Connected Vehicle Pilot Deployment Program Independent Evaluation

National-Level Synthesis Report

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16. Abstract

This report provides a national-level synthesis report of the Connected Vehicle Pilot Deployment sites. This national-level synthesis report summarizes the challenges, findings, critical lessons learned, and impacts from the three connected vehicle (CV) deployments and discusses the implications of these impacts on future CV deployment across the Nation. This report characterizes the objectives addressed in each CV pilot deployment site, as well as attributes of the deployments. This report is a qualitative summary of the challenges and implications in measuring the safety, mobility, environmental, and public agency benefits of the CV technologies. This report also recommends technical approaches, derived from the site experience with the goal of accelerating CV deployment nationwide.

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Executive Summary

On September 14, 2015, the Connected Vehicle Pilot Deployment (CVPD) Program initiated the pilot deployments of connected vehicle (CV) applications that synergistically capture and use new forms of CV, mobile device, and infrastructure data to improve multimodal surface transportation system performance and enable enhanced performance-based systems management.[(1)] The focus for improved performance is not only in the area of safety but also in the areas of mobility, environment, and public agency efficiency. The U.S. Department of Transportation (USDOT) Intelligent Transportation Systems Joint Program Office (ITS JPO) selected three sites to service pilot deployments:

- The downtown Tampa, FL, central business district (led by the Tampa-Hillsborough Expressway Authority [THEA]).
- The New York City, NY, Manhattan area (led by the New York City Department of Transportation [NYCDOT]).
- I-80 in Wyoming (led by the Wyoming Department of Transportation [WYDOT]).

The objective of this report is to provide a synthesis of the challenges, findings, key lessons learned, and impacts from the three CV deployments and implications for future CV deployment across the Nation.

Each pilot location measured, assessed, and reported on the performance of its deployment based on its concept of operations, site-determined goals, and site-specific evaluation plan. Issues associated with deployments, limited sample sizes and market penetration, and external factors (such as COVID, changes in DSRC Spectrum allocations, and equipment availability) impacted the site's ability to conduct extensive assessment of safety, mobility, environmental, and public agency (SMEP) benefits. Table 1 provides a summary of the SMEP benefits reported for each site.

To assist future deployers assess the transferability of the findings of the CVPDs to future deployments, TTI summarized the attributes and characteristics of each site. (Table 3 provides this summary.) This matrix was intended to help other locations looking to deploy CV technologies identify which pilot sites approximates their deployments.

Table 1. Summary of Safety, Mobility, Environmental, and Public Agency Efficiency Benefits for Connected Vehicle Pilot Deployment Sites.

Category	Tampa	New York City	Wyoming
Applications Deployed	• Electronic Emergency Brake Light (EEBL) • End of Ramp Deceleration Warning (ERDW) • Forward Collision Warning (FCW) • Intersection Movement Assis (IMA)t • Pedestrian Crossing Warning • Vehicle Turing Right in Front of a Transit Vehicle (VTRFTV) • Wrong-Way Entry • Intelligent Traffic Signal (I-SIG)* • Transit Signal Priority (TSP)*	• Speed Compliance (SPDCOMP) • Curve Speed Compliance (CSPDCOMP) • Speed Compliance in Work Zones (SPDCOMPWZ) • FCW • EEBL • Blind Spot Warning/Lane change Warning (BSW/LCW) • IMA • Red light violation warning (RLVW) • Vehicle turning right warning (VTRW) • Pedestrian in Signalized Crosswalk warning (PEDINXWALK) • Mobile Pedestrian Signal (PED-SIG) • Oversize Vehicle Compliance (OVC) • Emergency Communications and Evacuation Information (EVAC)** • CV Data for Intelligent Traffic Signal (I-SIGCVDATA) **	• FCW • Stationary Vehicle Alert (SVA) • Infrastructure-to-Vehicle Situational Awareness (I2V-SA) • Spot Weather Impact Warning (SWIW) • Work Zone Warning (WZW)
Safety-Crashes	• Insufficient evidence to conclusively report reductions in crash frequencies or crash potentials • Both FCW and EEBL experienced substantial number of false positives	• Injury rear-end and sideswipe crashes reduced by 5.3 percent and 1.5 percent (not significant) • 9.4 percent and 15.0 percent reduction in PDO rear-end and sideswipe collisions, respectively, during the post-deployment period (significant)	• No reports of crashes involving CV.s • Average number of vehicles increased from 1.29 to 1.43 (10.3 percent) when secondary crashes were not considered and from 1.41 to 1.53 (8.9 percent) when secondary crashes were considered.

