Texas CAV Task Force
2nd Comprehensive Report

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Executive Summary of 2nd Comprehensive Report

Texas Connected and Autonomous Vehicles Task Force

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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:

- Coordinating and providing information on CAV technology use and testing in Texas.
- 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.
- 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.

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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 consist of levels 0–4 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.

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.

White Paper Executive Summaries

As a part of its initial efforts, the task force was asked to provide white papers across several topics related to connected, automated and autonomous vehicle technologies. The task force focused on five areas and limited the scope of the white papers to discussing key concepts to (a) understand the current situation, and (b) identify issues and opportunities for these key topic areas. The white papers were developed by five related subcommittees.

Connected and Automated Vehicle Data Issues and Opportunities

A White Paper from the Subcommittee on Data, Connectivity, Cybersecurity, and Privacy

The connected vehicle market is growing at a fast pace, and cars are becoming more connected than ever before. This trend is expected to continue; a Counterpoint Connected Car study predicts that more than 70 percent of the cars sold will be connected by the year 2025. The data generated by the vehicle typically includes information about the vehicle's status and driver's behavior, as well as location-based data. With the continued emergence of advanced driving assistance systems (ADAS) features, vehicles that are connected back to the original equipment manufacturers (OEMs) become more relevant as a critical data source and insight into the traffic stream. Many newer vehicles also have an electric vehicle component, from which additional data may be available. Overall, the interest in connected and autonomous vehicle data comes from OEMs, suppliers, insurers, mobility providers, infrastructure owners/operators (IOOs), fleet owners, and others.

The various applications for vehicle data include but are not limited to the following:

- Predictive maintenance,
- Fleet management,
- Roadside assistance,
- In-car payments,
- Usage-based Insurance, and
- Traffic management.

In particular, IOOs can analyze the data in a multitude of ways to gain insight into roadway conditions. For example, hard-braking events are being examined in conjunction with other roadway characteristics to highlight areas where roadway improvements may need to be prioritized. As another example, video from dashcams or forward-looking cameras can be analyzed to detect missing roadside features (i.e., the feature was there on the previous video but is not there now), vegetation encroaching on roadway signs, striping and pavement conditions, and numerous other use cases.

Both raw and processed vehicle and roadside data add value to all parties involved. The sharing of these data among the multiple interest groups provides widespread opportunity to examine and improve work zones, provide insight into crashes, examine operational conditions, and more. This data sharing can be accomplished via a data exchange—essentially a data portal where participants can both send and receive data.

Data exchanges can also play an important role in piecing together disparate data. Combining these data sources will enable users to analyze road conditions in real time and communicate important travel information to the traveling public, state/local government entities, private-sector partners, and other stakeholders. In addition to real-time analysis, exchanges could also support analysis of long-term historic data, enabling data-driven infrastructure investments and various research initiatives. Public agencies and/or private companies will likely need to see a business case value to participate in a data exchange community. This value may increase as the number of partners grows and the types and amount of data exchanged become more substantial.

Before this is possible, issues such as the following must be addressed and clarified to the satisfaction of all participants:

- Standards,
- Privacy,
- Governance,
- Security, and
- Use cases.

Tackling these concerns will help Texas continue to be an innovation leader in this emerging sector and benefit all Texans.

Strategic Communication Plan for Advancing the Dialogue about Connected and Automated Vehicle Technology

A White Paper from the Subcommittee on Education, Communication, and User Needs

Connected and autonomous vehicle (CAV) technology holds much promise, but questions remain surrounding its widespread use and adoption. The issues include planning, policy making, regulatory and legal frameworks, institutional issues, operations, funding, and ultimately public trust and acceptance. The Texas CAV Task Force's Subcommittee on Education, Communication, and User Needs supports statewide efforts to inform and engage with agencies, stakeholders, industry, and the general public.

This document sets forth a strategic communication plan for the CAV Task Force. The strategic communication plan identifies four overarching goals:

- Educate,
- Generate awareness,
- Build trust, and
- Increase adoption.

The strategic communication plan is premised on best practices of communication including:

- Audience identification and segmentation,
- Market research,
- Message design, and
- Message delivery.

This plan recognizes that specific outreach and education messages and tactics, tailored to specific audiences based on their needs, serve to enhance overall education and outreach efforts. Based on guidance from the subcommittee, this plan identifies stakeholders and audiences. It presents communication techniques and tools, messages, and message delivery mechanisms. It is strategic but also suggests various tactics. Importantly, it recognizes the need for continuous evaluation and adaptation as audiences change and grow and technology advances. Public outreach plans can guide development of materials for specific audiences and provide a comprehensive roadmap for education and outreach efforts beyond the key messages.

The education subcommittee, with its broad multidisciplinary representation, is the forward-facing entity responsible for executing an engagement plan. The subcommittee's charge and responsibility are to develop tools and resources that allow for meaningful engagement. This strategic plan will guide those efforts.

Latest Considerations for Highway and Controlled Environment Freight Automation in Transportation Operations

A White Paper from the Subcommittee on Freight and Delivery

Texas is a leader in the adoption of connected and autonomous vehicle (CAV) technologies, with many companies testing or implementing automated goods movement technologies. It is recognized that the freight ecosystem remains a rapidly changing environment. The Texas Department of Transportation (TxDOT) and partners need to consider the future of emerging freight CAV concepts as it pertains to highway operations. This white paper reviews the latest opportunities, best and emerging practices, and implementation options to support the continued development and support of freight CAV activities in Texas. These activities include:

- Developing a transfer hub/terminal strategic plan: developing an automated trucking transfer hub/terminal strategic plan that includes a thorough evaluation of existing and planned implementation in Texas, how this will impact the freight network, what the development impacts and needs are, and some specific outlining of roles and responsibilities, including support to local governments.
- Assessing Texas Freight Network and automated truck impacts: assessing how automated trucking will change the Texas Freight Network, what infrastructure is needed (including business route optimization, and drayage and circuit identification), what operations coordination would help, and where priority corridors or circuits are that support automated trucking.
- Developing a freight CAV ecosystem: creating an opportunity to share information between the public and private sectors in robust ways; offering ways for the private sector to input activities, and for the public sector to provide data about the freight network, freight facilities, existing freight flows, projects, and more.

While border and law enforcement remain a critical area of concern for freight CAVs, these issues are being studied under different platforms, including the work related to Senate Bill 1308.

The main consideration of this paper is on highway and controlled environment locations. However, many CAV deployments in Texas are in urban areas like Dallas and Austin, and there is potential for activity on resource roads that needs additional research and coordination. The street locations further require in-depth coordination with local governments, as well as discussion of jurisdictional decision-making and how that impacts CAV development decisions.

During the development of this white paper, numerous changes occurred in the companies in the automated truck space. While this paper may refer to a company no longer in existence at the time of publication, it is important to document the activities that have taken place. Steps by companies no longer in the space can still be meaningful to the continued future development of the ecosystem.

Operations and Technology Education Needs for Automated Vehicle Users and Stakeholders

A White Paper from the Subcommittee on Licensing and Registration

Vehicles with automated features and autonomous vehicle deployments are rapidly growing in number. However, the public has a general level of confusion regarding what these automated and autonomous features are truly capable of, which can lead to a false sense of security or drivers operating vehicles in a manner in which they were not intended. Education and guidance are critical needs for the public so that they can fully understand vehicle technologies and operate them safely. This white paper details a literature review and stakeholder interviews conducted to gather information on how to best inform the public and automated and autonomous vehicle stakeholders about what is needed to improve and expand the education of owners and operators of automated and autonomous vehicles. The takeaways from this process include:

- Using consistent terminology is important,
- Automated vehicle technology is intended to increase safety by assisting in some of the driving tasks, such as lane-keeping assistance, automatic emergency braking, or adaptive cruise control, which can ultimately reduce the severity of or even prevent crashes.
- Automated vehicles still require a driver in the driver's seat or a safety operator in the case of shuttles and freight.
- Autonomous vehicles are those vehicles where no driver is needed at all. Further compounding the issue, naming conventions for vehicle technology and the description of how technologies can be used lead to greater misperceptions.
- There is a great need to use consistent terminology, accurately describe the intent of vehicle technology, and promote the general understanding of automated and autonomous vehicles.

Due to this continued high level of misunderstanding and misconceptions about CAV technologies and capabilities, several key opportunities exist, including:

- Collaborating with automobile manufacturers and dealers,
- Consider mandating manufacturer-led training for service and collision technicians,
- Using chat rooms or discussion boards for sharing information between service and collision technicians
- Providing educational materials in multiple formats for different audiences (e.g., a printed document versus a video distributed on the internet),
- Embracing autonomous vehicle deployments will enhance public understanding,
- Including the correct stakeholders in discussions,
- Recognizing the potential value of vehicle safety inspections,
- Updating crash reporting to reflect automated vehicles, and
- Planning for the use of data from connected and autonomous vehicles (CAVs) to improve safety and reduce congestion.

Connected and Automated Vehicle Digital and Physical Infrastructure Needs

A White Paper from the Subcommittee on Safety, Liability, and Responsibility

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.

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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.

APPENDIX A

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Connected and Automated Vehicle Data Issues and Opportunities

Texas CAV Task Force White Paper Subcommittee on Data, Connectivity, Cybersecurity, and Privacy

Authors:
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Table of Contents

List of Figures

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List of Terms and Acronyms

CAV	connected and autonomous vehicle; also, connected and automated vehicle
FDOT	Florida Department of Transportation
IOO	infrastructure owner/operator
JSON	JavaScript Object Notation
OEM	original equipment manufacturer
SME	subject matter expert
TxDOT	Texas Department of Transportation
UDF	user-defined function
V2X	vehicle to everything
WZDx	Work Zone Data Exchange

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Executive Summary

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Introduction

The data economy is growing at a meteoric rate. The world has never been so comprehensively recorded. More data are produced every year, and the conclusions that can be learned by examining these data also increase, from geographical positioning systems that guide us to our destination to smartwatches that monitor our heart rate. Digital devices all produce data. These data can be used to track various aspects of not only the device but also its surroundings.

Companies collecting these data can extract enormous amounts of value from it. However, processing and comprehending such a large volume of data can be a monumental task. The big data revolution has sparked renewed interest and innovation in areas such as artificial intelligence and machine learning. These data can help guide the creation of new products and services or predict current customers' preferences.

Data exchanges are developing as a key component of the data economy. By connecting data suppliers and consumers through an intuitive experience, data exchanges have created a modern-day gold rush to help modern digital organizations address their needs for data. Furthermore, by eliminating the friction from finding, acquiring, and integrating data, these exchanges make it easier to monetize data assets and create new revenue streams. Public agencies and/or private companies will likely need to see a business case value to participate in a data exchange community. However, one business use case that has become readily apparent is the two-way exchange of data. For example, an infrastructure owner/operator (IOO) may provide information about the location of work zones, and a connected vehicle might provide data from traveling through the work zone, which can be examined to ensure that roadway infrastructure is being set up and managed in a way to enhance machine understanding of the environment. The value to an IOO may increase as the number of partners grows and the types and amount of data exchanged become more substantial.

What Is a Data Exchange?

At the simplest mechanism, a data exchange is simply a methodology to exchange data between a source and a receiver. Data exchanges may have different levels of complexity, requirements, and policies.

Type of Data Exchanges

Some of the many types of data exchanges are briefly described as follows:

- **Peer-to-peer data exchange**—A peer-to-peer exchange enables data sharing directly between two companies or departments inside the same company that want to share data on an ad-hoc basis. These types of exchanges consist of a small or large network with each user operating as a node. Peer-to-peer networks include a user platform that allows individual participants to exchange content and information. For example, a use case for a peer-to-peer database would be a large university with two data warehouses, one for business operations and one for research, which might use a peer-to-peer exchange to share data back and forth.

- **Private data exchange**—A private data exchange can come in many shapes and sizes. For example, it could be a consortium, which collects and standardizes insurance data and distributes it to participating members and regulators. Also, many large companies use a private data exchange to share inventory data with their suppliers and collect shipment data in return. Alternatively, a service provider, such as a marketing firm, might use a private data exchange to share account activity with individual customers. Some providers provide platforms specifically to facilitate private data exchanges.
- **Data marketplace**—A data marketplace is a public data exchange open to any company that wants to supply or consume data. This platform allows users to buy or sell different data sets from various sources. These marketplaces usually use cloud services where companies and/or individuals can upload data ([1]).
- **Public/cooperative exchange**—A public/cooperative exchange provides data for mutual benefit such as the Work Zone Data Exchange (WZDx) and General Transit Feed Specification, which was developed by the Federal Highway Administration and is increasingly being supported by agencies across the United States.
- **Public/private partnership data exchanges**—A partnership where government and private companies work together to secure and share data for people, the public good and commercial operations. Data Privacy, Data Security, Data Trust and Data Sovereignty are foundational to these Data Exchanges. These data exchanges will allow secure, private transaction sharing of valuable data assets with trusted and approved partners and may become a new economic platform for the communities they serve. One of the most successful early examples of this type of exchange is the Human Genome Project. Another example of the variation in how these partnerships may exist is the Texas Strategic Mapping Program.
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Figure 1 shows an example of a simple data exchange incentive model that connects data providers and data consumers.

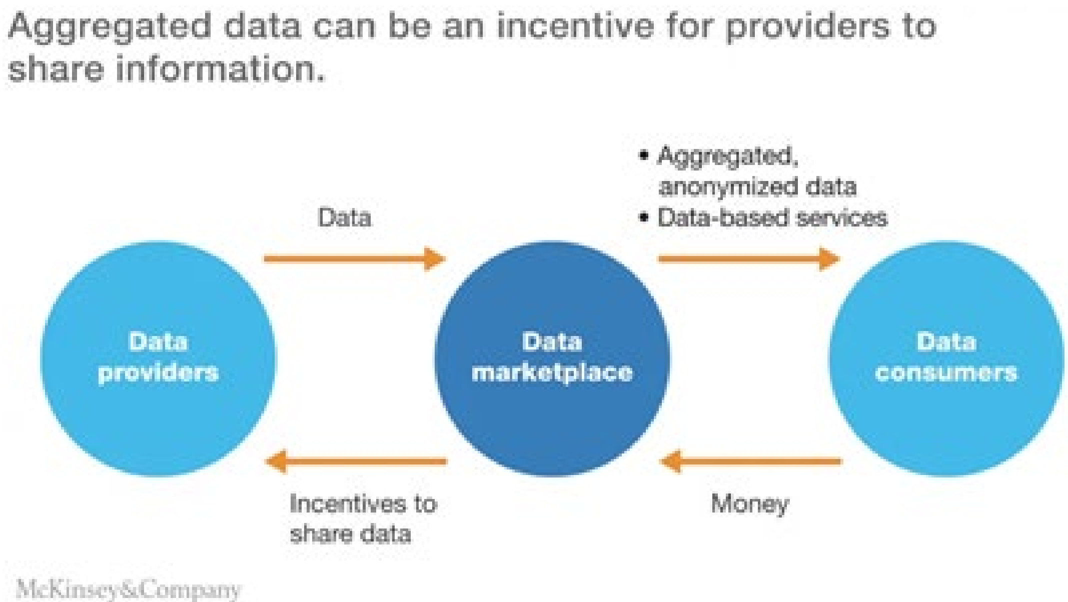

Figure 1: Data Marketplace

Baseline Functionality

For a data exchange to benefit all parties involved, it must enable data suppliers and consumers to share data securely and efficiently. As data exchanges develop and proliferate, the definitions, functionality, and overall usefulness will continue to be refined. For this to happen, the exchange must offer a baseline functionality that makes it easy for suppliers to publish data assets and for data consumers to find them. A data exchange will typically have the following baseline functions ([2]):

- **Searchable catalog**—Data consumers should be able to search a catalog of data assets in Structured Query Language (SQL) query or searchable tags. Each entry in the catalog contains a description of the data set and relevant details, such as the number of records, file type, statistics, and ratings.
- **Asset management**—A data exchange must make it easy for suppliers to upload, describe, manage, publish, and update data assets. It also allows suppliers to define licensing, access rights, and other terms and conditions and to manage their inventory.
- **Access control**—An exchange allows data suppliers to control who can access or purchase a data asset, in part or whole, and restrict access until an agreement or payment is complete. The four primary examples of data access control are:
    - **Discretionary access control**—The data owner grants access.
    - **Mandatory access control**—People are permitted access based on information clearance designed using a nondiscretionary method.
    - **Role-based access control**—Access is given to users based on a role assigned to them.
    - **Attribute-based access control**—Each resource and user receives attributes. This approach judges resource access by comparing the user's features, such as time of day, position, and location.

- **Data transfer**—A data exchange should support one or more ways for data suppliers to transfer data to consumers, including file transfer, application programming interface, and multi-tenant data sharing. Cloud-based file transfer uses object storage to hold files, simplifying access.
- **Transaction management**—Data exchanges should facilitate monetary transactions and offer payment terms, including bank transfers, credit cards, and account billing. Data consumers track their history of data purchases and subscriptions, see renewal terms, and cancel subscriptions. Likewise, data suppliers see a data set history of consumer transactions and activity.
- **Account management**—A data exchange lets consumers and suppliers create and manage accounts that contain information about users, administrators, authorized buyers and sellers, billing information, account activity, and payment mechanisms. Large organizations with multiple parties interested in acquiring external data can easily manage permissions and expenditures.
- **Authentication**—Data exchanges should have a way to authenticate that the supplier is sharing data it is entitled to share.

Currently, the industry has vast differences in the features and capabilities that are supported in data exchanges. For example, some of the developing cooperative exchanges between agencies may not have commercial features such as transaction and account management.

Value-Added Features

The following features and functions represent the evolution of the data exchange caused by competition. Most data exchange platform providers will soon require these features to do business ([2]).

- **Data enrichment services**—These data quality services include deduplication (removing duplicate items), address correction, standardization, data cleansing, file merging, and validation.
- **Selective sharing**—Some data exchanges let data suppliers selectively share data by filtering data for select consumers or by selecting consumers with whom to share data.
- **Data mapping**—Certain data exchanges analyze consumer data and then recommend supplier data within the exchange that best supplement or enrich those data.
- **Connector software developer kit**—Data exchanges can offer a software development kit that allows data exchange operators or suppliers to create a custom connector to less common data platforms.
- **Derived aggregate data**—Instead of giving consumers access to raw data that may contain sensitive data, data suppliers can instead offer user-defined functions (UDFs), such as analysis routines. Consumers run the UDFs against a described data set and receive the aggregated analytical output.
- **Enhanced onboarding**—This includes offering workflows and wizards to simplify the onboarding process for data suppliers. The workflows evaluate supplier data, assess compliance, and manage data ingestion.
- **Alerts**—Some data exchanges alert consumers when a newly published data set matches their interests. Some also alert data suppliers when potential customers join the exchange.

- **Enhanced reporting**—Data suppliers want a clear picture of their sales performance in the exchange. These reports can include top buyers to allow the suppliers to focus their efforts on the right consumers.
- **Custom data products**—Some data exchanges enable providers to create a data product by blending, segmenting, or engineering data to suit use cases and then publish that product to the exchange.

Data Governance

The Data Governance Institute defines *data governance* as "a system of decision rights and accountabilities for information-related processes, executed according to agreed-upon models which describe who can take what actions with what information, and when, under what circumstances, using what methods" (Error! Bookmark not defined.). The Data Management Association sees data management as a wheel, with data governance as the hub from which the following 10 data management knowledge areas come from ([1]):

- **Data architecture**—the overall structure of data and data-related resources as an integral part of the enterprise architecture.
- **Data modeling and design**—analysis, design, building, testing, and maintenance.
- **Data storage and operations**—structured physical data assets storage, deployment, and management.
- **Data security**—ensuring privacy, confidentiality, and appropriate access.
- **Data integration and interoperability**—acquisition, extraction, transformation, movement, delivery, replication, federation, virtualization, and operational support.
- **Documents and content**—storing, protecting, indexing, and enabling access to data found in unstructured sources and making these data available for integration and interoperability with structured data.
- **Reference and master data**—managing shared data to reduce redundancy and ensure better data quality through standardized definition and use of data values.
- **Data warehousing and business intelligence**—managing analytical data processing and enabling access to decision support data for reporting and analysis.
- **Metadata**—collecting, categorizing, maintaining, integrating, controlling, managing, and delivering metadata (data that provide information about other data).
- **Data quality**—defining, monitoring, maintaining data integrity, and improving data quality.

Data governance has three roles:

- Steering committee,
- Data owner, and
- Data steward.

Steering Committee

Steering committees often consist of senior management, C-level individuals (high-ranking executives in charge of various departments in a company, such as a chief financial officer), or individuals accountable for lines of business. Steering committee members' responsibilities include setting the overall governance strategy with specific outcomes, championing the work of data stewards, and holding the governance organization accountable for timelines and outcomes.

Data Owner

Data owners are individuals responsible for ensuring that information within a specific data domain is governed across systems and lines of business. Data owners are generally members of the steering committee though they may not be voting members. Data owners are responsible for the following ([3]):

- Approving data glossaries and other data definitions;
- Ensuring the accuracy of information across the enterprise;
- Directing data quality activities;
- Reviewing and approving master data management approaches, outcomes, and activities;
- Working with other data owners to resolve data issues;
- Performing second-level review on matters identified by data stewards; and
- Providing the steering committee with input on software solutions, policies, or regulatory requirements of their data domain.

Data Steward

Data stewards are accountable for the day-to-day management of data. Templar says data stewards are subject matter experts (SMEs) who understand and communicate the meaning and use of information. Data stewards work with other data stewards across the organization as the governing body for most data decisions. Data stewards are responsible for the following:

- Being SMEs for their data domain,
- Identifying data issues and working with other data stewards to resolve them,
- Acting as a member of the data steward council,
- Proposing, discussing, and voting on data policies and committee activities,
- Reporting to the data owner and other stakeholders within a data domain, and
- Working cross-functionally across lines of business to ensure their domain's data are managed and understood.

Challenges and Issues

Anyone who routinely consumes data has had a bad experience with third-party data. For a data exchange to be trusted, it must ensure it provides data integrity, quality, and consistency. Unless data consumers trust the data housed on a data exchange, they will not use it. Data exchange operator can do numerous things to ensure consumers trust the data, such as:

- **Curation**—While curation is challenging to scale, data exchange operators can certify and curate supplier data sets to ensure quality and consistency.
- **Profiling**—A data exchange should contain rich metadata about each data asset, including the number of rows, names and types of fields, cardinality, and other statistics, as well as the lineage of the data set, including source system collection methods and age.

- **Sampling**—Ideally, data exchanges allow consumers to query or sample data sets to validate data quality.
- **Ratings**—Much in the way e-commerce platforms provide ratings of products, data exchanges can allow consumers to give feedback on the quality and utility of data sets.

Data exchanges must reach a critical mass of data suppliers and consumers to gain traction and become viable, long-term operations. However, this is a chicken-and-egg situation: data consumers will not use a site that lacks sufficient breadth and depth of data assets, while data suppliers will not populate a site that lacks potential users. Unless a significant cloud platform runs a data exchange, it must target a specific market with built-in and demonstrated third-party data needs. Government agencies, industry consortiums, and membership organizations have a distinct advantage because they have a built-in audience and already serve as liaisons and intermediaries. However, even public-sector or cooperative data exchanges such as those referenced earlier need to embrace good data governance and cybersecurity principles to protect the data and potential users.

