MARYLAND DEPARTMENT OF TRANSPORTATION STATE HIGHWAY ADMINISTRATION

RESEARCH REPORT

Comprehensive Review of CV Testbeds, CAVe -in-a-Box and Industry Solutions

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1.1 Overview of CV Technologies

Connected Vehicles (CV) technology has evolved rapidly in recent years, demonstrating improved traffic efficiency, crash safety, and technological integration. These developments involve recent vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications advances. As researchers and transportation planners begin deploying the latest iterations of CV technology, testbeds, and CV pilot projects become critical for evaluating the feasibility and impacts in real-world roadway locations. The review conducted in this report attempts to aid the Maryland Department of Transportation (MDOT) by putting forth a comprehensive breakdown of existing CV deployments, thus offering vital insights for future projects.

CVs use a combination of sensors, software, and communication technologies to interact with their surroundings and reduce dependence on human drivers. These automobiles are equipped with features such as Vehicle-to-Everything (V2X) communication, which allows them to talk to each other and exchange information with other vehicles, infrastructure, and pedestrians (V2P) all in an integrated network (V2N). The benefits of CVs include reduced traffic congestion, reduced accident rates, enhanced fuel efficiency, and improved mobility for all road users, including vulnerable road users (VRUs) such as pedestrians, bicyclists, underage children, the elderly, and individuals with disabilities. Figure 1. illustrates four types of V2X communication applications essential to CVs - V2V, V2I, V2P, and V2N. The next section describes the four different types of integration modules for CV.

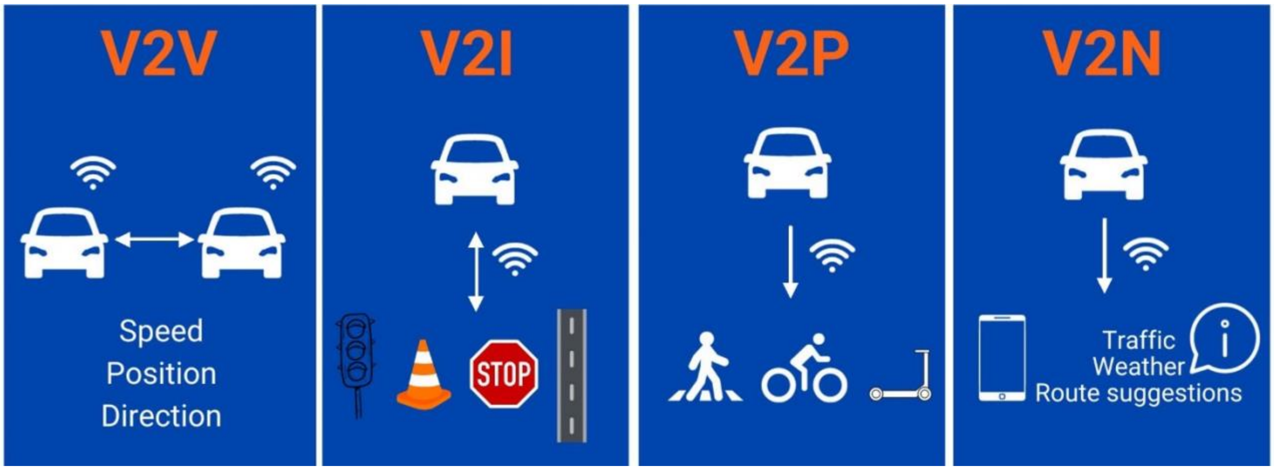

Figure 1. Types of V2X Communication
[https -//www.nearbycomputing.com/v2x-technology/](https://www.nearbycomputing.com/v2x-technology/)

- **Vehicle-to-Vehicle** – In V2V, communication occurs directly between automobiles, sharing important information such as speed, location, and direction of movement. It improves situational and locational awareness and allows features like collision avoidance, adaptive cruise control, and emergency vehicle alerts or warnings.
- **Vehicle-to-Infrastructure** – V2I communication describes data-sharing between vehicles and the road infrastructure. Vehicles receive data from traffic signals, road signs, and construction zones. This communication enables smooth traffic flow and enhanced safety by sending real-time alerts to road-users about upcoming road conditions, traffic signal phase, and potential hazards.
- **Vehicle-to-Pedestrian** – V2P communication connects the vehicles with pedestrians, cyclists, and other vulnerable road users. Using the V2P communication, automobiles can detect and interact with nearby pedestrians and cyclists, thus preventing accidents and enhancing the safety of road users.
- **Vehicle-to-Network** – V2N communication links vehicles to broader networks, including cellular networks and cloud services. It allows vehicles direct access to real-time traffic data, climate and weather updates, and route suggestions based on estimated travel time and road closure conditions, allowing informed decision-making and effective route planning.

Each type of V2X communication plays an important role in creating a safer, more efficient, and connected transportation ecosystem. The review process involved a comprehensive search and analysis of CV pilot projects and deployments across the United States. The data was collected from several DOT reports, project summaries, and resources. Each project was evaluated based on numerous criteria, including the type of CV technology deployed, the scale of deployment, the precise applications tested, and the experiential outcomes. [1] discussed the diversity of CV testing environments, identifying both closed-course and open-road setups designed to evaluate technology under various conditions before wide-scale implementation. This report has similar findings regarding the diversity of CV testing environments identifying 50 currently deployed projects across the United States. This diversity in applications underlines the flexibility of CV systems in addressing transportation challenges. Radchenko and Hudyakova [2] studied the use of distributed virtual testbeds (DiVTB) for integrating computer-aided engineering systems inside a grid environment, enabling complex simulations of CV technologies.

Diverse communication technologies, such as Dedicated Short Range Communication (DSRC) and Cellular Vehicle-to-Everything (C-V2X), are being tested across several projects. Whereas DSRC remains predominant, the adoption of C-V2X is growing due to its potential for wider applications and amalgamation with existing cellular networks. Raboy and others [3] evaluated a field experiment on cooperative lane change maneuvers using a model CV platform, demonstrating the integration of V2V communications without automated control to improve maneuver safety. Ma and others [4] highlighted the usage of hardware-in-the-loop (HIL) testing for CV applications like Cooperative Adaptive Cruise Control (CACC), which combines the physical test vehicles with virtual models to evaluate system performance under simulated V2V settings.

CV deployments are present across urban, suburban, and rural areas, highlighting the adaptability of these technologies in diverse environments. Projects in urban areas habitually focus on traffic congestion reduction and crash safety, whereas rural deployments highlight incident detection and response.

Successful CV projects involve collaboration among DOTs, academic institutions, and private companies. These partnerships enable knowledge sharing and resource pooling, augmenting the overall impact of the projects. The collective challenges met in CV deployments include technical issues, such as interoperability and communication reliability, in addition to regulatory and funding limitations. Chowdhury and others [5] provided insights from the Clemson University Connected Vehicle Testbed (CU-CVT), detailing lessons from the deployment of multiple CV applications and handling data through heterogeneous wireless networks. Addressing these challenges is vital for the extensive adoption of CV technologies.

This all-inclusive review of CV pilots and deployments provides crucial insights into the present state of CV technology implementation. By inspecting the different applications, technologies, geographies, and challenges associated with these projects, this report lays the foundation for informed decision-making and tactical planning for future CV initiatives in Maryland and beyond. The findings highlight the potential of CVs to transform transportation systems, improve safety, and augment the mobility experience for all road users.

The first part of the report provides an extensive list of connected initiatives across various states in Table 1 which highlights the different types of equipment, communication technologies, and specific applications tested in individual projects. Each project has its own operational and technological differences. For example, the Arizona project focused on transit signal priority and emergency vehicle preemption, whereas the California initiative demonstrated multi-modal intelligent traffic signal systems. By inspecting these deployments, we understand the current state of CV technology and its real-world applications in practical situations. Analyzing these diverse deployments provides insights into the current state of CV technology and its practical applications in real-world scenarios. By examining these deployments, the report aims to assess how these technologies can address specific traffic safety issues and improve operational efficiency. For example, transit signal priority and emergency vehicle preemption systems are critical in improving transit operations, reducing response times, and improving safety for emergency responders and other road users. Meanwhile, intelligent traffic signal systems are vital for minimizing congestion and enhancing the safety of pedestrians and cyclists. This detailed analysis provides valuable insights into how CV technologies can be implemented and scaled to meet diverse transportation needs, ensuring safer and more efficient transportation systems.

The establishment of CV testbeds is essential for advancing traffic safety and efficiency in real-world environments. These testbeds serve as controlled settings where CV technologies can be rigorously tested and refined before widespread deployment. By integrating V2V and V2I communications, CV testbeds enable researchers to evaluate how these technologies interact with existing transportation systems. In doing so, they provide valuable data on the effectiveness of various CV technologies. This controlled experimentation is vital for understanding how Connected and Automated Vehicles (CAVs) can reduce traffic congestion, improve traffic flow, and enhance overall roadway safety. The insights gained from CV testbeds can guide the development of standards and protocols, ensuring that CV technologies are reliable and effective when implemented on a larger scale.

CV testbeds are also pivotal in addressing traffic safety goals, particularly for VRUs such as pedestrians, bicyclists, children, the elderly, and individuals with disabilities. By employing V2X communication, which includes V2V, V2I, V2P, and V2N interactions, these testbeds create a comprehensive network that enhances situational awareness for both vehicles and road users. For instance, CVs can receive real-time information about pedestrians crossing the road, enabling automated systems to take proactive measures to avoid collisions. This level of integration not only protects VRUs, but also contributes to a safer and more inclusive transportation environment. Furthermore, CV testbeds improve crash safety and reduce crash rates. They also help with fine-tuning CV responses to potential hazards. This proactive approach to safety allows for the identification and mitigation of risks before they lead to crashes. Additionally, the data collected from these testbeds can inform the design of safer infrastructure, optimal traffic signal timings, and adaptive traffic management strategies, all of which are integral to creating safer roadways for CVs, AVs and human-driven vehicles.

This report examines the diverse applications, technologies, geographic contexts, administrative structures, and challenges associated with CV testbeds, providing a comprehensive foundation for informed decision-making and strategic planning for future CV initiatives in the US By analyzing these factors, the report highlights how CV technologies can fundamentally transform transportation systems, enhance safety, and improve the overall mobility experience for all road users, including vehicles and VRUs.

Figure 2 illustrates the US's planned and operational CV testbed projects [6]. As shown in Figure 2, a total of 70 operational sites and 101 planned sites have been acknowledged by the US Department of Transportation (USDOT) as of May 5, 2022.

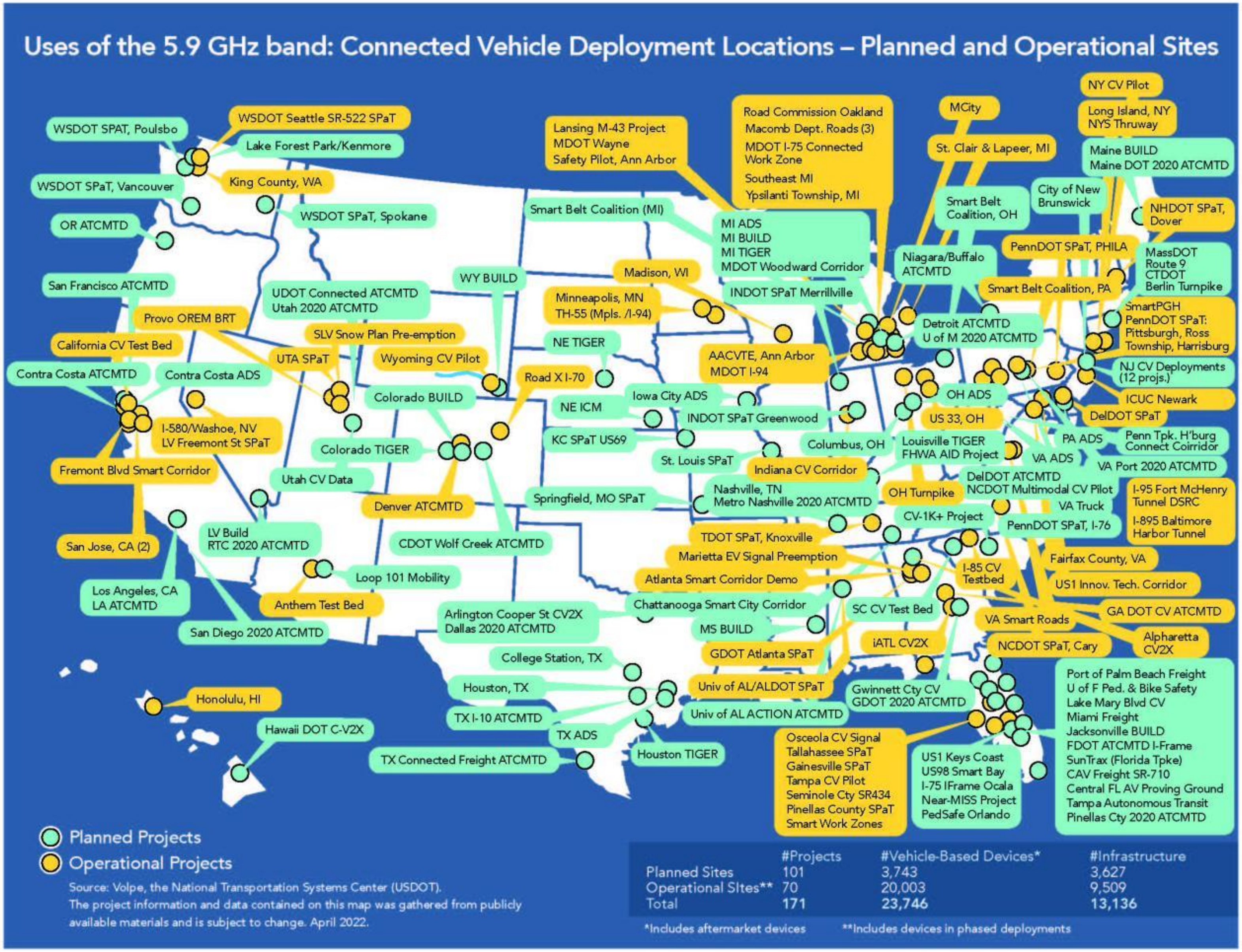

Figure 2. Operational Connected Vehicle Deployments in the US [6]

1.2 Review of CV Testbeds in USA

This report explores the role of various geographical contexts in shaping CAV deployments, recognizing that urban, suburban, and rural areas present distinct challenges and opportunities for traffic systems. Urban areas, for instance, may focus on reducing congestion and improving pedestrian safety, while rural areas might prioritize connectivity and emergency response efficiency. This geographic differentiation allows for a tailored approach to deploying CAV technologies. Effective governance models are essential for the successful implementation and scaling of CV technologies, as they ensure that regulatory frameworks, funding mechanisms, and public-private partnerships are aligned with the overarching transportation goals. By analyzing these factors, the report highlights how CV technologies can fundamentally transform transportation systems, enhance safety, and improve the overall mobility experience for all road users, including vehicles and VRUs. The adoption of advanced sensor technologies such as Light Detection and Ranging (LiDAR), Radar, and high-definition Closed-Circuit Television (CCTVs), enables CVs to detect and respond to obstacles, traffic signals, and road conditions with high precision. Additionally, the integration of CV technologies can lead to more efficient use of road space, reduced emissions through optimized traffic flow, and enhanced accessibility for individuals with mobility impairments. In essence, CV testbeds serve as a vital proving ground for the innovations that will shape the future of safe, efficient, and inclusive transportation systems. The following sections summarize the features of CV testbeds in the US.

Table 1 categorizes the CV testbeds into urban, rural, highway, Mixed (urban, rural, highway), and controlled test tracks. Within each category, the information on CV testbeds is alphabetically organized.

Table 1. Review of CV Pilot and Testbeds across USA

c	State	Project Title	Location	Equipment	Communication	Brief Description
URBAN Testbeds						
1.	**AL**	University of Alabama, Center for Advanced Vehicle Technologies & Alabama DOT	Tuscaloosa	85 RSUs on intersections.	DSRC	Broadcasting Signal Phase and Timing (SPaT) info.
2.	**AZ**	Arizona Connected Vehicle Test Bed (Anthem)	Along 5.5-mile area of West Daisy Mountain Drive, Anthem	RSUs at 11 intersections	DSRC	Providing pilot test opportunities for applications such as transit signal priority and emergency vehicle preemption.
3.	**DL**	DelDOT SPaT Challenge Deployment	Smyrna	11 RSUs at intersections	DSRC	Broadcasting SPaT information.
4.	**FL**	Gainesville SPaT Deployment	Along 4 corridors, Gainesville	27 RSUs on 27 signals, 71 OBUs on a variety of	DSRC	To improve travel time reliability, safety, throughput, and traveler information; also deployed and tested

				vehicles including emergency vehicles, transit buses, UF fleet, City of Gainesville vehicles, and research vehicles.		pedestrian and bicyclist safety smartphone-based applications.
5.	**FL**	Osceola County CV Signal Project	Osceola County	RSUs on two signalized intersections	DSRC	To test Dedicated Short-Range Communications equipment and intersection processing equipment to gain experience and compile lessons learned in the deployment of CV infrastructure and applications.
6.	**FL**	Pinellas County SPaT	Along a portion of US 19 corridor, Pinellas County	23 RSUs on intersections	DSRC	Broadcasting SPaT info.
7.	**FL**	Seminole County SR 434	Seminole County	RSUs on 6 intersections, OBU	DSRC	To implement CV technology and Signal Performance Metrics (SPM)

8.	**FL**	Tallahassee US-90 SPaT Challenge Deployment	Along US-90 Mahan Drive, Tallahassee	RSUs on 22 signals, OBU	DSRC	To evaluate the operational and safety benefits of the SPaT applications along US 90. The short-term goal is to verify if SPaT will work effectively in hilly and forested terrain along US-90. In contrast, the overall long-term goal is to evaluate Dedicated Short-Range Communications (DSRC) efficiency and safety for road users along a signalized arterial corridor.
9.	**FL**	Tampa Hillsborough Expressway Authority (THEA) Connected Vehicle Deployment	Tampa	1,000 enhanced rearview mirrors installed to display safety messages, 47 RSUs on intersections, 10 bus OBUs, 8 street car OBUs	DSRC, Satellite communication	To transform the experience of automobile drivers, transit riders, and pedestrians in downtown Tampa by preventing crashes, enhancing traffic flow, and improving transit trip time and greenhouse gas emissions.
10.	**GA**	City of Atlanta Smart Corridor Project	Atlanta	1000+ RSUs at intersections	DSRC, C-V2X	Emergency Vehicle Preemption Pilot, Transit Signal Priority Pilot, Incident Responder interchange preemption, Freight signal priority.

11.	**GA**	Georgia DOT SPaT Project	Atlanta	54 RSUs at intersections and 12 RSUs at freeways	DSRC	Broadcasting SPaT info and receiving basic safety messages.
12.	**GA**	iATL CV2X	Alpharetta	55 RSUs	C-V2X	to test a wide range of safety applications provided by C-V2X on public roads and in real traffic
13.	**GA**	Marietta GA Emergency Vehicle Signal Preemption	Marietta	RSUs on 120 Intersections, driver safety app	DSRC	First responders' preemption.
14.	**GA**	North Fulton Community Improvement District	Fulton County	RSUs on 44 intersections	4G LTE, DSRC, C-V2X	Green light priority for emergency vehicles and transit buses. Drivers can connect to the app with the Travel Safely app.
15.	**HI**	Nimitz Corridor Project	Honolulu	RSUs on 16 traffic signals	C-V2X	Red Light Violation Warning, Pedestrian and Cyclist Collision Warnings, Emergency Vehicle Preemption, Transit Signal Priority, Traffic Queue Warning, the TravelSafely™ smartphone app, and Signal-Phase and Timing (SPAT).

16.	**MD**	Prince George County Connected Vehicles Pilots	Prince George County, MD	30 RSUs, 12 OBUs	DSRC/CV2X	Broadcasting SPaT messages, intersection map data (MAP), pedestrian warning, Emergency Vehicle Preemption, Origin-Destination, and traveler and/or information messages
17.	**MD**	MDOT US-1 Innovative Technology Corridor, SPaT Challenge, MD 214 VRU Deployments	Howard County and Prince George's County, MD	40 RSUs, 4 OBUs	C-V2X	Piloting SPaT, BSM, Traveler Information Messaging (TIM), Origin-Destination, and VRU detection and alerts
18.	**MD**	Montgomery County (MCDOT) Connected Vehicles Pilot	Montgomery County, MD	10 RSUs, 3 OBUs	DSRC in-use, C-V2X capable	Broadcasting SPaT and BSM
19.	**MD**	Morgan State University Testbed	Baltimore, MD	2 RSUs at intersection, 2 OBUs, 2 Lidar and 4 CCTV cameras	C-V2X	Broadcasting Spat messages, intersection map data , and traveler and/or information messages.

