COOPERATIVE & AUTOMATED TRANSPORTATION PROGRAM

TEXAS DEPARTMENT OF TRANSPORTATION

What is CAT Infrastructure?

CAT Brief

Strategic Initiatives & Innovation Division

August 2024

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Acronyms and Abbreviations

3GPP	3rd Generation Partnership Project
5G	5th Generation Mobile Network
AI	Artificial Intelligence
API	Application Programming Interface
AV	Automated Vehicle
BIM	Building Information Modeling
CAT	Cooperative and Automated Transportation
CAV	Connected and Automated Vehicle
CCPA	California Consumer Privacy Act
CV	Connected Vehicle
C-V2X	Cellular Vehicle-to-Everything
EV	Electric Vehicle
FHWA	Federal Highway Administration
GDPR	General Data Protection Regulation
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HD	High Definition
IOO	Infrastructure Owner/Operator
IoT	Internet of Things
ITS	Intelligent Transportation Systems
JPO	Joint Program Office
LiDAR	Light Detection and Ranging
LTE	Long-Term Evolution
ML	Machine Learning
PNT	Positioning, Navigation, and Timing
SWOC	Statewide Operation Center
TMC	Transportation Management Center
TSMO	Transportation Systems Management and Operations
TxDOT	Texas Department of Transportation
USDOT	United States Department of Transportation
VRU	Vulnerable Road User
V2I	Vehicle-to-Infrastructure
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything

1. Introduction

The Texas Department of Transportation's (TxDOT) transportation network is the largest in the nation, with more than 80,900 miles of roadways, 271 general aviation airports, and 78 million tons of cargo moving through its seaports. It is critical for TxDOT to continue to investigate innovative and economical methods for creating a safe and reliable transportation system for all users. One path that offers numerous potential benefits to the traveling public is the integration of connected vehicles (CV), automated vehicles (AV), and other emerging transportation technologies into the state's multimodal transportation system. To support the efficient integration of these technologies, TxDOT launched the Cooperative and Automated Transportation (CAT) Program and developed the CAT Strategic and Program Plans.

The statewide CAT program integrates CV, AV, and related emerging transportation technologies into the state's multimodal transportation system supporting the agency's mission, Connecting you with Texas. This program tackles how to use emerging technologies for some of the state's greatest challenges in the areas of safety, mobility, and funding while executing strategies to combat disruptive changes and impacts. TxDOT seeks to proactively integrate CAT initiatives into transportation projects, from planning, design, and construction to operations and maintenance, rather than respond to its proliferation in the multimodal transportation system. Taking into consideration the transformative impact of these technologies, TxDOT is dedicated to engaging the public through system safety, transparent communication, and addressing concerns.

1.1 Project Background

This initial brief of the CAT Program, titled *"What is CAT Infrastructure?"*, aims to define essential infrastructure for CAT implementation, which includes physical and digital assets. These assets are supported by transportation system users and operational capabilities to form the basis for CAT deployment. Identifying these requirements is the first step towards integrated CAT systems, promoting connected and automated vehicle (CAV) deployment for safe, efficient, and reliable transportation. For this purpose, **CAT infrastructure refers to the physical and digital assets required to support communication, data exchange, and coordinated actions within the CAT ecosystem, directly or indirectly influencing transportation system users and operational capabilities.**

This CAT Brief provides an overview of infrastructure needed for an integrated CAT ecosystem, distinguishing between existing and future CAT deployments. This CAT Brief will also inform the remaining initiatives set forth in TxDOT's CAT Program Plan to establish the successful integration of CAT across the state's multimodal transportation system.

1.2 Organization of this CAT Brief

This CAT Brief is organized into the following sections:

- **Section 1: Introduction** – Provides an overview of information to be presented and introduces CAT infrastructure.
- **Section 2: What is CAT?** – Defines CAT and the key pillars of the CAT ecosystem, which include physical infrastructure and digital infrastructure.