	• ERDW delivered warning required fine-tuning to avoid false positive alerts • Loss of heading and inaccurate mapping of vehicle caused the WWE to issue alerts when vehicles not actually traveling the wrong way. • The initially deployed LiDAR-based PCW had reliability issues	• Simulation results suggest that the applications had a positive impact in increasing the TTC values between vehicles, • Field results showed no significant effect on increasing TTC values. • SPDCOMP application produced 16% increase in speed limit compliance • RLVW caused 41% reduction in red-light violation rates and 0.4 sec reduction in brake reaction time • CSPDCOMP reduced minimum speed in curve by 3.6 m/s • Work zone minimum speed increased by 0.2 m/s • FCW caused 25 percent reduction in near crash rates • EEBL reduced brake reaction time by 0.4 sec • LCW reduced unsafe lane change rate by 46 percent • BSW reduced unsafe lane change rate by 77 percent • 1.3 sec reduction in brake reaction time by IMA	• The percentages of work-zone-related crashes increased from 11.8 percent of total crashes to 14.6 percent, Truck work zone crashes also increased as a percentage (12.0 to 14.7 percent) along with a larger increase in crash rates (0.86 rate per million VMT to 1.18). • The overall crash rate for the corridor decreased from 0.860 to 0.700, The truck crash rate decreased from 0.840 to 0.762. • The number and percentage of fatal and incapacitating injury crashes (both total and those involving trucks) were slightly higher in the post-deployment year compared to the baseline period.
Mobility	• Mean travel times on REL reduced by 2.1 percent in AM peak • Time spent idling during AM peak reduced by 1.8 percent • Maximum queue length reduced by 1.8 percent • Travel time index reduced from 2.7 to 1.9	• Insufficient data available to allow a direct assessment of this application on mobility • Compliance with curve advisory speed limits increased after fleet vehicles started issuing CSPDCOMP alerts. • Likely red-light violations reduced by 152 per 1,000 events after the	• No conclusive evidence to indicate the Wyoming CVPD had any impact on mobility on I-80, either directly or indirectly • WYDOT made it possible for CV drivers to receive TIMs while traveling on any State or Federal highway instead of just I-80

		fleet vehicles began issuing RLVW alerts	
Environmental	• Applications reduced fuel consumption by equipped vehicles by 0.104 gallons per peak period.	• Potential fuel consumption savings ranged from 1.3 to 117.3 gallons if applications could eliminate 30-minute collision. • Eliminating a single collision at each of the four locations in the deployment network could potentially save approximately 1,287 Kg of carbon dioxide emissions	• Preventing a one-hour closure within the corridor could generate potential fuel consumption savings of approximately 23.8 gallons of gasoline from passenger cars and 46.5 gallons of diesel from trucks, assuming a 50-50 vehicle mix • For a one-hour closure, fuel consumption due to idling was estimated to range from 19.3 to 67.3 gallons of gasoline for passenger cars and 19.4 to 67.3 gallons of diesel for trucks for different sections of roadway. This also assumes a 50-50 mix of passenger cars and trucks
Public Agency Efficiency	• Experience gained by staff was invaluable for future projects	• SPDCOMP application was effective at achieving better speed limit compliance by fleet vehicles • CVs generated similar average and median 24-hour travel time profiles, which were comparable to those produced by the ETC system	• The quantity of road condition reports coming into the TMC increased from 4.3 reports per to 16.9 reports per section per day in the post-deployment. • The coverage of the network with road condition reports per hour during weather events increased from 5.0 in the baseline condition to 6.4 in the post-deployment period. • The latency of road condition reports per section during weather events dropped from 3.9 hours to 3.2 hours.

*Application not deployed as part of Phase III of the CVPD.
** Deployed in a test mode only.