Although the primary function of a data exchange is to facilitate the transfer of data between suppliers and consumers, that does not add business value for data consumers. Data exchanges need to integrate third-party data with their existing data management systems so business users can access and query the data and all other internal data. To facilitate integration, data exchanges need to validate supplier data. Exchanges also need to ensure the data are clean, consistent, and delivered as described. That means the schema does not alter mid-stream, a column field does not change its name or type, and the number of records remains consistent. Exchanges also need to ensure that the data supplier has documented all the requisite metadata so data consumers can make informed purchasing decisions.

Issues surrounding the liability associated with data collection, aggregation, use, storage, and exchange are also important items to address. Data could be shared with the wrong people, exposing industry-protected information. Personal information could be captured and used to identify particular people or trips. The potential for tort liability claims related to having awareness of an infrastructure concern but not yet repairing it might increase. These situations and many more like them in the overall area of liability are complex and evolving.

Industry Interviews

The Data, Connectivity, Cybersecurity, and Privacy Subcommittee of the Texas Connected and Autonomous Vehicles (CAV) Task Force conducted interviews with companies in the CAV industry to better understand their view of data exchange. A wide range of topics were covered, including the meaning of the phrase *data exchange*, potential hurdles for adoption, privacy concerns, security, management, specification, and use cases. The following is the interview guide used while conducting the interviews. Not all questions were asked in each interview. Instead, these questions were used as a guide to make sure interviewers captured information on vital topics.

Interview Guide

Data Exchange

1. What does a data exchange mean to your organization?
2. What types of data does your organization not have but would like to have?

3. What types of data are most important to your organization?
4. What types of data would your organization be able to contribute?
5. Are there any use cases that would benefit your organization that you are missing data for? (Specifically, what are you missing in this use case?)
6. What would be the biggest hurdle your organization faces in participating in a data exchange?
7. How would your organization benefit most from a data exchange?
8. What do you think would be the ideal uses cases for a data exchange (public and private)?

Privacy

1. Would there be privacy issues with your organization participating in a data exchange for these use cases?
    a. Nondisclosure agreements
    b. Personally identifiable information
2. What kind of data would you be willing to share in these use cases?
3. What mechanisms would your agency need to have in place to ensure that proprietary data stay non-public?

Security and Management

1. Please provide your opinions on who should own/manage/operate a data exchange.
2. What types of safeguards would your organization require to participate in a data exchange?
    a. Access controls
    b. Use notifications/approvals
    c. Cloud configuration
    d. Encryption
    e. Disaster recovery response
3. Please provide your opinion on any data exchange best practices you have encountered.
    a. Safeguards
    b. Management
    c. Standardized formats
    d. Repeatable processes

Specifications

1. Does your organization adhere to any published data standards, or do you use your own specifications?
2. Would your organization require data it receives through a data exchange to comply with a data standard?

Panasonic

Panasonic's smart mobility division's goal is to develop intelligent mobility solutions. The division uses a combination of software, hardware, and advanced analytics to provide value to customers in every part of the mobility ecosystem.

Panasonic views a data exchange as a way to collaborate with other entities. The company is currently working on a vehicle-to-everything (V2X) platform called Cirrus. This platform provides an open development space for sharing, collaborating, defining, and standardizing smart mobility data. In addition, Panasonic is working with departments of transportation and commercial transit vehicle fleets to scale connected vehicle deployment from concept to implementation, operations, and maintenance across states and municipalities. The company currently has several hundred participating vehicles but is looking to scale up soon.

Panasonic is most interested in how to achieve scale, techniques to merge multiple data sets, and development of standard ways for managing data. Panasonic's ideal use cases are intersections, safety, mobility operations, and maintenance. The company is currently developing connected vehicle data specifications and hoping to work with the data community to evolve them. The work the U.S. Department of Transportation has done with the WZDx specification is an example that it is taking lessons learned. In addition, Panasonic is currently developing a data exchange best practice document. It is still a work in progress, but one of the most significant issues encountered is the need for data dictionaries. Without a data dictionary, there is a high chance that people will assume the wrong unit of measurement.

Locomation

Locomation is working on autonomous relay convoys (i.e., platooning). Although the company's end goal is full automation, it has been working on lateral and longitudinal acceleration.

Locomation's long-term goal for data exchanges is to integrate them with its system to be a data source for convoys. A data exchange is not part of the company's initial product, but future generations could include data exchanges. The data exchange must be able to confirm data availability and data freshness. Being able to rely on the data is paramount for integration. Resources and penetration rate are other hurdles to potentially participating in data exchanges. While current resources are focused on building out a product line, future plans include a focus on data exchanges and data-exchange-related activities. With respect to penetration rate, Locomation wants to find out how much coverage there is nationwide. The company does not want to rely on work zone data without full coverage. Work zone data are viewed as its highest-priority need. This is echoed by other automated vehicle developers. Original equipment manufacturers (OEMs) want improved work zone data so their level 2+ and level 3 systems are not disengaged when their vehicles approach work zones. Other needs include weather, weigh station bypass, enforcement actions, and rail grade-crossing data. Locomation would be interested in sharing its data in a data exchange but would need more information on requirements and use cases.

Locomation's privacy concerns depend on the data. For example, it does not think sending an alert for a possible pothole on a roadway would be problematic, but anything that could be used to identify a truck or route would need to be scrubbed. When it comes to data specifications and standards for its V2X data, Locomation adheres to Society of Automotive Engineers standards although they are not a perfect fit for all data.

Case Studies

Work Zone Data Exchange

The WZDx enables IOOs to make standardized work zone data available for third-party use. The objective is to make travel on public roads safer and more efficient through universal access to data on work zone activity. Specifically, the project aims to get data on work zones into vehicles to help automated driving systems and human drivers navigate more safely (1). The WZDx continues to mature, allowing for more and varied contributors, users, and types of information.

Via the WZDx, the Federal Highway Administration is leading efforts to develop a nationwide standard approach for collecting, organizing, and sharing data on the when, where, and how of work zone deployment. As the nation develops an increasing reliance on technology and next-generation transportation management, ensuring the availability of consistent, reliable data describing work zone events is critical to enabling agency management of highway operations.

This national initiative aims to create and accelerate the adoption of a consistent language for communicating work zone activity data across jurisdictional and organizational boundaries. Adopting this common language will result in enhanced work zone management practices, leading to improved mobility and safety in and around work zones for workers and the traveling public. Numerous parts of the Texas Department of Transportation (TxDOT) and other jurisdictions across Texas are actively using or investigating WZDx as a methodology for sharing critical work zone activity data. It is believed that not only will these data help both CAVs but could also help improve work zone safety overall and provide a source for advanced traveler information for non-connected vehicles (4).

Common challenges experienced when implementing a WZDx data feed include the following (1):

- The project seems intimidating.
- There are budgetary restrictions.
- The benefit to consumers is unclear.
- The benefit to the agency is unclear.
- There is uncertainty about whether JavaScript Object Notation (JSON) elements within the data feed are correct.
- There is uncertainty about how to provide data for recurring work zones.
- Work zone examples within the WZDx GitHub repository do not align perfectly.

Best practices include the following:

- Start small. Focus on specific and clear work zone parameters already available, potentially from another project.
- Start with manual data entry. Then, only attempt to immediately automate some aspects of the agency's work zone information. Get a few elements working successfully first.
- Use contract resources when available.
- Solicit inputs from data consumers. Ask automakers, mapping companies, etc., why the data are important. Ask other state agencies how their data are being used.
- Take advantage of connected field devices deployed at active work sites.
- Leverage JSON validation tools available through the WZDx GitHub repository.
- Request technical assistance from the WZDx Help Desk or GitHub.

Florida Department of Transportation Data Exchange

A Florida Department of Transportation (FDOT) project is the first in the United States to develop a V2X data exchange, with the aim of capturing data from thousands of devices across CAV and infrastructure networks. A key aim of the project is to standardize the collection, analysis, and sharing of data from several proprietary systems, which have different coding and encryption methodologies, and to unify privacy and security mechanisms across different sources and users ([1]). Figure 2 illustrates the ecosystem of the FDOT platform.

The exchange will capture anonymous data both from standardized onboard units communicating directly with FDOT-owned roadside units and from the proprietary data feeds of various car manufacturers. These connected vehicle data will be fused with a range of other data from FDOT-owned infrastructure and third-party data feeds. This enriched data stream will be the basis for real-time and historical analysis, leveraging machine learning and traditional algorithms. Figure 2 illustrates how the data exchange ecosystem works.

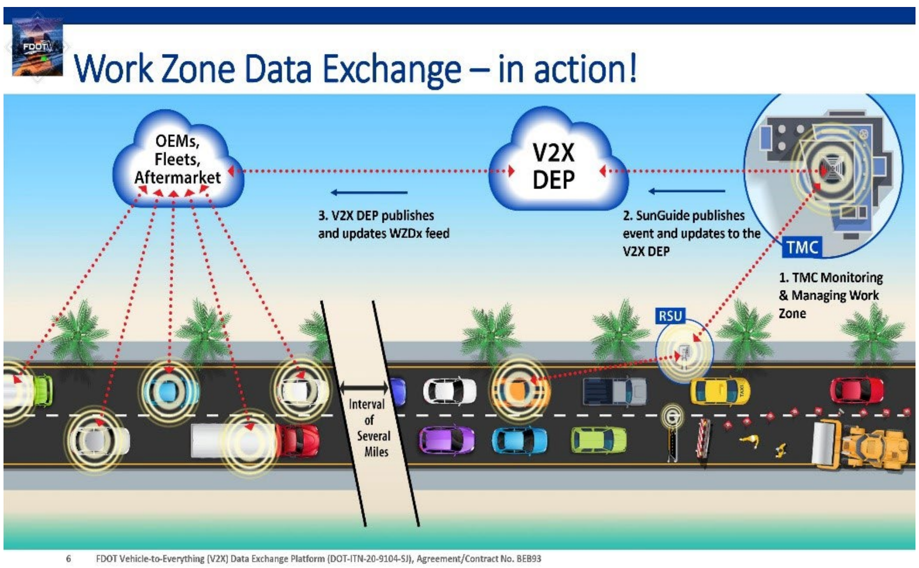

*Figure 2: Work Zone Data Exchange Ecosystem (**Error! Bookmark not defined.**)*

FDOT program participants include Ford Mobility, which will supply V2X data from its connected vehicle platform; Iteris, a smart mobility company based in California; Florida International University; Amazon Web Services; Google; several OEMs; and logistics and fleet companies.

Owned by FDOT, the resulting data exchange will be available for use by other public agencies throughout the United States. In addition, this enables platform standardization across agencies and users and provides mutually beneficial cost sharing to develop new and improved functionality over time. Figure 3 shows the partners and participants at each level of the exchange.

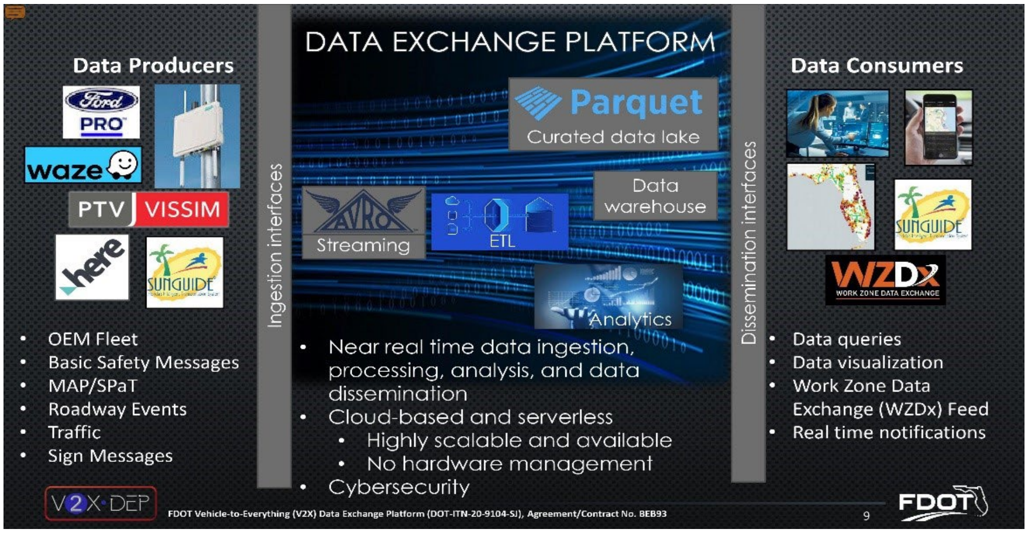

*Figure 3: FDOT Data Exchange Platform Participants (**Error! Bookmark not defined.**)*

Summary and Conclusion

This white paper discusses, at a high level, the definition of a data exchange, the various components, data governance, security and compliance issues, industry leader thoughts, and case studies of operational data exchanges for transportation. Creating data exchanges for CAV data presents a unique opportunity to be able to expand research, product offerings, traveler information, and potentially roadway safety through cooperation and sharing. As vehicles become increasingly connected with each other and their surroundings, the data that are produced will increase exponentially. No single agency or company will have the ability to collect, clean, store, and analyze all of the data. This represents an opportunity to identify and elaborate on mutually beneficial methods of sharing these data, particular among public agencies and the users of the roads these agencies own, operate, and maintain. Developing resources such as the WZDx and the FDOT data exchange demonstrates an appetite for a platform that allows this type of sharing.

Because CAV data are a new genre of data, there are still many questions about many aspects of sharing, including privacy, security, and formatting. The needs of various users may be different depending on the use case. For example, the privacy considerations related to pothole locations are substantially different than those for vehicle journey data that may identify discrete points of a trip for individual vehicles. Currently, in the United States, there is no comprehensive approach to data privacy regulations. The Federal Communication Commission's nonbinding fair information practices guide data privacy protections, but federal law does not require companies to have a privacy policy or notify consumers of their privacy practices. States such as California, Nevada, and Maine have data privacy laws, but only California's pertain to non-online business practices.

Data standards and specifications are a critical area that also needs to be addressed. Like privacy, standards and specifications could vary based on use case. Numerous companies are attempting to follow and/or develop data standards, but the industry has not yet defined what those are in all cases.

Solving these issues can help provide a path for data exchanges moving forward, particularly for high-priority use cases such as work zones, real-time traffic and road conditions, and roadway inventories.

Opportunities

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:

- Developing a comprehensive list of data exchanges that are pertinent to the development and deployment of CAVs and that also will improve operations and safety for human-driven vehicles. This would include an inventory of what private-sector companies would participate in data exchanges for any given use case.
- Identifying the most useful data exchange CAV and safety use cases for the state and its jurisdictions by collaborating with current and future users to identify needs.
- Developing 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.
- Identifying potential failure points of data exchange collaboration and mechanisms to mitigate the concerns that could impact acceptance and usage.
- Encouraging TxDOT, with the help of metropolitan planning organizations, private contractors, and cities, to make a push for improved WZDx reporting statewide.
- Continuing the procurement of third-party data sources because these data platform-sharing initiatives promote standardization, cooperation, and data fluency at all levels of roadway operations.

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APPENDIX B

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Strategic Communication Plan for Advancing the Dialogue about Connected and Automated Vehicle Technology

Texas CAV Task Force
Subcommittee on Education, Communication, and User Needs

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Education, Communication, and User Needs Subcommittee of the
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August 2023

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Table of Contents

List of Figures

List of Tables

Acknowledgments

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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:

- Coordinating and providing information on CAV technology use and testing in Texas.
- 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.
- 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

CAV	connected and autonomous vehicle; also, connected, and automated vehicle
FAQ	frequently asked question
TCP	tactical communication plan

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Executive Summary

Connected and autonomous vehicle (CAV) technology holds much promise, but questions remain surrounding its widespread use and adoption. The issues include planning, policy making, regulatory and legal frameworks, institutional issues, operations, funding, and ultimately public trust and acceptance. The Texas CAV Task Force's Subcommittee on Education, Communication, and User Needs supports statewide efforts to inform and engage with agencies, stakeholders, industry, and the general public.

This document sets forth a strategic communication plan for the CAV Task Force. The strategic communication plan identifies four overarching goals:

- Educate,
- Generate awareness,
- Build trust, and
- Increase adoption.

The strategic communication plan is premised on best practices of communication including:

- Audience identification and segmentation,
- Market research,
- Message design, and
- Message delivery.

This plan recognizes that specific outreach and education messages and tactics, tailored to specific audiences based on their needs, serve to enhance overall education and outreach efforts. Based on guidance from the subcommittee, this plan identifies stakeholders and audiences. It presents communication techniques and tools, messages, and message delivery mechanisms. It is strategic but also suggests various tactics. Importantly, it recognizes the need for continuous evaluation and adaptation as audiences change and grow and technology advances. Public outreach plans can guide development of materials for specific audiences and provide a comprehensive roadmap for education and outreach efforts beyond the key messages.

The education subcommittee, with its broad multidisciplinary representation, is the forward-facing entity responsible for executing an engagement plan. The subcommittee's charge and responsibility are to develop tools and resources that allow for meaningful engagement. This strategic plan will guide those efforts.

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Introduction

Communication, education, and outreach each have roots in many of the social science disciplines. Social marketing programs have been used for decades in everything from smoking cessation to litter control. The marketing campaigns have led to changes in social behaviors and attitudes, and this has had a positive impact on society.

In the transportation arena, messaging has been used to accomplish a wide range of goals including communication campaigns, education campaigns, and safety campaigns. Moreover, we know that education and awareness increase acceptance. This is a primary goal of the Education, Communication, and User Needs Subcommittee of the Texas Connected and Autonomous Vehicles Task Force. Previous research around acceptability, use, and trust of connected and automated vehicle (CAV) technology shows that familiarity and experience with the technology increase favorability, but the public still has concerns, even beyond the technology itself.

Education and outreach to multiple audiences can build awareness, generate trust, and increase adoption. Efforts should expand beyond the identification of benefits and should seek to answer questions and address issues across broad categories based on audience. Baseline research should inform these efforts by identifying the positions and interests of each audience. Overarching key messages will be supported by secondary messages that are relevant to each audience. Education and outreach should function in a continuous feedback loop so that as issues are raised, input can be gathered, and solutions can be formulated.

Background

In June 2021, the CAV Task Force published a white paper entitled *Understanding Perceptions and Opinions about Connected and Automated Vehicle Technology: Advancing the Dialogue.* The paper researched and synthesized recent efforts to educate the public about CAV technologies through pilots, demonstrations, and first-use operations. The paper documented the results of consumer acceptability following some CAV pilots projects and identified tactics that may be effective for future educational efforts. This white paper builds on that effort by documenting communication best practices and applying those principles. The result is a strategic communication plan. The plan will guide the work of the subcommittee as it implements specific tactics to achieve the goals of the communication strategy.

Communication Best Practices

Education and outreach about CAV benefits and opportunities in Texas will benefit from fundamental communication best practices for effectiveness. These include:

- Audience identification and segmentation—Identify the audience(s) and their motivations to develop messages that empower supporters, convince uncertain individuals, and minimize the impact of opponents.
- Market research—Learn about the audience, what they care about, and what messages will best convince them.
- Message design—Several principles define the best ways to design a message including keep it simple, stay positive, use metaphors, make it personal, and offer a call to action.

- **Message delivery**—Inconsistent delivery will derail even the best messages. Continually and consistently repeat the message so it will not get lost.

Communication Plan

This communication plan, developed by the Texas CAV Task Force Subcommittee on Education, Communication, and User Needs, broadly outlines the *communication strategy* for the CAV Task Force. The plan recognizes that specific outreach and education messages and tactics, tailored to specific audiences based on their needs, serve to enhance overall education and outreach efforts. Based on guidance from the subcommittee, this plan identifies stakeholders and audiences. It presents communication techniques and tools, messages, and message delivery mechanisms. It is strategic but also suggests various tactics. Importantly, it recognizes the need for continuous evaluation and adaptation as audiences change and grow and technology advances. Public outreach plans can guide development of materials for specific audiences and provide a comprehensive roadmap for education and outreach efforts beyond the key messages.

Development of such plans will ensure that messaging is consistent across formats. The plans will also serve to allocate adequate time and resources by identifying specific actions. The plans can prioritize activities. Subplans should be developed for different audiences. For example, a plan specific to the legislature should focus on why investment in these activities is important and how legislation can support that; a plan aimed at local government should include development of information that addresses local issues and why these activities are important.

Communication Process

As outreach occurs, it is imperative that its effectiveness be measured. This evaluation will reveal what messaging is resonating and what methods are most effective. Evaluation can identify gaps in knowledge that can be addressed. Evaluations can also uncover misperceptions that can be addressed before they become set in the public's opinion. Systematic and consistent evaluation will reveal trends over time that will aid in understanding outreach effectiveness. Polls and surveys are useful methods of evaluation, but qualitative research through structured interviews and focus groups allows for a deeper understanding of why a person feels a certain way about something. These rich data will inform subsequent outreach efforts. To be clear, this evaluation should focus not only on the public's perception of CAV technology but also on the effectiveness of the educational information that is being provided. Not assessing the effectiveness of outreach and educational campaigns is a misstep that results in wasted time and resources.

[redacted]

Not assessing the effectiveness of outreach and educational campaigns is a misstep that results in wasted time and resources.

In addition to tailoring messages for specific audiences, information should be provided in a manner that is appropriate to the audience. In all instances, the information should clearly communicate the key messages. It should be comprehensible to the intended audience without the need for additional research. Messages should be available in the media of choice for the receiver and should be accessible and available as requested by the receiver. Fact sheets, frequently asked questions (FAQs), myths, and truths are products that provide information in an easy-to-manage and -digest format. Moreover, this information can be provided in many forms such as printed materials, a website, videos, and social media. Figure 1 illustrates this progressive but not necessarily linear process that builds on the fundamentals identified previously.

The first step of the process is fundamentally stating the goals for the communication plan. These are likely to be the same regardless of the audience. Identifying and segmenting audiences allow messages to be targeted and focused on what is important to each cohort. And the messages can be delivered in a way that is most appropriate for that audience, by an appropriate messenger. This leads directly to message development. This step is critical because audiences are subjected to a barrage of messages daily. Messages need to be conveyed quickly, clearly, and simply with opportunities for more detailed information.

Message development will benefit from pre-implementation testing in much the same way that market research can inform the message development. This step is often skipped but can help determine how messages will be received and, perhaps more importantly, *interpreted* prior to a final campaign launch. Qualitative methods such as focus groups or interviews are useful for conducting pre-implementation testing because they allow for in-depth discussions of why a message does or does not resonate. Because there are so many mechanisms available for message delivery, it is necessary to give critical thought to which might be most effective. Knowing where, when, and how the audience receives its information will make this step easier.

The final step is another that is often overlooked. A well-formulated evaluation plan is imperative to gauge the success of the campaign. And mini evaluations during the campaign can allow the campaign to shift, pivot, or clarify during the campaign, thereby saving time and resources.

Figure 1 serves as a starting point for completing the necessary steps to develop an effective communication strategy. The strategy can then be used to develop specific outreach plans for each audience. It is likely that many of these components will overlap, so the user should not be dissuaded by the number of audiences or messages nor the complexity of those overlapping relationships. Conducting this exercise is a necessary first step, and it is important to be as comprehensive as possible; prioritization may be necessary and can be accomplished later.

Examples of Stakeholders and Organizations

- Texas Legislature
- Texas Department of Transportation
- Transportation agencies
- Transit agencies
- Toll authorities
- AAA
- Technology providers
- Original equipment manufacturers
- Vehicle manufacturers
- Vehicle dealerships
- Consumer organizations
- Research agencies/centers
- Universities and colleges
- Consumer technology associations
- Smart mobility initiatives
- Businesses deploying CAV for services
- Mobility-as-a-service providers

Figure 4: Important Components of a Communication Strategy

Stakeholders

The subcommittee benefits from the involvement of partners from various public agencies, private sectors, universities, and special interest groups. Stakeholders are key in the communication process because they can help identify audiences, perform message testing, and serve as conduits for message delivery. Collaboratively, the stakeholders can move the education and outreach efforts forward. The subcommittee, collectively, can assess program activities based on the needs identified by stakeholders.