- **Section 3: What is CAT Infrastructure?** – Identifies the physical and digital assets encompassing CAT infrastructure.
- **Section 4: The Evolution of CAT Infrastructure** – Summarizes the incremental stages of CAT infrastructure development, comparing the Existing-Phase to the Growth-Phase of CAT infrastructure.

1.3 Methodology

The identification of CAT infrastructure was guided by a review of existing literature from CAT efforts across the nation, focusing on physical and digital assets. The key references used for identifying CAT infrastructure are listed in **Table 1**. These sources helped to identify the base CAT physical and digital infrastructure necessary to enable the successful implementation of CAT systems in transportation systems.

Table 1: Key Literature Review References

Title	Source	Description
Cooperative and Automated Transportation Strategic Plan	TxDOT	Provides 35 strategies to prepare TxDOT for emerging CAT technologies, maximizes the benefits of CAT, and positions TxDOT as a national leader in CAT.
Cooperative and Automated Transportation Program Plan	TxDOT	Provides a work plan with specific operational initiatives recommended to achieve the goals of TxDOT's CAT Program.
Connected and Automated Vehicle Digital and Physical Infrastructure Needs	Texas CAV Task Force	Discusses the physical and digital infrastructure needs, challenges, and opportunities for future development of CAVs.
National Intelligent Transportation System Architecture	United States Department of Transportation (USDOT) ITS Joint Program Office (JPO)	Provides a definitive and consistent framework for planning, defining, and integrating ITS.
Connected Vehicle Deployment Environment	CAT Coalition	Describes a holistic view of the CV deployment environment necessary to support CV implementation.
Impacts of Automated Vehicles on Highway Infrastructure	Federal Highway Administration (FHWA)	Identifies the industry state of the practice, gaps in knowledge, and agency preparedness levels regarding the impacts of AV use on highway infrastructure.
Digital Infrastructure Strategy Report	ITS America	Summarizes the key findings from the ITS America Infrastructure Working Group that are crucial to achieving a strategic plan for digital infrastructure.

1.4 Other Resources

This CAT Brief is part of a series of initiatives that encompass topics related to CAT impacts and opportunities. The CAT Program initiatives pertaining to infrastructure include:

- **Statewide CAT Infrastructure Inventory** – Establishes a geographic information system-based benchmark inventory of existing CAT infrastructure, including age, location, and maintenance responsibilities.
- **CAT Brief: CAT and TxDOT Asset Management Practices** – Documents how CAT will influence asset management practices and makes recommendations related to updating asset management planning documents.

2. What is Cooperative and Automated Transportation (CAT)?

CAT is a cooperative ecosystem of physical and digital infrastructure aiming to enhance the safety, reliability, and efficiency of multimodal transportation supporting CVs and AVs. It integrates automation, connectivity, and collaboration to optimize operations, reduce congestion, and improve mobility. CAT leverages real-time data-sharing and cooperative operations for efficient traffic management to enhance transportation efficiency and user experience. The CAT ecosystem is divided into two key pillars:

- **Physical Infrastructure**: Tangible network of facilities and systems that support the seamless and efficient operation of intelligent transportation systems (ITS) and multimodal mobility solutions.
- **Digital Infrastructure**: An integrated network of systems, technologies, tools, and data that support CAT development and operation.

Physical and digital CAT infrastructure delivers safe, efficient, and reliable operational capabilities to transportation system users in the CAT ecosystem, as shown in **Figure 1**.

Figure 1: The CAT Ecosystem

3. What is CAT Infrastructure?

CAT infrastructure serves as the foundational element to CAT, enabling operations, communication, data exchange, and coordination between vehicles and infrastructure. This section summarizes the physical and digital infrastructure present within the CAT ecosystem. It is critical to note that this list is not representative of all CAT infrastructure, as the market is continuously evolving and new technologies emerge while existing technologies may become obsolete.