Source: Texas A&M Transportation Institute, 2022

Table 2. Summary of CVPD Site Attributes

Category	Tampa	New York City	Wyoming
Target users	• Daily commuters • Transit operators • Moderate population core • Pedestrians and other vulnerable road users	• Operators of NYCDOT fleet vehicles (professional) • Transit operators • Commercial truck operators • Fleet operators (snowplows, sanitation vehicles, etc.) • Dense population core • Vulnerable road users	• Freight operators: ○ Long-distance trips • Familiar with advanced technology in the cab

Vehicle population	• Personal vehicles
	• Transit buses (express)
	• Fixed-route transit:
	  ○ Express buses
	  ○ Trolleys
		• Auto-oriented fleet vehicles with high fleet turnover
		• Buses
		• Trucks
		• Maintenance fleet vehicles (sanitation, snowplows, etc.)
			• Long-distance interstate trucks (data consumer)
			• A high proportion of trucks and/or recreational vehicles (RVs)

Network characteristics (road types and geometries)	• Urban grid • Moderate driveway density • Moderate operating speeds • Exclusive transit ways • Moderate intersection spacing	• Urban grid • Corridor oriented • Low operating speeds • Tight intersection spacing • One-way pairs • Urban canyons	• Rural interstate • Linear corridor • High operating speeds (during ideal conditions) • Roadway vertical/ horizontal alignment
Operational conditions—weather	• (No CV applications were designed to operate only under specific weather conditions)	• (No CV applications were designed to operate only under specific weather conditions)	• Snow and rain events • High-wind events • Frequent closures due to hazardous travel conditions
Operational conditions—demand	• Moderate traffic demands • Moderate pedestrian traffic • Peak period (particularly AM)	• High traffic demands • High pedestrian traffic • Non-peak period (midday/shoulder of peaks) • Regional VMT	• Low traffic demands • A high proportion of truck traffic • Consistent demand levels (limited peaking) • Regional VMT

Category	Tampa	New York City	Wyoming
	• Pass-through to a major trip generator (e.g., Air Force base) • Regional VMT • Vehicle travel and delay	• Vehicle travel and delay	• Vehicle travel and delay
Issues to be addressed	• Point-specific safety issues: ○ Intersection oriented • Congestion-oriented issues: ○ Queuing ○ Improved signal progression • Conflicts between user populations: ○ Vehicle/pedestrian ○ Vehicle/trolley	• Individual driver safety/ performance • V2V conflicts • Corridor-level performance (secondary)	• Crashes during severe weather events: ○ Multi-vehicle collisions • Single-vehicle rollover (wind)

Source: Texas A&M Transportation Institute, 2022

Common issues and challenges encountered by the sites include the following:

- All the deployment sites indicated that the maturity level of the technology and applications was overstated
- Many of the CV standards were also immature, inaccurate, incomplete, and subject to interpretation.
- All three sites cited significant issues with false alerts during the initial stages of deployment. All three sites also reported spending considerable time and personnel resources tracking down the sources of errors. These errors were caused by many factors including errors in the MAP, transmission errors, processing requirements associated with the technologies, incorrect operation assumptions, incorrect threshold requirements, etc.
- Except for procurement practices, all the sites reported that their existing business policies and practices were sufficient to sustain current and expanded operations into the future. Business processes included formal scoping, planning, programming, and budgeting.
- Procurement was the biggest issue among the sites. Because the technologies were not readily available off the shelf, a couple of the sites had to use non-traditional means of procuring the devices.
- The contractual process also impacted the schedule and the project implementation.
- Making sure that the procurements were cost effective and, at the same time, that the units would work in a large-scale deployment took a lot of time and effort.
- All three sites engaged relevant stakeholders (e.g., USDOT, site state and local DOTs, transportation associations, etc.) early in the process to define performance measures, assessment approaches, and other evaluation needs. The sites identified the need for flexible and realistic deployment schedules that could be adjusted as new, unforeseen circumstances developed.
- Collaborations with internal and external stakeholders were essential for the success of each pilot deployment. The sites reported that collaboration required a strong champion. In addition to the collaboration specific to each deployment, collaboration was encouraged (and facilitated by FHWA) between deployment sites.
- Priorities among the stakeholders can change, especially when it takes a long time to get systems operational. The need to continue to educate new stakeholders and decision makers on the potential benefits of the CV technologies exists throughout the life cycle of the deployment.
- Each site dedicated significant resources to implement workable solutions to ensuring confidentiality and integrity of the data. One issue encountered by the sites was the tradeoff between the need for privacy protection and the data needed for a robust evaluation.
- The sites performed significant processing on the data before uploading it into the SDC. Of particular concern was the removal of personally identifiable information (PII).
- All three sites reported spending considerable time planning and executing tests to confirm the functionality of the applications. The sites noted a general lack of test equipment and procedures to conduct the necessary testing. The teams also found that testing in a real-life environment under different operating conditions and scenarios extremely valuable.
- External confounding factors had a significant impact on all three deployments. All three CVPDs were significantly impacted by the following external confounding factors outside their ability to control:
    - Failure of NHTSA to Issue Proposed Rulemaking on V2V Technologies
    - Changes in the DSRC Spectrum Allocation
    - COVID-19 pandemic