20.	**MI**	Ann Arbor Connected Vehicle Test Environment (AACVTE)	27-square miles of the City of Ann Arbor	25 RSUs, 2500 OBUs	DSRC	to assess the effectiveness of connected vehicle safety technology at reducing crashes.
21.	**MI**	Road Commission for Oakland County DSRC	Farmington Hills	17 RSUs	DSRC	Broadcasting SPaT information
22	**MI**	Michigan DOT Wayne County Project	Wayne County, MI	12 RSUs, 250 OBUs	DSRC	to document lessons learned, benefits, and evaluate potential business models for future deployment opportunities.
23.	**NC**	NC DOT DSRC	Cary	16 RSUs at intersections	DSRC	Signal Preemption, Transit Signal Priority, Broadcasting SPaT info.
24.	**NH**	SPaT Challenge	Dover	Traffic Controller, DSRC RSUs, DSRC OBUs, V2I Hub, Traffic Server, LTE Radio	DSRC, 4G LTE	Comparing performance of DSRC with 4G LTE

25.	**NJ**	Integrated Connected Urban Corridor in New Jersey (ICUC NJ) Initiative	Newark	8 RSUs, air pollution sensor	DSRC	provide traffic data analytics that can be useful in evaluating alternative traffic operation strategies.
26.	**NV**	Las Vegas SPaT Corridor	Freemont St. Las Vegas, NV	RSUs in 5 intersections	DSRC	Broadcasting SPaT and map information.
27.	**NY**	New York City Connected Vehicle Project Deployment	Manhattan, Brooklyn, NYC	450 RSUs, 3000 OBUs	DSRC	Emergency Electronic Brake Lights, Forward Crash Warning, Intersection Movement Assist, Blind Spot Warning, Lane Change Warning, Vehicle Turning Right in Front of Bus Warning, Red Light Violation Warning, Speed Compliance, Curve speed compliance, Speed Compliance in Work Zone, Oversize Vehicle Compliance, Emergency Communications and Evacuation Information, Pedestrian in Signalized Crosswalk Warning, Mobile Accessible Pedestrian Signal System

28.	**PA**	PennDOT Ross Township Test Bed	Baum Centre Ave Pittsburgh, PA	45 RSUs, 726OBUs	DSRC	The FHWA grant will be used to deploy adaptive traffic signal controls & DSRC along the McKnight Road corridor.
29.	**PA**	PennDOT Signal Phase and Timing (SPaT) Deployments & Test Beds	Cranberry Township, PA	11 RSUs at intersections	DSRC	Improve Safety, Enhance Mobility, Prepare Workforce, Foster and Sustain Partnerships, Increase Public Awareness, Strengthen Economic Collaboration
30.	**PA**	SmartPGH	Pittsburgh, PA	135 intersections, 293 CCTV, 37 Radio advisory transmitter, 200 microwave traffic detector, 24 RSUs, 93 Radar	DSRC	Transit signal priority implementation
31.	**TN**	TnDOT SPaT Challenge Project	Cumberland Ave, Knoxville	17 RSUs on intersections	DSRC	Broadcasting SPaT info.
32.	**UT**	Utah Transit Authority (UTA)	Redwood Road, Salt Lake City area	24 RSUs on intersections	DSRC	to keep UTA buses on schedule.

		DSRC Traffic Signal Pilot Project				
33.	**WA**	Washington State Transit Insurance Pool (WSTIP) Safety-Collision Warning Pilot Project	Washington State	4 cameras on 38 buses	Internet	to test and analyze a collision avoidance system that could help bus drivers reduce the number and severity of collisions
34.	**WI**	Connected Park Street Corridor	along Park Street, Madison	RSUs at 15 signalized intersections	DSRC	Transmit basic safety messages, give information about speed, location and heading
RURAL Testbeds						
35.	**NV**	Nevada DOT DSRC for Rural ITS (Washoe County)	I-580/Washoe County, NV	RSUs, CCTV, Radar, Thermal/infrared, Lidar, Microwave	DSRC	To optimize flow and respond to road conditions, including construction, special events, pedestrian and cyclist.
HIGHWAY Testbeds						

36.	**CA**	California CV Test Bed, Palo Alto	along Highway 82 also known as El Camino Real (approximately 2.1 miles) on 16 intersections, Palo Alto	replacing the DSRC RSUs with C-V2X RSUs on 16 intersections	C-V2X	to demonstrate Multi-Modal Intelligent Traffic Signal System (MMITSS), including CV-based traffic signal control and signal priority for transit, freight, and pedestrians, and Environmentally-Friendly Driving
37.	**GA**	I-85/"The Ray" CV Testbed	An 18-mile stretch of Interstate 85 in Georgia	6 RSUs	DSRC, C-V2X	to immediately detect a crash and generate an alert to warn drivers about a crash on the road ahead.
38.	**ID**	Ada County Highway District	Ada County	20 RSUs, 20 OBUs	DSRC	Validating communication architecture and control technology readiness
39.	**MD**	I-95 Fort McHenry Tunnel	Baltimore County, MD	-	DSRC	
40.	**MI**	American Center for Mobility (Willow Run)	Ypsilanti Township, MI	RSUs	DSRC	a facility for testing autonomous cars

41.	**MI**	I-75 Connected Work Zone (Oakland County)	3 Miles of I-75 in Oakland County, Michigan	CCTV, Vehicle detectors at every mile, DMS sign, RSUs at every mile, Environmental Sensor Station	DSRC	Automatically detect incidents and respond faster, Notify motorists about travel times, traffic queues, speeds and weather-related events, Notify motorist of adverse conditions through use of safety applications such as Curve Speed Warning and Bride Deck Warning Systems (read more about these systems below), Improve safety through the work zone through use of advanced connected vehicle applications
42.	**MI**	Macomb County Dept. Roads DSRC Deployment (MDOT/SMART Pilot)	Macomb County, MI	750 RSUs at signalized intersections, Wi-Fi Vehicle Detectors	DSRC	Broadcasting SPaT information
43.	**MI**	Michigan DOT Wayne County Project	Wayne County, MI	12 RSUs, 250 OBUs	DSRC	to document lessons learned, benefits, and evaluate potential business models for future deployment opportunities.

44.	**MI**	US Army Tank Automotive Research, Development & Engineering Center (TARDEC) "Planet M Initiative"	along a 21-mile portion of I-69 , St. Clair & Lapeer Counties,	6 RSUs	DSRC	curve speed warning, lane closure warning, speed recommendation and disabled vehicle warning
45.	**MI**	Southeast Michigan Testbed	Along I-96/I-696	22 RSUs	DSRC	Dynamic Speed Harmonization , Incident Scene Work Zone Alerts, Eco Approach and Departure at Signalized Intersections, Motorist Advisories and Warnings
46.	**OH**	Ohio Turnpike & Infrastructure Commission DSRC Projects	60 mile section of Ohio turnpike	15 RSUs	DSRC	Proof of concept project
47.	**OH**	NW US33 Smart Mobility Corridor	Marysville, Dublin, OH	800-1000 OBUs, 27 RSUs	DSRC	Improves Travel Time Reliability, Traffic Volumes Increase to Optimize Travel Lanes, Reduce Crashes

48.	**WY**	Wyoming Connected Vehicle Project Deployment	I-80 Wyoming	75 RSUs, 450 OBUs	DSRC	reducing delays, improving safety, reducing severe weather related accidents
Mixed Environments (Urban + Rural + Highway) Testbeds						
49.	**FL**	Smart Work Zones	6 state road corridors: US 1, Dixie Highway, Powerline Road, US 441, Hillsboro Boulevard, and Sample Road	2 RSUs, CCTV Cameras, 2 Vehicle Detectors	DSRC	Traffic Queue Warning, Travel Time Advisory, Alternate Route Advisory
50.	**IN**	Indiana Connected Vehicle Corridor Deployment Project	I-94	10 RSUs at intersections	DSRC	Part of SPaT Challenge,

51.	**MI**	Safety Pilot Model Deployment	US 23 and Plymouth Road, Ann Arbor, Washtenaw Avenue, MI	2700 OBUs, 29 RSUs, 12 TSCs	DSRC	to demonstrate the readiness of DSRC-based connected vehicle safety applications for nationwide deployment.
52.	**UT**	Salt Lake Valley Snow Plow Preemption	Salt Lake Valley	5 corridors , 55 intersections	DSRC	Preemption for Snowplow vehicles
53.	**VI**	Virginia Smart Roads	including sections of Interstate 66, Interstate 495, US 29, and US 50	49 RSUs	DSRC	The Virginia Smart Roads are controlled-access test tracks built to Federal Highway Administration standards. The roads are equipped with advanced research infrastructure and are supported by a full-time staff that serve to coordinate all road activities and oversee operations.
			Controlled Test Tracks			
54.	**MI**	American Center for Mobility (Willow Run)	Ypsilanti Township, MI	RSUs	DSRC	a facility for testing autonomous cars

55.	**MI**	Mcity Testbed	University of Michigan, Ann Arbor, MI	RSU, Edge Computing	5G, V2X	Transit Signal Priority, Emergency Vehicle Preemption, Dynamic Signal Optimization with Green Wave Advisory, and Vulnerable Road User Notification
56.	**MN**	Roadway Safety Institute (RSI) Connected Vehicle Testbed	Minneapolis	1 RSU, 1 OBU, 7 radars	DSRC	to implement and evaluate the next generation of vehicle-based freeway safety applications, to establish the backbone of the sensor communication network and data collection system along the testbed length.

1.2.1 Urban Testbeds

1. University of Alabama, Center for Advanced Vehicle Technologies & Alabama DOT

The CV testbed in Alabama, situated in Tuscaloosa, is a collaborative initiative spearheaded by the University of Alabama's Center for Advanced Vehicle Technologies and the Alabama Department of Transportation (ALDOT). This testbed is a sophisticated infrastructure system featuring 85 RSUs strategically deployed at various intersections. These RSUs utilize DSRC technology to broadcast Signal Phase and Timing (SPaT) information. The deployment of this testbed aims to enhance the efficiency and safety of urban traffic management by leveraging real-time data to optimize traffic flow and reduce congestion.

The primary motivation behind the implementation of the Alabam.a CV testbed was to address growing traffic congestion and safety concerns in urban areas. With the increasing number of vehicles on the road, the need for smarter traffic management solutions became evident. The integration of DSRC-based communication through RSUs allows for real-time monitoring and management of traffic, which can significantly reduce delays and improve the overall traffic flow. The Alabama CV testbed has been the site of numerous research projects and initiatives aimed at advancing CV technology. One key project involves the testing and validation of SPaT broadcasts to improve signalized intersection efficiency. By using real-time SPaT data, V2V and V2P communication, it is possible to enhance safety for all road users. Another significant project focuses on implementing and analyzing cooperative adaptive cruise control (CACC) systems, which allow vehicles to maintain safe following distances and respond more quickly to changes in traffic flow. Additionally, the testbed supports initiatives that explore the integration of CV technology with automated driving systems, examining how these technologies can work together to further enhance safety and efficiency on the roads in Alabama [7]. It is also worth mentioning that the University of Alabama Center for Advanced Vehicle Technologies implemented Advanced Driver Assistance Systems (ADAS) and other automated technologies to address safety concerns associated with large transit buses, such as blind spots and pedestrian detection [8].

2. Arizona Connected Vehicle Testbed (Anthem)

The Arizona CV testbed, located in Anthem, Arizona, spans 5.5-miles along West Daisy Mountain Drive. This testbed is equipped with Roadside Units (RSUs) installed at 11 intersections, utilizing Dedicated Short-Range Communication (DSRC) technology. This setup facilitates V2I communication, which allows vehicles to exchange real-time data with traffic signals and other roadway infrastructures. The primary objective of this testbed is to provide a controlled environment for piloting CV applications, with a focus on enhancing traffic management and safety through innovations such as transit signal priority and emergency vehicle preemption. Figure 3. illustrates the Anthem CV testbed.

Figure 3. The Maricopa County Department of Transportation (MCDOT) Implemented Testbed in Anthem, Arizona

The implementation of the Arizona CV testbed was driven by the need to explore and demonstrate the practical benefits of CV technologies in improving traffic efficiency and safety. By enabling real-time communication between vehicles and traffic signals, this testbed aims to reduce delays for public transit vehicles, thus improving the reliability and attractiveness of public transportation. Additionally, the emergency vehicle preemption feature allows emergency responders to receive priority at intersections, thereby reducing response times and enhancing public safety. It is worth mentioning that several projects have been conducted on the Arizona CV testbed to test and refine these technologies. For instance, pilot studies focusing on transit signal priority have shown the potential to reduce bus travel times and improve schedule adherence, benefiting both transit agencies and passengers. In terms of emergency vehicle preemption, the testbed has demonstrated the capability to effectively clear intersections for emergency vehicles, minimizing potential conflicts with other road users and improving safety [9,10].

In addition to Anthem testbed, the "Loop 101 Mobility" project is a CAV testbed initiative located along the Loop 101 freeway in Arizona, specifically in the Greater Phoenix area. This project is part of a larger effort by the Arizona Department of Transportation (ADOT) and the Maricopa Association of Governments (MAG) to enhance traffic management and safety on one of the region's busiest freeways. The testbed spans several miles and incorporates a range of advanced communication technologies, including DSRC and cellular-based vehicle-to-everything (C-V2X) communication. These technologies enable vehicles to communicate with each other and with roadside infrastructure, facilitating real-time data exchange to improve traffic flow and safety. The primary objective of the Loop 101 Mobility project is to explore how CAV technologies can be leveraged to reduce traffic congestion, improve safety, and enhance the overall efficiency of freeway operations. By implementing V2V and V2I communication, the project aims to provide drivers with critical information, such as traffic conditions, upcoming hazards, and optimal speeds. In the context of future mobility, the Loop 101 Mobility project serves as a testing ground for technologies that could be scaled across the state's transportation network. By providing real-world data and insights, the project contributes to the development of smarter, more adaptive traffic management systems [11,12].

3. Delaware CV Project (DelDOT SPaT Challenge Deployment)

The Delaware Department of Transportation (DelDOT) has worked on the SPaT Challenge Deployment in Smyrna, Delaware. This project includes 11 signalized intersections along US 13, each equipped with RSUs that utilize DSRC technology to broadcast SPaT information. The primary objective of the SPaT Challenge is to enhance the safety and efficiency of traffic management by enabling vehicles to receive real-time information about traffic signal statuses. This setup allows for the seamless exchange of information between infrastructure and vehicles. This project is a crucial part of the nationwide SPaT Challenge, which aims to deploy SPaT broadcasts at over 20,000 signalized intersections across the United States by 2025 [1]. The implementation of the DelDOT SPaT Challenge Deployment was driven by the need to improve traffic safety and operational efficiency on key corridors in Delaware. As traffic volumes continue to increase, ensuring that intersections operate efficiently and safely has become a priority for DelDOT. By deploying RSUs that broadcast SPaT information, the project enables real-time communication between vehicles and infrastructure, and it allows for more informed driving decisions. This capability is expected to reduce the number of traffic crashes caused by sudden stops or signal violations. Additionally, the testbed supports the broader goal of integrating CV technologies into the state's transportation infrastructure, which is essential for preparing for future advancements in autonomous and semi-autonomous vehicle technologies.

Several research projects and initiatives have been conducted using the Delaware CV testbed, each aimed at advancing CV technologies and improving transportation safety and efficiency. One of the primary projects involves evaluating the effectiveness of SPaT data in reducing traffic delays and enhancing safety at signalized intersections. The significant initiative is focused on the development and testing of applications that use SPaT data to provide advanced warning to drivers about impending red light changes and red-light running incidents. Additionally, the testbed is being used to study the potential benefits of CV technology in supporting emergency vehicle preemption, allowing emergency responders to navigate through intersections more efficiently and safely [13].

4. Gainesville SPaT Deployment

The Gainesville SPaT Deployment covers 27 signals across four corridors in Gainesville, Florida. The project involves the installation of RSUs on these signals and OBUs on a variety of vehicles, including emergency vehicles, transit buses, and research vehicles (CVs). This project is designed to improve travel time reliability, safety, throughput, and traveler information. The project also includes the deployment and testing of smartphone-based applications for pedestrian and bicyclist safety to improve overall mobility in the area [14].

5. Osceola County CV Signal Project

The Osceola County CV Signal Project incorporates Dedicated Short-Range Communications (DSRC) technology to facilitate real-time data exchange between Roadside Units (RSUs) and equipped vehicles. The deployed RSUs are configured to transmit Signal Phase and Timing (SPaT) data, Basic Safety Messages (BSMs), and other required information to improve vehicle-to-infrastructure communication. Osceola County tested CV technology by installing RSUs at two intersections, supported by the FHWA. RSUs were placed at Osceola Parkway/Orange Blossom Trail (span wire) and Orange Blossom Trail/Poinciana (mast arm). RSUs communications allow vehicles to process precise signal timings, lane geometry, and potential safety hazards. The system architecture integrates advanced processing algorithms at the intersection level. Additionally, the system architecture enables the collection and analysis of high-resolution traffic data to inform adaptive traffic signal control and optimize safety-critical applications. Furthermore, the RSUs support low-latency communication necessary for the timely relay of warnings, such as red-light violations and pedestrian crossings, contributing significantly to crash avoidance scenarios.

The project's methodology emphasizes rigorous field testing under real-world traffic conditions to assess DSRC reliability and scalability for CV applications. The data collected from this project is used to model intersection performance, assess network-level impacts, and refine deployment strategies for future CV infrastructure. Additionally, the testbed supports interoperability testing, ensuring that the RSUs and Onboard Units (OBUs) from different manufacturers meet industry standards, such as SAE J2735 for message formatting and IEEE 802.11p for DSRC communication [15,16].

6. Pinellas County SPAT

The Pinellas County SPAT project covers 23 traffic signals along a portion of the US 19 corridor in Pinellas County, Florida. It involves the installation of RSUs at these intersections. The project aims to broadcast SPaT information to improve traffic signal coordination and efficiency along the US 19 corridor. The project also tries to enhance traffic flow and safety through better signal management [17].

7. Seminole County SR 434

The Seminole County SR 434 project deploys CV technology with Signal Performance Metrics (SPM) along SR 434 from McCulloch Road to E Mitchell Hammock Road. The deployment includes RSUs at six intersections and OBUs. The project's key goal is to implement and assess CV technology applications such as SPT, Transit Signal Priority, and preemption. Additionally, the project tries to enhance traffic signal performance and improve transit operations along the SR 434 corridor [18].

8. Tallahassee US90 SPaT Challenge Deployment

The Tallahassee US90 SPaT Challenge Deployment is situated along US-90 Mahan Drive in Tallahassee, Florida. This project includes the installation of RSUs at 22 signalized intersections and OBUs inside the vehicles. The primary objective is to evaluate the operational and safety benefits of SPaT applications along this arterial corridor. The project aims to test the effectiveness of SPaT technology in a diverse terrain characterized by hilly and forested environments. The short-term goal is to verify the technology's functionality in these conditions. On the other hand, the long-term goal focuses on assessing the efficiency and safety improvements provided by DSRC for road users along signalized corridors [19]. Figure 4. illustrates plans for 22 signalized intersections equipped with DSRC along US 90 Mahan Drive.