Communication Goals

Messaging from the Texas CAV Task Force and the subcommittee seeks to:

- Educate,
- Generate awareness,
- Build trust, and
- Increase adoption.

Each communication technique, tool, or material developed will be designed to contribute to one or more of these communication goals. The four areas are overarching and common goals regardless of the audience.

Educate

Beginning with education, communication materials should provide information about why Texas, as a whole, has an interest in CAV technology. Education provides context to the audience. Education tells the audience why they should be interested and/or what might be important to them. It is not about persuasion but simply providing information. The technology(ies) should be explained in terms understandable and accessible to a general public audience. Examples can help to illustrate how CAV works and who might be impacted and how. Specific strategies can be developed to address the educate goal, based on the audience.

Education can also extend to stakeholders. Helping stakeholders to understand their role in advancing CAV technologies in Texas and providing them the tools to do so will multiply educate efforts.

Generate Awareness

Similar to educating, generating awareness is also a primary focus of communication from the subcommittee. Awareness of CAV advancements in Texas can be increased by providing available information about pilots and demonstrations that are happening in the state and beyond. Specific tools and techniques to general awareness should be based on the audience. A careful audience analysis and situational assessment will provide useful information about how specific audiences receive information, what factors increase the trust in or credibility of that information, and who is best to convey the information.

Moreover, the active pilots and demonstrations are unique opportunities to generate awareness and educate people about the technologies. Subcommittee activities should capitalize on opportunities to generate awareness by focusing on pilots and demonstrations when available. Events should focus on bringing the technologies to the people so they may experience CAV in action, firsthand.

Build Trust

The subcommittee's communication should help to build trust. The goal is to establish trust first in the communication materials and should extend to the CAV technologies themselves. It is important to consider research that has been conducted when considering messages to build trust. The issue of trust is multifaceted. Early research indicates there is some trust in the belief that CAV technology can improve safety. But that same research also states that individual trust in the technology is more limited, as is trust that the government will ensure the safety of the technology by enacting laws. Messages to build trust must provide reassurance about the technology and outline safeguards that have been enacted for consumer protection. Again, careful audience analysis and situational assessment will identify areas of mistrust or distrust, and messages can be crafted to address them.

Increase Adoption

One of the primary goals of the Texas CAV Task Force is to become a central point for CAV advancement in Texas. Research also reports that education and awareness help to build trust, which increases adoption rates. Communication about pilots and demonstrations contributes to adoption by helping the general public to become more familiar with the technology. Likewise, communication tools, techniques, and applications can serve as resources for other stakeholders. This, too, can increase adoption.

Audience Identification

The subcommittee determined that the intended audience of the communication plan is the general public. However, communication will be served best by grouping or categorizing portions of the general public so that message content can be tailored, and message delivery can be best suited to audience preferences. Understanding what each audience cares about and what motivates them will inform communication tactics. Some of the audiences are also stakeholders. This beneficial relationship allows information to flow freely back and forth and leverages outreach activities. Also, it will be necessary and useful to prioritize audiences to align resources. Based on discussions with the subcommittee, Table 1 represents potential audiences. A strategy work session with the CAV Task Force and all members of the subcommittees will further refine and prioritize the list.

Table 1: Universe of Audiences

Public Agencies	Quasi-public Agencies	Special Interest Groups	Industry/ Trade Groups	General Public
• Texas Department of Transportation • Texas Department of Motor Vehicles • Texas Department of Licensing and Regulation • Texas Department of Public Safety • Texas Department of Emergency Management • Texas Department of Insurance • Texas Economic Development Council • Texas Department of Economic Development • Texas Commission on Environmental Quality • Texas Railroad Commission • Texas Workforce Commission • Texas Association of Counties • County/city staff • Transportation/transit agencies • Toll authorities • Governor's Committee on People with Disabilities • Texas Council for Developmental Disabilities • Texas Health and Human Services, Department of Aging and Disability • EMS/fire departments • U.S. Customs and Border Protection	• Higher education • Research agencies/ centers • Texas A&M Engineering Extension Service • Economic development corporations • K-12 school districts (public and private) • Consumer protection agencies • Business improvement districts • Safety coalitions • Alternative transportation groups (e.g., first/last-mile connections and commute solutions) • Governors Highway Safety Association	• Texas Association of Metropolitan Planning Organizations • National Association of City Transportation Officials • National Association of Counties • Texas Municipal League • Texas Association of Business • Smart Mobility Initiatives • Coalition of Texans with Disabilities • ADAPT of Texas • Arc of Texas • American Automobile Association • Texas Farm Bureau • Rideshare companies • Partners for Automated Vehicle Education • American Association of Retired Persons • Texas Senior Advocacy • Elder Options of Texas • Travel and tourism • Chambers of commerce	• Technology providers • Mobility-as-a-service providers • Vehicle manufacturers • Vehicle dealers • Original equipment manufacturers • Businesses deploying CAV technologies • American Planning Association • American Society of Civil Engineers • Texas Society of Professional Engineers • Texas Trucking Association • Independent Owner Operator Association • Freight/ logistics • Insurance companies • Texas Towing and Storage Association	• Those 15 years old and younger (non-drivers) • Early adopters of technology • Late adopters of technology • People who do not own a personal vehicle • People who drive as their occupation (tow truck operators, rideshare drivers, etc.)
Elected Officials				
• Texas Legislature • Metropolitan planning organization policy boards • County elected officials • City elected officials				

Message Development and Testing

Key Messages

Two or three key messages should be communicated across the board to all audiences. More than that will dilute the focus. The key messages should be clear and concise and tie back to the communication goals. Research about attitudes and perceptions related to CAV can uncover the biggest misperceptions. The communication goals include education and awareness, so it is likely that key messages should focus on the misperceptions. The key messages should be broad enough that they are useful to all audiences.

Supporting Messages

Supplemental messages tailored to specific audiences can support the key messages. Market research will improve the understanding of the attitudes of particular audiences and help to guide supporting message development.

Message Development

Particularly with support messages, messages should center on the motivations of each group and address the issues that are important to each group. If previous market research is conducted, it can provide information about what kinds of information are most credible, whether a group prefers facts and figures, whether a group prefers a visual or narrative message, and what style or tone will be best received. This research will also answer more straightforward questions such as which language to use for communication.

As communication materials are developed, it is important to consider materials that address issues beyond the benefits of CAV technology. Research shows the public has many unanswered questions, especially related to the legal and regulatory nature of CAV technology. Acknowledge that some questions cannot be answered at this time and explain how they are being studied.

Another important consideration in communication planning is to assess plans and materials to ensure that outreach and education are made available to all citizens. Demonstrate how CAV technology deployment and investment will create benefits for all users of the transportation system.

Message Testing

After the messages are developed, they should be tested with the intended audience. Key messages can be vetted with the entire CAV Task Force and primary stakeholders. Qualitative research such as focus groups can test other supporting materials before time and resources are expended on a full-scale production and deployment.

Pre-implementation

Testing at this stage can answer questions such as:

- Is the message appropriate for the intended audience?
- Is the message understood as intended in the campaign goals?
- Is the message clearly stated?
- Is the message perceived as useful to the target audience?

- Is the message remembered?
- Is the message provoking unexpected feelings or reactions in the target group?

Message Delivery

Many factors determine how a message reaches an intended audience. There are many mechanisms for message delivery, just as there are many messengers. The tool, technique, material, and frequency should be based on knowledge and understanding of the audience. In all cases, there should be multiple mechanisms. Table 2 outlines options for message delivery. The key messages can be provided by a member of the CAV Task Force, who can then help to ensure message consistency even when partners use and/or adapt those messages to their constituencies. It will be important to maintain consistency as the messages are communicated.

Table 2: Message Type and Delivery Options

Techniques	Tools	Materials	Messengers
• Briefing presentation • Stakeholder meetings • Educational brown bags • Special event booths • Media partnerships • Career fairs • Specialized curriculum • Tabling at community events • Social media campaigns, such as Facebook, NextDoor, etc.	• CAV Task Force website • Surveys • Focus groups • Social media • Paid media • Town halls • Neighborhood meetings • Workshops • Conferences • Demonstrations	• FAQs/fact sheets • Newsletters • Animations/videos • Live demonstrations • Informational flyers/posters • PowerPoint slide deck • Media kit/news releases • Direct mail	• Key stakeholders • Task Force partners • Elected officials • Neighborhood advocates • Trade group spokespersons • Educators • Disability advocates • National or local celebrities • Religious leaders or respected elders • Friends/family • Other implementers

Message/Communication Evaluation

A thoughtful evaluation plan will determine if the communication is effective. The plan evaluates specific activities and allows for fine-tuning if something is not working as intended. Prior to deploying a communication program, key performance indicators, metrics, and thresholds should be defined. Evaluations should include both quantitative and qualitative data and measurement. The focus should be on the communication and not the technology though there will be some overlap.

Evaluation can occur at both strategic and tactical levels.

Strategic Evaluation

Strategically, goals are to educate about and bring awareness of CAV technology in Texas. These are precursors to building trust and increasing adoption. Therefore, it is necessary to measure people's awareness of the technologies and assess their knowledge of technologies. To assess the change, this evaluation should be conducted prior to initiation of the communication plan and post-deployment, at a minimum. Ideally, evaluation should occur at regular intervals or milestones of the communication plan deployment so that adjustments can be made if necessary.

Tactical Evaluation

Tactical evaluation centers on measuring specifics about the communication strategy such as measures of reach, the number of website visits, the number of messages retweeted, the number of media mentions, etc. But tactical evaluation also includes the quality of messaging. Measures may include message understanding, message clarity, trust in the message, message credibility, and changes in levels of support.

Specific measures should be identified for each indicator. Likewise, thresholds should be established. For example, an evaluation indicator might be the *percentage change of people that correctly identify at least five CAV technologies.* The metric is the percentage of people that correctly identify five technologies. The objective is to increase that percentage based on the communication goal to educate. And a threshold could be set, such as a 10 percent increase in the first six months.

Summary and Conclusion

The Subcommittee on Education, Communication, and User Needs has set four specific communication goals. This strategic communication plan outlines the steps necessary to implement strategies and tactics to achieve those goals. It identifies stakeholders that can support implementation and provides an initial categorization of primary audiences. Further, the plan describes activities for pre-implementation testing and evaluation.

The next step is for the committee to put the communication plan into action by determining roles and responsibilities for activation. Specific education and outreach plans can be developed based on the key messages of the communication campaign. The subcommittee needs to agree upon the two or three key messages first and then develop detailed plans targeted to specific audiences that detail audience-specific messages, tools, and techniques. The commitment to a comprehensive communication plan provides coordinated and consistent messaging about the CAV activities in Texas. This can build the trust and credibility of the Texas CAV Task Force as a knowledgeable and reliable source of factual, unbiased information.

Opportunities

Moving forward, the subcommittee has many opportunities to communicate about CAV activities in Texas, be they pilots, demonstrations, research findings, or workforce initiatives. In December 2022, the subcommittee convened a communication workshop to engage members of other CAV Task Force subcommittees. While the Education, Communication, and User Needs Subcommittee is leading communication efforts, the subcommittee will rely on the members from other subcommittees to expand the reach of the communication messages. For this reason, it is imperative that regardless of subcommittee, members of the CAV Task Force are speaking with one voice about CAVs in Texas.

This is the objective of the tactical communication plan (TCP). CD&P, the communication consultant engaged to support this effort, is responsible for the development and implementation of the TCP, guided by this subcommittee and with input from other subcommittees when appropriate. The TCP builds upon findings from the communication workshop that helped identify and prioritize audiences and their respective motivations. The key messages that provide the foundation for outreach, engagement, and communication will be created based on input from the communication workshop.

The TCP will outline collateral and associated messaging based on the prioritized audiences identified in the workshop. Specifically, an early opportunity is to develop information kits. The kits can include branded and formatted messages in a variety of pieces, such as fact sheets, FAQs, graphics, social media messages, infographics, short use cases, etc. This information will be packaged so that it is easy to share with partners and messengers. Providing ready-made information helps ensure the message from the CAV Task Force is consistent. Moreover, branding can help instill trust that the message comes from a reliable and reputable source.

Additionally, the TCP guides implementation practices and evaluation protocols. As noted in this strategic communication plan, measurement and evaluation are critical for any campaign. The TCP will identify specific metrics that can be used to gauge reach and effectiveness. The Education, Communication, and User Needs Subcommittee can provide guidance on appropriate metrics, establish thresholds and targets, and determine evaluation time frames and schedules. Moreover, evaluation should measure changes in attitudes and/or behaviors related to the communication goals and also the messages themselves, including factors such as clarity, comprehension, ability to affect change, etc.

Finally, the TCP should define communication protocols between the subcommittees of the CAV Task Force. Each subcommittee will likely be the conduit or messenger for outreach to audiences that are particularly relevant to that subcommittee. For example, the Licensing and Regulation Subcommittee may be the individuals to reach out to law enforcement and/or regulatory agencies. It is necessary to document these encounters to accurately and comprehensively measure the reach of the program and the effectiveness of the messages. The TCP can outline these protocols and establish a process to ensure each engagement is captured.

The TCP will provide the roadmap necessary for this subcommittee to effectively and efficiently reach the prioritized audiences and deliver a clear and consistent message about CAVs in Texas.

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APPENDIX C

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Latest Considerations for Highway and Controlled Environment Freight Automation in Transportation Operations

Texas CAV Task Force
Subcommittee on Freight and Delivery

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August 2023

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Table of Contents

List of Figures

Acknowledgments

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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 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

ATHN	autonomous transfer hub network
AV	automated vehicle
CAV	connected and autonomous vehicle
CDA	cooperative driving automation
CV	connected vehicle
DOT	department of transportation
GDOT	Georgia Department of Transportation
MARAD	Maritime Administration
MDOT	Maryland Department of Transportation
ROW	right of way
TCAT	Texas Congestion Analysis Tool
TCFC	Texas Connected Freight Corridor
TRB	Transportation Research Board
TxDOT	Texas Department of Transportation
V2I	vehicle to infrastructure
V2X	vehicle to everything

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Executive Summary

Texas is a leader in the adoption of connected and autonomous vehicle (CAV) technologies, with many companies testing or implementing automated goods movement technologies. It is recognized that the freight ecosystem remains a rapidly changing environment. The Texas Department of Transportation (TxDOT) and partners need to consider the future of emerging freight CAV concepts as it pertains to highway operations. This white paper reviews the latest opportunities, best and emerging practices, and implementation options to support the continued development and support of freight CAV activities in Texas. These activities include:

- Developing a transfer hub/terminal strategic plan: developing an automated trucking transfer hub/terminal strategic plan that includes a thorough evaluation of existing and planned implementation in Texas, how this will impact the freight network, what the development impacts and needs are, and some specific outlining of roles and responsibilities, including support to local governments.
- Assessing Texas Freight Network and automated truck impacts: assessing how automated trucking will change the Texas Freight Network, what infrastructure is needed (including business route optimization, and drayage and circuit identification), what operations coordination would help, and where priority corridors or circuits are that support automated trucking.
- Developing a freight CAV ecosystem: creating an opportunity to share information between the public and private sectors in robust ways; offering ways for the private sector to input activities, and for the public sector to provide data about the freight network, freight facilities, existing freight flows, projects, and more.

While border and law enforcement remain a critical area of concern for freight CAVs, these issues are being studied under different platforms, including the work related to Senate Bill 1308.

The main consideration of this paper is on highway and controlled environment locations. However, many CAV deployments in Texas are in urban areas like Dallas and Austin, and there is potential for activity on resource roads that needs additional research and coordination. The street locations further require in-depth coordination with local governments, as well as discussion of jurisdictional decision-making and how that impacts CAV development decisions.

During the development of this white paper, numerous changes occurred in the companies in the automated truck space. While this paper may refer to a company no longer in existence at the time of publication, it is important to document the activities that have taken place. Steps by companies no longer in the space can still be meaningful to the continued future development of the ecosystem.

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Introduction

The Freight and Delivery Subcommittee of the Texas Department of Transportation (TxDOT) Connected and Autonomous Vehicles (CAV) Task Force leads the way for TxDOT to support emerging CAV technology implementation in Texas. The CAV Task Force represents public- and private-sector stakeholders who share a common goal of ensuring continued awareness of CAV technology and who support TxDOT in its role to prepare and implement the types of policies, plans, infrastructure, and operations necessary to support current and future technology.

In 2021, the Texas CAV Task Force Freight and Delivery Subcommittee outlined the following questions related to automated freight:

- What would automated freight look like in Texas, and how would it impact border trade and new economic opportunities?
- What are the law enforcement interaction needs related to automated vehicles (AVs) and autonomous trucks?
- What are freight launch pads (transfer hubs or terminals) that allow AV trucks to get on the highway, perform autonomously, and get off the highway? How do they operate? What kind of relationship do they have with the highway network?
- How can TxDOT encourage pilots and trials of automated freight movement? How can TxDOT be a catalyst for the private sector, TxDOT, or federal government to engage in pilots and trials?
- Are hazardous materials allowed? Currently, Texas has no regulations preventing it, but is it something automation companies are looking to do ([1])?

This document provides an update on the latest in automated freight technology. This paper frames areas of focus and action items for TxDOT and its partners to pursue for planning, policy, and project development for automated trucking. Specifically, this paper seeks to answer questions such as:

- What are the key issues, and how can they be addressed?
- What can TxDOT do to continue to ensure forward-thinking operational opportunities for autonomous trucking?

Texas is already a leader in the adoption of CAV technologies, with many companies testing or implementing automated goods movement technologies and significant research to support development of uses and relationships for CAV related data that supports decision making and system operations. It is important, however, to organize the critical path planning, policy, and project elements that TxDOT and partners should consider for supporting emerging CAV technologies in highway operations. Therefore, this document reviews the latest opportunities, best and emerging practices, and implementation options to support the CAV industry. Furthermore, this paper provides a framework for next steps, actions, and coordination needed based on emerging freight CAV activity. The focus of this document is primarily strategies and updates for TxDOT and its partners to consider in planning and prioritizing actions to support emerging technology. While border and law enforcement interaction remain a critical area of concern for freight CAVs, these issues are being studied under different platforms, including the work related to Senate Bill 1308.

Though Texas is prominent among states that are testing, implementing, and growing CAV technology, TxDOT may wish to consider some new activities in the autonomous trucking space in terms of what the impacts might be to the transportation network and what planning, policies, or projects are needed. These include:

- **Transfer hub and terminal planning:** Automated trucking operations need a point of transfer, and companies are beginning to establish these hubs or terminals. These hubs support connections between automated truck activity. This may consist of human-driven or other automated middle-, first-, and last-mile connections. Hubs will require areas near freight generators and along roadway right of way (ROW), much like traditional truck parking locations do. Truck parking is difficult to develop, and while automated transfer hubs may have a different look, function, and feel, it is important for TxDOT to think about where these hubs might be developed, where there is ROW that could be used, how to transition traditional truck parking to automated terminals over time, and how to strategize and plan with local governments to help support terminal development and tackle some of the challenges that might occur, similar to traditional truck parking.
- **Business route optimization, drayage, and circuit route identification and impacts on planned freight networks**: Business route optimization entails assessing an existing business's operations and identifying how automated trucking could benefit the company and which routes in Texas, as well as transfer points, would best support an optimized network. For TxDOT, the impact might be that the identified freight routes of today may change as optimization makes operations more efficient. TxDOT will want to understand this and how it might impact critical freight routes or how freight routes might be dynamic. Because federal highway funding may be tied to states having fixed freight routes, it is important to understand what optimized routes look like in relation to the existing freight routes and what infrastructure or operational improvements are needed. Additionally, identifying Texas businesses with circuit routes, such as back-and-forth drayage between a port and a warehouse or an agricultural extraction point to a processor and back, might be useful for TxDOT because these locations might be easier opportunities for automation. Understanding where these activities are occurring or could occur can help TxDOT prioritize the best types of improvements or infrastructure. Being able to map and plan for routes with repetitive automated truck movements will help TxDOT work with local governments, especially on first- and last-mile routes, to invest in the type of pavement, intelligent transportation systems, and other infrastructure to support these truck movements and a successful transportation environment for the supply chains depending on them.
- **Continuation of the freight CAV ecosystem data development**: Continuing to support CAVs, particularly automated freight, in developing the ecosystem or transportation network in a comprehensive way that best supports emerging technology will help automated technology thrive. It is important to explore the current and potential investments in infrastructure that TxDOT might want to make that will help develop the CAV ecosystem.

The following sections provide an update on autonomous trucking and operations and information about the latest operations-related activities.

State of Autonomous Trucking and Operations

Autonomous trucking is dynamic and evolving. Several autonomous trucking companies are delivering freight using their autonomous technology in Texas and throughout the United States today. However, the next few years are expected to show major advancements and implementation efforts, including the first driverless deliveries at scale.

Figure 2 shows the locations of companies identified as recently as November 2022 as key players in the automated trucking space based on a synthesis by the industry publication *Transport Topics* on top companies involved in automated trucking. Some of the companies operating in Texas include:

- Aurora,
- Einride,
- Embark (now defunct),
- Gatik,
- Kodiak,
- Waymo,
- Torc Robotics, and
- TuSimple (2).

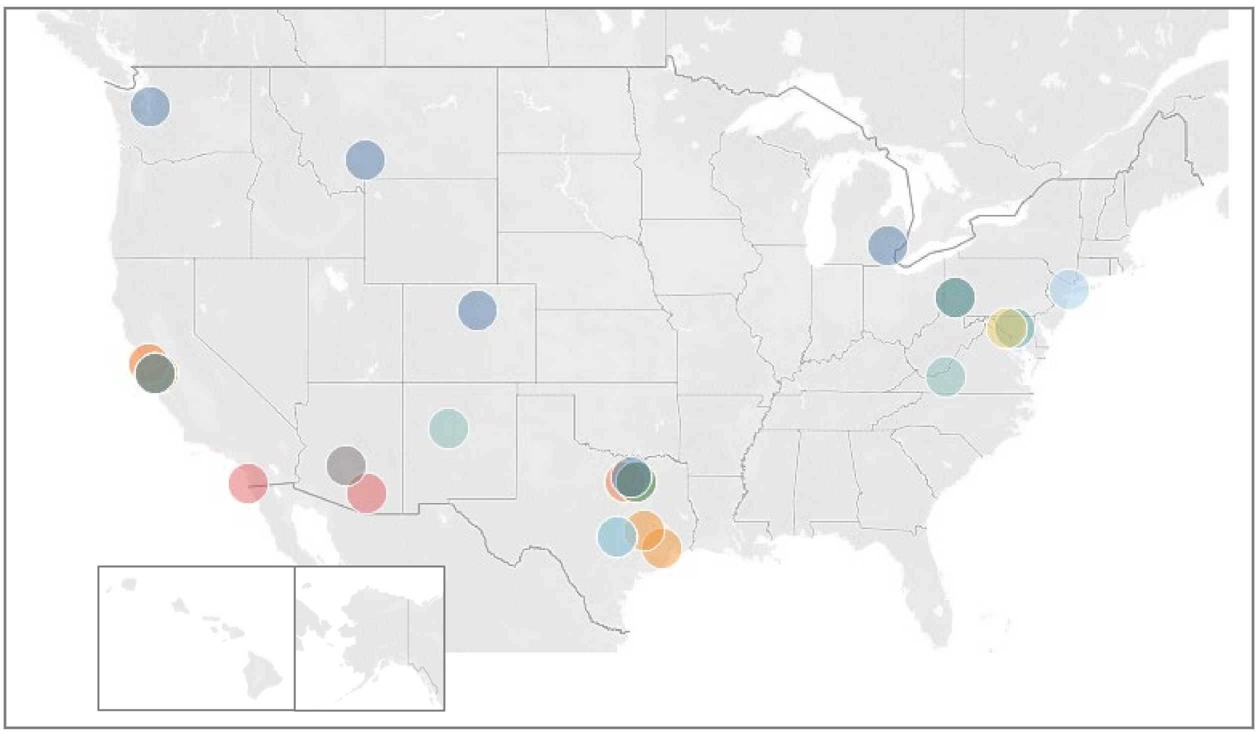

Figure 5: Locations of Companies in the United States Involved in Autonomous Trucking

Many of these companies focus on systems that provide automated truck activities for long-haul, hub-to-hub movements, but several also focus on short-haul operations with lighter-truck usage (2). Many partner with major trucking companies like Werner, Schneider, and Ryder, as well as major retail and manufacturing establishments like General Electric. Some have even delivered mail for the United States Postal Service (**Error! Bookmark not defined.**).