3.1 Physical Infrastructure

Physical infrastructure for CAT refers to the tangible network of facilities and assets that support the efficient operation of ITS and multimodal mobility solutions. Physical infrastructure consists of the following primary components:

- **Multimodal Transportation Assets**: Physical assets that support the integration of different modes of transportation, such as cars, buses, bicycles, and pedestrians, into a cohesive and interconnected system. Multimodal infrastructure includes pavements, bridges/culverts, intersections, bike/pedestrian paths, bus stops/shelters, electric vehicle (EV) charging infrastructure, and rail, maritime, and aviation facilities.

- **Traffic Control Devices**: Devices used on roads and highways to regulate, guide, and inform the movement of vehicles, pedestrians, and other transportation system users such as pavement markings, traffic signs, traffic signals, roadside barriers, work zone equipment, and other. These devices provide essential cues and instructions to CV/AVs to help them navigate through complex traffic scenarios and make informed decisions.
- **ITS Devices**: Technologies and equipment used to collect data and communicate within transportation operations systems. These devices typically consist of sensors, communication systems, and algorithms to collect and analyze data, facilitate real-time information exchange, and enable intelligent decision-making. They enable communication and coordination between vehicles, motorists, and infrastructure, allowing for real-time data-sharing, cooperative operations, and efficient traffic management.
- **Transportation Management Center/Statewide Operation Center**: Centralized facility that orchestrates the efficient and integrated functioning of different transportation modes within a designated region or corridor. The TMC/SWOC utilizes advanced technologies like ITS, real-time data analytics, and artificial intelligence to monitor and optimize traffic across multiple modes and across multiple jurisdictions.
- **Connectivity Infrastructure**: Physical communication infrastructure, including fiber optics, copper cables, and radio, that provides the link for communication and cooperation between vehicles, infrastructure, and transportation system users, allowing for the real-time exchange of information and enabling continuous monitoring, analysis, and decision-making to optimize traffic flow and minimize congestion.

3.2 Digital Infrastructure

Advancements in digital infrastructure support CAT systems to enable vehicles to communicate and cooperate with each other, resulting in smoother traffic flow, reduced congestion, enhanced road safety, and increased reliability across all transportation modes. Digital infrastructure consists of the following primary components:

- **Cybersecurity and Data Privacy**: Protective measures and protocols implemented to safeguard digital infrastructure components and data from cyber threats and unauthorized access. Cybersecurity technologies include firewalls, intrusion detection and prevention systems, antivirus software, access control systems, and data encryption that safeguard assets and communications from cyber threats. Data privacy digital infrastructure focuses on data confidentiality, integrity, and compliance with regulations like the General Data Protection Regulation (GDPR) and the California Consumer Privacy Act (CCPA).
- **Digital Communication Network**: The exchange of data between connected devices utilizing hardware, software, and protocols to establish and maintain communication within the network. This includes:
    - **Direct Communication Network**: Network channels for inter-vehicle communications (vehicle-to-vehicle [V2V] and vehicle-to-infrastructure [V2I]) to support vehicular networking under safety critical operations. They are developed to provide wireless access in vehicles. Cellular vehicle-to-everything (C-V2X) is based on dedicated cellular technology that uses 3rd

Generation Partnership Project (3GPP) standards for cellular communication, including long-term evolution (LTE) and the 5th Generation Mobile Network (5G), which use the same underlying technologies as mobile phones.

  - **Cellular Network and Satellite Communication**: For certain CAT operation scenarios, ultra-low latency, high reliability, and immunity to interference may not be necessary. In these cases, and under advisory circumstances, vehicles can use consumer mobile networks to access cloud-based services like real-time traffic and weather information, map and software updates, remote condition monitoring and diagnostics, data upload/download, and can access data and services from edge/field devices. In remote areas with limited mobile network coverage or during emergencies, satellite communication can keep vehicles under CAT operations connected.
  - **Ad-hoc Communication Networks and Technologies**: Support various advisory (non-safety critical) applications, such as infotainment, and road condition reporting, as well as safety critical communication with non-vehicle-to-everything equipped infrastructure such as vehicle-to-pedestrian (V2P) communication. They enable sensor data fusion and sharing between vehicles in platooning scenarios and are used for safety/tracking applications.