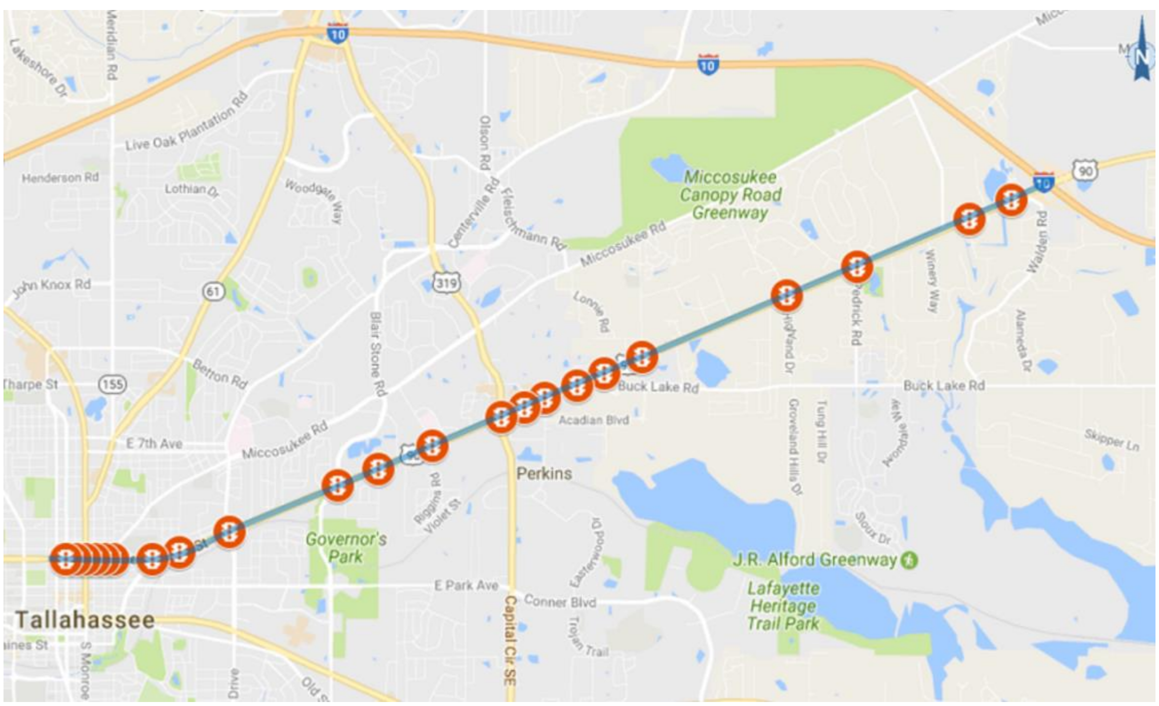

Figure 4. US 90 Signal Phase and Timing Tallahassee [18]

9. Tampa Hillsborough Expressway Authority (THEA) Connected Vehicle Deployment

The Tampa Hillsborough Expressway Authority (THEA) CV Deployment involves installing 1,000 enhanced rearview mirrors, 47 RSUs, 10 bus OBUs, and 8 streetcar OBUs. The deployment is concentrated on areas around reversible express lanes and major arterials in downtown Tampa. Furthermore, this project aims to alleviate congestion, improve safety during peak commuting hours, and enhance traffic flow. It aims at reducing crashes, improving transit trip times, and minimizing greenhouse gas emissions through advanced CV technologies [20]. Figure 5. shows the CV pilot deployment in downtown Tampa.

Figure 5. CV Pilot Deployment in Downtown Tampa [19]

10. City of Atlanta Smart Corridor Demonstration Project

The City of Atlanta is implementing a Smart Corridor Demonstration Project along North Avenue, stretching from the Georgia Tech Campus to Ponce City Market. This project involves upgrading 20 intersections with advanced CV technology as part of the Renew Atlanta program. The project is a collaborative effort with partners like AT&T Smart Cities, the Georgia Institute of Technology, and the Georgia Department of Transportation. The project also features a self-driving vehicle demonstration to evaluate and improve driving conditions on one of Atlanta’s busiest corridors. By integrating DSRC and C-V2X technologies, the project aims to facilitate emergency vehicle preemption, transit signal priority, and other smart traffic management solutions. The project also serves as a platform to test and demonstrate the capabilities of autonomous vehicles in an urban environment [21].

11. Georgia DOT SPaT Project

The Georgia Department of Transportation's SPaT Project in Atlanta includes the installation of SPaT technology at 54 intersections and 12 freeway locations. This project uses DSRC technology to broadcast SPaT messages and receive Basic Safety Messages (BSMs), providing real-time traffic signal information to CVs along critical corridors like SR 141, SR 8, and I-75/85 in downtown Atlanta. This project enables smoother traffic flow, reduces congestion, and improves safety at intersections by minimizing conflicts and optimizing signal timings based on real-time traffic conditions [22].

12. iATL CV2X Project

The infrastructure-Automotive Technology Laboratory (iATL) CV2X project, located in Alpharetta, Georgia aims to leverages C-V2X technology. The Federal Communications Commission (FCC) has issued an experimental license for this deployment, which operates within a five-mile radius of the iATL. The project includes the installation of 55 RSUs to test a variety of safety applications in real-world traffic scenarios. The iATL CV2X project aims to test and develop safety applications for CVs. By using C-V2X technology, the project seeks to enhance V2I and V2V communications. This testbed provides valuable insights into how CV technologies can improve road safety and traffic management [23].

13. Marietta GA Emergency Vehicle Signal Preemption

In Marietta, Georgia, an innovative project has installed traffic preemption software on emergency response vehicles, such as those operated by the Marietta Fire Department. This system ensures that first responders receive green lights at pre-clear intersections, enhancing response times and safety for both responders and the public. The project covers a 24-square-mile area, with RSUs installed at 120 intersections to facilitate these operations. The primary goal of the Marietta Emergency Vehicle Signal Preemption project is to improve the efficiency and safety of emergency response operations. By providing priority green lights for emergency vehicles, the project reduces response times and minimizes the risk of collisions at intersections [24].

14. North Fulton Community Improvement District

The North Fulton Community Improvement District (NFCID) project in Fulton County, Georgia, focuses on connecting 44 intersections with CV technology. This project, in partnership with Applied Information

Inc., aims to implement Glance 'hybrid' three-way CV technologies across the region. The use of 4G LTE, DSRC, and C-V2X technologies will enable green light priority for emergency vehicles and transit buses, as well as enhanced communication through the TravelSafely app. The NFCID project seeks to improve traffic management and safety in the North Fulton area. By providing priority signaling for emergency and transit vehicles, the project aims to reduce response times and improve transit reliability. The integration of multiple communication technologies provides robust and adaptable infrastructure capable of supporting various safety and mobility applications [25].

15. Ala Moana Boulevard/Nimitz Highway Corridor Project (Honolulu DOT), The state of Hawaii

The Nimitz Corridor Project in Honolulu, Hawaii aims to improve traffic safety and efficiency across a critical transportation route. This project involves the deployment of RSUs at 16 traffic signals along the Nimitz Corridor and utilizes C-V2X communication technology. The deployment supports a suite of advanced traffic management and safety features, including Red Light Violation Warning, Pedestrian and Cyclist Collision Warnings, Emergency Vehicle Preemption, Transit Signal Priority, Traffic Queue Warning, and SPaT information. Additionally, the Travel Safely smartphone app is integrated to provide real-time traffic updates and safety alerts to drivers and pedestrians. The project concentrates on communication between vehicles, infrastructure, and pedestrians, and it facilitates timely warnings and signal adjustments. The red-light violation warning system aims to prevent crashes caused by drivers running red lights, while pedestrian and cyclist collision warnings provide critical alerts to both drivers and non-motorized road users. Emergency vehicle preemption ensures that emergency vehicles can navigate intersections efficiently, and transit signal priority improves the reliability of public transit services. The Nimitz Corridor Project is expected to yield valuable data on the effectiveness of C-V2X technologies in real-world traffic scenarios. Research will focus on assessing improvements in traffic safety, reductions in collision rates, and the overall efficiency of traffic flow [26].

16. Prince George Counties Connected Vehicle Pilots

The Montgomery and Prince George Counties CV Pilots demonstrate a comprehensive effort to advance CV technology across a broad geographic area. This testbed involves the installation of over 30 RSUs at various intersections within Prince George County, MD. The pilot program utilizes both DSRC and C-V2X technologies to support a range of CV applications. These applications include broadcasting SPaT messages, intersection map data (MAP), pedestrian warnings, emergency vehicle preemption, and traveler information messages. The primary goal of this pilot program is to enhance traffic management and safety by providing real-time information to drivers and other road users. By broadcasting SPaT messages and intersection map data, the project aims to improve the coordination of traffic signals, facilitate better decision-making by drivers, and enhance overall traffic flow. Additionally, pedestrian warning systems are implemented to increase safety at intersections by alerting drivers to the presence of pedestrians. The operational phase of this pilot program reflects a significant commitment to integrating advanced communication technologies into urban and suburban transportation systems. The data collected from this testbed will contribute to the development of the best practices for deploying CV technologies and improving traffic management and safety [27].

17. MDOT US-1 Innovative Technology Corridor, SPaT Challenge, TIM, MD 214 VRU Deployments

US 1 Innovative Technology Corridor: The US 1 Innovative Technology Corridor project is a pioneering plan to advance traffic management and efficiency along Route 1 (US-1) in Howard County, MD. This project focuses on the deployment of SPaT systems at 20 signalized intersections starting from Montgomery Road to Route 175. The primary objective of this project is to enhance coordination between traffic signals, optimize traffic flow, and reduce congestion along this key transportation corridor. As part of the project, advanced communication technologies are used to ensure that SPaT information is accurately broadcasted to approaching vehicles. Drivers will receive timely updates on signal phases which can help them make informed decisions about their travel speed and time. Furthermore, the project aims to minimize stop-and-go driving, reduce travel times, and lower fuel consumption. The operational status of the US 1 Innovative Technology Corridor project highlights its role in advancing smart traffic management solutions. The data collected from this project will provide valuable insights into the effectiveness of SPaT systems and their impact on traffic management and safety [30-32]. In addition, the project has another 19 RSUs installed from MD 32 at the very south to I-195 to the very north, with a goal of providing origin-destination data and traveler information messages (on congestion, incidents, weather, etc.).

MDOT also has a single VRU pilot deployment in Prince George's County that covers pedestrian detection and alerts at MD 214 (Central Avenue) and Addison Road.

18. Montgomery County (MCDOT)

Montgomery County CV Pilot demonstrates a comprehensive effort to integrate CV capable technology within Montgomery County's standard infrastructure. This testbed includes 10 RSUs at signalized intersections along MD 124 (Quince Orchard Rd) and MD 28 (Darnestown Rd). MCDOT uses 3 OBUs utilizing DSRC technology to test/verify a range of CV applications. These applications include broadcasting SPaT messages and BSMs, but the system also supports TiMs, TSP/Preemption and detection. The primary goal of this pilot program is to provide an environment to test CV applications incorporated into existing, standard traffic signal infrastructure. By broadcasting SPaT messages the project aims to improve the coordination of traffic signals, facilitate better decision-making by drivers, and to enhance overall traffic flow. The data collected from this testbed will contribute to the development of the best practices for deploying CV technologies and improving traffic management and safety.

19. Morgan State University CAV Testbed, Baltimore, Maryland

The Morgan State University Connected and Automated Vehicle (CAV) Testbed in Baltimore, MD, is a state-of-the-art research facility for CAV technologies. Equipped with two RSUs, two OBUs, two LiDAR sensors, and four CCTV cameras operating under C-V2X technology, the testbed focuses on enhancing traffic safety, particularly for VRUs, at two signalized intersections: Cold Spring Lane–Hillen Road and East 33rd–Hillen Road. Smart signal controllers broadcast real-time SPaT, MAP, and TIM messages, enabling advanced traffic management and safety research. Key studies include statistical analysis of vehicle conflicts using LiDAR, evaluation of Post Encroachment Time (PET) thresholds for vehicle-pedestrian interactions, and mitigation strategies for jaywalking and vehicle-bicyclist conflicts. The testbed supports research on traffic signal failures, smart green time allocation, and sensor performance under varying conditions, providing insights into traffic flow and safety enhancements. Future research will explore pre-emption systems for emergency vehicles, dynamic safety messaging, and Time-to-Collision (TTC) analysis for V2V, V2P, and V2B conflicts. Additionally, the testbed will develop real-time warning devices to alert drivers and VRUs to potential conflicts, advancing CAV technologies and ensuring safer, more efficient intersections [28,29].

20. Ann Arbor Connected Vehicle Test Environment (AACVTE)

The Ann Arbor CV Test Environment (AACVTE) is a pioneering project managed by the University of Michigan Transportation Research Institute (UMTRI). This testbed covers a 27-square-mile area in Ann Arbor, and it has transitioned from a research-oriented deployment to an operational environment aimed at assessing the effectiveness of CV safety technologies in reducing crashes. The testbed includes 25 RSUs and 2,500 OBUs, making it one of the most extensive CV environments in the world. Research conducted on this platform has provided valuable data on the performance and reliability of DSRC-based safety applications, contributing to the development of national standards for CV technology. The AACVTE is a critical steppingstone toward achieving the USDOT's vision of a nationwide deployment of CV and infrastructure [33].

21. Road Commission for Oakland County DSRC

The Road Commission for Oakland County (RCOC) prioritizes safety and oversees approximately 900 square miles of land, including the maintenance of 1,400 traffic signals. As part of its commitment to improving transportation, RCOC is planning to update and expand its systems with the installation of roadside units capable of communicating with connected vehicles (CVs). In 2018, RCOC partnered with Oakland County to launch the Connected Vehicle Task Force, a pilot program aimed at testing CV infrastructure and developing a sustainable CV business model. The initiative, led by P3 Mobility, operates as a public-private partnership, leveraging expertise and resources from both sectors. While the project's scope is still being refined, it marks a significant step toward integrating CV technology to enhance traffic safety and efficiency in Oakland County [34].

22. The Michigan DOT Wayne County Project

This project located in Wayne County, Michigan, is a notable project focusing on CV technology. This project involves the deployment of 12 RSUs and 250 OBUs using DSRC technology. The primary objective of this project is to document lessons learned, assess the benefits, and evaluate potential business models for future CV deployments. By analyzing the operational data and outcomes from this project, Michigan DOT aims to refine its approach to CV technologies and explore sustainable models for broader implementation across the state. This project is an important step toward understanding the practical implications of DSRC-based systems and their potential to improve traffic safety and efficiency in urban environments [35].

23. North Carolina DOT (NCDOT) Projects and Testbed

The NCDOT DSRC project is part of the AASHTO SPaT Challenge and involves the deployment of DSRC technology at 20 intersections across the NC55 corridor and High House Road in Cary, NC. This deployment includes 16 RSUs strategically placed to manage various traffic control functions such as signal preemption for emergency vehicles, transit signal priority, and broadcasting SPaT information. By utilizing DSRC technology, the project aims to enhance traffic management, improve safety, and support the efficient movement of vehicles and transit. The project was implemented to address traffic congestion and improve safety at key intersections by providing real-time information on traffic signal phases and timing. The project's key achievements include evaluating the impact of DSRC technology on traffic management and safety. Studies making use of the testbed have assessed the effectiveness of SPaT broadcasting in reducing delays and improving traffic signal coordination, as well as the benefits of signal preemption and transit priority systems [36].

In another project, the NCDOT Multimodal Connected Vehicle Pilot (MMCVP) at North Carolina State University in Raleigh created a connected vehicle system to evaluate the effects of CV technology on both driver and pedestrian safety. Although still in the planning stages, the pilot aims to develop and test integrated CV systems that can enhance safety and mobility for various modes of transportation, including vehicles, pedestrians, and cyclists. The pilot project is being developed to understand how CV technologies can be utilized to improve safety and efficiency across multiple transportation modes. The project also involves planned research studies that will evaluate how CV systems can enhance pedestrian safety, improve traffic flow, and support multimodal transportation strategies [37].

24. Dover SPaT Challenge (New Hampshire DOT)

The New Hampshire DOT SPaT Challenge Deployment, situated in Dover, represents a significant advancement in evaluating CV technologies. This testbed includes a range of sophisticated equipment such as traffic controllers, DSRC, RSUs, OBUs, a V2I Hub, traffic servers, and LTE Radios. The core aim of this deployment is to compare the performance of DSRC and 4G LTE communication technologies in transmitting SPaT and other critical data. The testbed provides valuable insights into their respective strengths, such as DSRC's low latency and high reliability versus 4G LTE's broader coverage and higher data throughput. The testbed makes use of DSRC's reliability and low latency, which are crucial for safety-critical applications, while 4G LTE offers extensive coverage and high data rates, which are advantageous for broader, non-critical applications. The New Hampshire DOT SPaT Challenge Deployment has been involved in several research projects. One major project involves assessing the latency and reliability of SPaT data transmission using both DSRC and 4G LTE in various traffic conditions. Another key project explores the integration of a V2I Hub and Traffic Server to manage and process data from these communication technologies, aiming to optimize the delivery and accuracy of traffic information [38].

25. New Jersey CV Testbed

The Integrated Connected Urban Corridor in New Jersey (ICUC NJ) Initiative is a pioneering project designed to enhance urban mobility and environmental monitoring in Newark, New Jersey. This testbed features the deployment of eight RSUs equipped with DSRC technology and air pollution sensors. The RSUs are strategically placed to cover key intersections within Newark, enabling the collection and transmission of real-time traffic data. The implementation of the ICUC NJ testbed is driven by Newark's need to manage high traffic volumes and improve air quality. As a major urban center, Newark experiences significant congestion, leading to increased vehicle emissions and air pollution. The deployment of DSRC-equipped RSUs allows for real-time communication between vehicles and infrastructure, providing drivers with critical information about traffic conditions and potential hazards. The ICUC NJ Initiative supports various projects and research efforts focused on advancing CV technologies and improving urban traffic management [39].

The Route US 322 and US 40/322 Adaptive Traffic Signal (ATS) Project focuses on a 10.8-mile stretch of highway within Atlantic County. This project involves the deployment of Adaptive Traffic Systems (ATS) at five intersections along Route US 322 and twenty-two (22) intersections along US 40/322, which runs parallel to the Atlantic City Expressway. It features the installation of new fiber optic communications, mid-block system detectors, four camera surveillance systems, and upgraded signal controllers for adaptive operations. Additionally, this project marks the New Jersey Department of Transportation's (NJDOT) first deployment of CV RSUs. The fiber optic cables being installed along the entire corridor will support real-time data exchange, and all devices will be integrated into virtual servers to optimize traffic flow, reduce congestion, and improve overall safety in the City of Pleasantville and the Townships of Hamilton and Egg Harbor [40].

In another project, the Route 40, CR 606 to Atlantic Avenue Interchange, and Route 50 Adaptive Traffic Signal (ATS) project is a comprehensive initiative designed to enhance traffic management and safety in Atlantic City and Hamilton Township, New Jersey. The project covers Route 40 from milepost 45.89 to 47.84 and from milepost 62.98 to 64.32, as well as Route 50 from milepost 18.62 to 21.60. It involves the installation of ATS and ITS infrastructure at 15 intersections. Key components include new signal controllers, cabinets, and image detectors, along with advanced Camera Surveillance Systems, RSUs, and midblock detectors to provide real-time traffic data and monitoring capabilities. The integration of fiber optic and ISP communication ensures robust data exchange and coordination among the traffic control systems [41].

26. Nevada DOT DSRC and Las Vegas SPaT Corridor

The Las Vegas SPaT corridor is located on Fremont Street in Las Vegas, Nevada. This testbed spans five critical intersections: Las Vegas Boulevard/Fremont, Fremont/6th, Fremont/7th, Fremont/8th, and Carson/7th [42]. The testbed is equipped with RSUs utilizing DSRC technology and is capable of broadcasting real-time SPaT and map information. This infrastructure supports a range of CAV applications by providing precise data on signal phase and timing, as well as detailed mapping information. The testbed was implemented to enhance traffic flow, reduce congestion, and improve the overall safety and efficiency of urban mobility in one of Las Vegas's busiest areas. The implementation of the Las Vegas SPaT corridor was primarily motivated by the need to improve traffic management and safety in the urban environment of downtown Las Vegas. This area experiences significant pedestrian and vehicle traffic, making it an ideal location to test and refine CV technologies. The testbed allows for the timely broadcasting of SPaT information, which helps drivers and autonomous vehicles anticipate signal changes and make informed decisions, thus reducing the likelihood of crashes and improving traffic efficiency. One key project on this testbed uses real-time broadcasts of SPaT data to CVs to optimize speed and reduce idling time, which can lead to lower emissions and improved fuel efficiency. Another significant initiative includes testing the integration of SPaT data with autonomous vehicle systems, thus more reliable and efficient autonomous driving in complex urban environments [43].

27. New York City Connected Vehicle Pilot Project Deployment

The New York City CV Pilot Project is a large-scale project aimed at improving the safety and mobility of travelers across the city through advanced CV technologies. This project covers multiple areas, including Midtown Manhattan, Central Brooklyn, and a four-mile stretch of the FDR Drive in Manhattan. In total, the deployment involves 204 intersections equipped with V2V and V2I capabilities. The project aimed to facilitate communication between vehicles and traffic infrastructure to optimize traffic flow and enhance safety. This project is designed to address several traffic safety issues prevalent in a densely populated urban environment like New York City. Key applications tested and implemented in this deployment include Emergency Electronic Brake Lights, Forward Crash Warning, Intersection Movement Assist, Blind Spot Warning, Lane Change Warning, and Red-Light Violation Warning. These applications use DSRC to provide real-time alerts to drivers, and it helps them avoid collisions and navigate traffic more efficiently. Additionally, the project includes pedestrian safety measures such as the Pedestrian in Signalized Crosswalk Warning and the Mobile Accessible Pedestrian Signal System that are vital in protecting VRUs [44].

28. PennDOT Ross Township Testbed

The PennDOT Ross Township Testbed focuses on deploying adaptive traffic signal controls and DSRC technology along the McKnight Road corridor in Pittsburgh, Pennsylvania. Funded by a Federal Highway Administration (FHWA) grant, this testbed aims to improve traffic management and safety along a critical transportation corridor. The testbed was implemented to enhance traffic flow and safety through the deployment of adaptive signal controls and DSRC technology. The project addresses the need for advanced traffic management solutions in a high-traffic area. Additionally, projects on this testbed include the installation of adaptive traffic signal systems and DSRC units along McKnight Road. Research focuses on evaluating the effectiveness of these technologies in optimizing traffic flow and improving safety [45].