Recent meetings on automated transportation bringing together leaders in the CAV space have attempted to categorize and synthesize all the rapid growth of CAVs, especially with freight movement (specifically meetings sponsored by the Transportation Research Board [TRB]). These meetings have been an important part of bringing together the CAV industry with state departments of transportation (DOTs) to discuss the types of plans, policies, and projects that need focus for automation to grow.

For example, presentations from the recent gathering of stakeholders sponsored by TRB summarized the following points:

- Deployment of freight autonomous trucks is happening, but more is expected by 2024. There are currently limited operations without safety drivers, but more is expected in the next few years.
- This deployment is expected to especially impact long haul freight links. This trend means that automated freight activity will mostly take place on interstates and key highways with the use of transfer hubs to switch to human drivers for first- and last-mile connections because these are simpler operating environments than other roadways like busy urban streets.
- The CAV industry expects significant benefits regarding safety, efficiency, sustainability, fuel, and refrigeration of perishable goods. An additional expectation is a reduction of driver turnover and job satisfaction issues. This can also lead to improved customer satisfaction.
- It will be important to understand how to implement frameworks for inspections and handling of roadside processes with autonomous trucks by state and local safety personnel. The Commercial Vehicle Safety Alliance has made considerable progress towards developing processes to accommodate autonomous trucks.
- Many state and federal efforts assess off-highway freight operations for automated driver systems, but some of the technology is still getting started. By far, the focus is on-highway operations. It will be critical to establish broad public/private-sector partnerships for vehicle approval and safety reporting processes going forward ([3]).

In addition, while freight CAVs have been considered mostly at the long-haul, interstate level, there is recognition that freight CAVs are growing in several types of freight-centric locations ([4]). The following are four key location examples to consider in freight planning and CAV implementation:

- **Controlled environments** (e.g., ports, warehouse and distribution centers, and intermodal facilities): These locations are contained and may already have automation in place (e.g., robotic cranes). Characteristics include:
    - Low speed operations and
    - Dirty and dusty environments (important to consider for sensors and camera use).
- **Streets** (e.g., urban areas, suburban streets, and a strong mix of activities and modes [bike and pedestrian with urban delivery]): Characteristics include:
    - A complex environment (a lot of different elements),

- Low- to medium-speed movement,
- Customer facing (in this environment, the freight is usually going directly to the end user), and
- A strong market and growing (things like e-commerce are growing the day-to-day demand for freight delivery).

- **Resource roads** (i.e., access to facilities like oil and gas, forests, and agriculture): Characteristics include:
  - Unpaved roads typically,
  - Remote areas,
  - Medium-speed movements, and
  - A modest market for automation currently.

- **Highways** (i.e., interstates and major roadways): Characteristics include:
  - A well-ordered environment (i.e., not complex like urban streets),
  - High-speed movements, and
  - A huge market (one of the largest opportunities for autonomous trucks now).

The focus for this paper is the highway and controlled environment locations. However, many CAV deployments in Texas are in urban areas like Dallas, and there is potential for activity on resource roads that needs additional research and coordination. The street locations further require in-depth coordination with local governments, and discussion of jurisdictional decision-making and how that impacts AV development decisions.

Latest Considerations for Freight CAV and Operations Activities

Given the state of the practice as described previously, this section provides details about the latest areas of focus for operations and freight CAVs. The focus is primarily autonomous trucks, but some connected vehicle (CV) information is included.

Developing a Transfer Hub/Terminal Strategic Plan

The concept of autonomous trucking launchpads or connection points is primarily to support autonomous trucking freight/trailer exchanges. The vehicle would be a conventional (human-driven) truck. It could also be a robot that has either picked up freight to deliver for over-the-road carriage or that is receiving freight to take to a local destination. Autonomous trucks would carry freight in between hubs, and conventional trucks with human drivers would handle the first- and last-mile operations. Transfer hubs would work by applying automation on highway stretches, while humans would continue with more complex and local driving and customer contact.

Companies estimate that an autonomous truck and transfer hub system would provide an operational cost savings from 22 to 40 percent (**Error! Bookmark not defined.**). This estimate is based on the cost difference between driverless trucks and conventional trucks. Additionally, companies are assuming this kind of setup would work for roadway segments where there are driver-related (human) issues such as high turnover.

To work, however, freight transfer hubs would require establishment of “drop yards near interstates” where transfers of cargo (trailer transfers) could take place. The hubs would require ROW along highways and at major arterial access points to interstates that lead to and from freight generators to support full-scale implementation (**Error! Bookmark not defined.**).

In the past year or two, companies in the automated trucking space have discussed the property needed to support these hubs. Some companies would build their own transfer facilities, while others would rely on existing built facilities and retrofit for autonomous trucking transfer operations. Major intermodal players, including Alliance Texas, have also explored how to build open-access truck ports near their key operations hubs. Some companies describe a goal of not needing these transfer hubs once trucks are fully autonomous, but for now, the transfer hubs help propel the autonomous truck technology (**Error! Bookmark not defined.**).

This is a rapidly changing environment as during the development of this document, the types of companies in the automated truck space have changed, either starting up or becoming defunct. However, it is important to document the activities that have taken place, even if involving a defunct company, because the steps taken toward automated trucking operations appear to still be important, such as developing a network and transfer hubs.

For example, Ryder is a company that is working with several autonomous trucking companies to develop transfer networks and autonomous truck facilities throughout the United States. Ryder was planning logistics networks with Embark, a former autonomous trucking company, which would have included transfer points or hubs. This partnership was expected to produce a nationwide network of up to 100 transfer points. Ryder still has plans to help Waymo Via scale its autonomous trucking business by helping with standardized fleet maintenance and management. Further, Ryder and TuSimple are leveraging Ryder facilities as terminals for TuSimple ([5]).

Ryder is also working with Gatik, a company engaged in automating on-road transportation for short-haul and middle-mile logistics. Through this partnership, Gatik will lease a fleet of medium-duty, multi-temperature box trucks to support goods distribution to retail that supports e-commerce. According to Ryder, “Gatik will integrate its commercial-grade autonomous driving technology into the leased fleet, enabling Gatik to provide its Autonomous Delivery as a Service (ADaaS) model to its new and existing customers.” Ryder will both provide the leased vehicles and service the trucks including autonomous components. The initial focus of this is in the Dallas/Fort Worth area ([6]).

The reason that a company like Ryder is engaging in these business relationships is that it has large facilities for maintenance and a network of supply chain and logistics centers. Ryder will provide yard operations, maintenance, and fleet management and will provide advisory input on transfer points where freight will be moved from driverless long-haul trucks to driver-controlled trucks for first- and last-mile deliveries.

Waymo is another company that built a hub for autonomous trucking. The Waymo hub in Dallas is 9 acres and serves as Waymo’s primary operations center in Texas. The hub supports operations and testing and connects to Waymo’s operations center in Arizona. Waymo’s point of view is that these hub facilities must be large. The company says that a facility needs to support hundreds of people and trucks ([7]).

Additionally, TuSimple is teaming up with Hillwood, which is a large industrial and commercial real estate developer, to develop commercial properties that integrate the autonomous truck infrastructure specifications ([8]). TuSimple and Hillwood are starting with a 1-million-square-foot facility in Hillwood's 27,000-square-acre Alliance Texas development in the Dallas/Fort Worth area. Alliance Texas provides an ecosystem that can support testing of new technology to adopt, integrate, and scale level 4 autonomous truck operations. The facility is located off I-35 near the Fort Worth Alliance Airport, major freight partner facilities such as UPS and DHL, and major distribution centers (**Error! Bookmark not defined.**).

Little information is publicly available on what resources, space, and development capabilities are needed to support these transfer hubs, and more research is needed to understand the demand on the transportation network. It will be critical to understand the spatial needs, footprints, and potential impacts because implementing a transfer hub network could make major changes to the existing transportation system and create demands such as access to roadways and utilities, impacts on traffic patterns, and more. Most of the research points to outfitting Class 8 trucks, so this would be the primary size for these sorts of transfer hubs. Other types of autonomous freight vehicles like urban delivery hubs will need a different model.

An important element is understanding how to work with local governments and communities to obtain the necessary zoning and support. These hubs are an evolution of the truck parking issue that exists throughout the United States. Truck parking is notoriously difficult to develop and is often met with community opposition. Texas could have a role in working with local governments and industries to negotiate the best solutions for these facilities.

Another consideration is how other efforts in the AV space will work to support freight needs like transfer hubs. There are efforts to use traffic signal CV technology to improve the flow of freight vehicles through signalized intersections, which may help optimize flow of freight vehicles in and out of transfer hubs and expressways. It is necessary to look at transfer hubs as part of the surrounding system to understand the flow of traffic and how transfer hubs connect.

In addition to the transfer hub model helping companies achieve efficiencies in freight flow, transfer hubs would also support some of the driver issues that exist in the trucking industry. If autonomous trucks handle the long-haul leg of freight trips, driver jobs would be more local or regional and short haul, allowing for more home time (**Error! Bookmark not defined.**).

There is an emphasis for companies in this space to build off-highway transfer hubs as an essential function to support autonomous trucking. It may be important to support this requirement by having TxDOT identify property, especially state-owned ROW, and preserve it, which is akin to the preservation of ROW for highway and transit projects (i.e., rail banking and property banking). Identifying, acquiring, and preserving ROW are difficult and costly—yet necessary—tasks for DOTs, and the acquisition of transfer hub property is also expected to require capital and time to develop (**Error! Bookmark not defined.**).

Implications for Operations

The transfer hub and network development may create several impacts for DOT operations, such as:

- Networks may change travel patterns and freight flows.

- Coordination with local governments will be critical for developing or adapting existing areas for transfer hubs. It will also be important to explore how freight is broken down further, such as for urban delivery.
- DOTs may want to catalogue and grade available state-owned property, especially highway ROW, to support transfer facilities. This may be useful in efforts to see autonomous trucking grow, especially where facilities are needed that will be in or near highway ROW.
- DOTs may want to catalogue or hold property, as well as invest in or negotiate property, to support transfer hubs, especially near highways. This state-owned property may also be useful in developing public-private partnership arrangements and/or as match for funding opportunities.

The Maryland Department of Transportation (MDOT), for example, is doing something similar for truck parking. MDOT has assessed all state-owned excess property that MDOT would normally try to sell or that is highway adjacent with low land use potential for capability to support truck parking. MDOT graded each property using a set of criteria and then whittled down top candidates. MDOT uses an ArcGIS online app to show the properties in relation to truck traffic and industrial access ([9]).

A similar activity to MDOT could take place with TxDOT or State of Texas properties to assess which properties might support freight operations and transfer hubs, and to determine which ones should be banked. Additionally, this work could engage economic development entities and the private sector to offer potential properties for sale to support private autonomous freight trucking operations. In other words, it is important to think through how to get existing truck parking AV ready, and this may accelerate the development of automated trucking and related technologies.

Potential Activities to Further Developing a Transfer Hub/Terminal Strategic Plan

The following questions outline some of the potential activities to consider related to furthering the development of a transfer hub/terminal strategic plan:

- **How will the freight network change with new autonomous trucking networks, and where will these transfer hubs be needed?** While it may be impossible to know exactly where companies may build transfer hubs, it might be useful to assess where Ryder locations are in relation to Texas' network and to then use existing tools such as the Texas 100 Most Congested Roadways and the Texas Congestion Analysis Tool (TCAT) to understand freight mobility in their areas. Then, an assessment of future conditions could be done to understand the impact of increased truck activity, including a look at potential congestion, safety, and asset conditions. Having the ability to run scenarios of how the networks will change will help in discussions with regions and local governments about prioritizing projects or in deploying operational treatments.
- **Does TxDOT or the State of Texas have property along highway ROW that could support autonomous trucking?** A good exercise might be to catalogue state-owned property and determine where potentially suitable transfer hub property exists that could support transfer hub activity. There might be opportunities to sell excess property to private-sector interests, to use it in negotiating public-private partnerships, or to offer it as a match for funding programs.

Assessing Texas Freight Network and Automated Truck Impacts

A precursor activity for autonomous trucking companies is identifying optimum routes. This might be based on existing freight flows or potential future freight flows. This type of analysis would help to guide implementation and advancement of autonomous trucking to achieve optimum cost savings.

Ryder System, Inc., and the Georgia Institute of Technology worked together to assess Ryder's business routes and how autonomous trucking would provide a cost savings based on route optimization. Georgia Tech used real-world data from Ryder's dedicated transportation network in the Southeast and developed an autonomous transfer hub network (ATHN) that combines autonomous trucks on highways with conventional trucking operations for the first and final miles. Then, Georgia Tech introduced optimization models for routing and dispatching autonomous trucks. This was evaluated by comparing the ATHN with existing operations under different assumptions ([10]).

Georgia Tech found that the ATHN with optimization technology can reduce costs by 29 to 40 percent for a large network, depending on the price of the trucks and the direct and indirect costs of operating them. The lead researcher, Dr. Pascal Van Hentenryck of Georgia Tech, noted, "In the transfer hub network, there is no need to return back after a delivery, and there is no need to limit working hours or return to a domicile at the end of the day. As a result, only 35% of the automated distance is driven empty, compared to 50%. This means that even if autonomous trucks would be as expensive as trucks with drivers, costs would still go down by 10%" ([10]). Further, Georgia Tech found additional savings from reduced labor costs and idle time. Benefits also include increased flexibility in delivery appointments to keep autonomous trucks moving all the time ([10]).

The useful outcome from this type of work for DOT operations is the potential for DOTs to work with private-sector stakeholders to understand route optimization and where those routes would be, along with the required infrastructure such as transfer hubs to support those routes. DOTs could compare the autonomous trucking optimized routes to existing freight plans and freight performance information to determine how they match and what the automated network looks like, if different from the existing prioritized freight network. Then, decisions and investments could be made to determine if more capacity is needed or how to deploy use of operational treatments to facilitate the freight flow.

A focus for using autonomous truck technology is to support routes that are circuits such as drayage to and from a port or trucks that carry freight back and forth between parts of a factory or processing plant. Research is beginning to show ways that companies are looking at these routes and targeting them for use of automation.

The United States Department of Transportation Maritime Administration (MARAD) is also working on port drayage with cooperative driving automation (CDA) technologies. The goal is for CDA to improve port performance and involves development and testing of use cases for port drayage and commercial motor vehicle operations that leverage CDA-equipped commercial vehicles to increase efficiency and safety. MARAD hopes that the work will advance the adoption of CAVs and CDA technology for U.S. ports and that there will be more information about the benefits and costs of CAVs and CDA in port areas. The project started in 2019 with a goal of completion in 2022 ([11]).

Implications for Operations

Again, the key issue here is understanding how the freight network is going to change. If companies adopt autonomous operations (which they will if there is a cost savings and increased efficiency), how will they optimize the use of these vehicles? Where will they place terminals? How will those terminals change existing freight flows? These are critical questions to research, plan, and incorporate into the statewide freight plan and to develop more specifically region to region.

A challenge will be knowing what those optimized routes look like, especially if the private sector is unwilling to share or provide details. Strong partnerships and conversations may help navigate some of these issues, and perhaps the private sector will advocate for their routes and transfer hub locations so that TxDOT can support improved freight flow to these facilities.

TxDOT's system operators, especially in districts, should expect that as automation matures, the network will change. In this case, there might be dedicated routes for platooning or automated trucks to move freight in a circuit. If this is the case, this may impact the current network setup and asset condition. There is some concern for pavement condition from repeated truck operations, so these sections may need to be improved for the trucks the road will support if there is growth or concentration of truck activity to a particularly efficient route. In addition, system operators may need to adjust roadway tools and practices and establish strong coordination with local governments because first- and last-mile connections are likely local roadways.

Some research is available on the pavement issue. Since circuits have the potential to be optimized as well-traveled autonomous truck routes, pavement condition challenges are likely. For example, research that analyzed the trade-off between fuel savings and pavement fatigue found that a slight lateral offset of the trucks (100 to 150 mm) would reduce pavement damage by 30 percent while maintaining a fuel savings of 8 percent ([12]). Assessments will be needed to determine the impact to the roadway network and how slight changes in the operation of platoons or autonomous truck circuits can offset asset decline.

Potential Activities to Further Assessing Texas Freight Networks and Automated Truck Impacts

It is important to understand existing and future freight flows more than ever and to plan for changes, especially on the parts of the freight network that TxDOT can best control. Parts of any supply chain will be fully operated by the private sector. However, understanding what is expected on the Texas Freight Network will help determine the types of capacity and infrastructure needs or operational treatments.

An important planning activity is assessing existing and future freight flows in the statewide freight plan and engaging Texas industries about how they might be thinking of optimizing routes for autonomous trucking. The answer may be unknown by many or well known by some, but the dialogue needs to begin. Perhaps TxDOT can commission an assessment of how the existing freight flows and performance might change with expected changes in routes.

In addition to planning, TxDOT maintains several resources such as its TCAT. These tools and newer freight fluidity tools available can help assess freight networks and tie commodities and industries to networks in ways TxDOT has not been able to do before. This will help TxDOT know where the key routes are, what commodities they support, and the user (business) experiences on Texas' roadways. Therefore, continuing these resources and using them ubiquitously can help improve awareness of the existing freight networks. Use can help identify points that might change or shift when autonomous trucks saturate the network.

One starting point for drayage and circuits is evaluating truck flows at key freight locations. It is possible to use truck probe data to assess the truck activity and identify drayage and circuit operations that may be best targeted for autonomous trucks or platooning.

Another planning activity would be to work with TxDOT district staff to identify these routes and what might need to be considered from an operational perspective that would support freight movement while ensuring safety, efficiency, and environmental improvements. For example, repeatable routes that can be pre-mapped will be the easiest to use for autonomy in the near term. Judging the complexity of the routes, such as by speed, intersections, unique features, traffic density, etc., will also affect autonomous vehicle implementation. Companies may make different judgments about the complexity of routes, given their technologies.

It may also be important that operations staff work with TxDOT planning, asset management, and pavement staff to research ways to offset asset decline or optimize asset performance given new, repetitive levels of activity on these segments.

Developing a Freight CAV Ecosystem

Texas is one of the key states in the nation developing the concept of CAV ecosystems in which CAVs can grow and thrive. Texas has the Texas Connected Freight Corridor (TCFC), which is a collaborative effort with public and private stakeholders to deploy CV technology to more than 400 commercial and TxDOT fleet vehicles to improve freight movement and increase safety for all road users. The goal is to help long-haul freight and infrastructure communicate to optimize safety and freight mobility (**Error! Bookmark not defined.**).

The current scope of the TCFC is the 865-mile Texas Triangle of I-35 (including an extension to Laredo), I-45 (linking Houston to Dallas-Fort Worth), I-10(connecting Houston with San Antonio), and the I-30 technology corridor between Dallas and Fort Worth.

Some of the short-term activities envisioned by the TCFC are that trucks operated by companies partnering with TxDOT will receive more timely and accurate information about traffic and roadway conditions. Receiving these alerts is expected to help improve safety and efficiency. Plans are to incorporate smarter traffic intersections around distribution centers to help improve freight flow and reduce idling. In the long term, the TCFC will transfer technology to other Texas freight corridors to help improve freight flows, safety, and environmental impacts (**Error! Bookmark not defined.**). As part of the TCFC, TxDOT created the Connected Vehicle Data Framework (CVDF) with a goal of reducing physical intelligent transportation system (ITS) infrastructure and mediating coverage with a cloud-based option and data exchange that relies on cellular coverage and existing third-party services ([13]). TxDOT is expanding the CVDF through research to leverage existing CVDF for the TCFC to expand its efficacy through applications, data partners, and corridors. This will help create new benefits like improved real-time traveler information, increased adoption in freight markets, and strategic infrastructure investments ([14]).

Another similar project is the I-35 Traveler Information During Construction project. The purpose of this project is to create a connected work zone for enhanced traveler information. Using the data from the I-35 traveler information initiative, the first phase provides advanced freight traveler information for pre-trip and en-route planning to participating freight carriers. The information conveyed to dispatchers and vehicle cabs includes work zone closure locations, capacity reductions, queue lengths, and delay. The second phase of the project develops and deploys a connected work zone using 5.9-GHz vehicle-to-infrastructure (V2I) communication and dedicated short-range communication to warn of work zone locations, delays, and traffic queues. The work zone testing includes mapping procedures and both low- and high-fidelity work zone information transfer to vehicle onboard units ([15]).

In addition, there is much discussion and new research focused on CVs and vehicle-to-vehicle and V2I communications throughout the state. Many of the discussions focus on feeding information to drivers (passenger and freight) and having infrastructure, vehicles, and other information systems (e.g., weather) all in communication for a safer and more efficient experience on the transportation network.

One area that TxDOT has explored and that should be continued is the collection of data from V2I vehicles that can support DOT decision-making. For example, do the sensor and camera data collected by automated trucks have utility if shared (anonymously or in aggregate) with a DOT where the DOT can use the information to understand the freight user experience on the network? This information, such as pavement condition, performance during various weather conditions, autonomous truck perception of roadway markings and signs, the capture of the spatial placement of roadway features, and the vehicle's perception and maneuvering around other vehicles, bicycles, and pedestrians, would all be useful information for a DOT to support its role in collecting or overseeing operations for things like:

- Asset condition information for asset management;
- Roadway features;
- Equipment placement (barrels and cones);
- Detours;
- Traffic mix and freight vehicle interaction with other vehicles, bicycles, and pedestrians;
- Incident response; and
- Transportation system management operations treatments.

There are two TxDOT projects focused on using data and images from automated trucks to improve routine maintenance operations. One project is the RTI Project 0-7129 led by the University of Texas at Austin Center for Transportation Research. This research will test and end-to-end Intelligent Routine Maintenance Framework through use of real-time data on pavement, signage and other assets that can help to modernize maintenance operations ([16]). Another project is part of the Texas Connected Freight Corridor (TCFC) I-30 Supplementary Project led by the Texas A&M Transportation Institute to expand on the existing TCFC applications and explore options for using collected data in decision-making.

In addition, a wealth of data comes from CVs and can help support DOT decision-making, especially for freight. Some companies like Wejo, Kodiak, and General Motors are making some of the CV data available. Initial discussions and tests are taking place ([17]). TxDOT has a data sharing contract in place, and this provides a platform for growth in data services and support for decision making.

