geospatial Data Requirement to Support the Operation of Autonomous Cars.* Project Report SDFE, Danish Ministry of Energy, Utilities and Climate, December 2017. https://sdfe.dk/media/2918928/geospatialdata_cavs_final_report.pdf.

15 Cracknell, M. "Geospatial Requirements for the Self-Driving Future." Geospatial World, July 31, 2020. https://www.geospatialworld.net/blogs/geospatial-requirements-for-the-self-driving-future/.

16 University of Southern California. "Self-Driving Cars and the Role of GIS in Transportation's Future." GIS Technology, June 2, 2021. https://gis.usc.edu/blog/self-driving-cars-and-the-role-of-gis-in-future-transportation/.

17 Kim, K., Kim, J., Jeong, S., Park, J., and Kim, H. "Cybersecurity for Autonomous Vehicles: Review of Attacks and Defense." *Computers and Security*, Vol. 103, 2021, 102150. ISSN 0167-4048. https://doi.org/10.1016/j.cose.2020.102150.

18 National Highway Traffic Safety Administration. "Vehicle Cybersecurity." https://www.nhtsa.gov/technology-innovation/vehicle-cybersecurity.

19 Juliussen, E. "Automotive Cybersecurity: More Than In-Vehicle and Cloud." EE Times, May 2, 2022. https://www.eetimes.com/automotive-cybersecurity-more-than-in-vehicle-and-cloud/.

20 Rafie, M. "Autonomous Vehicles Drive AI Advances for Edge Computing." 3D In-Depth, July 22, 2021. https://www.3dincites.com/2021/07/autonomous-vehicles-drive-ai-advances-for-edge-computing/?cn-reloaded=1.

21 WinSystems. "Cloud, Fog and Edge Computing—What's the Different?" December 4, 2017. https://www.winsystems.com/cloud-fog-and-edge-computing-whats-the-difference/.

22 Gopalakrishna, D., Carlson, P., Sweatman, P., Raghunathan, D., Brown, L., and Serulle, N. U. *Impacts of Automated Vehicles on Highway Infrastructure*. 2021.

23 Koopman, P., and Fratrik, F. "How Many Operational Design Domains, Objects, and Events?" Safe AI 2019: AAAI Workshop on Artificial Intelligence Safety, January 27, 2019. https://users.ece.cmu.edu/~koopman/pubs/Koopman19_SAFE_AI_ODD_OEDR.pdf.

24 Zhou, F., Hu, S., Xue, W., and Flintsch, G. *Optimizing the Lateral Wandering of Automated Vehicles to Improve Roadway Safety and Pavement Life*. SAFE-D, December 2019. https://safed.vtti.vt.edu/wp-content/uploads/2020/08/02-008_Final-Research-Report_Final.pdf.

25 Noorvand, H., Karnati, G., and Underwood, S. "Autonomous Vehicles: Assessment of the Implications of Truck Positioning on Flexible Pavement Performance and Design." *Transportation Research Record: Journal of the Transportation Research Board,* January 2017. DOI: 10.3141/2640-03.

26 Pape, D., and Habtemichael, F. *Infrastructure Initiatives to Apply Connected- and Automated-Vehicle Technology to Roadway Departures.* Federal Highway Administration, September 2018. https://www.fhwa.dot.gov/publications/research/safety/18035/index.cfm.

27 Boateng, R., Zhang, X., Park, H., and Smith, B. *Providing Traffic Control Device Information in a Connected and Automated Vehicle Environment.* Virginia Department of Transportation, May 2019. https://www.virginiadot.org/vtrc/main/online_reports/pdf/19-r19.pdf.

28 Minnesota Department of Transportation. *Connected Autonomous Vehicles: Frequently Asked Questions.* April 2022. http://www.dot.state.mn.us/research/reports/2022/2022RIC02.pdf.

29 Crute, J., Riggs, W., Chapin, T., and Stevens, L. *Planning for Autonomous Mobility*. PAS Report 592, American Planning Association, September 1, 2018. https://www.planning.org/publications/report/9157605.

30 National Association of City Transportation Officials. *Blueprint for Autonomous Urbanism, Second Edition.* 2019. https://nacto.org/publication/bau2.

31 National Association of City Transportation Officials. *Blueprint for Autonomous Urbanism, Second Edition.* 2019. https://nacto.org/publication/bau2.

32 Giarratana, C. "Our Cities Are Designed around Roads." Safety Resource Center, February 14, 2017. https://www.trafficsafetystore.com/blog/autonomous-cars-construction-zones/.

33 DeDene, C., and Dupont, B. *Orange Work Zone Pavement Markings: Experience Gained from Early Field Trials.* Transportation Research Board 96th Annual Meeting, Washington, DC, January 8–12, 2017.

34 Goodison, S. E., Barnum, J., Vermeer, M., Woods, D., Lloyd-Dotta, T., and Jackson, B. *Autonomous Road Vehicles and Law Enforcement: Identifying High-Priority Needs for Law Enforcement Interactions with Autonomous Vehicles Within the Next Five Years.* RAND Corporation, 2020. https://www.rand.org/pubs/research_reports/RRA108-4.html.

35 Autonomy Institute. Website. https://autonomy.institute/.

36 Kodiak Robotics, Inc. "The KodiakDriver." https://kodiak.ai/technology/.