29. PennDOT SPaT Deployments

The PennDOT SPaT deployments project includes installations along routes 19 and 228 in Cranberry Township and the Baum Centre Avenue corridor in Pittsburgh, Pennsylvania. This project features 11 RSUs at intersections, utilizing DSRC technology to enhance traffic management and safety. The SPaT deployments were implemented to improve traffic safety and mobility through real-time dissemination of SPaT information. The project aims to develop the transportation workforce, foster partnerships, and strengthen economic collaboration by leveraging CV technology. This research focuses on the impact of real-time traffic signal information on safety and traffic flow [46].

30. SmartPGH Project

The SmartPGH project, based in Pittsburgh, Pennsylvania, focuses on implementing transit signal priority across the city's “Smart Spine” corridors. This initiative expands the network of connected, real-time adaptive signal controllers to enhance transit operations. Additionally, the project includes the conversion of nearly 40,000 streetlights to LED technology, equipped with traffic detection and air quality sensors. SmartPGH was implemented to improve transit efficiency and reduce delays through advanced signal priority systems. The streetlight conversion aims to provide additional benefits such as energy savings, enhanced traffic detection, and environmental monitoring. Projects at SmartPGH also include the implementation of real-time adaptive signal control systems, deployment of LED smart streetlights, and integration of traffic detection and air quality sensors [47].

31. Tennessee DOT (SPaT Challenge Project and CV Projects)

The Tennessee Department of Transportation (TDOT) participated in the SPaT Challenge, focusing on enhancing traffic signal systems to improve road safety. As part of this initiative, the CV testbed was established along Cumberland Avenue in Knoxville, Tennessee. This testbed features 17 RSUs strategically installed at intersections. These RSUs utilize DSRC technology to broadcast SPaT information to CVs in the area. TDOT aims to create a more responsive traffic environment. This initiative not only supports the efficient flow of vehicles but also reduces emissions by minimizing idling times at traffic signals. Additionally, the system provides a platform for further research and development in CV technologies. One of the primary focuses of TDOT testbed has been on assessing the effectiveness of SPaT data in reducing crash rates at intersections, particularly those prone to high crash rates [48].

In another project conducted by TDOT, the Metro Nashville 2020 Advanced Transportation and Congestion Management Technologies Deployment (ATCMTD) project tries to modernize the city's transportation infrastructure to enhance safety, reduce congestion, and improve the overall efficiency of urban mobility. This planned deployment is set to take place in Nashville, Tennessee, and focuses on implementing CV technologies across the metropolitan area. The project aims to facilitate real-time data exchange between vehicles, infrastructure, and traffic management centers. This project aligns with the goals set forth in the federal ATCMTD program, which seeks to demonstrate the efficacy of CV technologies in reducing urban traffic problems and supporting sustainable transportation solutions [48].

TDOT also conducted another project that focuses on I-24 Corridor Nashville as a large-scale CV deployment planned along the I-24 corridor between Nashville and Murfreesboro, Tennessee. This ambitious initiative aims to enhance traffic management, improve safety, and reduce congestion along one of the state's busiest highway segments. The project aims to optimize traffic flow by using CV data to adjust traffic signal timing dynamically, manage lane use, and provide speed harmonization. The key goals of this project are to reduce the likelihood of crashes caused by sudden stops or traffic bottlenecks. By enhancing situational awareness and enabling more proactive traffic management strategies, the I-24 Corridor project aims to reduce crash rates, improve emergency response times, and create a safer, more efficient travel environment for all road users [48].

32. Utah Transit Authority (UTA) DSRC Traffic Signal Pilot Project

The Utah Transit Authority (UTA) DSRC Traffic Signal Pilot Project is aimed at improving bus schedule reliability and reducing delays along Redwood Road, a major thoroughfare in the Salt Lake City area. This project utilizes DSRC technology to enable UTA buses to communicate directly with traffic signals at 24 intersections along the route. By doing so, the project facilitates dynamic traffic signal adjustments that prioritize transit vehicles and helps keep buses on schedule. The primary motivation for implementing the UTA DSRC Traffic Signal Pilot Project is to enhance the efficiency of public transit operations in a region experiencing significant growth and congestion. The ability to prioritize buses at intersections reduces the time buses spend idling at red lights. The project aims to encourage higher ridership and reduce the overall number of vehicles on the road, thus reducing emissions and improving air quality. The UTA DSRC Traffic Signal Pilot Project provides valuable insights into the deployment and interoperability of CV technologies. By using hardware from multiple vendors, the project tests the compatibility and performance of different DSRC platforms. The project's success may lead to the expansion of DSRC applications across Utah, including the integration of additional transit routes and the potential deployment of other CV technologies, such as V2I communications for passenger cars [49].

33. Washington State Transit Insurance Pool (WSTIP) Safety-Collision Warning Pilot Project

The Washington State Transit Insurance Pool (WSTIP) Safety-Collision Warning Pilot Project is designed to enhance bus safety through advanced technology. This project equips 38 buses with a total of 152 cameras (four per bus) and leverages internet connectivity to test and analyze a collision avoidance system. The primary objective is to assess the effectiveness of this system in reducing the frequency and severity of collisions involving transit buses. This pilot project was implemented to address the increasing need for advanced safety measures in public transportation. The use of multiple cameras on each bus enables comprehensive coverage of the vehicle's surroundings, and it allows the system to detect potential hazards and provide timely warnings to drivers. The data gathered from this project will be used in evaluating the system’s impact on collision rates and driver performance [50].

34. Wisconsin CV Testbed

The Connected Park Street Corridor project in Madison, Wisconsin, represents a pioneering effort to integrate CV technology into a major urban thoroughfare. Spanning 20 to 30 signalized intersections along Park Street, this operational testbed aims to enhance traffic management and safety through advanced V2I communications. By equipping these intersections with sensors and communication technologies, the project enables real-time data exchange between vehicles and traffic signals. This setup allows for dynamic adjustments to signal timings based on current traffic conditions, optimizing flow and reducing congestion throughout the corridor. The testbed also facilitates the collection of valuable data on traffic patterns, vehicle interactions, and system performance. The primary motivation behind the Connected Park Street Corridor project is to address the increasing traffic congestion and safety concerns associated with urban growth. Madison's Park Street, a critical transportation link connecting various neighborhoods and business districts, experiences significant traffic volumes that can lead to delays and crashes. Additionally, key studies conducted in this testbed include evaluating the effectiveness of adaptive signal control systems, which adjust signal timings based on real-time traffic data to reduce delays and improve intersection performance. The Connected Park Street Corridor testbed also focuses on transmitting basic safety messages to CVs, including critical information about speed, location, and heading [51].

1.2.2 Rural Testbeds

35. Nevada DOT DSRC for rural ITS (Washoe County)

The Nevada Department of Transportation (NDOT) DSRC for Rural ITS (Washoe County) testbed aimed at enhancing the safety and efficiency of transportation along the I-580 corridor between Reno and Carson City. Comprised of 32 miles corridor, this pilot corridor features 18 DSRC locations, making it a crucial component of the Nevada Integrated Mobile Observations (NIMO) project. The testbed utilizes a variety of advanced communication and sensing technologies, including RSUs, CCTV cameras, radar, thermal/infrared sensors, LiDAR, and microwave sensors. This multimodal approach enables real-time monitoring and data collection, supporting the optimization of traffic flow and responses to dynamic road conditions such as construction, special events, and the presence of pedestrians and cyclists. The primary objective of the Washoe County DSRC testbed is to establish a sustainable platform for CV applications that is compliant with the National Transportation Communications for Intelligent Transportation System Protocol (NTCIP). This initiative aims to enhance rural ITS by leveraging a hybrid communication approach that integrates DSRC with other technologies to create a robust, real-time information network [52].

1.2.3 Highway Testbeds

36. California CV Testbed, Palo Alto

This testbed is located along Highway 82 (El Camino Real). The California CV Testbed in Palo Alto serves as a vital research and development site for CV technologies. This testbed features the deployment of DSRC units across 11 intersections. The testbed aims to evaluate the performance of a multi-modal Intelligent Transportation Systems (ITS) traffic signal system. The project has recently transitioned to using C-V2X technology across 16 intersections. Thus, the testbed demonstrates the Multi-Modal Intelligent Traffic Signal System (MMITSS). The key objectives include enhancing traffic signal control, providing signal priority for transit and freight, and promoting environmentally friendly driving practices. This testbed is operational and supports ongoing research into advanced traffic management solutions [53]. Figure 6. illustrates the California CV testbed, Palo Alto.

Figure 6. California CV Testbed, Palo Alto

37. I-85/"The Ray" CV Testbed, Georgia

The I-85/"The Ray" CV testbed spans 18 miles of Interstate 85 in Southern Georgia. This project deploys six RSUs along the highway to communicate with CVs. The equipped vehicles can send data such as speed, location, and operational information (e.g., windshield wiper use, hard braking) to a traffic management platform. The testbed aims to enhance highway safety and efficiency by using DSRC and C-V2X technologies to detect incidents immediately and warn drivers of potential hazards. This real-time data exchange can significantly reduce the risk of secondary crashes and improve traffic conditions by providing timely information to drivers and traffic managers [54].

38. Idaho CV Testbed (The Ada County Highway District)

The Ada County Highway District (ACHD) in Idaho has established a CV testbed to evaluate the effectiveness of communications infrastructure and control technologies. This testbed is located in Ada County and involves the deployment of 20 RSUs and 20 OBUs utilizing DSRC technology. The primary objective of this deployment is to validate the readiness of these communication systems for real-world applications, focusing on improving traffic management and enhancing road safety. The ACHD testbed represents a crucial step in Idaho's efforts to integrate advanced transportation technologies that can interact seamlessly with CVs [55]. The motivation for implementing the CV testbed in Ada County stems from a need to address the high incidence of traffic fatalities and the significant economic costs associated with motor vehicle crashes in Idaho. In 2018, Idaho experienced 231 fatalities due to traffic crashes, with a 10-year total of 2,131 fatalities. The annual economic cost of motor vehicle crashes in the state is estimated to be around $886 million, based on 2010 data [56, 57]. By deploying CV technologies, the Ada County Highway District aims to reduce the frequency and severity of traffic crashes.

The Ada County CV testbed supports a variety of projects and research initiatives focused on advancing the capabilities of CV technologies. One major project involves testing the reliability and performance of DSRC communication in different traffic scenarios, which is critical for ensuring the consistent and accurate exchange of information between vehicles and infrastructure. The potential of integrating DSRC with traffic signal control systems is assessed to optimize signal timings and reduce congestion and improve traffic flow. Additionally, the testbed is being used to evaluate applications for enhancing pedestrian safety, such as providing alerts to drivers when pedestrians are detected near crosswalks [57].

39. American Center for Mobility (Willow Run): The American Center for Mobility (ACM) at Willow Run, Ypsilanti Township, is a 500-acre testing facility dedicated to the development and testing of CAVs in Michigan. This testbed is equipped with RSUs, OBUs, and self-driving cars. The ACM offers a variety of testing environments, including urban, rural, and off-road scenarios. This facility plays a vital role in advancing mobility technologies by providing a controlled environment where automotive manufacturers, technology companies, and research institutions can test and refine their systems. The ACM is particularly focused on V2X communications, with a strong emphasis on DSRC technologies. Research conducted at this facility has been instrumental in advancing autonomous driving technologies and understanding the complexities of integrating CAVs into existing transportation networks [60].

40. I-75 Connected Work Zone (Oakland County): The I-75 Connected Work Zone project in Oakland County, Michigan, represents a collaboration between MDOT and 3M aimed at enhancing work zone safety through CV technologies. Spanning three miles, this project integrates advanced all-weather lane markings, retroreflective signs, and DSRC devices to improve V2I communication. The project also includes CCTV cameras, vehicle detectors, and Dynamic Message Signs (DMS) placed at every mile, alongside Environmental Sensor Stations to monitor weather conditions. These components work together to automatically detect crashes, notify motorists of travel times, traffic queues, and adverse conditions, and provide critical safety alerts such as curve speed and bridge deck warnings. Research on this testbed has focused on evaluating the effectiveness of these systems in real-time incident detection and response [61,62].

41. Macomb County Dept. Roads DSRC Deployment (MDOT/SMART Pilot)

The Macomb County Department of Roads, in collaboration with MDOT and SMART, has launched a comprehensive three-year DSRC deployment across the county. This project involves the installation of 750 RSUs at signalized intersections, along with Wi-Fi vehicle detectors, to enhance communication between vehicles and infrastructure. The primary objective of this project is to broadcast SPaT information to CVs, improving traffic flow and safety at intersections. The data collected from these RSUs are vital for ongoing research, particularly in understanding the impact of real-time SPaT information on reducing intersection-related crashes and optimizing traffic management. Studies conducted on this testbed have explored the potential for reducing delays and improving safety, especially in high-traffic urban areas. This project stands out due to its scale and the comprehensive nature of the data it generates, which has significant implications for future city-wide deployments of CV technology [63].

42. Michigan DOT Wayne County Project

The Michigan DOT Wayne County Project is located in Wayne County, Michigan, is a notable project focusing on CV technology. This project involves the deployment of 12 RSUs and 250 OBUs using DSRC technology. The primary objective of this project is to document lessons learned, assess the benefits, and evaluate potential business models for future CV deployments. By analyzing the operational data and outcomes from this project, Michigan DOT aims to refine its approach to CV technologies and explore sustainable models for broader implementation across the state. This project is an important step toward understanding the practical implications of DSRC-based systems and their potential to improve traffic safety and efficiency in urban environments [64].

43. US Army Tank Automotive Research, Development & Engineering Center (TARDEC) "Planet M Initiative"

The US Army's TARDEC "Planet M Initiative" is a pioneering project focusing on testing and developing CV technologies along a 21-mile of I-69 in St. Clair and Lapeer Counties, Michigan. This project is supported by the Michigan Department of Transportation (MDOT), which has installed roadside infrastructure to facilitate testing. The initiative primarily employs DSRC systems integrated with six RSUs to provide crucial safety warnings such as curve speed warnings, lane closure alerts, speed recommendations, and disabled vehicle warnings. This project is important for advancing military and civilian applications of CV technologies by leveraging real-world conditions to test and refine V2I communication systems. Research conducted on this platform has focused on evaluating the effectiveness of these warning systems in enhancing driver safety and operational efficiency [65].

44. Southeast Michigan Testbed

The Southeast Michigan testbed is a comprehensive CV test environment that integrates several existing infrastructure assets across the Ann Arbor area and the broader Southeast Michigan region. This project connects various RSU deployments along major corridors such as I-96 and I-696, enabling the testing and implementation of advanced CV applications. Key features include dynamic speed harmonization, incident scene work zone alerts, eco-friendly approaches and departures at signalized intersections, and motorist advisories. The testbed supports extensive research on the efficacy of these applications in real-world scenarios, with particular emphasis on improving safety and reducing environmental impacts. The Southeast Michigan testbed serves as an efficient platform for advancing CV technology, providing valuable insights into the operational benefits and challenges associated with large-scale deployments [66].

45. Ohio Turnpike & Infrastructure Commission DSRC Projects

The Ohio Turnpike & Infrastructure Commission is an efficient project involving the deployment of DSRC technology along a 50-mile section of the Ohio Turnpike. This project includes 15 RSUs and aims to evaluate the effectiveness of DSRC in enhancing communication between vehicles and infrastructure. The initiative is part of a broader effort to improve road safety and traffic management through CV technologies. Additionally, the project aims to provide real-time information to drivers, reduce traffic congestion, and enhance the overall efficiency of the turnpike [67].

46. NW US33 Smart Mobility Corridor

The NW US33 Smart Mobility Corridor is a CAV testbed located in Ohio. This project involves using DSRC technology along 35 miles of the US 33 corridor from the City of Dublin to the City of Marysville. With 800-1000 OBUs and 27 RSUs, this corridor is designed to enhance travel time reliability and accommodate increased traffic volumes. The project supports the development and testing of CAV technologies by optimizing travel lanes and decreasing crash risk. The corridor is operational, and it serves as a live test environment for various research initiatives focused on improving traffic management and traffic safety [68].

47. Wyoming CV Project Deployment

The Wyoming CV Project Deployment is aimed at enhancing transportation safety and efficiency along the Interstate 80 (I-80) corridor, a critical freight route spanning 402 miles between Wyoming Department of Transportation's Maintenance Districts 1 and 3. This project was conducted to address the needs of commercial vehicle operators who frequently navigate this stretch of highway. The main objectives of the project are to reduce the number and severity of adverse weather-related incidents and to mitigate incident-related delays, which are common challenges in this region. The testbed integrates advanced CV technologies with the state's Traffic Management Center (TMC) that enables real-time monitoring and management of traffic conditions on this corridor.

By focusing on the specific needs of commercial vehicle operators, who are particularly vulnerable to weather-related incidents, the project aims to enhance road safety and operational efficiency. The testbed is equipped with 75 RSUs and 450 OBUs that utilize DSRC technology. This extensive deployment enables the collection and dissemination of critical real-time information, such as weather alerts, road conditions, and traffic incidents, directly to drivers. By providing timely and accurate data, the testbed helps drivers make informed decisions. Numerous projects have been conducted within the Wyoming CV testbed to evaluate the effectiveness of CV technologies in reducing weather-related crashes and improving traffic management. One key project involves the use of DSRC-enabled devices to transmit real-time weather data, such as visibility and road surface conditions, to both commercial and passenger vehicles. This project aims to enhance driver awareness and enable proactive responses to changing weather conditions. Another significant initiative is the integration of CV data with the Wyoming Department of Transportation's Traffic Management Center (TMC). Figure 7. illustrates Wyoming's CV testbed [69].

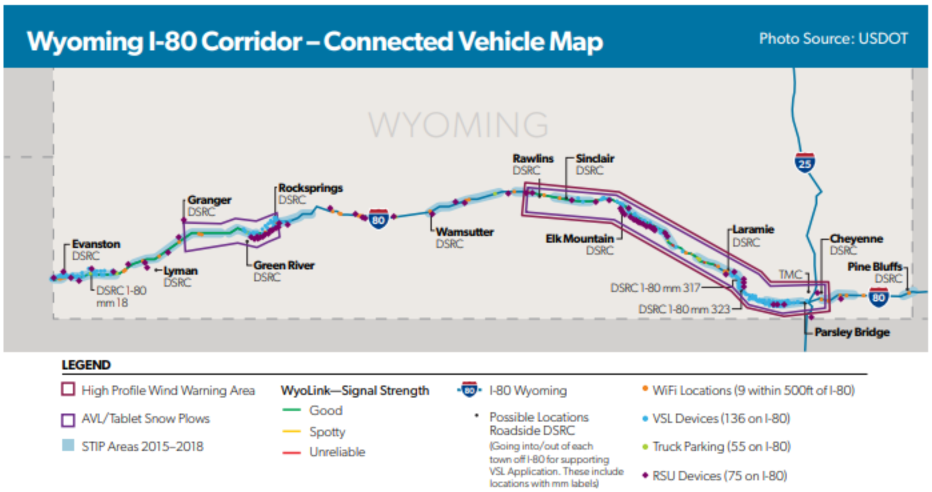

Figure 7. Wyoming Connected Vehicle Project Deployment Testbed [69]

1.2.4 Mixed Environments (Urban + Rural + Highway) Testbeds

48. Florida Smart Work Zones

The Smart Work Zones Project in Florida provided advanced CV infrastructure to enhance traffic safety and management across six major state road corridors, including US 1, Dixie Highway, Powerline Road, US 441, Hillsboro Boulevard, and Sample Road. The project deploys a combination of RSUs, CCTV cameras, and vehicle detectors, all equipped with DSRC technology to facilitate real-time data exchange V2I communication. This infrastructure enables the delivery of critical safety and operational information, such as real-time traffic conditions, queue warnings, and travel time estimates, to drivers in work zones. By using DSRC-enabled communication, the system aims to provide low-latency alerts for incidents like traffic slowdowns or stoppages. Hereupon, the system ensures enhanced situational awareness for drivers and reduces the risk of crashes due to sudden deceleration or erratic behavior in work zones. The project focuses on real-time decision-making tools, including Traffic Queue Warning, Travel Time Advisory, and Alternate Route Advisory, to mitigate congestion and improve traffic flow within work zones. These systems rely on V2I communication to alert drivers of potential delays and provide timely detour recommendations. Hence, the system reduces the likelihood of rear-end collisions and improving overall road safety [70].