- **Advanced Sensing Technologies**: Enhance and complement existing traffic detection methods by incorporating edge computing, communicating capabilities, and information fusion. This provides a more comprehensive and accurate understanding of the transportation environment, including traffic management, infrastructure monitoring, and maintenance. The three main components under advanced sensing technologies are:
  - **Physical Sensors**: Includes inductive loops, ultrasonic sensors, high-definition video sensors, radar sensors, light detection and ranging (LiDAR), and sensors to enhance existing sensors. They are often tested in pilot projects before being implemented on a larger scale as technology costs decrease.
  - **Mobile Devices Tracking**: Refers to tracking using mobile networks, global positioning systems (GPS), Wi-Fi, Bluetooth, mobile apps, floating vehicle data (e.g., taxis), CV/AVs, data brokers (e.g., fleet and public transport operators), and vehicle telematics data.
  - **Ad-hoc Communication Protocols**: Depending on requirements and the implementation environment, some sensors employ dedicated communication protocols to save energy and transmit data over long distances.
- **Data Management Platform**: Cost-effective, flexible, scalable, and secure technology which utilizes advanced digital capabilities to facilitate real-time automated decision-making, manage and optimize CAT infrastructure and operations, facilitate integration of emerging technologies, and enable information exchange among new and legacy systems. These capabilities provide opportunities for innovation in CAT program operations and business models through business intelligence. Elements of data management platforms can reside in the cloud, be hosted on premise, or delivered as a service with no agency ownership involved. The data management platform consists of:

  - **Storage and Data Warehouse**: Scalable infrastructure for secure storage of data from CAT infrastructure, sensors, Internet of Things (IoT) devices, connected technologies, and mobility sources.
  - **Communication and Information Exchange**: Messaging and streaming services, application programming interfaces (API) and communication gateways, protocols and encryption, firewalls, and information dissemination/sharing to transportation system users' devices.
  - **Development Platform and Digital Tools**: Support system development, testing, deployment, and integration. They enable iterative, agile development, prototyping, collaborative research, and knowledge sharing. If cloud-based, they also enable scaling resources, improving workforce agility, and enhancing security.
  - **Data Analytics and Big Data Computing Capacity and Services**: Transforming data into meaningful insights using artificial intelligence (AI), machine learning (ML), data science/engineering, business intelligence, data intelligence, digital twin, and building information modeling (BIM) for the planning, design, construction, and maintenance of CAT and associated processes.

- **Edge Computing Infrastructure**: Involves deploying computing power and storage at the network's edge to efficiently process data, execute critical applications, reduce data transport times, enhance customer experiences, and improve operational efficiencies in CAT systems. This includes:
  - **Edge Devices**: Tangible hardware or assets located at the road network edge, such as roadside equipment and traffic sensors, which are equipped with communication capabilities, and data analytics/computing power, enabling them to collect and transmit data, as well as perform data cleansing/filtering and simple analytics directly at the edge.
  - **Edge Servers**: Equipped with embedded operating systems and software for local data analytics, such as masking vehicle number plates to protect data privacy. They also facilitate decision-making for tasks requiring rapid performance at the edge, particularly for traffic safety-related functions.
  - **Local Communication Hub**: Gateways and base stations/communication brokers that collect data from multiple edge devices and securely transmit it to the cloud platform.
  - **Communication and Central Interfaces**: Interfaces between the BackOffice and field computing infrastructure to remotely monitor, control, and maintain field devices, usually achieved through the digital or serial transmission of data that supports the connectivity with edge infrastructure using network communication mediums.
- **High Accuracy Positioning and Mapping**: Utilize technologies like Global Navigation Satellite Systems (GNSS) to provide accurate and real-time location data for vehicles. They enable vehicles to accurately navigate through complex road networks, make informed decisions based on real-time mapping and geospatial data, and communicate information with other vehicles. High accuracy GIS supports

precise positioning, reliable navigation, and effective communication among vehicles This includes:

- **High-Definition Digital Mapping**: Provide accurate geospatial information that enables vehicles to perceive the road environment, achieve precise localization, plan safe and efficient routes, and make informed decisions in real-time. Ideally, these are continuously updated and integrated with vehicle sensors and control algorithms
- **High Accuracy Location Services**: Use real-time data from GNSS, sensors, maps, and the environment to support safe and precise vehicle navigation. These services help vehicles comply with traffic regulations and make informed decisions based on their exact positions.
- **Positioning, Navigation, and Timing:** System comprising three capabilities: Positioning, which determines one's precise location and orientation; Navigation, which involves determining and adjusting the course to reach a desired location; and Timing, which ensures accurate timekeeping based on Coordinated Universal Time (UTC). Combined with map data and other information, PNT forms the basis of modern navigation systems like GPS.

4. The Evolution of CAT Infrastructure

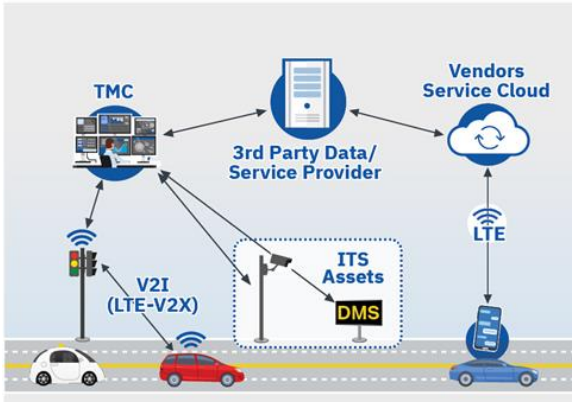
As technology advances, the transportation ecosystem is rapidly changing, with innovations constantly emerging and existing infrastructure becoming insufficient to support advanced capabilities, thus requiring CAT infrastructure to be characterized by development stage. The three stages of CAT infrastructure development, visualized in **Figure 2**, include:

- **Existing-Phase of CAT Infrastructure**: Primarily relying on traditional ITS devices, this system is capable of detecting, monitoring, and managing traffic conditions. It has limited integration and digitization, with emerging CV/AV under development and deployed in controlled environment, often at a pilot stage.
- **Growth-Phase of CAT Infrastructure**: Represented by the growing adoption of CV/AV in open environment and more advanced physical and digital infrastructure. This supports large-scale deployment of CV/AV, but still in a mixed fleet environment, accompanied by digital transformation.
- **Mature-Phase of CAT Infrastructure**: Fully integrated, connected, cooperative, and automated transportation ecosystem.

Figure 2: Evolution of CAT Infrastructure

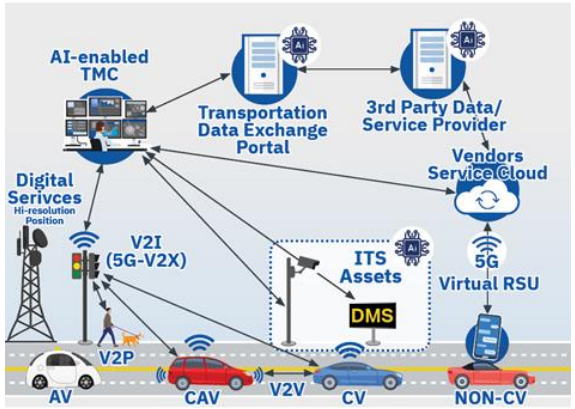
Existing Phase

- Primarily relies on traditional ITS devices.
- Majority of transportation system users are not CAT compatible.
- Lack of direct C-V2X coverage.
- Lack of integration and digitalization.
- Requires human decisions and actions.



Growth Phase

- The road traffic will comprise both CAT technology adopters and traditional transportation system users.
- Traditional roadside ITS devices and traffic control devices remain crucial.
- Digital infrastructure will be deployed to enhance operational capabilities.
- Physical infrastructure will be more integrated and connected as new technologies emerge.



Mature Phase

- **Safer**: Effective, impactful reduction of fatalities, serious injuries, and near misses on Texas roadways for all transportation system users.
- **Greener**: Reduce pollution from transportation sources.
- **Accessible**: Provide affordable, convenient access for all travelers to promote economic opportunity.
- **Reliability**: Build a reliable communications system to support CAT operations.
- **Data**: Implement a digital ecosphere to provide the right information, to the right people, at the right time, with the right policies to make the right actionable decisions.