Key lessons learned from the deployment include the following:

- From inception to deployment, the process of planning, designing, deploying, testing, and operating a CV deployment was long. The sites found that having dedicated champions for the deployment was essential to the success of the deployment. Without clear and strong champions, interest in deployment waned and commitments faltered. Each of the sites had a core group of champions dedicated to achieving the deployments goals and objectives.
- Each deployment had significant obstacles and uncertainties that had to be overcome. Deployment teams were able to overcome many of these impediments through strong cooperation and collaborations.
- The systems engineering processes proved to be a valuable tool for the sites. The sites found that using the system engineering process helped flesh out issues and provided solutions associated with technology and kept the deployment on-track.
- The CV applications were not at the level of maturity expected to allow for off-the-shelf deployment. Each site devoted a considerable amount of time and resources to making the applications function in their deployment. Better knowledge of functional and operational requirements of the applications was needed, including system documentation.
- The sites needed to documented installation procedures and manuals for each type of participant vehicle used in the deployment. The installation procedures were customized to each vehicle type. The sites found that proper installation procedures minimized installation errors and damage to vehicles, and reduced the time needed for installation. The sites also found that the installations needed to be performed in a professional manner. Vehicles were inspected after device installation to ensure that installation procedures were followed precisely.
- Adequate system documentation of applications was critical for ensuring the applications met user needs. Lack of vendor user and administrative documentation presented challenges for troubleshooting, training, and operations.
- Considerable gaps, discrepancies, and ambiguities existed in many of the CV applications standards, and that some standards were open to interpretation. The sites needed to develop verifiable system requirements that worked with evolving standards. The critical part of this process was to have a solid set of user needs and well-formed concept of operations.
- Without position correction, many of the CV applications did not function correctly. Two of the sites found that without position correction, the device's GPS were not suitable for applications requiring a high degree of location accuracy to operate properly. Inclusion of vertical elevation in MAP messages was also needed to allow vehicle to properly locate themselves in the network.
- Collaborations with both internal and external stakeholders were critical for a successful deployment. Each CVPD site benefited from sharing information about issues and solutions from the other sites. Other sites were used as sounding boards to develop solutions that promoted interoperability between deployments.
- Equipment design and placement were not the same for every vehicle. The same antenna placement used with automobiles cannot be used with commercial heavy-duty trucks. The installations of OBUs and antenna testing were unique to each truck type. Truck antennae needed additional testing to make sure that the range of coverage was maintained. Antenna testing documentation was useful to other deployers as well.
- Substantial time was needed to appropriately address contractual issues, testing planning, and execution. All three deployment sites spent a considerable amount of time finalizing contracts with device contractors and coordinating and executing memoranda of understanding with multiple user

groups. They also spent a considerable amount of time developing test plans and processes, and then testing (and re-testing)