There are additional efforts to grow data sharing opportunities and exchanges with CV data worth noting. One is the Texas Work Zone Data Exchange Dataset. TxDOT's highway system provides land closure information to the Federal Highway Administration (FHWA) Work Zone Data Exchange (WZDx). The WZDx is a cooperative effort led by the United States Department of Transportation (USDOT) and stakeholders to share work zone data and make it available for third-party users. These users include mapping companies, vehicle manufacturers, and automated vehicles. Work zones are especially difficult for trucks, so FHWA is hoping that by collaborating on the exchange of work zone data, this will support the advancement of existing trucking operations and future automated activities ([18]).

Another is the North Central Texas Council of Governments (NCTCOG), which selected Blyncsy, Inc. to supply a situational awareness app testing sandbox with a goal of understanding how CV data can help in real time to support operations, safety, and decision making ([19]). Blyncsy Inc. was selected to support the sandbox beginning with monitoring work zones in real time. Blyncsy will provide its data to the Federal Highway Administration (FHWA) Work Zone Data Exchange (WZDx data feed). "Harmonized work zone data will be available for third-party use as part of the Work Zone Data Exchange. The new ability to openly share work zone data from roads will increase safety and efficiency for drivers, construction workers, and transportation employees and provide critical data to advance the upcoming development of autonomous vehicles. The date comes from Blyncys' Payver technology, which leverages "artificial intelligence and crowdsourced visual imagery from dashcams to provide automated work zone surveys" ([20]).

Examples of Ecosystem Development in Other Locations

Some recent advancements in the development of an ecosystem and data/vehicle-to-everything (V2X) analytics include projects out of Georgia. Like Texas, the Georgia Department of Transportation (GDOT) has set up a testbed for CAV technology called the Ray (which is broader than the TCFC), which has a goal to provide data to support operations among many other critical transportation goals. For example, the Ray is proposed as a zero-carbon, zero-waste, zero-death highway system, and GDOT has partnered with companies like 3M to test various technologies to support this. Figure 4 shows a graphic from the Ray's website about its V2X vision ([21]). The Ray is an 18-mile stretch of I-85 in southwest Georgia. Primarily, the testing involves smart road infrastructure such as:

- In-road and roadside connected infrastructure that communicates with vehicles in an evolving capacity (as technology evolves). The communication should provide GDOT with real-time, location-specific data from vehicles to improve safety, ease congestion, and identify maintenance needs.
- Smart road markers that are solar powered and convey different alerts to drivers such as incidents and wrong-way driving. The markers are dynamic and can help inform and direct traffic.
- Digital data management platforms that work to analyze and articulate data collected by the smart infrastructure so that the data can be used by law enforcement, first responders, and traffic safety officials (**Error! Bookmark not defined.**).

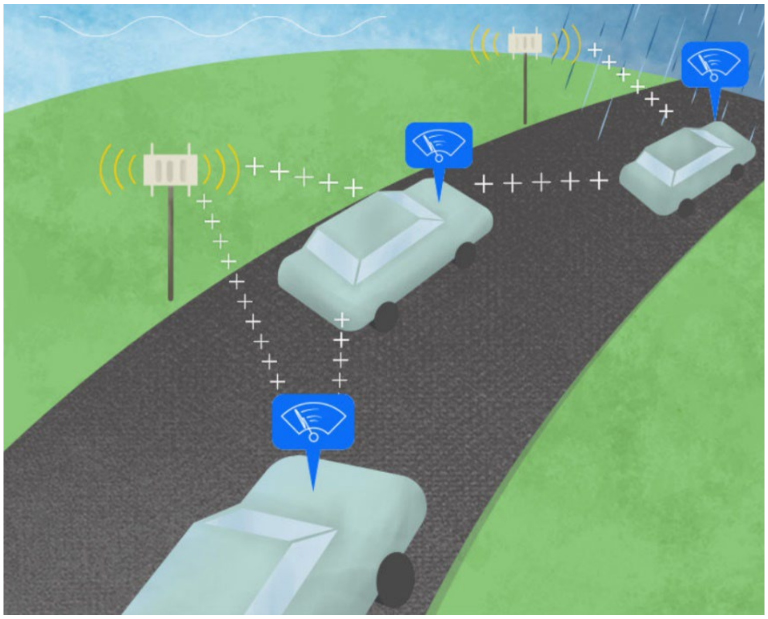

Figure 6: Illustration of Vehicle-to-Infrastructure Technology

Another element of a freight ecosystem is signal prioritization. GDOT has had success in the past decade using signal prioritization in operations. GDOT has established regional coordination to proactively manage and maintain traffic signals statewide ([22]).

GDOT is now working with freight operators to implement freight signal priority. GDOT is working on a pilot that will provide the same operational benefit as transit vehicles to freight operators in port areas. The goal is to improve freight movements to and from ports, but GDOT has identified future options such as supporting autonomous trucks on highways and platoons.

Finally, GDOT is developing a concept design for the I-75 Commercial Vehicle Lanes project under GDOT's Major Mobility Investment Program. This project is expected to produce recommendations for operations impacts and actions to support autonomous trucks and commercial vehicle lanes that TxDOT will want to consider ([23]).

Implications for Operations

Evolving to a new transportation ecosystem will change the roles, resources, and practices of any transportation system operations staff. Everything is changing, and technology is making it possible to do more than ever before to support emerging technology that is expected to help safety, efficiency, and more.

Some opportunities relevant for operations include:

- Expand TxDOT's Connected Vehicle Data Framework (CVDF) – a two-way data exchange – to support the system operators and decision-makers, autonomous trucking, and conventional trucking. Collect data to inform real-time operations and longer-term planning.
- Stay up on all communications technology development and the resources needed to support it. Understand what is emerging and try to develop an ecosystem that can adapt.
- Review and/or establish and update operational procedures that can be flexible with technology as it evolves. Ensure the procedures work with autonomous trucking and

conventional trucking for now. Consider incident management and inspection procedures to facilitate autonomous trucking.

- Determine cost versus benefit of outfitting the network with sensors and devices to have as much opportunity as necessary to collect freight user experience and determine ways to use that information to provide to autonomous trucks and conventional drivers. Partnerships will be necessary with autonomous trucking companies to determine the data feeds their technology can use to ensure safe and efficient operations.
- Assess V2X technology data reliability. Understand the data's limitations for automated trucking and identify gaps and ways partners can work to improve the data.

Potential Activities to Further Developing a Freight CAV Ecosystem

Texas is already considering many, if not all, of these recommended actions and is implementing the ecosystem that states are seeking. In fact, Texas is a leader. However, Texas can work toward automated trucking development by considering some of the following:

- Continue testing V2I data for state DOT decision-making purposes related to automated trucking, as described above. Identify what is useful, what kinds of intel the data provide, and the best way to access and process the data. This will require some pilots and experiments with companies willing to share data. Tesla, for example, picks up asset elements (e.g., road barrels, cones, traffic lights, guard rails, and mixed traffic) for its drivers. These data have value for DOTs and may help DOTs optimize the information the DOTs have available to improve the network for safety, efficiency, asset maintenance, and more. Current activities throughout the states are looking at data sharing and evaluating the utility of various types of CV data, so this would build on these efforts. Review, update, and establish new operational procedures for inspections, incident management, routing, etc. that work with autonomous trucking as they do with conventional vehicles. Consider how anything might need to change, what data feeds are needed, and what format is needed for messaging the driving community.

Additional Findings

In addition, a few key efforts are under way in other states and internationally that might be important for operations staff to consider.

Public Acceptance

Many of the articles and resources used for this paper have mentioned public acceptance. Discussions speak about needing to get the public comfortable with autonomous, as well as other automation, in addition to all the things described like developing transfer hubs. Considering the public-facing side of this may be an important activity for TxDOT as it seeks to advance autonomous trucking operations in the state.

For example, public acceptance of platooning semi-automated trucks in Germany and California was studied and compared. Some interesting insights are as follows:

- Most responders (70 percent) from both areas have a positive attitude toward truck platooning driving (technology acceptance).

- The primary concerns of sharing the road with platooning vehicles is the reliability of technology, followed by problems when entering/exiting highways and issues with cut-in vehicles.
- There may be differences culturally in what people perceive as a safe gap between vehicles, and this may be worth exploring in setting standards.
- Expected usefulness and expected ease of sharing were the most influential factors in attitudes toward sharing the road.
- Negative attitudes to regular (conventional) truck drivers were related to the positive perceived ease of road sharing with platooning trucks. This means that the more people disliked conventional trucks, the more positive expectation for having to interact with semi-automated truck platoons ([24]).

TxDOT may wish to get a head start on the public coordination and acceptance of autonomous trucking including the changes in expected networks and development of transfer hubs. This may need to involve public information campaigns, community outreach, and coordination with planning entities and elected officials.

Automated Trucks and Border-Crossing Transfer Hubs

While this paper does not include border crossing as a focus, recent research has some findings that TxDOT may wish to review in its parallel border-crossing freight CAV work.

First, the Ciudad Juarez bi-national metropolitan area has been proposed as part of a smart city because it includes one of the largest international trade crossings in the United States. The border connection between El Paso, Texas, and Ciudad Juarez, Mexico, has growing freight congestion. Research on autonomous truck operations around the border proposes several ideas:

- Apply the autonomous truck system to smart logistics border planning such that autonomous trucks can transfer cargo across the border and the general entry process that requires documentation and review can be negated. This may include transfer hubs at the border.
- To support automated truck operations, provide a high-speed data network to support V2I or V2X communications and traffic signal control at the border.
- Separate trucks from personal vehicles and pedestrians when crossing the bridge at the border and establish a transfer hub for autonomous trucks.
- Potentially implement a conveyor system to transfer products at the border, which may require a partnership of public- and private-sector stakeholders along with proper security from both the United States and Mexican customs agencies ([25]).
- Coordinate with Border Patrol to create processes for autonomous trucks in the border zone.

Build an open-access truckport that will allow for autonomous trucks to efficiently service border trade.Other research coming out of Canada for the northern border focused on border crossings and automated trucks by raising several concerns that United States–Mexican crossings may also experience:

- **Challenges of managing the importing process:** The normal customs process is now mostly digital with documents completed electronically. However, drivers are often asked questions when border agents have questions or concerns. Researchers propose trying to increase the information provided in electronic documents available to border officials ahead of the truck's arrival at the border, but researchers recognize that many security and safety concerns cannot be mitigated that way and require in-person, visual inspection, and observation.

- **Navigation through inspection plazas:** Many border inspection plazas are not easy to maneuver through, and it will be important to test autonomous truck technology's ability to navigate them. Additionally, when there are many autonomous trucks are coming through, it will be necessary to rethink border plazas both physically and technologically. Secure intelligent transportation systems and networks will need to be in place to not only ensure safe navigation but also prevent cybersecurity threats ([26]).

Focus Areas and Actions Necessary to Support DOT Operations for Automated Trucking

Freight CAVs are a dynamic area. Things are changing rapidly. The technology of today will be quickly outdated, and the transportation network in place now may significantly change to accommodate the growth of freight automation, especially if the estimated benefits are realized in initial pilots and implementation efforts.

It is important to identify areas of focus and specific actions for the immediate future for what the State of Texas can do to facilitate automated trucking. While it is helpful to identify longer-term items, these may be less specific and more general due to the dynamics of automated technology.

Based on the state of the CAV industry and current rollout of automated trucking activity, several areas are important for TxDOT and its partners to consider in the immediate future (Figure 5). These are:

- **Transfer hubs/terminals:** What is the state's role?
- **The Texas Freight Network:** How will the network change? What are the impacts of automation? Are there key routes or circuits to prioritize?
- **Development of a freight automated ecosystem:** How can the state support testing and implementation? What information is needed?

State’s role in transfer hubs	State’s role in the freight network	State’s role in the ecosystem
• Is this the new truck parking? • How can we set up for success? • Where are these hubs needed?	• Provide information about the National Highway Freight Network (NHFN) • Discuss how freight route optimization might impact the NHFN • Identify areas where automation can be easily implemented (routes, circuits, and drayage)	• Set up an information repository—who is doing what in Texas? • Identify key efforts throughout the state • Identify and support pilots, testing, or implementation for freight projects

Figure 7: Immediate Areas of Focus for Automated Trucking in Texas

Developing a Transfer Hub/Terminal Strategic Plan

Based on the findings, automated trucking requires a point of connection to transfer freight, charge vehicles, and perform maintenance. The industry has described these hubs in several ways:

- **Privately built** serving only one company,
- **Open source:** an opportunity to serve many, and
- **Public:** publicly supported (like public truck parking).

In addition, the way these are being developed appears to fall into the following categories:

- **Industrial property:** using existing areas or properties already involved in intermodal or warehouse/distribution or other transfer facilities, and
- **New industrial facilities:** developing new facilities and siting new properties.

However, other options appear less explored. These include:

- **Existing truck parking:** identifying ways to evolve existing truck parking to automated truck terminals, and
- **New truck parking/transfer hubs:** developing new parking/transfer locations since existing truck parking is in short supply.

The way these terminals are beginning to develop seems to serve the automated trucking companies individually, despite discussions of open-source options. Reports show companies developing terminals or using existing properties by converting locations.

It will be important to identify the state’s role in terminal development. For example, will the state need strategies to work with local governments on planning and zoning to ensure successful development of an automated network. The state can help determine where these hubs are needed and where property and partnerships may support hub development. Identifying the state’s role raises several questions. First, is the development of these transfer hubs like the efforts underway to identify electric vehicle charging locations, and is there a government role in planning and siting these locations? Tesla, for example, led the development of a robust charging network, and there are fewer other charging options. Tesla plans to open its charging network to other electric vehicles, and the federal government plans to invest in developing more electric vehicle charging options.

Like the electric vehicle charging network situation, automated trucking companies are developing their own networks of terminals (which may also be charging stations). Will this create a situation of winners and losers depending on who can establish transfer points quicker and in the most advantageous locations for freight mobility? Is there a need for TxDOT to understand this or to have a sense of how and where these hubs are developing, if they are private, open source, or both, and if there needs to be public support of hubs? TxDOT investments may be best focused on drawing autonomous trucks to strategically important corridors, particularly on the border in line with TxDOT's plans for the "Third Coast" strategy to develop Texas ports as the third national international, maritime gateway ([27]).

It is important to explore this development in further detail and determine the public-sector role. It is critical to understand how and where companies are establishing these terminals and who gets to use them. Support may be needed for an open-source market of terminals or even publicly supported terminals.

Similarly, development of these transfer hubs appears to have occurred or is being planned with little or no opposition. However, truck parking development for human-driven trucks receives significant opposition. Even though these transfer hubs serve a function to transfer containers or charge, they are a form of truck parking and trucking operations, which historically receives community opposition even when sited in industrial areas. The Federal Highway Administration Jason's Law report from 2015 and 2019 found that community opposition was a major reason truck parking does not get built and a shortage exists.

As the need for transfer points grows throughout Texas, it is important to understand where these locations might be sited, what existing facilities might be retrofitted, and what the trucking activity looks like, as well as if there is a role in the state working with impacted local governments to support the development and mitigating community impacts where needed. It may be necessary to look at the freight network to identify important locations for transfer operations, assess what kinds of existing property or ROW exists, evaluate what might be needed, and develop a strategy with those operating in Texas to retrofit and/or site these truck terminals.

Therefore, the following specific actions are recommended related to transfer hub development:

- Develop understanding of existing plans by companies operating in Texas.
- Evaluate private versus open source and the potential impacts or issues.
- Develop understanding of freight flows and the freight network, as well as where it makes sense to have transfer hubs.
- Assess real estate needs including ROW along highways, land use issues, local government planning and zoning conventions, and community mitigation needs.
- Identify the role of Texas, the level of support, and other actions that are needed to help coordinate, facilitate, and mitigate development of transfer hubs and rollout of automated trucking including resources for local governments. This may include identifying strategic

lanes where TxDOT may want to incentivize AV truck service through investments in transfer hub infrastructure.

Assessing Texas Freight Network and Automated Truck Impacts

Like the understanding of the siting of automated truck transfer hubs, automated trucking may impact the existing Texas Freight Network and local roadways. Due to past surface transportation laws, states are required to plan for freight, establish a State Freight Advisory Committee, and have an approved freight plan to use federal freight formula funding. Federal freight formula funding may only be used on the official freight network although states may use other funding sources anywhere, they wish. If a state were to use freight formula funding to support automated freight improvements including transfer hub development or information systems, the state would need to do so on the official freight network.

However, automated trucking entities describe network optimization and potential for more dynamic routes depending on things like congestion, work zones, demand, and other impacts. Automated trucking is expected to offer companies significant cost savings in the movement of freight. Algorithms to evaluate how automation can be used on optimized freight networks may offer a lucrative opportunity for companies. Using data from connected and automated trucks, companies can evaluate routes and quickly reroute or move freight differently to increase cost savings. Therefore, the freight routes and the level of activity on them may be dynamic. While the existing significant freight routes, especially the interstates, may not change as much, there might be changing dynamics related to first- and last-mile routes, as well as non-interstate roadways depending on mobility and reliability.

Currently, it is difficult to know how freight route optimization aligns with the way Texas has identified its freight network and how Texas operates and invests in it. It may be important to evaluate the existing network, assess it in relation to the expected optimization that automated trucking companies are describing, determine if the network might become more dynamic, and determine how to best plan for and operate the network in relation to how automated trucking will operate. For example, it is important to explore the following questions:

- How does autonomy change freight flows?
- What infrastructure changes should TxDOT consider in support of those changed freight flows?
- How should existing planning processes consider the potential impacts of autonomy?
- Where should TxDOT make strategic investments to guide those changes?

Specific activities to explore these questions include:

- Assess the existing freight network in relation to locations of automated trucking activity (i.e., routes and transfer hubs).
- Discuss and document how automated trucking network optimization might cause the routes to be dynamic and if there is an expected impact on the network or what other infrastructure support is needed.
- Understand where in the state circuits or specific freight routes are in order to prioritize locations for automated trucking implementation.

- Develop relationships to understand freight routing in detail and set up information flows between system operators and autonomous trucking companies to understand route plans and changes.

Developing a Freight CAV Ecosystem

Given the existing and planned automated trucking activities and the saturation of the commercial market that is predicted, it is important to continue to cultivate a CAV ecosystem. While Texas' broader CAV efforts all contribute to developing this ecosystem in Texas, the state needs to continuously evaluate the needs of industry at different geographies (state level and local government) and functional class roadways.

Areas of focus in developing the ecosystem include the following:

- **Information repository:** TxDOT maintains an existing website with limited information on where automated trucking companies are operating, but in developing this document, researchers found a need for more information, details, and understanding from the companies operating in Texas. Additionally, companies operating in Texas may need information from the state such as details of freight infrastructure, freight flows, land uses, and other intel. A more interactive information repository might help to improve communication among the public and private sectors including awareness of who is doing what and where. Such a repository might help improve opportunities for testing by organizing information that industry may want to know when selecting sites. Figure 6 provides an example of this sort of repository. The figure shows an ArcGIS online application where users can see deployments, get specific information about them, and understand them in relation to other Texas information like the freight network, percentage of trucks on the road, freight infrastructure, land uses, and more. This might help industry in looking for location and testing opportunities and serve as a two-way platform for information sharing. Other platforms like Tableau or web-based sources would work as well. ArcGIS allows people to easily access the information to use as they need.

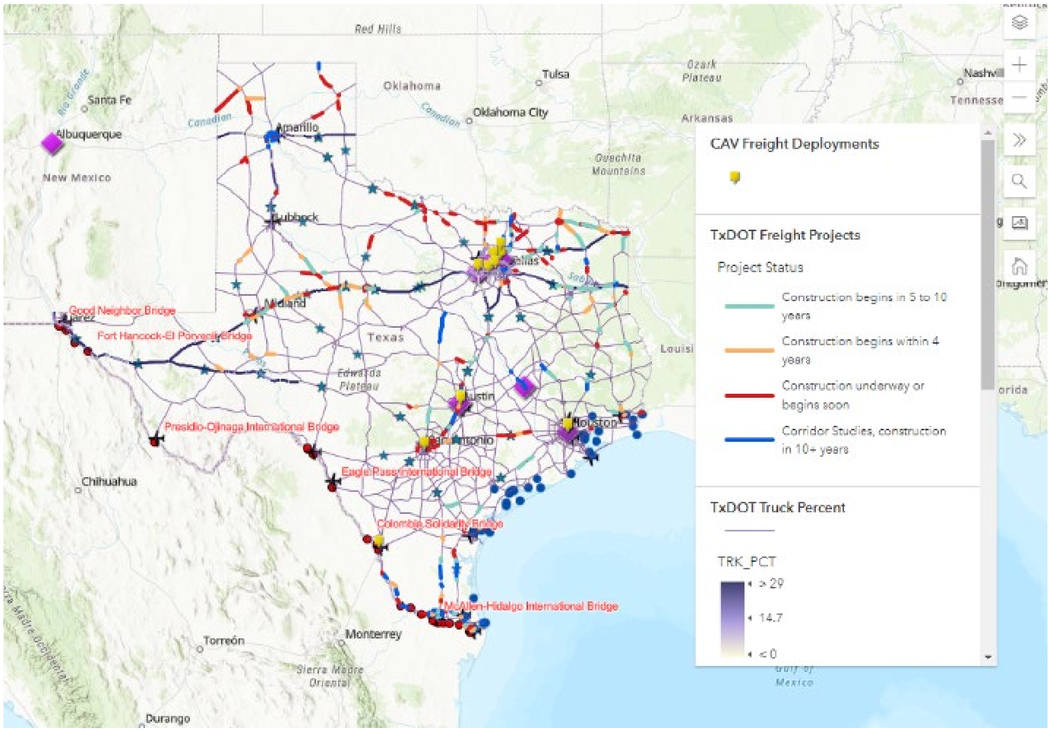

Figure 8: Example of Information Repository for Freight CAV

- **Data sharing:** In addition to an automated trucking repository to support planning and implementation, it is important that there be information-sharing components as projects progress. One example is the Work Zone Data Exchange in Texas, which enables infrastructure owners and operators to make harmonized work zone data available for third-party use, which helps make travel on public roads safer and more efficient through data on work zone activity. The goal is to get data on work zones in vehicles to help automated driving systems and human drivers navigate more safely (Error! Bookmark not defined.). In addition, TxDOT has worked to improve data sharing in work zones to truckers on I-35. These types of data exchanges and prioritization of sharing information can help support automated trucking testing and implementation. Setting up data and information exchanges will ensure everyone has access to the information and that awareness is improved.
- **Assess and inventory:** Part of the information repository is to update or create available resources to keep track of freight flows, critical routes, performance, and commodities. TxDOT already has robust freight planning and tracking of freight fluidity (i.e., commodity type, tonnage, value, and bottlenecks), and this will help in supporting and conversing with freight CAV companies and industries as technology evolves. It will be useful for TxDOT to continue strong awareness of freight movement and to assess how networks will change when autonomous truck infrastructure is implemented. Additionally, different types of locations will attract different types of autonomous trucks or vehicles for freight movements. It is important to know the different types of freight networks supporting Texas industry (e.g., drayage and circuits) versus long-haul and regional routes to work with the private sector to support the types of infrastructure that will help these networks. Keeping up with freight information and then sharing it in a repository will help make sure the right information is available to develop a testing and implementation environment. Figure 7 depicts some of the

rich freight commodity and performance flow information available at TxDOT to inform this effort.