The Existing-Phase of CAT infrastructure, illustrated in **Figure 3**, consists of traditional ITS that primarily caters to human drivers and lacks full support for mature CAT functions. This includes CCTV, DMS, TMC communications, and other traditional ITS infrastructure and is evident in limited C-V2X coverage and integration.

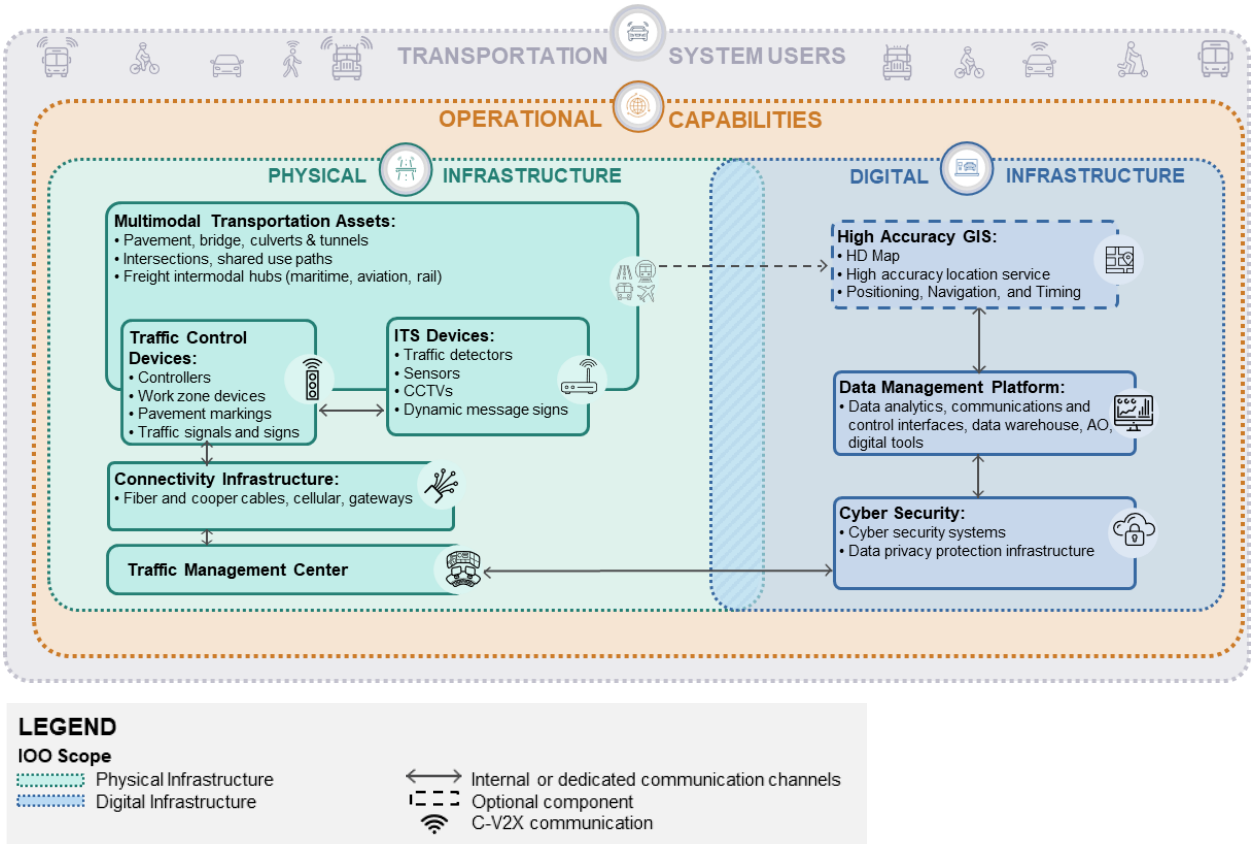


Figure 3: Existing-Phase of CAT Infrastructure

Technological advancements are driving increased connectivity, autonomy, and data sharing, marking entry into the Growth-Phase of CAT infrastructure depicted in **Figure 4**. This stage necessitates the coexistence of existing and emerging technologies in both physical and digital infrastructure to accommodate a mixed environment of CAT technology adopters and traditional transportation system users. Infrastructure readiness for commercial CAT operations and a comprehensive legal framework supporting CAT infrastructure deployment may characterize the Growth-Phase, alongside widespread public acceptance, and adoption of CAT systems. **Figure 3** and **Figure 4** show the key relationships of assets, systems, and tools within the Existing-Phase and Growth-Phase of the CAT infrastructure environment, respectively.