- Interoperability did not happen by accident. The sites were cognizant of the elevated risk of non-interoperability associated with several different applications being deployed and took steps to ensure that applications result in consistent alerting and messages across multiple platforms.
- Data sharing needs and requirements were incorporated into the planning stages of the architecture. Requirements related to data storage and retention, isolation of computer resources, and data security protocols were addressed early in the planning phase. It can be extremely difficult and time consuming to retrofit data-sharing capabilities once the system has been developed.
- Over-the-air (OTA) updating of application software, device firmware, and configuration parameters was essential for keeping the system up to date, correct and error free.
- The sites found that applications should be tested with the security credentialing service active. Much of the testing and fine-tuning of the applications was performed without the security credential management service active. After the credentialing services were engaged, several of the sites reported issues and challenges with applications not performing as intended. All sites agreed that conducting testing with security credentialing engaged was needed to ensure that the applications performed as originally intended and without delays.
- The sites needed to develop systems and tools to monitor the operational status of the RSU. Because of the critical nature of the data to support safety applications, agencies need to be able to rapidly detect and correct malfunctioning RSUs, especially in remote locations. The tools were needed to perform remote diagnostics and alert the agency when the RSU has gone off-line. The sites noted challenges with RSU certificates having a cascading effect that caused the RSUs to malfunction. Some sites also had challenges getting initial OBU certificates to download via RSU.
- Many freight fleets lease vehicles. Therefore, equipment installations that impacted the vehicle's original condition (e.g., making holes to install antennae) was something that needs to be discussed early on to make sure the fleet owner/operator understood and approved these modifications.
- Several techniques were used for protecting the privacy of applications users; however, a tradeoff existed between preserving privacy and data availability for evaluation. The sites found that agreements needed for a robust evaluation conflicted with some of their privacy policies. The sites engaged Institutional Review Boards to ensure that data collection requirements did not violate privacy protection requirements.
- Defining evaluation and performance assessment data needs early in the process allowed the sites to design appropriate strategies and mechanisms for collecting, storing, and processing data. Incorporating data needs early in the process allowed the sites to ensure that data considerations were appropriately factored into their system requirements and communications architectures, vendor selection, data processing approaches, privacy considerations, and other crucial design decisions.
- Without significant market penetration, the sites found it difficult to effectively assess the safety, mobility, environmental, and public agency benefits of the technology. The amount of data generated by equipped vehicles to support deployed applications depended on CV penetration rates. Without sufficient deployment numbers, the sites found it difficult to identify and assess the benefits of the technologies.
- Leveraging existing traffic management systems and technologies and traveler information systems helped extend the benefits of the deployment and provided a pathway for future expansion for two of the sites; however, it can be difficult to isolate benefits if the technologies are introduced concurrently. Proper the experimental designs are required for isolating the benefits for each technology.

The following provides some recommendations for agencies to consider when planning, designing, installing, and operating future CV deployment:

- Ensure that the deployment addresses identifiable needs based on an assessment of current and forecasted operating conditions. The needs assessment should consider current challenges, solutions, practices, limitations, gaps, and improvement potential. Understand the level of maturity of the applications and technologies supporting the deployment. Thoroughly test and verify the functionality of equipment before committing to full-scale procurement, especially with new and unproven technologies.
- Ensure that the systems being planned and procured do not extend beyond the capabilities of the agency to support or maintain it. Agencies should ensure that operations and maintenance personnel have adequate knowledge, skills, ability, and resources to support the deployment. Additional, agencies may want to ensure the rapid repair and replacement of critical system components.
- Keep deployment simple and implementable. Focus on getting one or two applications working well and leave more complex applications until after gaining an understanding of the limitations of technologies. Keep the scope of the deployment relevant and implementable.
- Develop approaches for integrating the CV technologies with existing transportation systems' management and operations. Think about how to use CV technologies to expand existing capabilities as opposed to introducing new functionality to existing programs. Insist on the release of fundamental operating requirements for existing applications, including test procedures.
- Avoid building a system that can only be supported by a single vendor. Agencies should consider how they plan to recover from poor equipment and maturity issues of applications. If possible, an agency may want to include a second vendor or technology that can be turned to in case vendor-related issues with original device vendors arise.
- Communicate frequently with other deployers/partners and continue outreach efforts to recruit participants throughout the project.
- Make sure that procurement practices can meet the needs of the deployment. Most government agency processes are not designed to meet the unique challenges encountered during the CVPDs. For new technologies, agencies should consider procuring equipment/devices as a vendor contract. Because of the amount of probable troubleshooting that will be needed, this should be procured as professional or engineering services.
- Engender consensus on the goals of the deployment among the various stakeholders early in the deployment planning. Maintain consensus throughout the deployment through regularly scheduled stakeholder meetings and phone calls that keep all team members up to date regarding the progress of the deployment.
- Strong documentation is needed to safeguard against this risk. Agencies should consider using living documentation methods to ensure that information about the system is current, accurate, and easy to understand. Agencies need to develop accurate project assumption logs and concepts of operations documentation early in the development process. These documents need to be review and updated on a regular basis. The use of metadata to describe processes and data elements is also important critical for removing ambiguities on logged data. As part of the initial project development, agencies should also develop a maintenance plan for ensuring that the system continues to function within its design elements.
- Much of the technology used in these kinds of project is in the early development stages and cannot be procured off the shelf using normal procurement practices. Engage procurement and contracting personnel early in the procurement process to ensure conformance with the existing procurement practices. Because of the uncertainties associated with developing CV technologies, agencies should