49. Indiana CV testbed (Indiana DOT SPaT Deployment - Greenwood)

The Indiana Department of Transportation (INDOT) implemented a CV testbed known as the SPaT Deployment along US 31 in Greenwood, Indiana. This project will include the installation of SPaT capabilities at approximately six signalized intersections. The primary goal of this deployment is to enhance traffic management and safety by utilizing advanced communication technologies that enable real-time data exchange between traffic signals and CVs. This testbed forms part of Indiana's broader strategy to modernize its transportation infrastructure and prepare for the increasing integration of CAV technologies. The implementation of the SPaT Deployment in Greenwood is driven by the need to improve traffic efficiency and safety in one of the region's major corridors. US 31 serves as a vital transportation route that experiences significant traffic volumes, leading to congestion and delays, especially during peak hours. By deploying SPaT technology, INDOT aims to optimize signal timing and improve coordination across multiple intersections to reduce congestion and travel times.

Another project, the Indiana CV Corridor Deployment Project, is a significant initiative aimed at enhancing traffic safety and efficiency along Interstate 94 (I-94). This deployment is part of the national SPaT Challenge and involves the installation of 10 RSUs at key intersections along the corridor. These RSUs utilize DSRC technology to broadcast SPaT information to CVs [71].

50. Michigan Safety Pilot Model Deployment

The MI Safety Pilot Model Deployment, located at US 23 and Plymouth Road, Ann Arbor, and Washtenaw Avenue, Michigan, is a comprehensive CV testbed designed to assess the operational readiness of DSRC-based safety applications. This testbed integrates 2,700 OBUs, 29 RSUs, and 12 Traffic Signal Controllers (TSCs). This testbed enables extensive data exchange between vehicles and infrastructure as V2I communication. The primary objective of this testbed is to demonstrate the capabilities and effectiveness of DSRC technology in real-world environments, particularly in improving traffic safety and reducing crash risks through communication-based interventions. The project utilizes DSRC technology to facilitate a variety of safety applications, such as forward collision warnings, intersection movement assistance, and emergency vehicle alerts. These applications are designed to improve situational awareness and provide real-time alerts, helping drivers make informed decisions to avoid crashes [72].

51. Utah Salt Lake Valley Snowplow Preemption

In addition to the UTA project, the Salt Lake Valley Snowplow Preemption project, spanning five corridors and 55 intersections, also employs DSRC technology for traffic signal preemption, specifically designed for snowplow vehicles. This system allows snowplows to preemptively change signal phases to ensure that plows can clear critical routes efficiently, particularly during snowstorms. It is worth mentioning that the UTA DSRC Traffic Signal Pilot Project is designed to optimize traffic signal operations through V2I communication, with a primary goal of improving the efficiency and reliability of public transit. The system dynamically adjusts signal phases to prioritize buses, reducing delays and maintaining schedules. A key objective is to enhance the operational efficiency of transit systems in high-congestion areas, ensuring smoother traffic flow and reducing the environmental impact of idling buses. The project also tests the scalability and interoperability of DSRC-based systems, assessing the integration of multiple hardware vendors to ensure compatibility across different infrastructure and vehicle platforms [73].

52. Virginia Smart Roads CV Testbeds

The Virginia Smart Roads CV Testbed located on sections of major highways such as Interstate 66, Interstate 495, US 29, and US 50, the testbed encompasses a controlled-access environment that meets the Federal Highway Administration's standards. With 49 RSUs employing DSRC technology, this facility provides a robust infrastructure for real-time data exchange between vehicles and the surrounding environment. As urban areas continue to expand, the demand for more efficient and safer transportation systems becomes increasingly critical. The Virginia Department of Transportation (VDOT) established this testbed to serve as a proving ground for new technologies that can alleviate these issues. Figure 8. illustrates the location of CV testbeds.

Figure 8. Virginia CV Testbeds [69]

The Virginia Smart Roads Testbed has hosted numerous projects aimed at advancing CAV technologies. Key research initiatives have focused on testing V2I communication protocols that enable vehicles to interact with traffic signals, signage, and other roadside equipment. Studies have also been conducted to evaluate the effectiveness of DSRC technology in various traffic scenarios, including congestion management and incident response. Additionally, projects have explored the integration of CV data with advanced traffic management systems (ATMS) to optimize signal timings and enhance the coordination of traffic flow across multiple intersections [74].

1.2.5 Controlled Test Tracks

53. Michigan, American Center for Mobility (Willow Run)

The American Center for Mobility (ACM) at Willow Run, Ypsilanti Township, is a 500-acre testing facility dedicated to the development and testing of CAVs in Michigan. This testbed is equipped with RSUs, OBUs, and self-driving cars. The ACM offers a variety of testing environments, including urban, rural, and off-road scenarios. This facility plays a vital role in advancing mobility technologies by providing a controlled environment where automotive manufacturers, technology companies, and research institutions can test and refine their systems. The ACM is particularly focused on V2X communications, with a strong emphasis on DSRC technologies. Research conducted at this facility has been instrumental in advancing autonomous driving technologies and understanding the complexities of integrating CAVs into existing transportation networks [75].

54. Mcity Testbed

Mcity, located at the University of Michigan in Ann Arbor, is a 32-acre CAV testbed designed to simulate urban and suburban driving environments. The facility features a wide range of testing scenarios, including intersections, roundabouts, and pedestrian crossings, allowing for comprehensive testing of V2X technologies. Mcity is equipped with RSUs, OBUs, and edge computing infrastructure to support advanced research on transit signal priority, emergency vehicle preemption, dynamic signal optimization, and VRU notification. This testbed has been instrumental in advancing the development of autonomous driving technologies and understanding the interactions between CV and urban infrastructure. The research conducted at Mcity has had a profound impact on the automotive industry, helping to accelerate the deployment of safe and efficient CAV systems [76].

55. Minnesota Roadway Safety Institute Connected Vehicle Testbed

The Roadway Safety Institute (RSI) CV Testbed is a permanent facility located in Minnesota, specifically designed to advance the development and testing of CV technologies. Situated on a high-crash segment of Interstate 94 Westbound in Minneapolis, between Hiawatha and Portland Avenues, this testbed provides a real-world environment to evaluate the effectiveness of various CV applications. The RSI CV testbed was implemented to address pressing safety concerns on Minnesota's roadways, particularly on high-crash segments such as the designated portion of I-94. The primary purpose of this testbed is to serve as a research and development hub where cutting-edge CV technologies can be tested and refined. By simulating real-life traffic conditions, the testbed provides invaluable data and insights into how vehicles equipped with advanced communication systems interact with each other and with road infrastructure [77].

Several notable projects have been conducted at the RSI testbed. Research initiatives include testing V2I and V2V communication systems to improve traffic flow and reduce collision risks. Additionally, the RSI CV testbed in Minneapolis is equipped with one RSU, one OBU, and seven radars, utilizing DSRC technology. This setup is designed to implement and evaluate next-generation vehicle-based freeway safety applications. The integration of these components establishes an efficient sensor communication network and data collection system along the testbed's length. This infrastructure enables real-time communication between vehicles and roadside infrastructure, facilitating the exchange of critical safety information, such as collision warnings and traffic condition alerts [77].

1.3 Case Studies

1.3.1 Tampa Hillsborough Expressway Authority (THEA) Connected Vehicle Deployment, Florida

This section focuses on the "Tampa Hillsborough Expressway Authority (THEA) Connected Vehicle Deployment" as one of the key connected vehicles (CVs) testbeds in Florida. The Tampa Hillsborough Expressway Authority (THEA) is leading a CV project to improve traffic flow, safety, and environmental outcomes in downtown Tampa. This project includes installing 1,000 advanced rearview mirrors, 47 Roadside Units (RSUs), 10 Onboard Units (OBUs) for buses, and 8 OBUs for streetcars. The project focuses on reversible express lanes and major downtown arterial roads, where traffic is often heaviest during peak hours. By using CV technology, the project seeks to reduce congestion, cut down on crashes, shorten transit times, and lower greenhouse gas emissions. This project serves as a large-scale, real-world application of CV technology, where testing and data collection help reveal how CV systems can improve transportation efficiency, safety, and sustainability. Acting as a testbed, it provides researchers and transportation planners with a practical environment to assess how CV technology affects traffic flow, reduces conflicts and crashes, and impacts the environment within a realistic urban setting. This section focuses on the project’s details, the infrastructure used, and published reports and papers related to this testbed.

CV testbeds offer significant benefits for modern urban transportation, particularly with respect to safety and efficiency [78]. By creating an environment for testing CV technology in real-world conditions, testbeds help improve the flow of traffic and minimize delays [79]. In doing so, CV testbeds lead to smoother and more predictable vehicle movement. One key advantage of these testbeds is the ability to reduce collisions, especially in urban areas where pedestrians, cyclists, and other Vulnerable Road Users (VRUs) are at higher risk [80]. CV systems can also detect and communicate with nearby vehicles and infrastructure to prevent potential crashes. One way they do this is by issuing alerts or automated responses to protect VRUs. Through continuous data collection and analysis, CV testbeds allow transportation authorities to make data-driven improvements that lead to safer, more reliable urban transportation networks [81-84].

The Tampa Hillsborough Expressway Authority (THEA) CV Testbed is a notable project within the US Department of Transportation's Connected Vehicle Pilot Deployment Program [81]. This testbed is in Tampa, Florida. The initiative emphasizes the use of advanced vehicle-to-vehicle and vehicle-to-infrastructure communication systems to enhance driving conditions and reduce traffic-related crashes. The testbed is located within the CBD and on the Lee Roy Selmon Expressway. This location was chosen due to its diverse mix of commuters, pedestrians, and transit systems [85]. Therefore, this location provides an ideal environment to test CV technologies under varied traffic and weather conditions. The testbed covers approximately ten intersections within the CBD and a segment of the expressway, and it creates a controlled environment for real-time testing.

The infrastructure for THEA's CV testbed includes RSUs and OBUs equipped in vehicles to enable seamless V2V and V2I communication. CV technology relies on Dedicated Short-Range Communications (DSRC) to support data transfer between vehicles and infrastructure. The pilot deployment also integrates sensors to collect real-time traffic and environmental data. The testbed was comprehensive, including nearly 1,000 equipped vehicles in Tampa's Central Business District (CBD) along the Selmon Expressway [86].

The primary goals of THEA CV testbed are to: “reduce collision rates by providing real-time alerts for crashes such as sudden braking, speed adjustments, and pedestrian crossings;” “mitigate congestion by offering rerouting options and providing precise travel time predictions;” “reduce emissions through smoother traffic flow that leads to energy efficiency and lower carbon emissions;” and “collect comprehensive data to assess the operational effectiveness of CV technology that contribute to the refinement of future intelligent transportation systems” [87].

One of the primary safety goals of the THEA CV testbed is to reduce vehicle collisions by using advanced communication systems to provide real-time alerts to drivers. Imagine a driver receiving an alert on their dashboard just seconds before encountering a pedestrian crossing unexpectedly or being warned of a sudden traffic slowdown due to a stalled car just ahead. This immediate warning allows the driver to adjust their speed, brake, or switch lanes in time to avoid potential crashes. The THEA CV testbed also tackles common safety challenges in urban areas. For example, CVs equipped with sensors can “see” around corners or through other vehicles using shared data, which helps drivers anticipate pedestrians and cyclists who might otherwise be hidden from view [88].

In terms of “improving mobility”, the THEA CV testbed aims to ease traffic congestion by helping drivers navigate traffic more efficiently. Congestion, a persistent problem in urban areas, often results from limited visibility in traffic conditions and lack of real-time route guidance. In the CV-enabled environment, vehicles continuously communicate with nearby infrastructure and other vehicles as V2V communication. They also share information about current travel speeds, upcoming delays, or lane closures. This interconnected system allows the THEV testbed to offer drivers precise travel time predictions and suggest rerouting options. For instance, if a vehicle detects heavy traffic on the usual route, it can guide the driver to alternative routes to avoid delays. This predictive capability is especially beneficial for commuters who regularly travel the same route but would benefit from route guidance during high-traffic hours [87].

In terms of “environmental benefits”, one goal of THEA’s CV testbed is to improve environmental health by reducing traffic-related emissions. Congestion not only causes delays but also leads to higher emissions, as idling or slow-moving cars burn fuel. By improving traffic flow through real-time data sharing and route adjustments, the THEA CV testbed can help vehicles maintain more consistent speeds and reduce idle times. As drivers avoid high-traffic areas or take more efficient routes, they spend less time accelerating and braking, which are the most fuel-intensive driving behaviors when done in frequent succession. These changes lead to smoother traffic patterns that ultimately reduce fuel consumption and lower carbon dioxide emissions. The THEA CV testbed can also provide important environmental data to city planners, who can use it to design traffic management policies that prioritize energy efficiency and lower emissions [87].

Finally, in terms of “evaluating deployment impact”, the THEA CV testbed offers critical insights into the performance and practicality of CV technology in a busy, real-world environment. With comprehensive data from vehicle interactions, the testbed can assess the effectiveness of each application—be it V2V collision alerts, V2I rerouting information, or data on traffic flow patterns [88, 89]. By evaluating performance data from these applications, the testbed helps engineers and policymakers refine and expand the testbed. It can also identify how similar models might be deployed in other regions. Data from THEA testbed also helps address practical concerns, like the costs of maintaining a CV infrastructure, identifying the most effective types of alerts, and ensuring compatibility across different car manufacturers. In doing so, THEA's CV project doesn't just test technology, it builds a knowledge base that can support the future of intelligent transportation systems on a broader scale in the state of Florida and across the nation [90].

1.3.1.1 Submitted Reports, Journal/Conference Papers Regarding THEA CV testbed

The THEA CV Testbed in Tampa is one of several locations across the nation designed to allow public and private agencies to test CV technology in real-world settings [91]. These testbeds support V2V and V2I applications, and they concentrate on the exchange of critical safety and operational data between vehicles and infrastructure. Through these deployments, the THEA testbed aims to provide insights into how CV technology can enhance roadway safety, improve traffic flow, and reduce congestion in urban areas. Part of the US Department of Transportation's Intelligent Transportation Systems Joint Program Office (ITS JPO) Connected Vehicle Program, these testbeds bring together a network of partners and collaborators, including transportation authorities, research institutions, and technology providers [84]. By fostering these partnerships, testbeds like THEA's are driving advancements in CV technology and laying the groundwork for safer, smarter cities. In the published report entitled "Connected Vehicle Infrastructure: Deployment and Funding Overview" by Texas A&M Transportation Institute on January 2018 [86], the report offers insights into the infrastructure requirements, funding, and deployment strategies for CV testbeds like THEA's connected vehicle testbed, and the report focuses on the integration of RSUs and OBUs on the CV testbeds.

In another published report entitled "Connected Vehicle Pilot Deployment Program Independent Evaluation: Tampa" in May 2018 [87], the report tries to discuss about the pilot deployed a CV system in Tampa, Florida, and it concentrates on enhancing communication between vehicles, infrastructure, and pedestrians. Key achievements include the deployment of over 1,000 equipped vehicles and installation of RSUs to support real-time alerts. The program addressed common urban traffic challenges, such as congestion, crashes, and pedestrian safety, by leveraging Vehicle-to-Everything technology. THEA's CV Testbed pilot also involved collaboration with government agencies, academia, and private sector partners. In doing so, the THEA CV testbed has facilitated an exchange of technical expertise, resources, and innovative ideas. These partnerships enabled thorough testing and integration of V2X applications, such as red-light violation warnings and pedestrian safety notifications. The report underscores how these collaborations contributed to developing a scalable CV model, supporting research that shapes future transportation systems aimed at reducing crashes and improving city-wide traffic flow.

In the report entitled “Connected Vehicle Pilots Phase 2 Interoperability Test-Test Report” published on November 2018 [88], the authors highlight several advanced technological achievements within THEA's CV Testbed. Among these, the deployment of DSRC stands out for enabling seamless data exchange between vehicles and infrastructure. The testbed incorporated innovative V2X applications like Forward Collision Warning and Wrong-Way Entry notifications, which significantly improved situational awareness for drivers. Additionally, the integration of real-time signal phasing and timing (SPaT) allowed vehicles to receive precise signal change timings, which enhanced safety and traffic efficiency by reducing sudden stops and traffic delays.

The November 2018 report titled “Connected Vehicle Pilot Deployment Program Phase 2: System Architecture Document – Tampa (THEA)” [78] mainly focused on deploying the following V2I safety applications:

- End of Ramp Deceleration Warning (ERDW)
- Pedestrian in Signalized Crosswalk (PED-X)
- Pedestrian Collision Warning (PCW)
- Pedestrian Transit Movement Warning (PTMW)
- Wrong Way Entry (WWE)

Additionally, the THEA CV testbed achieved notable advancements in V2V and V2I safety and mobility applications. For V2V, vehicles share data via safety applications to prevent unseen hazards through essential functions like Emergency Electronic Brake Lights, Forward Collision Warnings, Intersection Movement Assistance, and alerts for vehicles turning in front of transit. These applications support drivers by providing critical, real-time alerts when both vehicles are equipped with V2V technology. On the V2I front, the testbed emphasizes applications that improve traffic flow and decision-making for travelers. Intelligent Traffic Signal Systems (I-SIG) help optimize signal timing, while Transit Signal Priority (TSP) benefits transit efficiency. Additionally, Mobile Accessible Pedestrian Signals (PED-

SIG) enhance pedestrian safety by enabling signal adjustments for better accessibility. Through these mobility applications, the testbed fosters safety, reduces environmental impact, and encourages informed travel decisions. The key V2V and V2I technologies provided in the published report are listed below [78-91]:

V2V Safety Applications:

- Emergency Electronic Brake Lights (EEBL): Alerts drivers when a vehicle ahead brakes suddenly.
- Forward Collision Warning (FCW): Warns of potential front-end collisions.
- Intersection Movement Assist (IMA): Prevents collisions at intersections.
- Vehicle Turning Right in Front of Transit Vehicle (VTRFTV): Notifies transit vehicles of turning cars.

V2I Mobility Applications:

- Intelligent Traffic Signal System (I-SIG): Optimizes traffic signal timing.
- Transit Signal Priority (TSP): Enhances traffic flow for public transit.
- Mobile Accessible Pedestrian Signal (PED-SIG): Provides safer pedestrian crossing signals

Report [90] also discusses the architectural design of the THEA CV testbed, which incorporates several key components to ensure seamless integration and functionality. Central to this design are the OBUs, which include a Human Machine Interface (HMI) and utilize GPS and DSRC antennas. The system supports 1,500 OBUs, with an additional 84 using SiriusXM technology for enhanced satellite data distribution. The OBUs, which are integrated into vehicles through rearview mirrors or mounted displays, provide crucial safety messages and alerts to drivers. Furthermore, the roadside infrastructure is designed to optimize communication between vehicles and the environment. Forty-one (41) RSUs were deployed, equipped with DSRC antennas to facilitate V2I communications and collect vital data for performance measurement. These RSUs connect to a Master Server, which archives and sanitizes data for further analysis. The system also includes pedestrian applications that allow qualified users to engage through their smartphones via Wi-Fi, and they enhance overall mobility and safety within the CV pilot program. In other words, qualified users are able to interact with the connected vehicle system using their smartphones. This could mean that qualified users (like pedestrians) can access certain features or receive safety alerts and mobility updates through a mobile application or interface on their devices.

In the May 2018 published report titled "Connected Vehicle Pilot Deployment Program Phase 2: Comprehensive Installation Plan – Tampa (THEA)" [78], the authors explored the installation of CV devices in the THEA testbed, which involved a comprehensive process guided by detailed specifications and collaborative vendor outreach. The project initiated with the publication of the RSU Requirements Specification version 4.0, which included enhancements based on prior testbed experiences. Specific requirements for the THEA installation included Wi-Fi capabilities for pedestrian safety, cellular backhaul for data collection, and advanced processing features in RSUs to run multiple applications effectively. Collaborations with suppliers like Cohda Wireless facilitated the integration and testing of RSUs aligned with these specifications. Furthermore, the project implemented a robust procurement process to source various detection technologies, including radar, LiDAR, and video systems for vehicle and pedestrian detection. This comprehensive approach ensured that all equipment met stringent performance requirements. The installation also included inventory management practices using Siemens SAP software to track materials and manage logistics.

The installation process begins with a comprehensive site survey, where technicians assess intersection geometry, existing electrical systems, and optimal RSU locations. They ensured the proper documentation of controller types, communication media, and any potential issues with existing conduits. This meticulous approach ensures technicians the accurate creation of engineering drawings and adherence to project schedules for installation and acceptance tests in the THEA CV testbed. Once participant vehicles arrive, technicians perform inspections to verify vehicle specifications and additional features. Technicians then conduct functionality tests and provide training to participants on the new system's safety features and operational protocols to ensure they understand the CV technology before joining the pilot program.