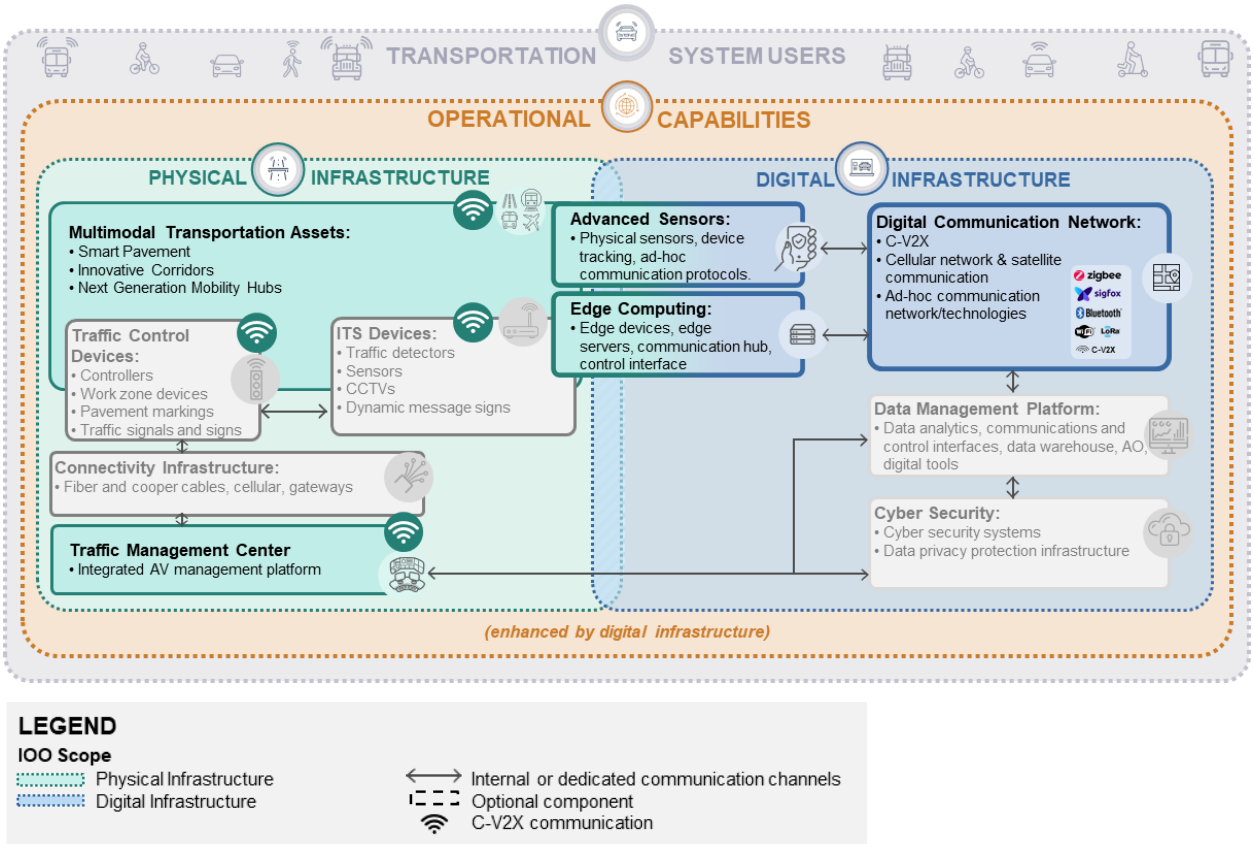


Figure 4: Growth-Phase of CAT Infrastructure

Expansion and enhancement of both physical and digital infrastructure are anticipated to support CAT functionalities, progressing toward the long-term vision or the Mature-Phase of CAT infrastructure. This stage envisions a fully integrated, connected, cooperative, and automated transportation ecosystem, prioritizing safety, reliability, and intelligence.

The development of CAT infrastructure presents both challenges and opportunities. While the Mature-Phase of CAT infrastructure remains difficult to visualize due to inherent uncertainties, prioritizing the transition to the Growth-Phase is crucial as it builds on emerging technologies and infrastructure. This phase involves integrating emerging CAT technologies with existing systems, paving the way for more advanced applications. As CAT infrastructure evolves, it is critical to recognize that traditional transportation infrastructure

will coexist with advanced systems for the foreseeable future. This Growth-Phase must consistently consider accommodating both early adopters and those who may not have access to or choose not to use such advancements. A hybrid approach that balances both CAT and traditional ITS infrastructure is likely to be the model for the foreseeable future, supporting access to multimodal transportation options and facilitating a gradual transition towards more advanced solutions.

Distinguishing between present and future CAT infrastructure is crucial for recognizing current limitations and planning necessary expansions. This differentiation offers a clear vision for strategic development and investment in technology and infrastructure.

Understanding this evolution ensures readiness to support growing connectivity, autonomy, and data sharing in CAT systems. This preparation fosters a future CAT system that is safe, efficient, reliable, and accessible to all.

4.1 The Way Forward

To prepare for the Growth-Phase, and ultimately the Mature-Phase, of CAT infrastructure, the TxDOT CAT Program will prioritize the following initiatives as immediate next steps:

- **Understand the Existing-Phase of CAT Infrastructure**