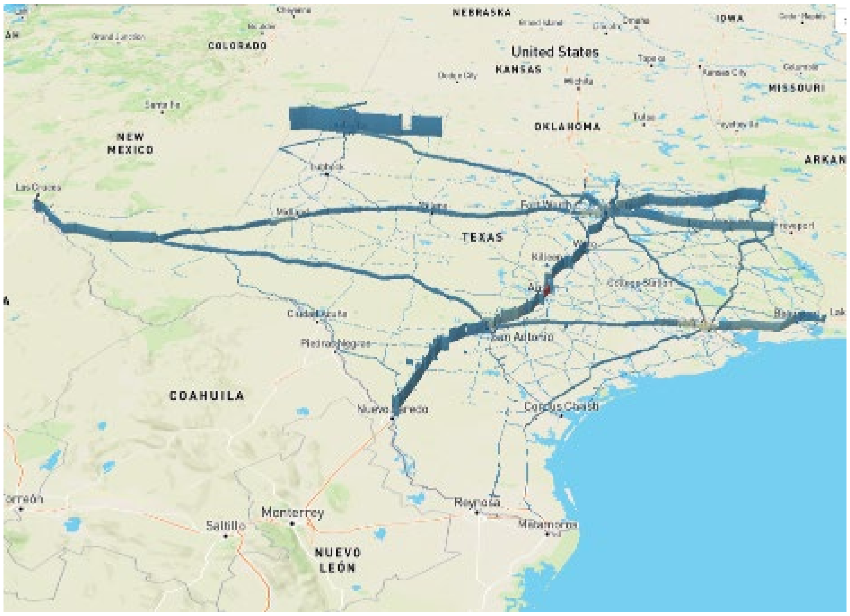

Figure 9: TxDOT's Freight Fluidity Visualization Resource

Additionally, it will help to have an inventory of property (state-owned or available) to support changing networks and needed highway ROW or transfer hub development. While property may be needed by the private sector, TxDOT can facilitate this by potentially offering property as well as helping with the community support needed for development of new infrastructure facilities. Property may be an important contribution or match in seeking federal transportation grants. The contribution of property may help support a private-sector investment, as well. This may be especially important in strategic corridors or freight-generating areas like borders, ports, and major facilities (e.g., Alliance Texas).

A good resource for this is existing truck probe data and the Texas Truck Parking Visualization Resource (Figure 8). It shows where truck parking demand is occurring statewide and provides usage statistics for truck parking locations throughout the state. This intel might be informative to industry partners in identifying areas to implement automation.

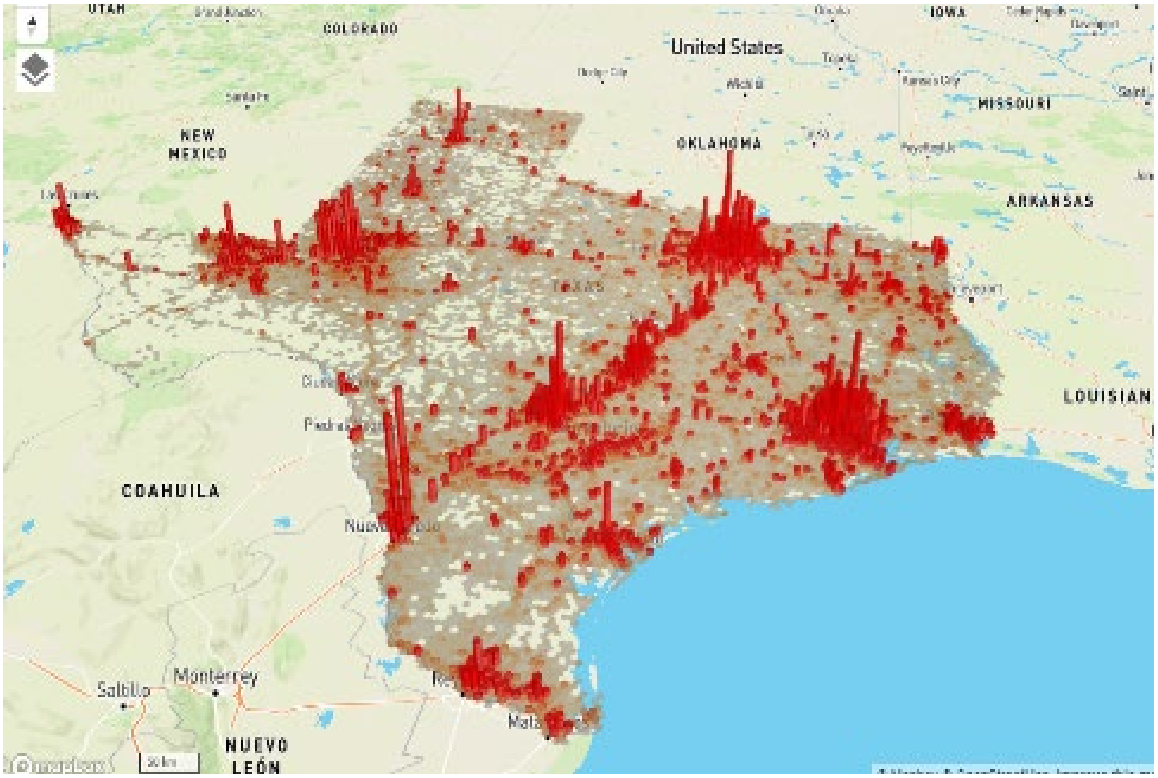

Figure 10: Traditional Truck Parking Demand Statewide (Texas Truck Parking Visualization Resource)

- **Get comfortable with data analytics**: TxDOT has sophisticated tools and resources available to support both planning and operations, and these will provide a strong foundation for the waves of data that can flow to and from autonomous trucks through V2X facilities. These data have the potential to provide significant intel for transportation operations that can illuminate in real time how trucks are experiencing Texas roadways. This kind of information can help with routing, treatments, and longer-term decisions such as where assets need attention. These data can also support TxDOT's ability to communicate with the driving community about safety, queuing, weather conditions, and more.
- **Develop public communications and outreach:** Though not an operational activity, public communications are critical for any transportation agency. A head start on identifying how autonomous trucking might impact communities may be critically important as 2024–2027 approaches and higher volumes of autonomous trucks are operating, in addition to the need to develop transfer hubs.
- **Remain flexible for future growth in operational changes:** As autonomous truck operations grow; operational changes will ensue. Operations centers will likely be located remotely, and communications with autonomous trucks will be conducted from afar. There may be a need for remote assistance. This may include full operation centers, where remote operators observe, operate, and interact with autonomous trucks. TxDOT operations staff will need to have a strong relationship and transparency with these centers so that staff can know what is moving and where and can safely operate the network, especially through V2X communications.

Therefore, specific action items for the immediate future may include:

- Setting up a data/information exchange and repository for more robust sharing of automated trucking activities and state information that can support industry;
- Taking inventory of assets, conditions, property, freight flows, and other important information to support the repository;
- Developing an effort to focus on CAV data, data exchanges, and V2X operations;
- Developing concepts of operation and identifying workforce needs, technology development, and other needs to support advanced data analytics and communications; and
- Focusing on an outreach and communications strategy that helps Texas citizens and local governments understand the changes that are occurring and brings them into the discussion on how transfer hubs are developing, what they can expect on freight routes, and other options to keep communications open that will help grow the ecosystem.

Opportunities

The following summarizes the opportunities for advancing the three key categories of actions to support freight CAV activity in Texas.

Developing a Transfer Hub/Terminal Strategic Plan

The following opportunities may help the state prepare for and support transfer hub development.

- Assess where there are potential terminal locations in relation to Texas' network and the use of existing tools to understand freight mobility in those areas.
- Assess future conditions to understand the impact of increased truck activity including a look at potential congestion, safety, and asset conditions.
- Develop a catalog of state-owned property and determine where potentially suitable transfer hub property exists that could support transfer hub activity.
- Develop a strategic plan focused on transfer hub development to include:
    - Understanding of existing plans by companies operating in Texas;
    - Evaluation of private versus open source and the potential impacts or issues;
    - Understanding of freight flows and the freight network, as well as where it makes sense to have transfer hubs;
    - Assessment of real estate needs including ROW along highways, land use issues, local government planning and zoning conventions, and community mitigation needs; and
    - Identification of Texas' role, level of support, and other actions that are needed to help coordinate, facilitate, and mitigate development of transfer hubs and rollout of automated trucking including resources for local governments.

Assessing Texas Freight Network and Automated Truck Impacts

The following opportunities can support an assessment of the transportation network, specifically the Texas Freight Network, to support automated trucking.

- Assess existing and future freight flows in the statewide freight plan and engage Texas industries concerning how they might be thinking of optimizing routes for autonomous trucking.
- Commit to maintaining and using resources (i.e., TCAT and newer freight fluidity tools released in 2023) to assess freight networks, tie commodities and industries to networks, and help identify points that might change or shift when autonomous trucks saturate the network.
- Evaluate truck flows at key freight locations to help identify drayage and circuit operations that may be best targeted for autonomous trucks or platooning.
- Identify potential drayage and circuit routes and what might need to be considered from an operational perspective that would support the freight movement while ensuring safety, efficiency, and environmental improvements.
- Have operations staff work with TxDOT planning, asset management, and pavement staff to research ways to offset asset decline or optimize asset performance given new, repetitive levels of activity on drayage and circuit segments.
- Assess the existing freight network in relation to locations of automated trucking activity (routes and transfer hubs).
- Discuss and document how automated trucking network optimization might cause the routes to be dynamic, and whether there is an expected impact on the network or other infrastructure support is needed.
- Understand where in Texas the circuits or specific freight routes are in order to prioritize for automated trucking implementation.

Working with District Offices to Understand Freight Routing and Build a CAV Ecosystem

Multiple opportunities exist to develop a deeper understanding of the existing autonomous freight network in more detail, share information between the public sector and autonomous trucking companies, and advance a freight CAV ecosystem. These include:

- Continue development of pilots and experiments with companies willing to share data, and test V2I data for state DOT decision-making purposes related to automated trucking. Identify what is useful, what kinds of intel it provides, and the best way to access and process the information. This should build on the TxDOT efforts described earlier, especially for areas like work zones.
- Review, update, and establish new operational procedures for inspections, incident management, routing, etc. that work with autonomous trucking as they do with conventional trucking. Consider how things might need to change, and what data feeds are needed and in what format for messaging the driving community.
- Establish a data/information exchange and repository for more robust sharing of automated trucking activities and state information that can support industry.
- Inventory assets, conditions, property, freight flows, and other important information to support the repository.
- Build on existing efforts such as the Connected Vehicle Data Framework to continue development of CAV data uses, data exchanges, and V2X operations, developing concepts of

operation and identifying workforce needs, technology development, and other needs to support advanced data analytics and communications.
- Focus on an outreach and communications strategy that helps Texas citizens and local governments understand the changes that are occurring and brings stakeholders into the discussion on how transfer hubs are developing, what stakeholders can expect on freight routes, and other options to keep communications open that will help grow the ecosystem.

Conclusion

The purpose of this paper is to present a framework for the next steps, actions, and coordination needed based on emerging freight CAV activity. The focus of this document is primarily strategies and updates for TxDOT and its partners to consider in planning and prioritizing actions to support emerging technology within the highway and controlled environment locations in Texas. Based on the expansion of the recommendations related to the current and planned emergence of automated trucking, Figure 9 illustrates the opportunities for TxDOT and its partners to support automated trucking in Texas.

The action items can be categorized into three categories:

- **Developing a transfer hub/terminal strategic plan:** developing an automated trucking transfer hub/terminal strategic plan that includes a thorough evaluation of existing and planned implementation in Texas, how this will impact the freight network, what the development impacts and needs are, and some specific outlining of roles and responsibilities, including support to local governments.
- **Assessing Texas freight network and automated truck impacts:** assessing how automated trucking will change the Texas Freight Network, what infrastructure is needed, what operations coordination would help, and where priority corridors or circuits are that support automated trucking.
- **Developing a freight CAV ecosystem:** creating an opportunity to share information between the public and private sectors in robust ways; offering ways for the private sector to input activities, and for the public sector to provide data about the freight network, freight facilities, existing freight flows, projects, and more.

These activities are possible to begin immediately and would likely take a year to collect and complete. However, in getting started and throughout the process, these activities would help TxDOT and its partners to organize information and additional actions in an optimized way and to strengthen (already strong) relationships with the private sector. This will help improve coordination, support, and success.

Developing a Transfer Hub/Terminal Strategic Plan

- Understand plans and needs for transfer hubs
- Evaluate private versus open source and potential impacts
- Assess freight flows and network to identify areas of demand
- Assess real estate/right of way options, land use, planning and zoning, and local government coordination needs
- Identify state and local roles, support, and mitigation actions

Assessing Texas Freight Network and Automated Truck Impacts

- Assess existing freight network and automated trucking plans/opportunities
- Understand key freight routes, circuits, and priority corridors
- Partner with district offices to identify network changes, impacts, and operational needs

Developing a Freight CAV Ecosystem

- Set up a robust information sharing platform (where automation is occuring, plans, and geospatial data on the freight system)
- Take inventory of assets, conditions, freight flows, and other freight intel
- Support data analytics and related technology, skills, and applications
- Develop outreach and communications to positively engage local governments, citizens, and other stakedholders

Figure 11: Specific Near-Term Action Items to Support Automated Trucking

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APPENDIX D

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Operations and Technology Education Needs for Automated Vehicle Users and Stakeholders

Texas CAV Task Force
Subcommittee on Licensing and Registration

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Licensing and Registration Subcommittee of the
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August 2023

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Table of Contents

List of Figures

List of Tables

Acknowledgments

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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:

3. Coordinating and providing information on CAV technology use and testing in Texas.
4. 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.
5. 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

AAA	American Automobile Association
ACC	adaptive cruise control
ADAS	advanced driver assistance system
ASA-Texas	Automotive Service Association of Texas
BSW	blind spot warning
CAV	connected and autonomous vehicle
NHTSA	National Highway Traffic Safety Administration
OEM	original equipment manufacturers
PAVE	Partners for Automated Vehicle Education
POI	program of organized instruction
RSO	right-seat operator
SAE	Society of Automotive Engineers
TDLR	Texas Department of Licensing and Registration
TTI	Texas A&M Transportation Institute
TxDOT	Texas Department of Transportation
UTA	University of Texas at Arlington

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Executive Summary

Vehicles with automated features and autonomous vehicle deployments are rapidly growing in number. However, the public has a general level of confusion regarding what these automated and autonomous features are truly capable of, which can lead to a false sense of security or drivers operating vehicles in a manner in which they were not intended. Education and guidance are critical needs for the public so that they can fully understand vehicle technologies and operate them safely. This white paper details a literature review and stakeholder interviews conducted to gather information on how to best inform the public and automated and autonomous vehicle stakeholders about what is needed to improve and expand the education of owners and operators of automated and autonomous vehicles. The takeaways from this process include:

- Using consistent terminology is important,
- Automated vehicle technology is intended to increase safety by assisting in some of the driving tasks, such as lane-keeping assistance, automatic emergency braking, or adaptive cruise control, which can ultimately reduce the severity of or even prevent crashes.
- Automated vehicles still require a driver in the driver's seat or a safety operator in the case of shuttles and freight.
- Autonomous vehicles are those vehicles where no driver is needed at all. Further compounding the issue, naming conventions for vehicle technology and the description of how technologies can be used lead to greater misperceptions.
- There is a great need to use consistent terminology, accurately describe the intent of vehicle technology, and promote the general understanding of automated and autonomous vehicles.

Due to this continued high level of misunderstanding and misconceptions about CAV technologies and capabilities, several key opportunities exist, including:

- Collaborating with automobile manufacturers and dealers,
- Consider mandating manufacturer-led training for service and collision technicians,
- Using chat rooms or discussion boards for sharing information between service and collision technicians
- Providing educational materials in multiple formats for different audiences (e.g., a printed document versus a video distributed on the internet),
- Embracing autonomous vehicle deployments will enhance public understanding,
- Including the correct stakeholders in discussions,
- Recognizing the potential value of vehicle safety inspections,
- Updating crash reporting to reflect automated vehicles, and
- Planning for the use of data from connected and autonomous vehicles (CAVs) to improve safety and reduce congestion.

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Introduction

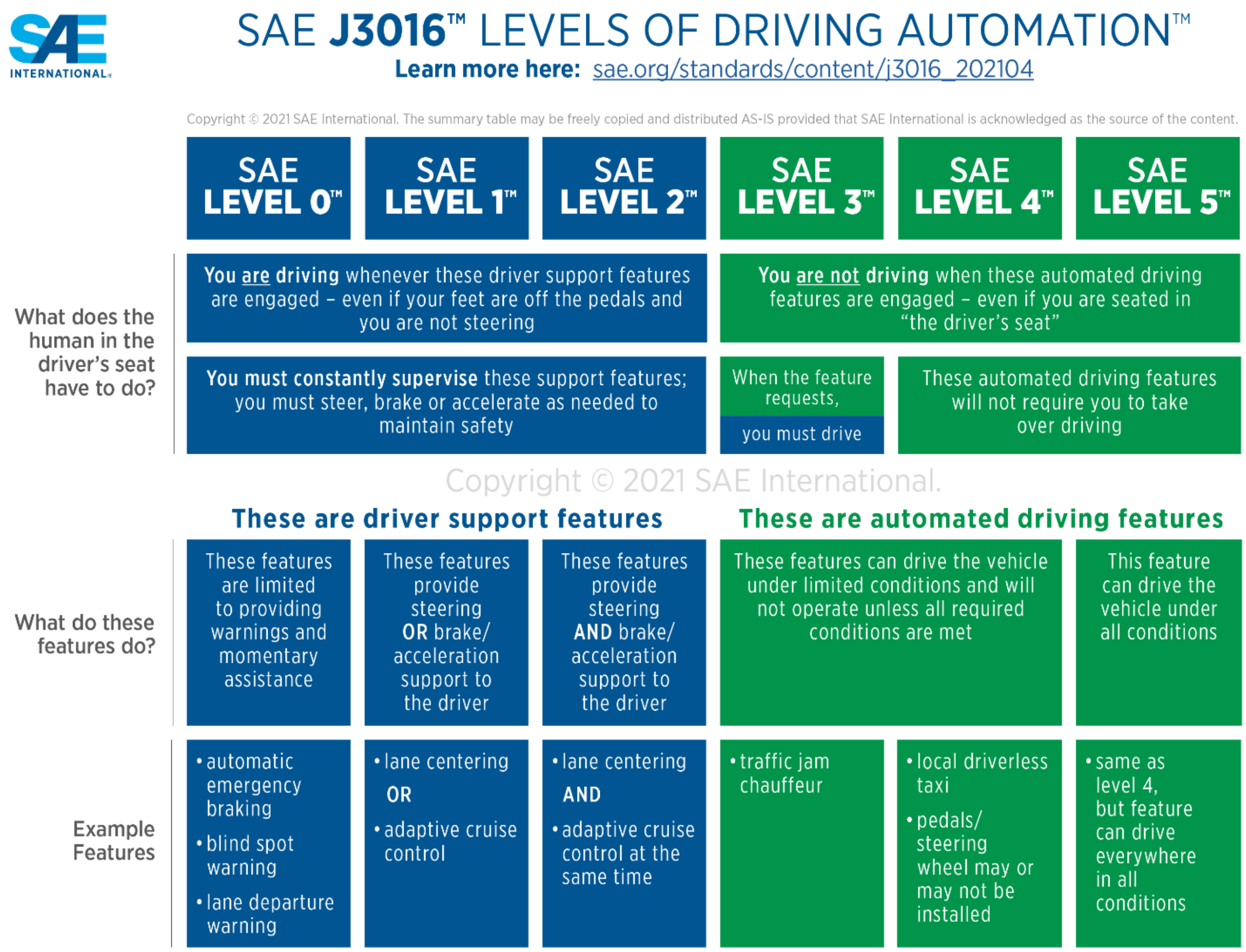
Vehicles with automated features and autonomous vehicle deployments are rapidly growing in number. However, the public has a general level of confusion regarding what these automated and autonomous features are truly capable of, which can lead to a false sense of security or drivers operating vehicles in a manner in which they were not intended. Education and guidance are a critical need for the public so that they can fully understand vehicle technologies and operate them safely.

The purpose of this document is to identify the public perception issues related to automated and autonomous vehicles, as well as document the needs for industry partners as automated and autonomous vehicle technologies continue to advance. Relevant literature was reviewed to form a basis for how the public understands the technology on automated and autonomous vehicles. Stakeholders were interviewed to identify agency and stakeholder needs and concerns.

Background

According to the American Automobile Association (AAA) ([1]), in May 2018, more than 90 percent of new cars in the U.S. market had at least one automated technology feature available. As of February 2021, 58 percent of the respondents in the annual AAA Annual Automated Vehicle Survey wanted an advanced driver assistance system (ADAS) feature on their next vehicle, and nearly 96 percent of 2020 vehicle models had at least one ADAS feature ([2]). As of May 2021, 38 states have active self-driving vehicle deployments ([3]). Automated vehicle technology is expanding, and drivers are becoming more comfortable with the technology. This paper discusses how people understand automated technology and what the different automated vehicle stakeholders want to be included in operations education for users of automated vehicles, including freight, passenger vehicles, and shuttles.

ADASs are automated features, such as automatic emergency braking, lane-keeping assistance, and adaptive cruise control that can help drivers with driving tasks and enhance safety by preventing crashes. Automated technology features help drivers alleviate some driving tasks and increase safety by preventing and mitigating accidents. When automated technology features are engaged, drivers should remain aware and engaged with the driving task and be ready and able to take over control of the vehicle at any point in time. Level 2 automated vehicles include vehicles with ADAS features and are not intended to be self-driving. Figure 1 highlights the Society of Automotive Engineers (SAE)–defined levels of automation and includes feature descriptions, which were created by SAE International ([4]).



Source: SAE International

Figure 12: SAE-Defined Levels of Automation

Self-driving pilot deployments (e.g., freight, passenger vehicle, and shuttle operations) are occurring across the United States, with safety operators in the driver's seat in many of the deployments. Uncertainty, media scrutiny, and a general lack of understanding can lead the public not to trust automated and autonomous vehicles. If the public lacks trust and confidence in the ADAS features or finds them confusing or intimidating, people may be less likely to use them. Individuals spending more time around automated and autonomous vehicles are more likely to have increased understanding, and their stress related to automated vehicles and the technology is alleviated (**Error! Bookmark not defined.**,[5]). The first step is getting the public to use the technology so that their general understanding of how the technology works can improve. As market penetration continues and more people begin to use more automated features on their vehicles, their trust that the technology is safe improves. Owners of automated vehicles can share their experiences with others, further generating public acceptance. Autonomous shuttle deployments with safety drivers and other public events where the public can interact with the vehicles can also improve general understanding and acceptance.

The National Highway Traffic Safety Administration (NHTSA) recommends that original equipment manufacturers (OEMs) develop education and training programs to help users safely and adequately use the different ADAS features. Education can reduce the risk of misuse and misunderstanding ([6]).

A 2018 survey completed by the Advocates for Highway and Auto Safety discovered that 87 percent of respondents wanted a website to find information on safety features for automated vehicles ([7]). In 2014, the University of Iowa partnered with the National Safety Council to develop the website MyCarDoesWhat (http://mycardoeswhat.org) to help the public better understand ADAS features and technologies. The website offers information about how the different technologies work, when they should be used, which vehicles have ADAS features, and more. Consumer Reports also has a tool available online for the public to determine which automated technology features are standard, optional, or not available on vehicles ([8]).

Several studies have been completed to determine how drivers learn and understand different ADAS technologies. Forster et al. studied different methods to educate users about ADAS features before driving in a simulator ([9]). The researchers used three different education methods with participants:

- A general overview of the technology,
- A review of the owner's manual, and
- An interactive computer-based tutorial.

The researchers found that reviewing the owner's manual and completing the interactive tutorials increased operation and understanding of the system and features compared to those who only received general guidance *([9])*.