In the February 2017 report [89] titled "Connected Vehicle Pilot Deployment Program Phase II: Data Privacy Plan – Tampa (THEA)", the Data Privacy Plan (DPP) for the THEA CV Pilot outlines essential policies for safeguarding participants' Personally Identifiable Information (PII). This document emphasizes the requirement for informed consent from data owners, detailing their rights, the purpose of data collection, and protections against unauthorized disclosures. It also establishes that Hillsborough Area Regional Transit Authority (HART), as the owner of transit vehicles, is responsible for obtaining consent, with a focus on ensuring that no PII from HART drivers is collected during the pilot. Key security measures are derived, focusing specifically on privacy protections rather than overall security. The DPP introduces strict handling guidelines for Sensitive PII (SPII) and mandates a scrubbing process to filter non-sensitive data before sharing. The report also highlights the importance of adhering to the CIA triad—Confidentiality, Integrity, and Availability—that ensures data is securely managed and access is tightly controlled throughout the THEA CV testbed. It is worth mentioning that the THEA CV testbed collects various categories of Personally Identifiable Information (PII) and Sensitive Personally Identifiable Information (SPII) from participants. This data encompasses individual identifiers, socio-demographic details, vehicle identifiers, contact information, and eligibility data for driver participants. Additionally, the THEA CV testbed collects vehicle sensor data and dynamic information regarding vehicle interactions. Certain data categories are specifically aimed at validating the statistical sample rather than directly measuring performance. To protect participant privacy, collected data will be anonymized and used only for combined socio-demographic reporting. Participants are informed about the types of data collected and the purposes behind it, to ensure transparency and compliance with regulatory standards.

Additionally, the THEA CV testbed employs a comprehensive security framework that classifies controls into three types: preventive, detective, and corrective. Preventive controls aim to inhibit harmful events, detective controls discover such events, and corrective controls restore systems post-incident. The security plan is tailored based on factors such as risk tolerance, data value, potential damage, and cost-effectiveness. Additionally, controls can be implemented with three approaches, including administrative (policies and training), logical or technical (encryption and access controls), and physical measures (guards and locks). This multi-faceted approach ensures robust protection of participant data throughout the Pilot.

In another derived published report, titled "Connected Vehicle Pilot Deployment Program Phase 3, System Requirements Specification (SyRS) – Tampa (THEA)" [90], the authors explore how the THEA CV testbed utilizes advanced technology to improve transportation safety by enabling communication between vehicles and infrastructure. This system comprises OBUs installed in vehicles, which send and receive data related to traffic conditions, while RSUs facilitate this communication. The implementation process highlights challenges, such as smartphone GPS limitations and connectivity issues in urban settings, which have implications for effective data transmission and user experience. In terms of system functionality, the THEA CV testbed operates in distinct modes to ensure operational reliability. The

Normal mode indicates all systems are functioning correctly, while the Degradation mode signifies partial operational failures affecting specific applications. Error mode indicates a total failure, preventing communication between devices. The THEA CV testbed also aims to deploy communication devices without extensive construction, utilizing RSUs installed in signal cabinets and along roadways and OBUs in vehicles and public transport. The design emphasizes unobtrusive installations and minimal visibility that ensures user safety and compliance with durability standards set by certification bodies like OmniAir. Environmental factors in Tampa, such as extreme weather and flooding, are considered in the deployment strategy, with specific measures for lightning protection and device durability. The system is designed to adapt and expand geographically while maintaining performance through established DSRC standards with an emphasis on reliability and lifespan comparable to existing traffic control devices.

In the latest published report from July 2022 [91] titled "Connected Vehicle Pilot Deployment Program Independent Evaluation, Financial & Institutional Assessment—Tampa (THEA)", the authors evaluate the financial and institutional aspects of the Tampa Connected Vehicle Pilot Deployment (CVPD). The financial evaluation examines changes in financial structures to determine the site's sustainability, focusing on key influencing factors and metrics. Concurrently, the institutional evaluation addresses organizational changes stemming from the CVPD, assessing governance, public and private partnerships, and legislative impacts to identify strategies for minimizing institutional risks. Ultimately, the evaluation aims to measure the effectiveness of Tampa's CVPD in managing these challenges. This report investigates the financial evaluation of the Tampa CVPD to ascertain its financial sustainability, focusing on whether the project could maintain operations for over seven years without additional federal funding. The evaluation framework included assessing various financial factors, determining the site's current financial conditions, and projecting future sustainability based on business inputs. Additionally, this report highlighted the importance of collaboration with technology vendors and addressing unexpected costs arising during deployment. Despite initial willingness to invest in CV technologies, subsequent surveys showed a decline in users' willingness to pay for retrofitting their vehicles. Initially, many respondents expressed a willingness to pay less than $500; however, later surveys indicated a significant portion of participants would not pay anything for the retrofit. This trend illustrates the challenge of sustaining financial support for the deployment beyond the pilot phase, as maintaining and expanding the CV technologies will require demonstrating tangible benefits to users.

In the published journal paper entitled “Lessons Learned from the Real-World Deployment of a Connected Vehicle Testbed” by Chowdhury et al. [5], the THEA CV testbed has been investigated in terms of the locations of the testbed and the CV technologies used in the testbed. The Tampa CVPD focuses on enhancing traffic flow and safety by utilizing CV technologies to reduce congestion and prevent wrong-way entries at the Selmon Reversible Express Lanes exit. It also aims to improve pedestrian safety and bus operation efficiency. This deployment includes 1,600 vehicles, ten buses, ten trolleys, 500 pedestrians using smartphone applications, and 40 RSUs, all interconnected via DSRC in Tampa, Florida.

1.3.1.2 Advanced Infrastructure for Connected Mobility Technologies at THEA CV testbed

The THEA CV testbed integrated several key strategies, including "rush hour collision avoidance," "wrong-way entry prevention," "traffic management strategies," "traffic flow optimization strategies," "streetcar safety," "pedestrian safety," and "bus priority." These components were designed to enhance movement, improve safety, and reduce emissions in the Central Business District (CBD) of Tampa [90]. The THEA CV testbed enhanced traffic efficiency and safety within downtown Tampa. This initiative includes the deployment of 1,000 enhanced rearview mirrors, which facilitate V2V communication and enable drivers to receive real-time alerts about nearby vehicles’ actions. In addition to the rearview mirrors, 47 RSUs have been strategically installed along major corridors and reversible express lanes. These RSUs serve as communication hubs that relay critical data between vehicles and the surrounding infrastructure, such as traffic signals and transit systems. The integration of ten bus OBUs and eight streetcar OBUs allowed for V2I interactions, which enhance transit signal priority (TSP) and optimize traffic flow for public transportation [92]. This interconnected system aims to minimize transit delays and enhance the overall efficiency of bus and streetcar operations. The combination of these CV technologies not only aims to reduce congestion but also targets improved environmental outcomes by lowering greenhouse gas emissions.

The THEA CV testbed has achieved notable milestones in enhancing urban mobility and safety through its advanced CV technologies. One of its primary contributions is the integration of various V2X communication systems that significantly improve real-time traffic management. By deploying intelligent traffic signals and facilitating communication between vehicles and transit systems, the project has reduced transit delays and led to shorter travel times for buses and streetcars while maintaining efficient traffic flow for personal vehicles. Additionally, the THEA CV testbed focused on data-driven decision-making that has empowered city planners and transportation officials to analyze traffic patterns more effectively. The comprehensive framework established by THEA not only paves the way for future smart city initiatives but also serves as a valuable model for other cities aiming to adopt similar CV technologies to improve transportation systems. Figure 9. illustrates the THEA CV testbed framework [79].

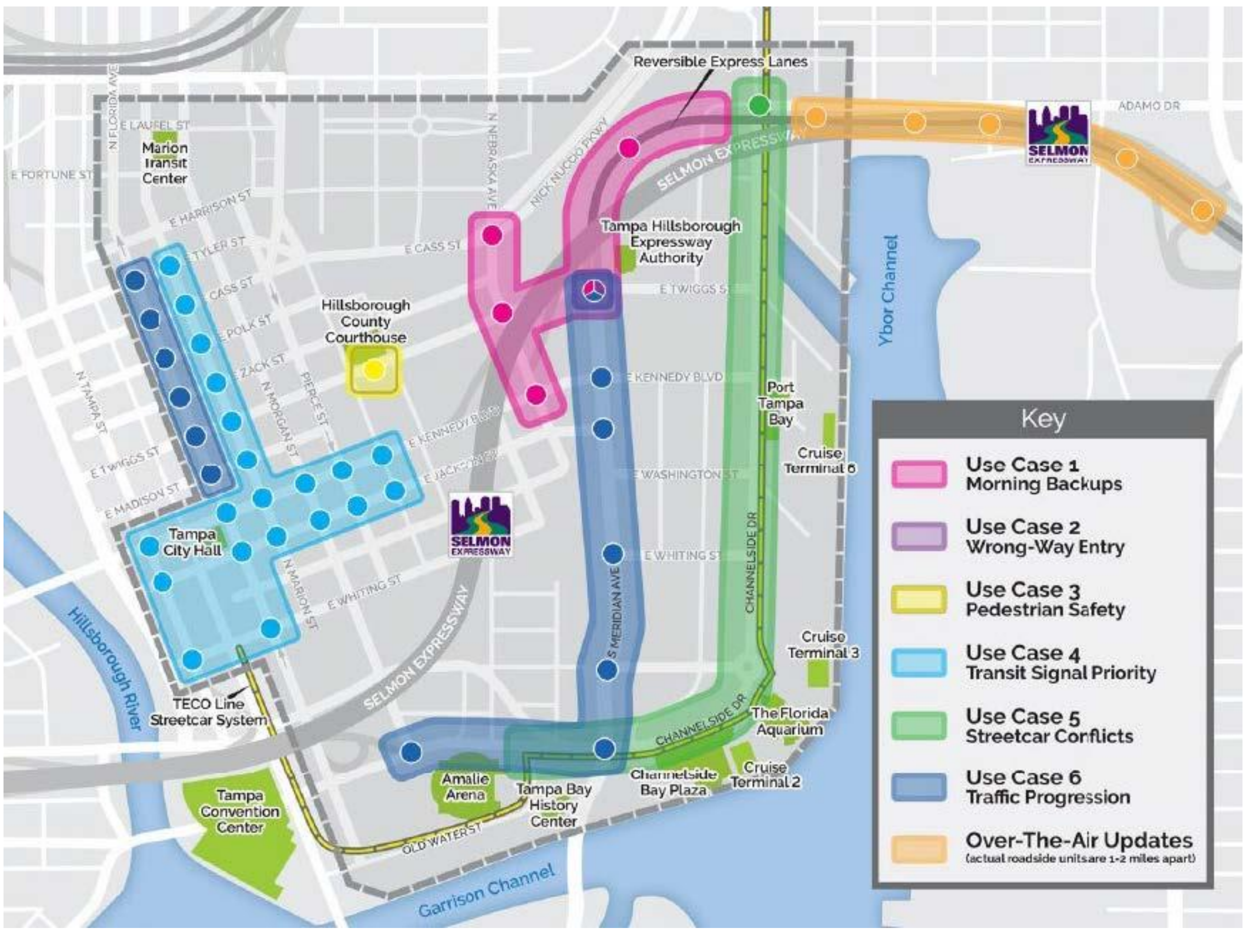

Figure 9. Mapping the Deployment Area and Use Cases of the THEA CV Pilot Project

The THEA CV Pilot Project exemplifies the power of collaboration among diverse stakeholders, combining the resources and expertise of state and local agencies with the private sector. THEA forged partnerships with organizations such as the City of Tampa, Hillsborough Area Regional Transit Authority

(HART), and the University of South Florida's Center for Urban Transportation Research (CUTR), along with various hardware and software providers. The installation of wireless modems at signalized intersections, coupled with the pre-existing fiber network, formed a robust backhaul system that supported the over-the-air updates necessary for maintaining the technology efficiently in the THEA CV testbed. In addition to forming new partnerships, THEA actively engaged the community and involved local students in the project. Through a partnership with Hillsborough Community College, students from the Master Mechanic Program installed onboard CV equipment in over 1,000 participant vehicles, enhancing their educational journey while contributing to the project's success. This innovative approach not only facilitated significant savings but also fostered community engagement. The project's performance evaluation, led by CUTR, focused on metrics reflecting safety, mobility, environmental impact, and agency efficiency, emphasizing general improvements rather than arbitrary targets.

THEA aims to attract collaboration from agencies and vendors seeking to develop and refine CV technologies. As part of the project's evolution, THEA plans to integrate onboard technology from various automobile manufacturers. THEA has also sought to maintain and enhance the capabilities of the system through extended cooperative agreement. This phase involves partnerships with major Original Equipment Manufacturers (OEMs), including Hyundai, Honda, and Toyota, focusing on spectrum testing to ensure uninterrupted communication among CVs. The collaboration enables OEM vehicles to interact with existing participants in the CV Pilot, showcasing the seamless integration of new technologies into the established network.

1.3.1.3 Future Studies in THEA CV testbed

The THEA CV testbed represents a significant step forward in advancing urban mobility and safety through innovative technologies. As the project evolves, several key areas of future study will be prioritized to maximize the potential benefits of CV systems. One of the foremost objectives is to enhance V2X communication, which allows vehicles to share information with each other as well as with traffic infrastructure, VRUs, and transit services. Future research will focus on optimizing these communication channels to ensure that data is transmitted seamlessly and in real time. This integration of V2X technology is expected to reduce traffic conflicts and crashes, improve navigation, and create a more coordinated transportation ecosystem that is responsive to the dynamic needs of urban environments. In conjunction with V2X enhancements, the THEA CV testbed will also explore the impact of CV technology on public transportation systems. By integrating CV applications into buses and streetcars, the THEA testbed aims to improve operational efficiency and passenger experience. Future studies will evaluate how CV-enabled vehicles can communicate with traffic signals to receive priority at intersections. In doing so, the project will attempt to minimize delays for public transit and encourage greater ridership. The potential for real-time updates on transit schedules and vehicle locations will enhance the user experience, making public transport a more attractive option for commuters in the Tampa area.

Safety improvements will remain a central focus of the THEA CV testbed as it progresses. The central focus of the THEA CV testbed is to improve the effectiveness of CV alerts in preventing crashes, particularly in high-risk areas such as intersections and pedestrian zones. Future studies will analyze the data generated from the THEA CV testbed to identify patterns in traffic crashes. Moreover, the THEA CV testbed will serve as a valuable research platform for evaluating the long-term implications of CV technology on urban infrastructure. Future studies will focus on the scalability of CV applications, examining how these systems can be integrated into existing transportation frameworks and how they can adapt to future technological advancements. Lastly, stakeholder engagement will be a critical component of future studies within the THEA CV testbed. Collaboration with local communities, government agencies, and private sector partners will ensure that the key contributions and achievements of the THEA CV testbed are relevant and aligned with the needs of the public. The involvement of residents in pilot programs and feedback mechanisms will be essential for assessing the effectiveness and acceptance of the THEA CV testbed. By prioritizing community engagement, THEA aims to foster an inclusive approach to the development of smart transportation systems that benefit all users.

1.3.2 Mcity Testbed, University of Michigan, Ann Arbor, Michigan

Mcity is in Ann Arbor, Michigan, and was intended to replicate real-life driving experiences, making it one of the world's most complete CV and AV test centers. With an area of 32 acres, Mcity incorporates several less and more developed infrastructure elements typical of city and suburb areas, such as roads and road intersections, traffic lights, road crossings, and various other types of roads. This simulated setting permits the evaluation of Vehicle-to-Vehicle, Vehicle-to-Infrastructure, and Vehicle-to-Pedestrian interaction under realistic but controlled settings, which contributes to the enhancement of safe and robust CV systems. Environments like Mcity by the University of Michigan are important sites where these high-tech systems can be effectively tested, assessed, and improved without deployment [92]. These environments are vital in creating communication protocols, meeting safety requirements, and constructing intelligent infrastructure for autonomous and connected vehicles. The center allows us to explore in detail the possibilities of V2X communication, including V2V, V2I, and V2P, which are required for self-adjusting. At Mcity, the researchers also focus on guaranteeing the proper operation of these systems under a multitude of circumstances, such as heavy traffic, severe climatic conditions, and possible cyber-attacks .

This section details the assessment of Mcity's infrastructure, core technologies, and research activities to illustrate how the testbed accommodates the progress of CVs and AVs. In showing this, the study highlights Mcity's endeavors regarding the safety, efficiency, and sustainability of the connected vehicle systems by examining the testbed's equipment, sensor technologies, and data management practices. The following sections will describe Mcity's achievements as a developer of traffic management systems, safety analysis, and the use of real-time data applications, thus presenting the center as a trendsetter in research on intelligent transport systems.[92-94].

The section will then explain the building structure, sensor technology, and data collection methods available at Mcity. Mcity's role in CV and AV provision will be demonstrated by using safety and conflict analysis methods developed for use at signalized intersections through innovations in real-time traffic management, ending with major research publications produced by Mcity. In addition, future research directions of Mcity's vision in advancing connected mobility will be described.

Mcity is situated on the 32-acre portion of the North Campus of the University of Michigan. It was designed explicitly to advance the testing of connected and autonomous vehicle technologies. To replicate actual cities, Mcity is a controlled test environment where CAV research can be performed before and outside the early stages of the technology deployment on real roads [93-94]. Figure 10 Shows the layout for the facility.

Mcity has roads totaling over 16 acres, which mimic the essential parts of a city. This simulation environment has been thoughtfully designed with straight roads, curvy roads, intersections, traffic lights, roundabouts, road signs, and many road surfaces. The diversity in infrastructure provides a real-world context for testing the V2X communications imperative for CAV systems, encompassing V2V , V2I, and V2P scenarios [95].

Figure 10: Layout for the Mcity Facility [93]

The placement and features allow Mcity to examine and solve issues related to real-world intelligent transportation systems, as vehicles and infrastructure would react in a particular manner within a controlled and flexible environment. This set of factors provides ample opportunities for testing the vehicle response AV system under different traffic conditions, from everyday commuting to the more intricate but dangerous intersections and pedestrian crossings. [96]. Figure 11 Is a photograph of the Mcity facility.

Figure 11. Photograph of Mcity [96]

<u>Physical Infrastructure and Road Configurations -</u> Mcity includes substantial CAV testing facilities in terms of physical infrastructure, such as:

- Mixed Road Design and Layout: Mcity replicates assorted road designs and combinations of straight, curved, and Léonard junctions, circles, and Gyratory to assist performance and behavioral analysis of vehicles' control systems under diversified driving conditions. A 1,000-foot stretch inside the Mcity mini-dome is also included to facilitate fast vehicular testing, urban blocks for testing V2I applications, and roundabouts in other urban case scenarios.
- Traffic Signals and Smart Intersections: The new intelligent signal controllers at Mcity's intersections allow the evaluation of complex AV and Traffic Management Center algorithms. Such controllers can transmit messages like SPaT, MAP, and TIM.

- Testing Obstacles and Urban Elements: To make testing scenarios realistic and challenging, Mcity integrates a range of simulated urban features such as facades, pedestrian crossings, and tree covers. This adds visual and spatial complexity and provides AV systems with the necessary capabilities to handle blockages that these systems are likely to encounter within natural urban environments. Other features, such as garages and houses with ramps, are added to test first-mile/last-mile related efforts within the context of urban logistics and ride-hailing research.

Data Capture and Control Operations - Data capture and control are integral to the structure of Mcity, thus making it possible to observe the traffic and how the AVs respond to interactions with a lot of precision. Some of the critical systems are:

- Improvements to Data Collection Devices: A sophisticated control network for data collection and handling in the Mcity, onsite wireless systems, fiber optics, Ethernet, and real-time kinematic statistical systems are integrated. This makes it easy to document and analyze how people and vehicles move and interact, which enhances safety and performance assessments. The facility has various measurement devices that help track the car's movement, speed, and actions of other road users, making it easier for the researcher to understand how AV functions in different environments.
- Augmented Reality (AR) Testing Platform: Mcity is one of the few institutions that utilize a patent-pending augmented reality system that enables augmented reality to overlay authentic images on virtual ones, allowing real-world vehicles to superimpose over digital cars. This capability leads to intricate hybrid testing modes whereby actual vehicles and virtual ones can both be present on the testing site, thereby drastically minimizing the amount of unnecessary physical resources to be deployed while exponentially increasing the amount and diversity of possible tests. The AR platform is essential for safely conducting test cases with above-average risk factors since researchers can virtually recreate difficult situations without subjecting real-life test objects to the risk.
- Mcity Operating System (Mcity OS): Mcity OS supports the facility's administration and manages the infrastructure, including the testing conditions. With the support of the Mcity OS, a researcher can modify vehicle settings and test parameters. This system ensures that every

element within the facility is accounted for and operates toward facilitating the test, enhancing the chances of successful instantiation of the critical tests necessary to test AV and CAV models. Mcity OS, by enabling quick data gathering and control, allows nuanced analysis on every test performed in Mcity and gives researchers a relatively wide range of scenarios to test by modifying the real-time plans of the simulations.

Communication Technologies: V2X and 5G Connectivity - Mcity offers a communication network that stands out as an essential part of V2X communications, which are pivotal for CAV systems. These communications include.