    - **Statewide CAT Infrastructure Inventory –** Develops an inventory of CAT infrastructure to aid in determining the remaining usable life of existing assets.
- **Prepare TxDOT for CAT Data Needs**
    - **CAT Brief: What are the Challenges of CAT Data?** – Investigates and documents the challenges of CAT data, including privacy, security, size, and format.
    - **CAT Brief: Can TxDOT Keep Up with CAT Data?** – Reviews requirements for the exchange of CAT data and identifies gaps between current CAT data standards and TxDOT's data standards.
    - **CAT Brief: How Can TxDOT Utilize CAT Data?** – Documents the type of data generated by CAT and determines how TxDOT can benefit from the use of that data.
    - **CAT Brief: A Guide to Being CAT Data Ready** – Prepares a guide to successfully integrate CAT data across the agency, including best practices for accommodating CAT data challenges and use cases.
    - **CAT Brief: What are the Minimum CAT Data Elements and Needs for TxDOT?** – Documents the minimum CAT data elements and needs for TxDOT, including a data dictionary defining specific terminology.
- **Integrate CAT with TSMO**
    - **Maintenance and Operations CAT Opportunities Workshop** – Conducts and internal workshop to discuss maintenance and operations activities and use cases that may be enhanced by CAT applications.

  - **CAT Brief: Maintenance and Operations CAT Opportunities** – Investigates and documents CAT applications used to improve maintenance and operations that the agency should consider.
  - **CAT Brief: TSMO Opportunities with CAT** – Reviews existing TSMO practices and determines potential impacts from CAT projects and deployments and provides recommendations to aid integration of CAT into TSMO practices.

- **Address Legislative Issues for CAT**
  - **Develop CAT Informational Resources for Legislators, TxDOT Staff, and Partner Agencies** – Develops informational flyers and materials related to the CAT Program catered to various internal and external stakeholders.

As the CAT infrastructure evolves, TxDOT continues to develop and implement other initiatives as laid out in the TxDOT CAT Program Plan.

Appendix A: References

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