Llaneras et al. completed a study on training and how participants responded to system alerts ([10]). The researchers found that while the training helped, it did not eliminate the misunderstandings the participants had about the ADAS features. The researchers also found that when the participants were penalized (e.g., the ADAS feature was shut off) for ignoring system alerts, they remained more engaged in the driving task and were more mindful of the vehicle warnings while driving *([10]**Error! Bookmark not defined.**)*.

Public Confusion about Terminology

For the public, understanding automated and autonomous vehicles is complicated because OEMs, research organizations, and other automated vehicle stakeholders and agencies use different terminology to describe the same features. Furthermore, misleading feature names can lead drivers and the public to think that some features are capable of performing in ways for which they were not designed. One of the common misconceptions is related to the term *autopilot*, which can lead the public to believe the car can drive itself. However, that is not the current intent of that feature because the driver is still required to be engaged in the driving task.

In 2019, AAA found that adaptive cruise control and lane-keeping assist can each have up to 20 different names (**Error! Bookmark not defined.**). AAA and Consumer Reports have recommended that OEMs and other agencies normalize the terminology for ADAS features, especially when they perform the same task. Using the same terminology can decrease the misconceptions that drivers and the public face (**Error! Bookmark not defined.**, **Error! Bookmark not defined.**). A group of 10 organizations, including AAA, the Insurance Institute for Highway Safety, J.D. Power, the National Safety Council, and several others, have agreed to use these six common terms: forward collision warning, automatic emergency braking, adaptive cruise control, blind spot warning, lane departure warning, and lane-keeping assist ([11]). Table 1 provides these terms, their acronyms, and a feature description.

Table 3: Consumer Reports' List of Acronyms, Terms, and Descriptions

Acronym	Automated Technology Feature	Description
ACC	Adaptive cruise control	Uses lasers, radar, cameras, or a combination of these systems to keep a safe following distance between the ACC-fitted car and the car ahead.
AEB	Automatic emergency braking	Automatically applies brakes to prevent a collision or reduce speed when the system detects an imminent collision with a vehicle directly in front.
BSW	Blind spot warning	Provides visual and/or audible notification of a vehicle in the blind spot. The system may provide an additional warning if the driver uses the turn signal when a car is in another lane next to the BSW-fitted car.
FCW	Forward collision warning	Provides visual and/or audible warning to alert the driver and prevent a collision.
LDW	Lane departure warning	Provides visual, audible, or haptic warning to alert the driver when the vehicle crosses lane markings.
LKA	Lane-keeping assist	Provides automatic corrective steering input or braking when crossing lane markings.

Source: Consumer Reports

The naming conventions and resulting misconceptions are just one reason drivers need to understand the true intent and limitations of the automated technology features. As a result of misconceptions, drivers misuse the technology and subsequently engage in risky behavior while driving. For instance, a 2018 AAA survey found that 13 percent of respondents would feel comfortable performing a separate task outside of driving while an ADAS feature was engaged ([12]). This result could indicate problems with the use of the term *autonomous* and not with the ADAS technology itself.

Current Perspectives and Understanding

Texas A&M Transportation Institute (TTI) staff reviewed relevant literature to understand how people understand automated vehicles and technology. This information can help the Texas Department of Transportation (TxDOT) understand what information needs to be shared with automated and connected vehicle users. The literature review attempts to address the following questions:

- What educational or outreach strategies are others using to inform drivers (e.g., videos, websites, social media campaigns, etc.)?
- Do users understand the technology on the vehicles? How is this comprehension being assessed or measured?
- Are any feature-based educational tools or strategies available through manufacturers, associations, or third parties?
- How are states preparing for crashes or emergencies involving automated vehicles?

Automated Vehicle Technology and Human Behavior

An area of concern when implementing automated technology relates to human behavior. Recent surveys have shown that there is fear and a lack of trust among the public regarding automated vehicle technology. There is also concern that individuals may intentionally and sometimes even maliciously interact in risky ways with automated vehicles. For example, Banks et al. conducted a study in the United Kingdom that found that drivers were more likely to try to test the ADAS features in risky situations by purposefully trying to make the technology interact in unintended ways ([13]). At times, drivers want to try to break the technology to prove or disprove whether the technology will perform in an intended way. Another example of risky situations where the public tries to test out the technology is when nearby pedestrians run in front of an automated shuttle to see if it will stop, which was often witnessed in the City of Las Vegas automated shuttle deployment. The public may be told the technology is sound, but the public often needs to see it to believe it. As more people participate in automated shuttle and automated vehicle pilot programs, these people can see firsthand that the technology works. Automated vehicles must also learn how to interact with their environments and adapt to different situations. An automated vehicle that works well in one location may not work well in other areas or may take additional time to learn about the new environment.

Oliver et al. found that automated vehicles face challenges in understanding human behavior, but the researchers argued that automated vehicles would improve the more they are used in real-world situations ([14]). After an incident occurs with an automated vehicle, the lessons learned from the incident can be added to the software and updated on all automated vehicles in the area or owned by a manufacturer, thus increasing safety. They conclude that the continued advancement of the technologies will take place when they are in the driving environment and interacting with other vehicles. ([14]).

Public Knowledge and Perceptions of Automated Vehicle Technology

The general confusion about the functionality of automated technology and features and, in some cases, the deliberate misuse of the technology are causes for concern. In January 2014, the University of Iowa received grant funding to see how well drivers understood and to what level they used the different ADAS features available in their vehicles. In 2015, researchers completed the National Consumer Survey of Driving Safety Technologies, highlighting the need for public education because many respondents did not fully understand ADAS features. More than half of respondents (65.2 percent) had at least some confusion regarding ACC, and only 35 percent had any knowledge of or experience with it. Moreover, 40 percent of respondents reported that they experienced the vehicle behaving in a way that they did not expect ([15]).

A 2018 study completed by AAA surveyed owners of vehicles with ADAS features and found that 83 percent of the respondents were first-time owners of ACC. In addition, 52 percent of respondents reported that they did not know how the ADAS feature worked when they purchased the vehicle. Only 45 percent remembered being offered any training on any ADAS features at the dealership. Ninety percent of the respondents revealed that they had since gained knowledge of the features and felt more comfortable the more they used ADAS (**Error! Bookmark not defined.**).

Since 2016, AAA has also completed annual national vehicle technology surveys using a total of 1,832 interviews among drivers who are 18 years of age or older. The survey completed in January 2017 found that 78 percent of respondents were scared to ride in fully automated vehicles. However, public acceptance has been shifting in recent years. More people are opening up to the idea of riding in fully automated vehicles, as indicated by the survey completed in December 2017. The survey found that only 63 percent of the respondents were scared to ride in a fully automated vehicle, meaning public acceptance had increased by 15 percent within the year ([16]). As the public spends more time interacting with the technology, the trust and understanding of the technology will likely increase. AAA also contends that "transparent, accurate and frequent information from the industries involved in developing self-driving vehicles will ease consumer concerns" (**Error! Bookmark not defined.**). Table 2 summarizes the AAA Annual Automated Vehicle Survey results from 2016 through 2019 ([17, 18, 1, 19]).

Table 4: Summary of 2016–2019 AAA Annual Automated Vehicle Survey Results

Survey Information	Phase I	Phase II	Phase III	Phase IIIB	Phase IV
Survey period	January 2016	January 2017	December 2017	April 2018	January 2019
Respondents	1,832	1,012	1,004	1,014	1,008
Percent of respondents afraid to ride in a fully automated vehicle	75%	78%	63%	73%	71%
Percent of women afraid of fully automated vehicle	81%	85%	73%	83%	N/A
Percent of men afraid of fully automated vehicle	67%	69%	52%	63%	N/A
Percent of respondents who want at least one automated technology feature on their next vehicle	61%	59%	51%	55%	N/A

Source: AAA

In 2020, AAA changed the methodology for the Annual Automated Vehicle Survey, so the results are not directly comparable to previous years. The new survey methodology used a probability-based panel that was more characteristic of the U.S. household population, providing sample coverage of roughly 97 percent of the U.S. household population. The survey results indicated that only 12 percent of the respondents would trust a self-driving vehicle, and 28 percent of the respondents were not sure how they would feel about the self-driving technology ([19]). In the 2021 Annual Automated Vehicle Survey, the results were similar to those from the previous year, with only 14 percent of the respondents indicating that they would trust a self-driving vehicle, and 32 percent of the respondents were not sure how they would feel about the self-driving technology ([1]). AAA believes that reliable information will build customer trust for automated and autonomous vehicle technologies ([1]). Table 3 summarizes the AAA Annual Automated Vehicle Survey results from 2020 and 2021 ([Error! Bookmark not defined., Error! Bookmark not defined.]).

Table 5: Summary of 2020–2021 AAA Annual Automated Vehicle Survey Results

Survey Information	January 2020	January 2021
Respondents	1,301	1,010
Percent of respondents who would trust a self-driving vehicle	12%	14%
Percent of respondents unsure of how they felt about self-driving vehicles	28%	32%

Source: AAA

A 2016 survey sponsored by State Farm found that less than 11 percent of respondents had ridden in some form of automated vehicle, and less than 40 percent were willing to ride in a vehicle with automated capabilities. The survey also found that educated men under the age of 40 were more likely to be comfortable with and use automated vehicles (20). A 2016 national survey sponsored by Kelley Blue Book found that 60 percent of respondents knew little to nothing about automated vehicles, with 76 percent of respondents between the ages of 51 and 64 feeling like they knew little to nothing and 19 percent of respondents between the ages of 25 and 34 feeling like they knew a lot. The survey revealed that current owners of vehicles with ADAS features were more open to the idea of using even more automated vehicle technologies (21). These survey results may indicate that younger drivers who understand technology may be more open to the idea of automated vehicles.

A 2017 survey completed by the Pew Research Center found that only 6 percent of respondents did not have any knowledge of fully automated vehicles, while 35 percent of respondents thought that they knew a lot about them. The survey also found that 54 percent of the respondents were scared of fully automated vehicles and that educated men were more likely to have heard more about and be more open to fully automated vehicles. In addition, 39 percent of respondents thought that fully automated vehicles would reduce the number of injuries and fatalities in automobile accidents (22). The State Farm and Pew Research Center surveys both indicate that educated men are more likely to be open to the idea of automated vehicles. A 2017 survey completed by the Advocates for Highway and Auto Safety found that 64 percent of respondents were worried about having fully automated vehicles on the roadways, and 84 percent believed that there should be a way to guarantee that the driver stays engaged in the driving task (23).

Finally, a study by Pradhan et al. found that owners generally felt safer as a result of the automated technology features but were concerned that drivers could become overly dependent on the technology and would lead them to participate in distracted and risky driving behaviors (24). The researchers argued that OEMs should take more time to understand human behavior and develop these ADAS features accordingly, ultimately increasing safety in automated vehicles and improving public perception *(24)*.

As the technology continues to advance, it is important to make sure that drivers fully understand the capabilities and limitations of automated vehicles. Without this understanding, public acceptance may be diminished, and society may not fully realize the safety and other societal benefits of automated vehicles.

Stakeholder Interviews

Outreach to several stakeholders was conducted in late 2021 and early 2022 to determine how automated vehicle users understand the technology. TTI staff conducted interviews with several organizations, manufacturers, and operators. Table 4 shows the stakeholder interview information.

Table 6: Stakeholder Interview Information

Type	Stakeholder	Interview Date
Association	Texas Automobile Dealers Association	January 21, 2022
	Automotive Service Association of Texas (ASA-Texas)	January 4, 2022
	Texas Trucking Association	December 13, 2021
Private company	Audi and Partners for Automated Vehicle Education	March 16, 2022
	Wejo	February 25, 2022
	May Mobility	January 26, 2022

	Kodiak Robotics	December 20, 2021
Government	Texas Department of Licensing and Regulation	January 6, 2022
	City of Arlington, Texas	December 20, 2021

The American Automobile Association (AAA) provided information via email. TTI staff contacted the following organizations, but representatives did not respond to TTI's request for an interview:

- American Association of Motor Vehicle Administrators,
- American Car Rental Association,
- Governors Highway Safety Association,
- Motor and Equipment Manufacturers Association,
- Cadillac,
- Tesla,
- Volvo,
- EasyMile,
- TuSimple, and
- Embark.

TTI staff developed an interview guide, but based on the interviews, additional questions were asked, and questions that were not relevant to the stakeholder were eliminated. The following questions guided the interviews:

- How does the technology work with the driver?
- What are the gaps in the technology?
- Is an educational component offered for users to understand vehicle features and services?
- How might different ownership models affect driver use of automated vehicles—rental, mobility as a service, and subscription models?
- Is anything being done to address licensing and registration that needs to be identified?
- Do users understand the technology on the vehicles? How is this measured or assessed?
- Are there any feature-based educational tools or strategies available (i.e., how do dealers educate car owners on features)?
- How are vehicles and associated technologies monitored and maintained?
- What policies exist for when an accident or emergency occurs? What are the unique or special circumstances of the vehicle's technologies that can pose issues for occupants or first responders?

TTI staff conducted the interviews using Microsoft Teams. TTI staff informed each stakeholder that any proprietary information discussed in the interviews would not be included in the paper without permission. TTI staff recorded each interview, except the Texas Automobile Dealers Association interview because it was a phone call only. Each interview lasted approximately 30 minutes.

Texas Automobile Dealers Association

TTI staff interviewed a Texas Automobile Dealers Association representative on January 21, 2022. Many automobile dealers now use product specialists to provide automobile consumers with the necessary information to safely operate their new vehicles with full knowledge. These product specialists review the vehicle's manual and often walk through all the vehicle's features and answer any questions with the owner.

As more automated vehicles enter the market, automobile dealers consider it critical that they have the ability and tools to fix malfunctions associated with the automated features. Manufacturers also need to provide training materials to automobile dealers because every car is different. The key to the successful deployment of automated vehicles will be coordination and collaboration between dealers and manufacturers. If vehicle features are difficult to repair, this could lead to extended periods of time without a driver's ability to use them, which could encourage drivers to use the features less when they do get repaired.

Automotive Service Association of Texas

TTI staff interviewed representatives from ASA-Texas on January 4, 2022. ASA-Texas has been actively engaged in the automated vehicle space for several years. One of its primary concerns related to automated vehicles is vehicle safety inspections. ASA-Texas believes that vehicle safety inspections for automated vehicles will be critically important because the ownership model may change from individuals to a fleet-owned or shared-ownership model. In either case, clear responsibility for the inspections must be identified. In the future, autonomous vehicles could be owned by individuals or groups and used by multiple different people, so the user may not know or trust the owner, which could lead to increased fear about the safety of the vehicle from the user's perspective. ASA Texas suggested ensuring that automated and autonomous vehicle features undergo vehicle safety inspections can help inform passengers that the vehicle is safe to operate on roads.

While service technicians are working on vehicles with ADAS features and there have not been any major problems, service provider training is another area of concern for ASA-Texas because there is a need for direct training from the car manufacturer. ASA-Texas would prefer that the manufacturer-led training be mandated at the state or federal level. Otherwise, the training would be too slow. Training is needed now, especially for collision repair technicians. For the many automated vehicles that are still under warranty, the owner can go directly to the automobile dealer for service. For those vehicles not under a manufacturer's warranty or those involved in a collision, non-dealer service and collision repair technicians need training now.

Service technicians have been continually active in chat rooms to discuss any questions about the innovative technologies in vehicles today. The chat rooms are extremely popular and serve as an excellent resource for service technicians. A threat in the industry is that if the training and specialized equipment, which are often expensive, are not provided, it will be harder to prepare and retain qualified technicians.

Texas Trucking Association

TTI staff interviewed representatives from the Texas Trucking Association on December 13, 2021. Many companies are actively pursuing automated trucking and are working with carriers and cargo owners. There are concerns about how law enforcement agencies are prepared for the inevitable crashes or incidents with automated trucks. For example, how will accident investigations be conducted, and how will information be captured in crash-reporting forms? How should state law be adjusted to ensure public agencies have access to the necessary information to investigate crashes and collect applicable details?

Audi and Partners for Automated Vehicle Education

TTI staff interviewed representatives from Audi and the Partners for Automated Vehicle Education (PAVE) on March 16, 2022. PAVE is a coalition of industry nonprofits and academics that supports and promotes the education of automated vehicles to the general public to raise awareness about the benefits of driverless technology ([25]).

Audi currently has level 2 automated vehicles on the market, which means that the driver is still engaged in the driving task. The level 2 systems are becoming increasingly sophisticated, and Audi hopes to get to the point where these systems can monitor the driver's attention to the driving task. This action could lead Audi to develop technology that can limit the number of distractions that take away from the driving task and relieve the driver's cognitive overload.

New-owner training occurs at the dealership, and the sales personnel receive abundant training to train the new owner on the technologies in the automated vehicle. Sales personnel attend classes and have on-demand video training that they can complete. The owner's manual is another resource for new owners regarding the technologies in their automated vehicle. Audi is looking to develop short pamphlets that can be used for owner education. When educating owners on the innovative technologies, it is essential to remember people learn in different ways (e.g., auditory, kinesthetic, or visual), so different training methods will be necessary.

Wejo

TTI staff interviewed representatives from Wejo on February 25, 2022. Wejo is a company that collects data from autonomous and connected vehicles to improve vehicle safety by providing indirect benefits to users. Wejo primarily works with OEMs and research organizations to analyze and evaluate connected and autonomous vehicle data. The data collected from vehicles can be analyzed to identify the location of potholes in the roadways or if the windshield wipers are being used (i.e., to indicate that there is a weather event occurring and, as a result, traffic management and congestion may be impacted). Another goal for the company is to elevate the driving experience so eventually a person can enter a fast-food order, and it will be ready when the car arrives because the connected data can coordinate and streamline the experience in real time. States could also use the data to help navigate traffic during evacuations, mitigate safety concerns, and address congestion.

Based on results from collecting the connected and autonomous data in Paris, France, the data have been used to help reduce vehicle congestion. While the data result in positive experiences across the board, the company still needs to work on increasing education on how connected and autonomous vehicle data can improve safety and reduce congestion. Wejo is currently only collecting connected and autonomous data on passenger vehicles, not autonomous trucks, but the company is beginning to investigate how truck data can be collected.

May Mobility

TTI staff interviewed a representative from May Mobility on January 26, 2022. May Mobility currently has two pilot deployments for automated passenger vehicles in Arlington, Texas, and Fishers, Indiana. The vehicles must abide by local regulations, including inspections, licensing, and registration. The Arlington, Texas, vehicles are registered in Tarrant County. One aspect that May Mobility would like to see improved in the licensing and registration process is requiring documentation of technology in use in the vehicles being registered and sold and expanding crash reporting documentation to indicate which (if any) automated technologies were engaged at the time of an incident. Correctly and consistently reporting information about the types of automated technology included in vehicle-involved crashes is vital. Different manufacturers have different technologies, which cannot always be lumped together in the same category. May Mobility suggests the benefit of a license endorsement or certification for automated vehicle safety operators. However, not all companies and groups agree that endorsements are necessary.

Automated vehicle safety operators at May Mobility undergo extensive training before operating the automated vehicles. The safety operator training lasts four to six weeks and includes two written exams and an evaluation. Safety operators must also complete in-vehicle shadowing, training behind the wheel, and two evaluations with a supervisor; and must successfully pass a screening and background check. Safety operators have several check-ins and quality assessments with supervisors and team huddles daily. Safety operators receive weekly newsletters containing important information, including information about updates to the software. May Mobility also conducted several training courses with local first responders, with overwhelming attendance. The training was successful, and first responders learned about vehicle technology and what to do in case of an incident.

May Mobility found that many riders would use the service for the first time primarily to test the technology and see how the vehicles worked. Before the pilot deployment in Fishers, Indiana, another six-month deployment took place at the Indiana University–Purdue University Indianapolis campus. Initial survey results indicated that 60 percent of riders used the service to test out the technology. Within two months, 57 percent of riders used the service for needed trips. The riders seemed comfortable with the technology and often asked when the vehicle was in autonomous mode, indicating that they could not tell the difference between when the vehicle was operating in autonomous mode and when it was not.

Kodiak Robotics

TTI staff interviewed a representative from Kodiak Robotics on December 20, 2021. Kodiak automated trucks operating in Texas are registered as regular trucks. No special licensing requirements currently exist for drivers of automated trucks. Several automated truck interest groups have discussed using an endorsement, which is an approval on a license to operate in a special capacity. The interest in a special endorsement is relatively limited. However, if an endorsement become necessary, it would likely be developed as an in-house concept in addition to the rigorous internal training for safety operators.

Kodiak provides an intense amount of in-house education to truck safety operators. The driver-screening and -hiring process is a major event, and drivers undergo intense scrutiny. They must have a spotless driving record with a great deal of experience. Kodiak also focuses on hiring drivers interested in the technology that want to be employed there. Safety operators must complete a variety of training activities prior to getting on the road, including classroom training, mentoring, and on-the-job training, which includes several weeks of driving with an experienced safety operator.

Kodiak also spends a great deal of time ensuring that the safety operators understand the software updates and test the new features before going out on the road.

Kodiak also ensures that its safety operators follow the rules while in the truck, including remaining in the driver's seat at all times and staying off of cell phones. The safety operator in the driver's seat is responsible for monitoring the roadway but does not deal with the vehicle's operation. A right-seat operator (RSO) is in the cab and is responsible for communication with the operations base. At the point when only one safety operator is needed, the RSO will operate out of the remote operations center, where the RSO will continually monitor the truck's operation.

Kodiak has not had any incidents involving any of its automated trucks. Still, there is a policy in place for the safety operator to work with law enforcement in the event of an incident or law enforcement response. Kodiak has engaged with the Texas Department of Public Safety because there is a significant difference between cars and trucks: automated trucks will primarily operate on interstates for the near future. In contrast, automated passenger vehicles would be more engaged with local jurisdictions and city police, so it is important to remember to engage with the correct audience.

Kodiak understands the need for and importance of public awareness education so that all highway users are comfortable with the technology operating on the roadways. Safety cannot be understated in the realm of automated trucks, but when people see the vehicles and interact with them, they begin to understand that the vehicles are very safe. Kodiak also takes feedback from the safety operator very seriously. If the vehicle is operating in a way that the operator does not like, the safety operator needs to recognize the problem and take corrective action.

Texas Department of Licensing and Regulation

TTI staff interviewed representatives from the Texas Department of Licensing and Registration (TDLR) on January 6, 2022. Driver education is mainly conducted by private businesses and in parent-taught online curricula; public schools are a tiny part of driver education. Commercial driver's license training is managed/regulated by the Texas Workforce Commission. The state specifies a program of organized instruction (POI), which is a relatively flexible set of content requirements. The POI has lots of content on driver distraction and driving while intoxicated/driving under the influence but only a short section on vehicle technology. The Texas Legislature could consider amending the Education Code driver education content (the statement of assurance) to require more technology training. TDLR could also be engaged to work on technology training for State of Texas employees who travel on state business in their personal vehicles or rental cars.

City of Arlington, Texas

TTI staff interviewed a representative from the City of Arlington, Texas, on December 20, 2021. The City of Arlington has been involved in three autonomous vehicle pilot deployments:

- The first deployment was a collaboration between EasyMile and First Transit with an off-street shuttle deployment. Because the shuttles were operated off-street, there were no licensing, registration, or NHTSA interactions. Some challenges involved acquiring the necessary insurance. The city attorney wanted EasyMile to carry insurance it had not had in other deployments because this was one of EasyMile's first U.S. deployments.