- 5G and Dedicated Short-Range Communication (DSRC): Mcity's fully connected 5G network, together with DSRC, makes it possible for V2X communication to occur in a high-speed and low-latency environment. This type of interaction facilitates the exchange of information among vehicles, people, and their surroundings in situations where immediate action is necessary, like pedestrian notifications, vehicle strike averting, and even the prioritizing of emergency cars. With 5G and DSRC availability at Mcity, several V2X applications can be studied in different traffic conditions and allow for the determination of optimal technology for environments.
- Integration with Vehicle-to-Infrastructure Systems: Mcity V2I functionalities are equally valuable for testing vehicle interactions with traffic signals and other infrastructure assets, making tests of applications such as dynamic signal control, emergency vehicle preemption, and green wave systems possible. These functionalities are vital in enhancing cooperative automation and forming more intelligent and responsive transportation networks.

Collaborative Ecosystem: Partnerships with AACVTE and ACM - Mcity collaborates with its partners, the Ann Arbor Connected Vehicle Test Environment (AACVTE) and the American Center for Mobility (ACM), to be part of a more extensive network of mobility testing environments within Michigan. Through these partnerships, Mcity enhances its capacity to engage in CAV research by utilizing shared resources, extending the scope of resources in the CAV research, and promoting facility integration.

- Ann Arbor Connected Vehicle Test Environment (AACVTE): The environment in Colorado comprises more than 2500 vehicles. The documents on Mcity indicated that the Colorado environment has more than 2500 vehicles, enabling applications such as V2V communication applications, including forward collision warnings and intersection movement assist devices. This large integrated environment offers a significantly designed research opportunity for collecting vehicle interactions with a comprehensive database on Certificate Authorities and interaction mechanisms for regular safety environments and architecture. The latter systems include intersection ensure and mid-block crosswalks. The ICUs manage these systems and have the capabilities and infrastructure to integrate and broadcast real-time signal phase and timing messages to the vehicles and other services in that region. Also, these capabilities enable them to gather and transmit traffic and safety data to the University of Michigan Transportation Research Institute (UMTRI) in real-time.

Live data uploaded on AACVTE acts as input and enrichment for the research activities at Mcity. For example, as Mcity researchers have access to real-time data of vehicle-to-vehicle and vehicle-to-infrastructure interactions, they can contextualize the usage of connected vehicles in virtual and real-world settings. This integration enhances research on red-light violation warnings, curve speed warnings, and pedestrian detection, enabling better continuity between testing within Mcity and real-life situations in Ann Arbor.

- American Center for Mobility (ACM): Located in Ypsilanti, Michigan, ACM covers an area of 500 acres, a test site designed to enable extensive testing on connected and autonomous vehicle technologies. Whereas Mcity emphasizes an urban city environment, ACM has a highway loop, curved tunnels, and other areas for high speed, providing a variety of more complex road conditions and enabling tests with a wider geographical area and higher speeds. The cooperation between Mcity and ACM is beneficial as it creates a broader testing environment, allowing scientists to study cars in a city setting and a highway environment. In cooperation with ACM, Mcity gets data that enables an understanding of various driving conditions and times, which helps develop robust CAV technologies that would be perfect under different conditions.
- Control Networks and Data Collection Systems: The control network uses wireless technology, fiber optics, and Ethernet to acquire exact and high-resolution information useful at Mcity. The control network comprises all three components. The data collection systems are outfitted with

systems that can register the location, speed, and even trajectories of all the vehicles and pedestrians at the test site. The combination of a real-time kinematic (RTK) positioning system, which produces data of almost or exact latitude and longitude, is of great importance in assessing vehicular activities.

- Unified and Encrypted Communication Protocol: In the case of CAV solutions, Mcity respects US and international norms to guarantee efficient and secure communication. Communication protocols comply with the requirements of SAE J2735, SAE J2945, and IEEE 1609, which specify the structure of messages, their security elements, and the ability to communicate with other systems. This enables uniform protocols that facilitate data interchange, confirms that Mcity's experimentations are in sync with international standards for CAVs, and strengthens its position as an exemplar for other test centers.
- Systems to Monitor and Visualize Data in Real-Time: The Institute employs sophisticated data visualization tools that render the monitoring of live test scenarios possible. With real-time surveillance, the researchers can see how the vehicle behaves in real-time and as specific actions happen, allowing for quicker changes and a more detailed look at certain events. So, this system enables Mcity to make rapid decisions and perform minute evaluations, particularly in time-critical situations.

<u>Mcity's Role Towards Safety and Efficiency Testing</u> - At Mcity, the available infrastructure and technology allow for large-scale safety and efficiency testing that provide solutions to fundamental problems in CAV technology:

- Collision Avoidance and Prevention of Injuries of Pedestrians and Vulnerable Road Users (VRUs): Mcity's V2X communication and intelligent traffic intersection technology provide a platform for thoroughly testing collision avoidance systems. For instance, AVs and VRUs can react and adapt to situations such as the simulation of safety scenarios involving red-light violation warning systems or controls. The automated pedestrian crosswalk systems and pedestrian detection system that works in tandem with intelligent cameras and RSUs assembled at the intersections safeguards the AV responding mechanism to the potential risk of pedestrians rushing towards the crossing, providing VRUs protection under such scenarios.

- Dynamic Traffic Management (DTM): Another objective of Mcity is to design intelligent traffic systems that would manage the flow and bottling of the traffic. Through the optimization of the signal dynamically, the shift of Phase, and the transmission information in real-time, Mcity has been testing the following measures: green wave advisory measures, preemption measures for emergencies, and other measures related to public transportation priority.

- Wireless Communication Technologies in Connected Vehicle Systems: Connected Vehicle systems depend on various wireless technologies that are grouped to facilitate real-time information sharing between vehicles, infrastructures, and other road users. Such connectivity allows for improved safety, traffic efficiency, and a cleaner environment through advanced applications like collision avoidance, traffic management systems, and alert systems for pedestrians crossing the roads.

  Figure 12. Illustrates a schematic view of a robust connected vehicle environment in which vehicles and torsions between transits and infrastructure are established with V2X communication technologies. This arrangement allows the exchange of information and enhances movement within the urban structure of roads in a safer way.

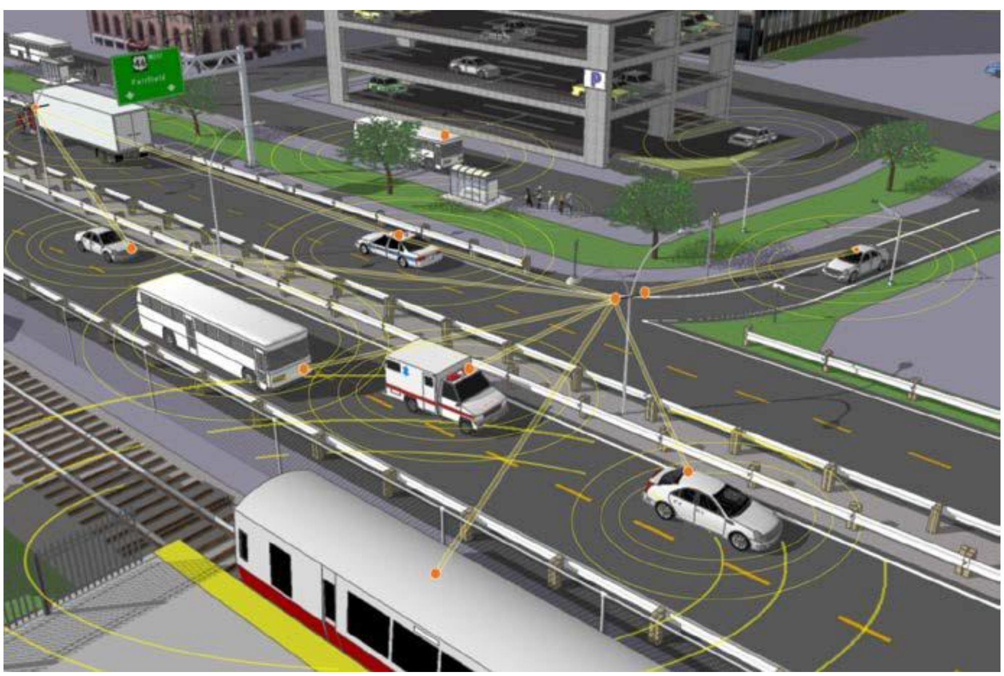

Figure 12. CV Environment

CV Data Collection Devices

- The CV-CID (Connected Vehicle-Centric Interface Device), The CV-CID device (as seen in Figure 13.) incorporates multiple connectors and wiring into its design to seamlessly interface with different components of the CV system for the acquisition of speed and location as well as communication information from different sensors and vehicle modules.

Figure 13: The CV-CID

- Econolite CoProcessor: Such a module helps in the collection, subsequent processing, and transmission of the data captured to urban households, which improves the interactions between vehicles and infrastructural elements. It assists in traffic simulation that requires understanding detailed event timing, such as traffic signals and vehicle interactions at intersections. These are essential in formulating control strategies to enhance traffic and safety management.

Figure 14: Econolite CoProcessor

These devices are interrelated to the primary CV data collection and management scheme since this enables the researchers at Mcity to extract appropriate, accurate, and rich information for testing, evaluating, and fine-tuning the CV technologies in place.

To sum up, Mcity's testing campus integrates modern, sophisticated physical infrastructure and complex digital systems, providing a conducive environment for CV R&D. With the collaboration of AACVTE and ACM, Mcity can extend its reach beyond its test facilities and made significant contributions to the field of intelligent transport systems at both local and global levels.

1.3.2.1 The submitted Journal/Conference Papers Regarding the Mcity CV Testbed

The literature published on Mcity's testbeds highlights numerous advancements and key research initiatives that contribute to understanding intelligent transportation systems. One such initiative is a traffic simulation model developed to leverage SimEvents for studying Intelligent Transportation Systems (ITS) capabilities at Mcity, focusing on CAV traffic scenarios and control algorithms [98]. Expanding the testing landscape, Mcity OS was introduced as a cloud-based tool enabling repeatable and cost-effective automated vehicle testing [96]. Motion sickness prevention technologies were tested using preemption strategies at Mcity to enhance passenger comfort [97].

1.3.2.2. Future Studies in Mcity Testbed

Mcity, the most significant test location in the United States for connected and autonomous vehicles, is based at the University of Michigan. It also sustains progress that supports the most advanced research activities in mobility technologies. Recent changes have increased the available resources, giving even more room for study in the area.

<u>Remote Testing and Mcity 2.0</u> - In 2022, Mcity received a National Science Foundation grant of $5.1 million to develop "Mcity 2.0," an advanced test environment that mixes physical testing and virtual reality simulation. This modification enables researchers across the United States to use Mcity facilities remotely, making studies without physical attendance. This program seeks to provide advanced testing facilities to all interested stakeholders and, in the process, make mobility research more equitable. [117]. Figure 15. Shows the architecture of Mcity.

Figure 15. Mcity Architecture

<u>Collaborative Research Opportunities - </u>Because of Mcity's remote capabilities, collaborations which would have been impossible in the past can now be done. For instance, in November 2023, the path planning algorithms developed by researchers from Purdue University were tested remotely with Mcity's automated research vehicles. Such partnerships allow institutions that do not possess the

necessary testing infrastructure to evaluate their technologies in real-world settings, thus speeding up the evolution of CAV technologies. [97].

Equipped with advanced infrastructure, Mcity is now ready for many future studies, which also include Cybersecurity in CAVs: Exploring weaknesses in the connected vehicle protocol and identifying appropriate countermeasures to mitigate such risks. Traffic Flow Optimization: Investigating the potential of collaborative autonomy and connected vehicle technologies for emissions reduction and traffic efficiency improvement [119]. Infrastructure Readiness: Evaluating existing infrastructure's capability to cater for mass deployment of CAVs and the enhancement requirements. Policy and Standards Development: Taking part in developing federal regulations for CAV safety testing, trying to fill an existing topical gap on how this can be accomplished.

Mcity offers an integrated space for testing, research and development. The technological base of the center allows for the development and testing of new safety and traffic control methods. With the center's assistance, it is possible to interact with vehicles and infrastructures comprehensively, using the most up-to-date intelligent transport systems tailored to ever-changing conditions. This will assist in improving traffic flow and safety. Mcity is also significantly advancing practical solutions in transport by introducing green driving or energy-efficient technologies in the development process. Such a practice should only improve the prospects of bringing automated eco-friendly vehicles through the door. Not forgetting that connected cars and autonomous ones are prone to cyber-attacks, Mcity assists in bridging the gap in understanding V2X footprints and how to mitigate vulnerabilities that CVs and AVs have.

Mcity broadens its research on cooperative vehicle technologies by engaging with the American Center for Mobility and the Ann Arbor Connected Vehicle Test Environment, which expands everything from the testing and data collection to creating systems improving vehicle-to-vehicle interactions. Tackling such crucial issues allows Mcity to push significantly forward the advancement and the introduction of connected and autonomous vehicle technologies into the market, which aims to build a safer, more efficient, and more sustainable transport system.

1.3.3 Morgan State University, Baltimore, Maryland

The Morgan State University Testbed in Baltimore, MD, serves as an important research and development facility for CV technologies. This testbed is equipped with two RSUs, two OBUs, two LiDAR sensors, and four CCTV cameras, all operating under C-V2X technology. The primary objectives of the testbed include improving the safety of all road users, especially VRUs, at two signalized intersections along the testbed, which includes the Cold Spring Lane – Hillen Road and East 33rd – Hillen Road intersections.

The latest generation of smart signal controllers was also installed at those two intersections to broadcast real-time SPaT messages, intersection map data (MAP), and Traveler Information Messages (TIMs). The testbed provides a controlled environment for evaluating and refining CV systems and their impact on traffic management and safety. The integration of LiDAR sensors and CCTV cameras into the testbed allows for comprehensive data collection on vehicle and VRU movements. Thus, it provides valuable insights into traffic flow and safety.

The use of RSUs and OBUs facilitate communication between vehicles and infrastructure and provide real-time updates and coordination of traffic signals. This setup supports various research activities, including the assessment of traffic signal control strategies, the development of safety measures, and the evaluation of data collection methods. The operational status of the Morgan State University testbed underscores its importance in advancing CV research and development. Figure 16. illustrates the Morgan State University's CAV testbed.

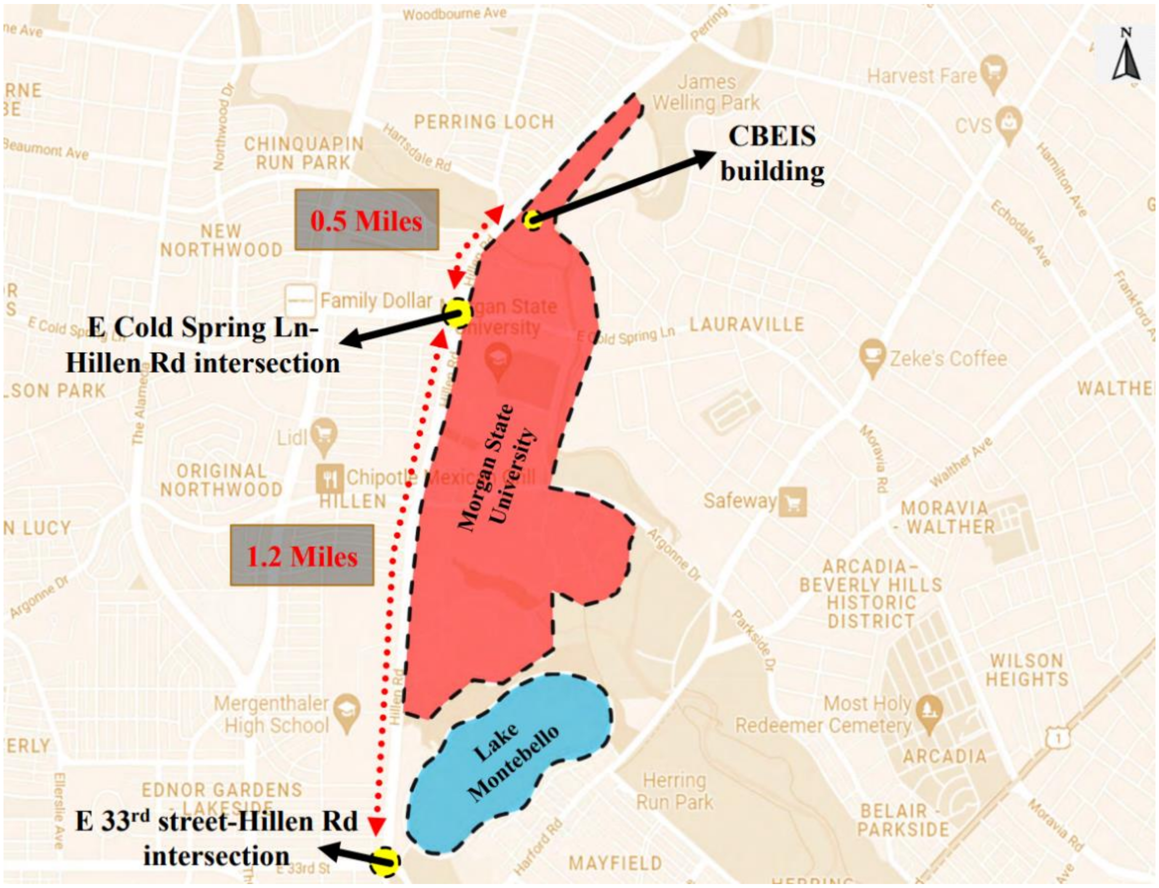

Figure 16. Morgan State University's CAV Testbed

Various research studies have been conducted on this testbed since 2022. One significant area of research involves the statistical analysis of vehicle-vehicle conflicts using LiDAR sensors. Studies have investigated the accuracy of LiDAR technology in detecting and quantifying these conflicts, comparing its performance with microsimulation tools like VISSIM and AIMSUN. These studies provide insights into the precision of conflict detection and the effectiveness of LiDAR technology in enhancing traffic safety. Additionally, research has focused on vehicle-pedestrian conflicts, employing a new Post Encroachment Time (PET) threshold classification to assess the interactions between vehicles and pedestrians at signalized intersections. This innovative approach aims to improve the accuracy of conflict detection and enhance pedestrian safety. Another critical research focus has been on jaywalking conflicts, with statistical analyses conducted to assess how LiDAR sensors can identify and mitigate these incidents. Similarly, studies have examined vehicle-bicyclist conflicts and the effectiveness of LiDAR technology in managing these interactions at signalized intersections. These investigations contribute to the development of targeted safety measures for VRUs.

The testbed has also been instrumental in exploring real-time traffic control and safety measures during traffic signal failures. Research has assessed how LiDAR sensors can be used to manage traffic effectively under such conditions. Additionally, the testbed has facilitated studies on smart green time allocation, utilizing LiDAR sensors to optimize traffic signal timings and improve intersection efficiency. Comparative analyses of LiDAR and CCTV sensor accuracy have been conducted to evaluate their performance under various weather conditions. These studies provide valuable insights into the reliability of different sensor technologies for traffic monitoring and delay time estimation. Overall, the research conducted at the Morgan State University testbed underscores its role as a leading facility for advancing CV technologies and improving traffic safety and efficiency through innovative sensor applications and data-driven analyses [28, 29].

Future research studies at Morgan State University's CAV testbed will focus on several advanced and vital areas to enhance traffic management and safety. A key area of exploration will be the development and optimization of preemption systems for emergency vehicles, including fire department preemptions and Morgan shuttles. This will involve integrating dynamic safety messages with real-time data from LiDAR sensors, RSUs, and OBUs to prioritize the passage of these vehicles through signalized intersections. Additionally, the testbed will investigate the efficacy of dynamic safety messages transmitted by RSUs. Research will also address the impact of these preemption systems on traffic congestion and emergency response times. Furthermore, future research at Morgan State University's CAV testbed will also focus on calculating Time-to-Collision (TTC) for various types of traffic conflicts, including vehicle-to-vehicle, vehicle-to-pedestrian, and vehicle-to-bicyclist. This involves using data from LiDAR sensors to precisely measure the TTC, which helps in understanding the potential severity and risk of these conflicts. Additionally, the development and implementation of real-time warning devices for VRUs will be a key research area. These devices aim to alert both drivers and VRUs to imminent V2P and V2B conflicts at both signalized intersections on the CAV testbed.

1.3.4 Comparative Analysis of Mcity with Morgan State University's CAV Testbed

Mcity at the University of Michigan and the Connected Vehicle testbeds at Morgan State University are critical in developing autonomous vehicle technologies. Although they have some common objectives, their methods and areas of emphasis are somewhat different.

Mcity is an all-encompassing facility that spans 32 acres and imitates the complex structure of an urban or suburban community with its many intersections, traffic signals, and building frontages. This arrangement helps foster CAV testing in different circumstances. Recent developments like the National Science Foundation grant of $5.1 million have enabled researchers to combine physical testing with virtual reality to do remote testing nationwide.

Mcity's research activities are wide-ranging. They include studying vehicle dynamics, sensor integration, cyber security, and policy making. The facility's dimension and resources enable large-scale testing and collaboration with various stakeholders, such as industry and government agencies.

Morgan State's CAV testbed incorporates the city of Baltimore, enabling its focus on natural traffic conditions. The testbed includes the SMART Intersection with LiDAR sensors, roadside units, and connected vehicle technology to improve the safety of pedestrians and traffic. The focus is on safety and equity, especially for pedestrians and cyclists who are at-risk road users. Objectives include developing intelligent safety warnings and traffic conflict assessment routines to foster sustainable transportation systems.

Mcity has a more extensive controlled environment that can be used for various tests, including speed searching and complex geographical structures. In contrast, the Morgan State testbed is in a natural urban environment, which provides real-world challenges and interactions.

Mcity's broad research strategy includes technology development, policy formation, and large-scale case studies. At Morgan, the emphasis is placed on safety, equity, and the effective integration of CAV technologies into urban transportation networks for disadvantaged groups.

Morgan State's location within the City of Baltimore enables the community to participate in the research immediately, making it possible to conduct studies on community sentiment and the impact of

CAV technologies on society. Mcity, for its part, while working with different partners, is focused more on technology and policy perspectives in a more controlled environment.

In summarizing the above in Table 2., Mcity and Morgan State's CAV testbeds perform different but complementary roles. Mcity performs the theoretical role by providing a wide range of technological and policy development. In contrast, Morgan State provides the practical side of CAV, focusing on safety and equity issues in urban environments.

Table 2. Comparison between Mcity and Morgan State University Testbed

Feature	Mcity (University of Michigan)	Morgan State University's CAV Testbed
Location	Ann Arbor, Michigan	Baltimore, Maryland
Scale	32-acre purpose-built facility simulating urban and suburban environments.	Integrated within actual urban intersections: Cold Spring Lane at Hillen Road and East 33rd Street at Hillen Road.
Infrastructure	Diverse road types and intersections, traffic signals, signage, and building facades. Controlled environment for testing various scenarios.	It has two roadside units (RSUs), two Onboard Units (OBUs), two LiDAR sensors, and four CCTV cameras. It operates under Cellular Vehicle-to-Everything (C-V2X) technology.
Technological Features	V2X and 5G wireless communication, augmented reality testing capabilities, and software-controlled infrastructure for dynamic testing scenarios.	Real-time Signal Phase and Timing (SPaT) messages, Intersection Map Data (MAP), and Traveler Information Messages (TIM). Focus on real-time data exchange and coordination.
Research Focus	Broad spectrum, including vehicle dynamics, sensor integration, cybersecurity, and policy development. Large-scale testing and collaborations with industry	Emphasis on safety and equity, particularly for vulnerable road users (VRUs) like pedestrians and cyclists. Development of dynamic safety warnings and customized traffic conflict assessments. Sustainable transportation planning.

	partners and government agencies.	
Community Engagement	Collaboration with various stakeholders, including industry partners and government agencies, focusing on technological advancements and policy development.	Direct integration within Baltimore City facilitates community involvement, allowing studies on public perception and societal impacts of CAV technologies.
Unique Capabilities	Remote access for researchers nationwide through the Mcity 2.0 initiative. Integration of physical testing with virtual reality simulations. A comprehensive environment for diverse scenario testing.	It focuses on real-world traffic conditions and interactions. It is equipped with the SMART Intersection to enhance pedestrian and traffic safety. It utilizes LiDAR and connects vehicle technology for comprehensive data collection.

Chapter 2

Connected and Automated Vehicle Education (CAVe)-in-a-Box (FHWA)

2.1 Components of (CAVe)-in-a-Box

The second part of this report assesses the (CAVe)-in-a-Box setup by FHWA, which provides an overview of the key components and tools used in CV deployments. The components of the (CAVe)-in-a-Box system consist of the traffic signal controllers, RSUs, V2X hubs, and the onboard units (OBUs). These components are combined into an interconnected system that facilitates V2V and V2I communication. The (CAVe)-in-a-Box setup also includes a wired network switch, Wi-Fi router, power supply, and a touchscreen tablet or PC (laptop) for control and monitoring.

The present-day availability of open-source connected vehicle tools such as CARMA, V2X Hub, Operational Data Environment (ODE), and Secure Data Commons (SDC) makes for easy integration of the (CAVe)-in-a-Box with traffic signals. These tools enable the development, testing, and placement of CV technologies by providing standardized platforms and compatible data environments.

The V2X Hub, an imperative component of the system, is equipped with several plugins designed to enhance V2I communication. These plugins contain Curve Speed Warning, Dynamic Message Sign, MAP, SPAT, Location, and RTCM, among others, which permit real-time data exchange and enhance traffic management and safety. Figure 17(a) & (b). shows the components of the (CAVe)-in-a-Box.

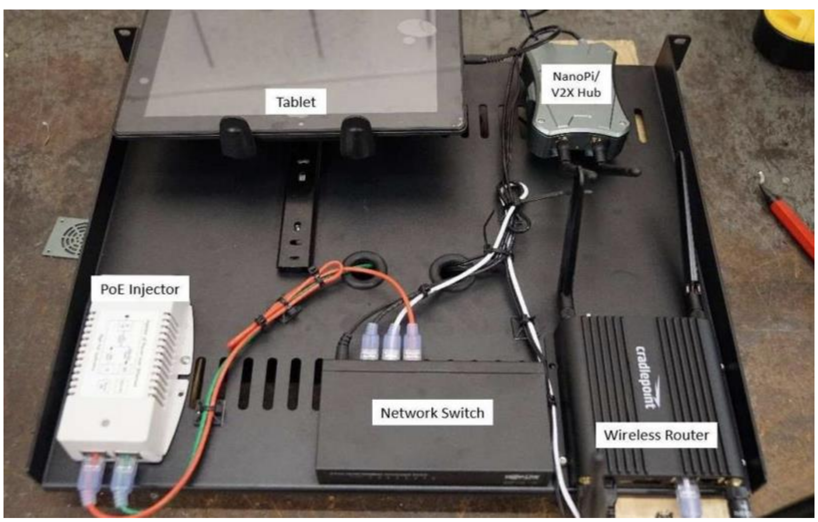

Figure 17. (a) Components of the (CAVe)-in-a-Box

https://www.its.dot.gov/pcb/documents/CVe_in_a_box_Network_Instruction_Set_2022.pdf

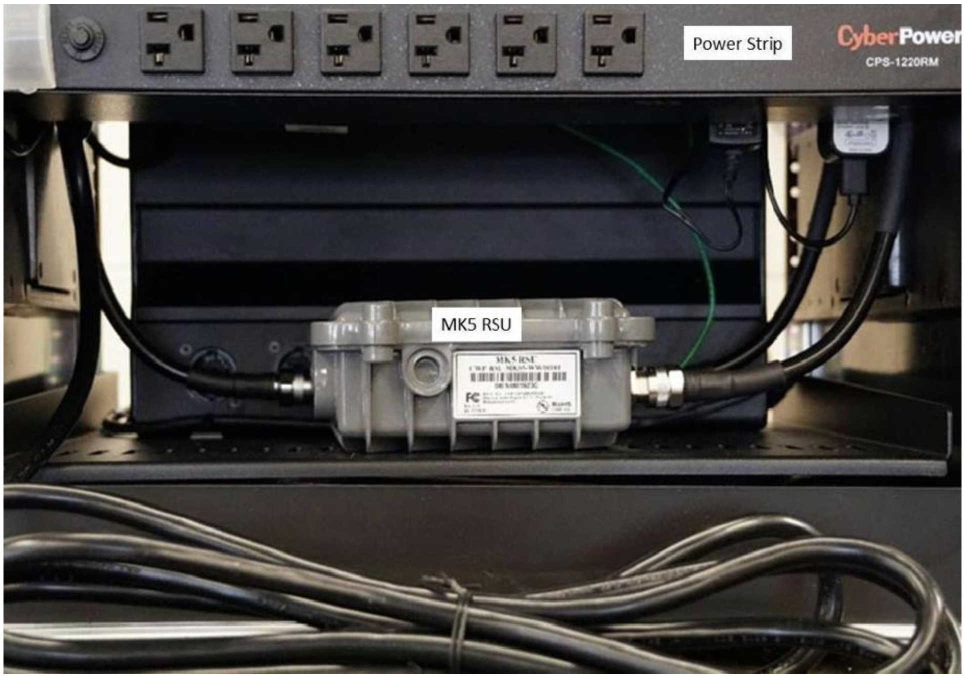

Figure 17(b) Components of the (CAVe)-in-a-Box

https://www.its.dot.gov/pcb/documents/CVe_in_a_box_Network_Instruction_Set_2022.pdf

- *Traffic Signal Controller* - This element manages the operation of traffic signals, permitting them to communicate with connected vehicles to optimize traffic flow and enhance safety at intersections.
- *Roadside Units (RSUs)* - RSUs are installed along the roadways to simplify communication between vehicles and infrastructure. They transmit information about traffic conditions, potential and current road hazards, and signal phases to connected vehicles.
- *V2X Hub* - The V2X Hub is a central communication node which integrates various V2X communication technologies, including DSRC and C-V2X. It manages the exchange of data between vehicles and infrastructure, guaranteeing seamless data flow.
- *Wired Network Switch and Wi-Fi Router* - These networking devices facilitate the wired and wireless connectivity necessary for the (CAVe)-in-a-Box system. They make sure that all components are interconnected and are able to communicate effectively.
- *Power Supply* - A dependable power source is vital to ensure the continuous operation of all components within the (CAVe)-in-a-Box system.
- *Touchscreen Tablet or PC* - This user interface device enables operators to monitor and control the (CAVe)-in-a-Box system, providing real-time data visualization and system management capabilities.
- *Onboard Unit (OBU)* - OBUs are installed in vehicles to enable V2X communication. They receive and transmit data to and from RSUs and other vehicles, playing an important role in the overall connectivity of the system.
- *Controller Area Network (CAN)* - The CAN network allows various electronic components within a vehicle to communicate with each other, ensuring coordinated operation of the vehicle's systems.

The (CAVe)-in-a-Box Network Connection as shown in Figure 18. illustrates the interconnected components of the (CAVe)-in-a-Box system. It displays how the traffic signal controller, RSUs, V2X hub, and onboard units (OBUs) communicate via a wired network switch and a Wi-Fi router. The power supply ensures continuous operation, whereas the touchscreen tablet or PC acts as the control interface. This entire setup permits seamless data conversation between vehicles and infrastructure, enabling real-time traffic management, safety alerts or warnings, and V2X communication. The well-integrated network infrastructure supports consistent and efficient operation of connected and automated vehicle technologies.

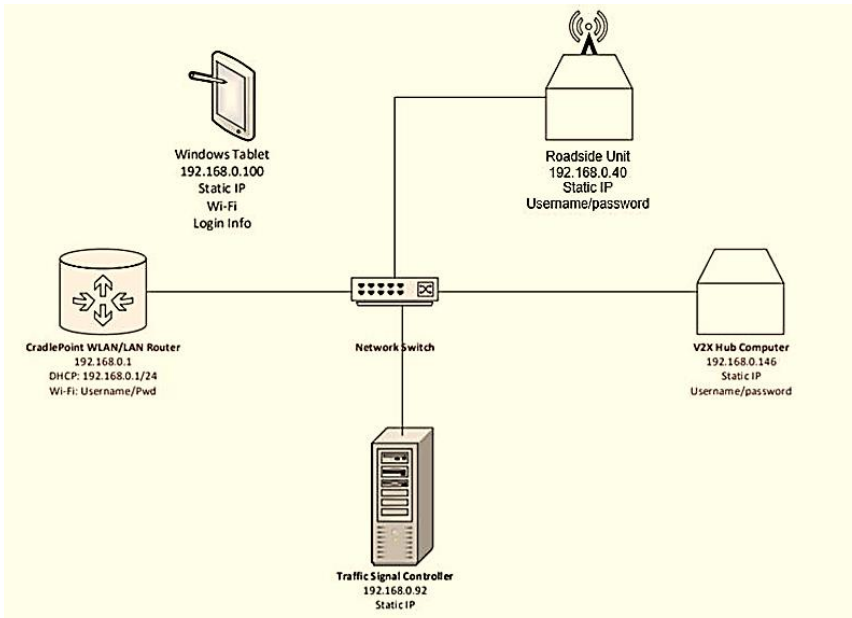

Figure 18. Network Connection for CVe in a Box Setup

https://www.its.dot.gov/pcb/documents/CVe_in_a_box_Network_Instruction_Set_2022.pdf

the (CAVe)-in-a-Box system includes various components and tools essential for vehicle-to-everything communication, enabling robust testing environments for CV applications.

2.2 Open-Source Connected Vehicle Tools

Several open-source tools that can be integrated into the (CAVe)-in-a-Box system are as follows:

- *CARMA* - A platform that enables cooperative driving automation, facilitating the vehicles to work together to optimize traffic flow and enhance safety in vehicle operations.
- *Operational Data Environment (ODE)* - This tool provides a centralized platform for gathering, processing, and analyzing data from connected vehicle installations.
- *Secure Data Commons (SDC)* - SDC ensures the secure storage and exchange of data collected from CV deployments, enabling resilient collaboration and research.

2.3 V2X Hub Plugins

The V2X Hub supports various plugins that enhance its functionality -

- *Curve Speed Warning Plugin* - Alerts drivers to reduce speed when approaching a curve.
- *Dynamic Message Sign (DMS) Plugin* - Displays real-time information to drivers via electronic signs.
- *MAP and SPAT Plugins* - Provide detailed mapping and signal phase and timing information.
- *Pedestrian Plugin* - Enhances safety by alerting drivers to the presence of pedestrians.
- *Preemption Plugin* - Prioritizes emergency vehicles by adjusting traffic signals.

Chapter 3
Industry Solutions

3.1 Built-In OBU (On-Board Unit)

Several automotive manufacturers offer vehicles equipped with built-in On-board Units (OBUs) as part of their connected car technologies or for specific functionalities such as electronic toll collection.

1. **General Motors (GM) OnStar:** OnStar is GM's comprehensive connected car service. OnStar offers features like emergency assistance, vehicle diagnostics, navigation, and remote services. The built-in OBU in OnStar-equipped vehicles enables these functionalities seamlessly. Additionally, GM vehicles, including Chevrolet, GMC, Cadillac, and Buick models, come equipped with OnStar services, which include built-in connectivity features that function similarly to on-board units (OBUs). Starting from the 2024 model year, GM vehicles have OnStar connectivity as a standard feature for three years. This includes services such as remote vehicle commands, automatic crash response, and stolen vehicle recovery. These features integrate through apps like Alexa and Google Assistant. More advanced OnStar features, such as Super Cruise and unlimited Wi-Fi streaming, are available in premium models like Cadillac Escalade, Buick Avenir, and GMC Denali. Furthermore, by 2025, GM will offer an enhanced "OnStar One Essentials" package across its vehicle lineup. This package provides even more connected services, such as navigation and voice assistance, at no additional cost for eight years in new vehicles [98-99]. In GM models from 2023, 2024, and 2025, a built-in On-Board Unit (OBU) enhances safety with advanced crash detection technology. GM includes OnStar Automatic Crash Response in the new models. Using integrated vehicle sensors, the system connects the driver immediately to a trained OnStar Advisor who can provide assistance. Even if the driver unbales to respond, the Advisor can share the driver’s location with First Responders and use Injury Severity Prediction to assess the likelihood of serious injuries [100].

2. **BMW:** BMW provides built-in OBUs in several of its cars. The OBUs are typically included in newer models equipped with BMW’s ConnectedDrive features, which are available across a wide range of models. For instance, models like the BMW 3 Series, 5 Series, X5, and i3 come equipped with ConnectedDrive, supporting both navigation and advanced telematics. Additionally,

ConnectedDrive services such as real-time traffic updates, remote vehicle diagnostics, and vehicle-to-infrastructure communication are offered in these models. BMW ConnectedDrive integrates OBUs to ensure connectivity and safety. It offers features like real-time traffic information, and even remote 3D view. This system is available for free for the first three years with new BMW models, after which a subscription is required to continue using certain features [101-102].

3. **Mercedes-Benz:** In the latest versions of Mercedes products (after 2024), the company integrates connectivity features into its vehicles. As a result, it enables V2X (Vehicle-to-Everything) communication capabilities in certain models. This technology is designed to enhance safety and improve driving experience by facilitating communication between vehicles and infrastructure. However, the specific availability of a built-in OBU may vary by model and market, with newer models generally incorporating these advanced technologies more extensively [103]. It is worth mentioning that Mercedes-Benz tried to advance driver-assistance systems (ADAS) by incorporating LiDAR technology from Luminar. This partnership allows Mercedes to expand its Drive Pilot system, which will enable Level 3 autonomous driving capabilities, permitting hands-free driving under certain conditions. The integration of LiDAR enhances the vehicle's ability to perceive its environment with greater precision, detecting obstacles, pedestrians, and road conditions even in challenging scenarios such as low light or adverse weather [104].

4. **Audi:** Audi integrates connectivity features, including a built-in On-Board Unit (OBU), in its vehicles through the Audi connect system. This system often includes a permanently installed SIM card that allows for various services and connectivity options, such as access to data for navigation, vehicle-related services, and connectivity with smart objects on the road [105]. The Audi connect system enables functionalities like traffic information, navigation assistance, and in-car internet access [105-107].
5. **Tesla:** Currently, Tesla vehicles do not come equipped with built-in On-Board Units (OBUs) specifically designed for V2X (Vehicle-to-Everything) communication. Tesla's vehicles, such as the Model S, Model 3, Model X, and Model Y, are equipped with extensive sensor suites and communication capabilities, they do not have OBU technology comparable to the dedicated units that enable V2X communication in some other vehicles or fleets. Tesla vehicles primarily utilize their

onboard technology for navigation, autopilot features, and vehicle communication with other Tesla vehicles and infrastructure, but they are not currently configured for the standardized OBU systems used in specific traffic management and communication systems [108].

6. **Ford:** The FordPass Connect module in Ford vehicles is integrated within the vehicle's systems and it provides functionality for remote access, navigation, and diagnostics. This module is part of the vehicle's electronic control systems rather than a standalone OBU device. It is worth mentioning that unlike some manufacturers who provide dedicated OBUs for toll collection systems (e.g., EZ-Pass, FasTrak), Ford does not currently offer a separate, dedicated OBU in its new vehicles specifically for electronic toll collection. Instead, vehicles can use the FordPass Connect for various functionalities, but toll payments typically require additional arrangements depending on the region. Consequently, Ford does offer built-in On-board Units in its vehicles through the FordPass Connect system [109].

7. **Toyota:** Toyota has introduced its V2X communication system that focuses on enhancing road safety and connectivity. Their system is based on Dedicated Short-Range Communications (DSRC), which facilitates direct communication between vehicles, infrastructure, and pedestrians. This technology enables vehicles to exchange critical data such as safety warnings, road conditions, and traffic information without relying on cellular networks. Toyota has deployed this in models like the "2022 Toyota Mirai", where the DSRC-based system helps in communicating with other equipped vehicles and infrastructure, improving situational awareness and reducing the likelihood of crashes. The global policy of Toyota company is also shifting toward integrating Cellular V2X (C-V2X) technologies, which combine the benefits of both short-range and long-range communication through cellular networks like 4G and 5G [110-111].

8. **Volvo:** Volvo integrates advanced V2X communication capabilities in its newer vehicles, starting with models like the EX90. These cars are designed with built-in OBUs that allow for V2X communication. This technology enables vehicles to interact with each other (V2V) and with surrounding infrastructure, such as traffic signals or road safety units. Additionally, Volvo vehicles equipped with Google built-in software are connected to various digital services and updates, with over-the-air

(OTA) updates for continuous improvements to the car's system. This connectivity can support features that are vital for V2X communication. This system allows real-time data exchanges for enhanced safety measures in connected vehicle environments [112].

9. **Volkswagen:** Volkswagen provides a built-in OBU for V2X communication in some of their new car models, particularly in Europe. The 8th generation Volkswagen Golf was the first European model to include this technology as a standard feature. The system is based on Wi-Fi (DSRC) and allows vehicles to communicate with each other, road infrastructure, and other road users like cyclists and pedestrians. This communication enhances road safety by enabling real-time alerts about hazards and road conditions without relying on cellular infrastructure or subscription fees. The Volkswagen ID. family of electric vehicles, such as the ID.3, ID.4, and ID.5, are among the models that feature this technology. These OCUs allow the cars to be "online," enabling functions like over-the-air software updates, traffic hazard alerts, and swarm-based semi-autonomous driving [113-114].

10. **Hyundai:** Some luxury models like the Genesis and Equus 2023 and afterward are reported to have advanced connected features, which may include built-in OBUs. These models often come equipped with sophisticated telematics systems that support various connected services [115].

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