- The second deployment was with DriveAI, which no longer exists. DriveAI retrofitted a Nissan Envy 200 van with the hardware and software to make it automated in this deployment. The vehicle met NHTSA safety standards, so DriveAI did not need to obtain any waivers for the operation. The vehicle had all the standard license plates, registration, and insurance that a normal vehicle had.
- The third deployment was with May Mobility in collaboration with Via, a ride share service. This deployment used automated Lexus sport utility vehicles licensed and registered in Texas.

The City of Arlington offered educational components about the May Mobility deployment in several ways, such as on a website (https://www.arlingtontx.gov/city_hall/departments/transportation/rapid) and social media. The City of Arlington also focused on student education at the University of Texas at Arlington (UTA), where the deployment routinely operated. Citizen education was one of the primary goals, and the website hosts a robust frequently asked questions section. Based on survey results for the deployment, respondents have been incredibly positive about the automated experience. The deployment has many repeat riders, indicating that the passengers are pleased with the service. UTA students also ride for free.

The safety operators for the deployments complete a rigorous onboarding program, and the interview process is designed to pick candidates with a good aptitude for the technology. To be a safety operator, a person needs to be able to pay close attention to the vehicle's operations while not actually being in control of the vehicle—a trait that can be challenging to find. The safety operators also complete classroom training and training in the vehicle, first with a few days of ride-along training and then several more with a training supervisor in the passenger seat. Safety operators undergo frequent retraining and receive information on any software or hardware updates.

May Mobility has an incident-reporting form in case of any issues, which can range from a disgruntled passenger (e.g., refusing to wear a mask) to a vehicle not operating appropriately or at the ideal level (e.g., wheels rubbing the curb) or an actual crash, which they have not had. While the issues May Mobility has reported are not NHTSA safety violations, the company still reports the issues for maintenance and historical documentation. May Mobility and the City of Arlington invited local first responders to attend safety training for deployments, which allowed the first responders to become familiar with the vehicles to know how to respond in case of an incident. The first responders learned how the vehicles work, how to shut off the vehicle, where the battery is located, and where all other electronics are located.

American Automobile Association

TTI staff contacted AAA via email, and AAA provided educational information in response. The results from AAA's Annual Automated Vehicle Survey between 2016 and 2021, which highlight the public's perceptions of automated vehicles, are discussed in previous sections of this report. According to the email communication received from AAA, AAA produces the following educational information on ADAS features:

- The AAA Foundation for Traffic Safety has produced the following reports:
    - *The Impact of Information on Consumer Understanding of a Partially Automated Driving System*,

  - *Understanding the Impact of Technology: Do ADA and Semi-automated Vehicle Systems Lead to Improper Driving Behavior*, and
  - *An Examination of Longer-Term Exposure and User Experiences Affect Drivers' Mental Models of ADAS Technology*.

- The National AAA Advocacy team has testified in Congress about the standardization of automated system terms so that consumers can more easily understand what the various degrees of automated systems provide to the consumer.
- AAA has included occasional articles in the AAA member publication, which has been newly minted as *AAA Explorer* (previously *AAA Journey Magazine*).

Conclusion

Automated vehicle features and autonomous vehicle deployments are rapidly expanding across the country. However, there is still a high level of misunderstanding and misconceptions about these vehicle technologies and capabilities. Automated vehicles are intended to increase safety by assisting in some of the driving tasks, such as lane-keeping assistance, automatic emergency braking, or ACC, which can ultimately reduce the severity of or even prevent crashes. Automated vehicles still require a driver or safety operator in the driver's seat. Autonomous vehicles, on the other hand, are those vehicles in which no driver is needed at all. Further compounding the issue, differing naming conventions for vehicle technology and the varied description of how technologies can be used lead to greater misperceptions. There is a great need to use consistent terminology, accurately describe the intent of vehicle technology, and promote general education about automated and autonomous vehicles.

Opportunities

This section provides strategies for TxDOT and other organizations to help educate the users of automated and connected vehicles. This information will help Texas state agencies and other stakeholders understand how to best move forward and prepare their citizens for automated vehicle technologies. Based on the literature review and stakeholder interviews, the following key takeaways allow decision makers to prepare for and educate the users of automated and autonomous vehicles, including freight, passenger vehicles, and shuttles:

- It is critical that all automated vehicle stakeholders use consistent terminology that accurately reflects the capabilities of the technology.
- Collaboration between automobile manufacturers and dealers is important to guarantee successful educational efforts for the consumer regarding the automated features of new vehicles.
- States may consider mandating manufacturer-led training efforts for service and collision technicians that can ensure the prompt transfer of knowledge regarding automated vehicles.
- Chat rooms can be another tool to provide educational elements of automated vehicles, which can apply to automobile dealers, service centers, and collision technicians.
- It is critical to remember that individuals may have different learning styles, so redundant forms of educational tools in assorted styles (e.g., written, video, chat rooms, etc.) will be extremely beneficial for all individuals who interact with automated vehicles.

- States may want to embrace autonomous vehicle deployments because survey results from other deployments have indicated that users have positive experiences. However, the public needs to become familiar and comfortable with the technology before they are willing to use the services on a more frequent basis.
- It is critical that states include the correct stakeholders in the conversations. For example, the state police will be a critical stakeholder concerning automated trucks because these trucks will primarily operate on interstates. Passenger vehicles and shuttles will require interaction with local police because passenger vehicles and shuttles will primarily operate in local jurisdictions.
- Because the ownership model may change with automated and autonomous vehicles, states may want to recognize the value that vehicle safety inspections could play in ensuring that automated and autonomous vehicles are safe for transportation purposes. Vehicle safety inspections in Texas do not currently, by law, require the evaluation of ADAS or autonomous features. This factor could become important when another individual or group owns the vehicle after its initial purchase from a licensed dealer because there will likely be multiple users of the vehicle during its useful life. This is similar in concept to fleet vehicles or car rentals that have multiple users.
- States may want to plan how crash reporting can be updated to reflect automated vehicles. As more data are recorded, states can accurately reflect the safety of autonomous vehicles, but if the data are not recorded, there is no way to tell consumers honestly and transparently about the safety of automated vehicles.
- States may want to plan on how data from connected and autonomous vehicles can and should be used to improve safety and reduce congestion.

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APPENDIX E

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Connected and Automated Vehicle Digital and Physical Infrastructure Needs

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

Authors:
Safety, Liability, and Responsibility Subcommittee of the
Texas Connected and Autonomous Vehicles Task Force
Beverly Storey, Texas A&M Transportation Institute

August 2023

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Table of Contents

List of Figures

List of Tables

Acknowledgments

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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

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

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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.

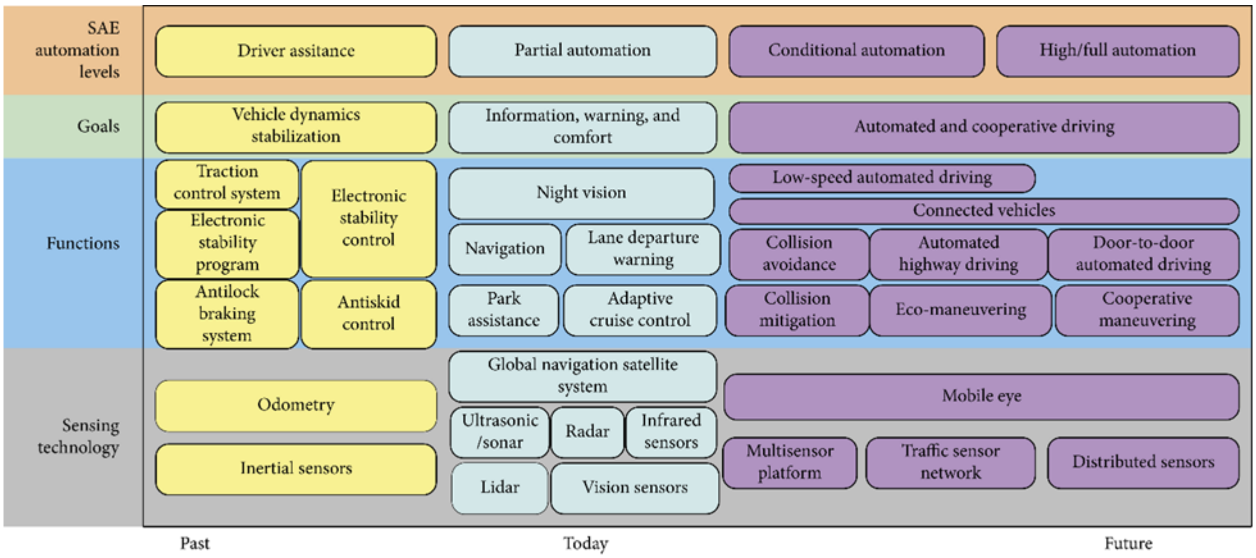

Figure 13: Past and Potential Future Evolution of Autonomous Vehicle Technology (2)

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 (Error! Bookmark not defined., 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.

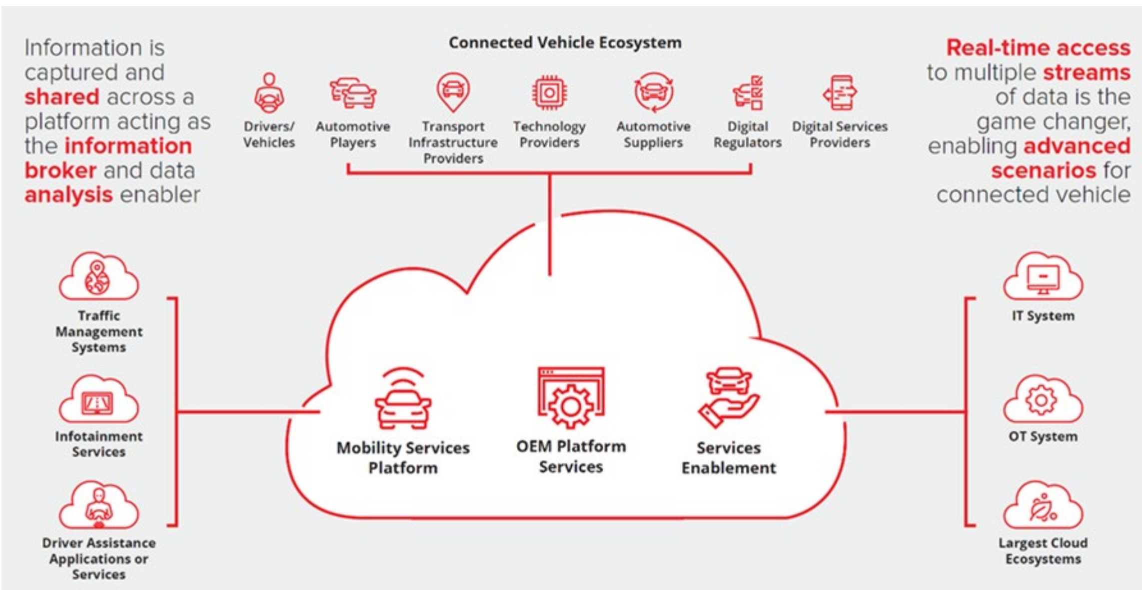

Figure 14: Connected Vehicle Ecosystem (5)

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.

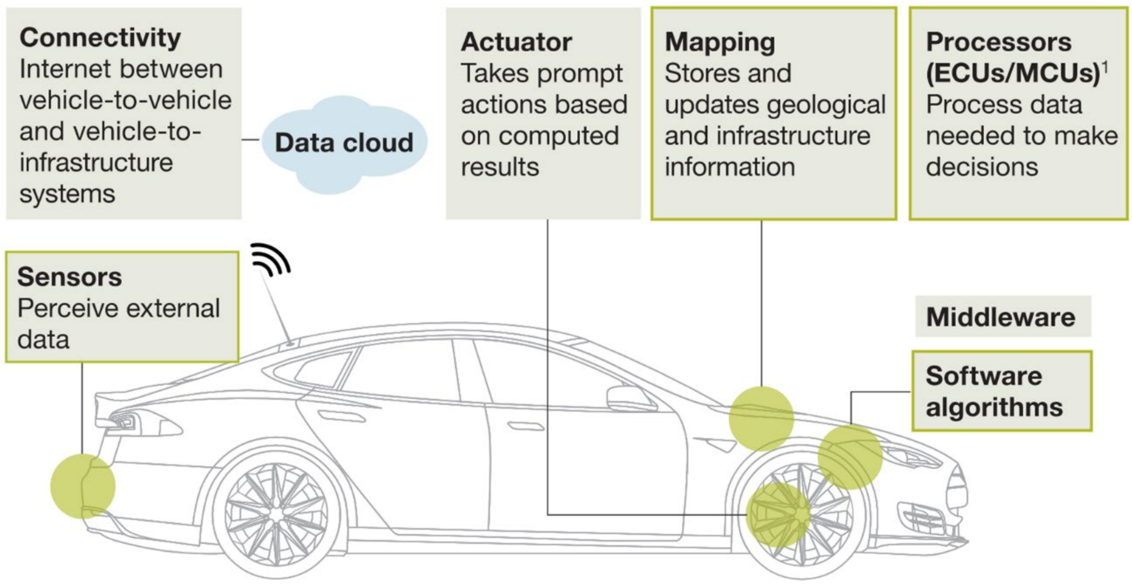

Figure 15: Key Components of Advanced Driver Assistance Systems (5)

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 7: 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.

	TomTom	waze	NIRA	here	HM	CARUSO	otonomo	GEOTAB
Data acquisition	Sat-nav devices, in-vehicle software, and cloud-to-cloud OEM data	Connected devices and users of their apps	Software installed in vehicles	In-vehicle software and V2V OEM data	Cloud-to-cloud OEM data	Cloud-to-cloud OEM data	Cloud-to-cloud OEM data	Data acquisition through dongles (OBD II)
Data transformation, contextualization and sharing	Contextual and cleaned data. Open sharing of sharing SRTI	Contextual and cleaned data.	Contextual and cleaned data.	Contextual and cleaned data. Open sharing of sharing SRTI	Contextual and cleaned data.	Contextual and cleaned data.	Contextual and cleaned data.	Contextual and cleaned data.
Value added services	Harmonized multi-brand in-vehicle data of different vehicle manufacturers, and maps	Traffic services	Harmonized multi-brand in-vehicle data of different vehicle manufacturers in one location	Harmonized multi-brand in-vehicle data of different vehicle manufacturer, and maps	Harmonized multi-brand in-vehicle data of different vehicle manufacturers in one location	Harmonized multi-brand in-vehicle data of different vehicle manufacturers in one location	Harmonized multi-brand in-vehicle data of different vehicle manufacturers in one location	Harmonized cross-brand data, even from "legacy" cars through OBD II port.

Figure 16: 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 ([Error! Bookmark not defined.]) 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 (**Error! Bookmark not defined.**).

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 8: 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.

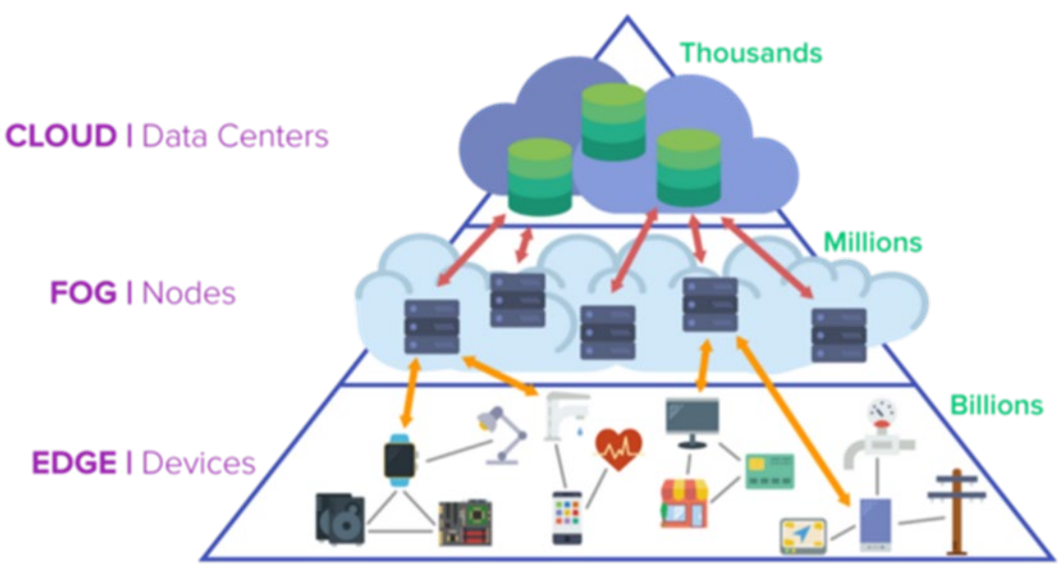

Figure 17: Data-Processing Examples ([21]*)*

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 ([Error! Bookmark not defined.,22]).

AV America ([Error! Bookmark not defined.]) 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. (Error! Bookmark not defined.) 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 (Error! Bookmark not defined.,23)

Gopalakrishna et al. (Error! Bookmark not defined.) 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 9: Potential Early Strategies Identified by Stakeholders for AV Readiness (**Error! Bookmark not defined.**)*

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	• 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
	• Minimize/ eliminate confusing speed limit signs on parallel routes			
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 10: Pavement-Related Issues for CAVs (**Error! Bookmark not defined.**)*

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. (**Error! Bookmark not defined.**), 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. (**Error! Bookmark not defined.**), 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 11: Example Prioritized List for Pavement Markings (**Error! Bookmark not defined.**)*

Types	Details	Digital Traffic Control Devices (DTCD) Included		
		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	

Types	Details	Digital Traffic Control Devices (DTCD) Included		
		1st Priority	2nd Priority	Exclude
Roundabout markings	White lane line pavement markings for roundabouts		x	
	Edge line pavement markings for roundabout circulatory roadways		x	
	Yield lines for roundabouts		x	
	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 12: Example Prioritized List for Pavement Messages (**Error! Bookmark not defined.**)*

Types	Details	DTCD Included		
		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

Types	Details	DTCD Included		
		1st Priority	2nd Priority	Exclude
	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. ([Error! Bookmark not defined.]) 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 13: Example Prioritized List for Pavement Marking (27)

Type	Static/Dynamic Signs	DTCD Included		
		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 14: Example Prioritized List for Pavement Message ([27])

Type	Static/Dynamic Signs	DTCD Included		
		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. (Error! Bookmark not defined.).

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 (**Error! Bookmark not defined.**). 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 18: Curb Usage Examples (**Error! Bookmark not defined.**)*

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 (**Error! Bookmark not defined.**).

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.

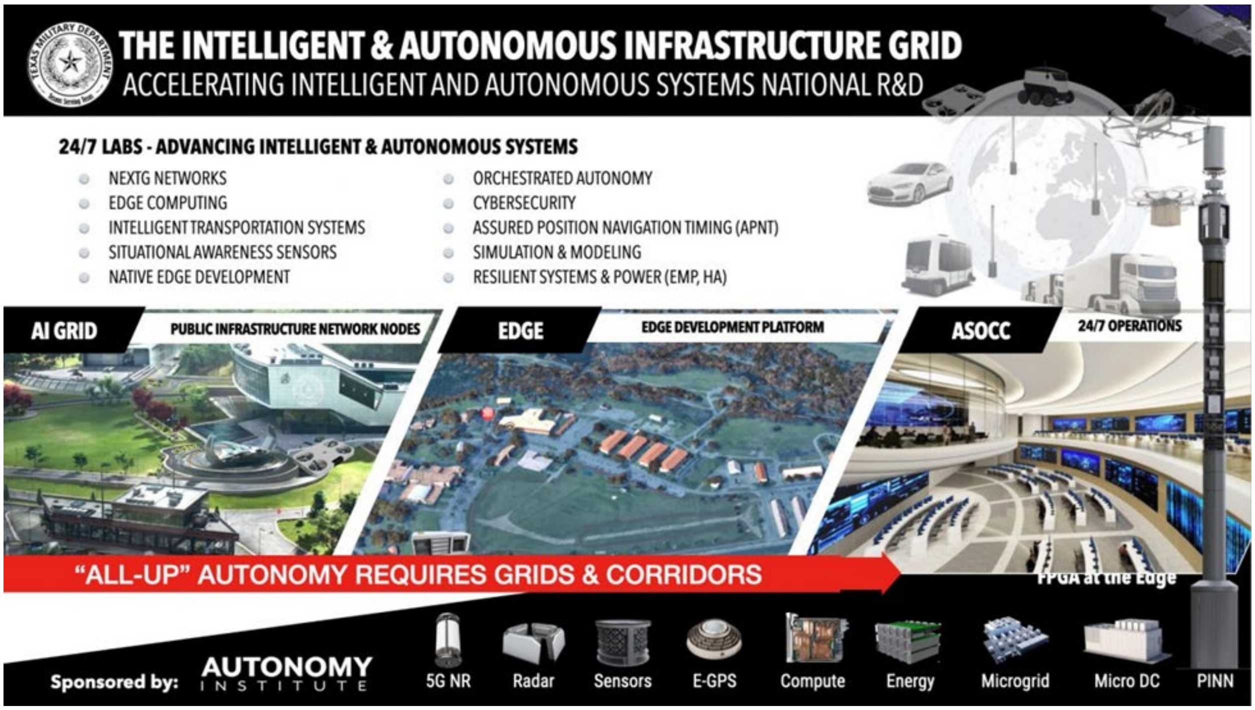

Figure 19: Data Exchange and PINN Clusters [35]

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.

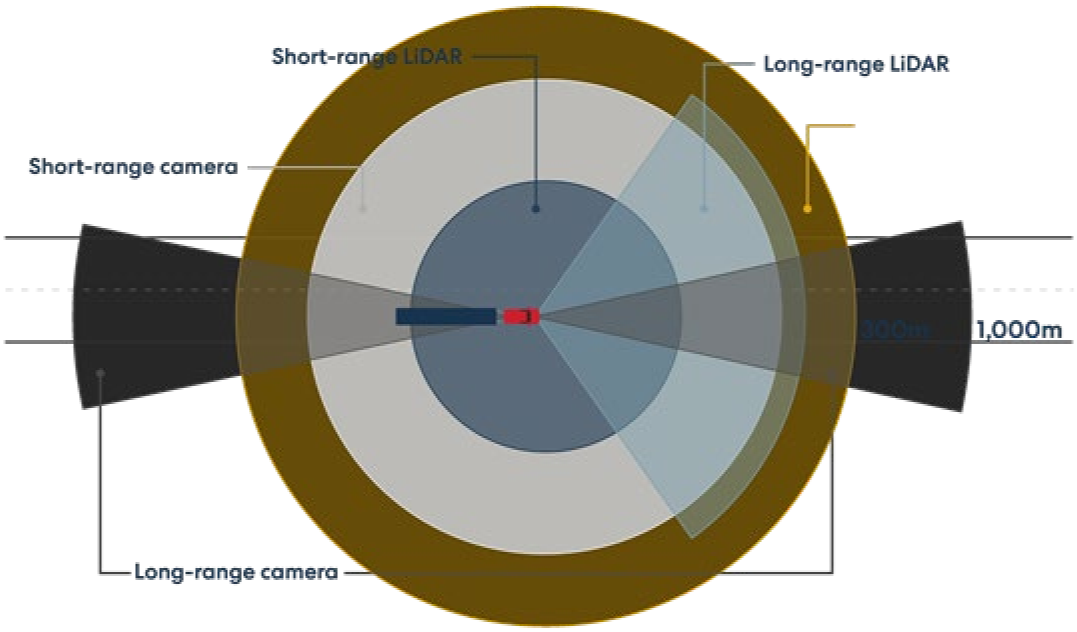

Figure 20: Physical Infrastructure for Surroundings Awareness (36)

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.

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