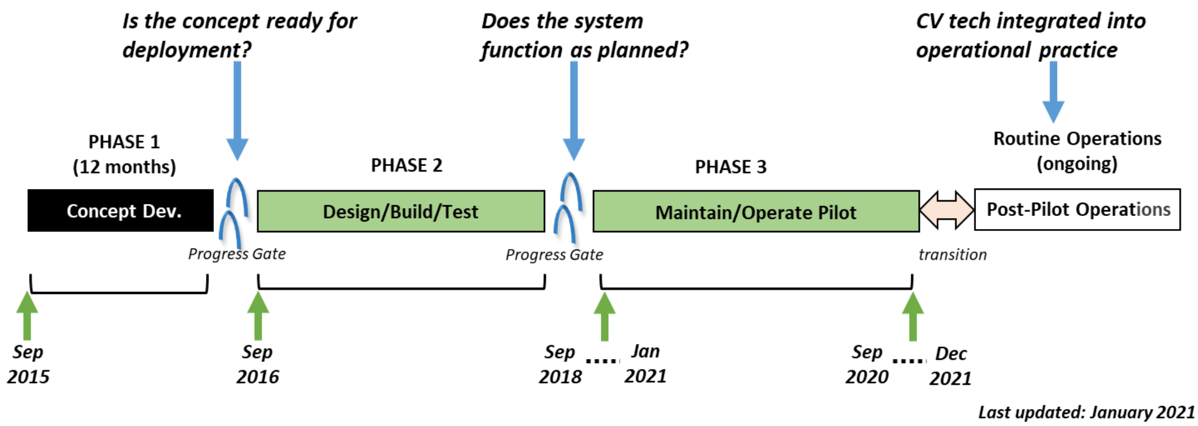
consider the early establishment of a contingency fund/budget line item to address unanticipated issues.

- Deployments can be long and people in decision-making/influential positions within an organization will leave. Their replacements may not be as committed to the deployment as their predecessor. Agencies may want to consider developing a succession plan as part of the project planning documentation to ensure continuity of personnel throughout the deployment.
- Agencies need to consider data use rights and privacy when using data from equipped vehicles and infrastructure for the evaluation effort, under certain constraints. Agency need to be aware of legal requirements related to the collection and use of data collected from human subjects. Obtaining the data needed for a robust evaluation may have some conflicts with a robust privacy policy. Consideration of agreements to allow robust data collection may be needed to obtain the data to permit a robust evaluation. The use of an opt-in agreement/contract like those already in use with many cell phone apps where individuals agree to share their data might be a viable method of obtaining user data. Agencies should engage an Institutional Review Board to ensure adequate privacy protection for human use subjects are in place.
- Test early and test often. Develop an appropriate test plan to test the functionality of the system end to end and at different stages of development. Detailed testing is required for OBU and RSU software, and in most cases, every aspect of the tests must be re-tested after each modification and firmware update to ensure that end-to-end functionality is not affected by any firmware upgrades.
- Reserve ample time in the schedule to account for testing, both test planning and test execution. Do not underestimate the time required to fine-tune and calibrate applications. Accurate delivery of alerts and messages can be compromised by configuration issues.
- Agencies need to develop strategies for conducting upgrades and enhancements of applications using over-the-air messaging.
- Define data and performance measurement/evaluation needs early in the project so that decisions regarding data, CV system design, back-office processing strategy, CV vendor selection, and others would be better informed.
- Have a tested and functioning SCMS in place prior to deployment to avoid ongoing refinements and schedule adjustments. Add in the SCMS from the beginning when the CV system is being built. Testing done without the security turned on slows down the deployment.
- Maintain the accuracy and quality of information used to produce alerts. Incorrect or erroneous information can erode user acceptance and trust in the system.
- Minimize time between user recruitment/installation and going live. If the lag time is too great, users will forget about their commitment and/or lose interest.
- Be prepared to spend considerable time configuring application parameters. Agencies need to conduct established performance standards.
- Develop a clear protocol for prioritizing warning alerts to drivers when multiple applications could produce simultaneous alerts. The sites noted that a clear protocol for prioritizing alerts was needed to avoid driver confusion.
- Supplement CV device penetration rates with non-CV sensor data to generate timely and adequate information to support relevant CV application operations that rely on such data to operate and meet functional and performance objectives. Non-CV sensor data as well as third-party data or crowd-sourced data could be used to support operation and evaluation of deployments, including calibration. These systems could also be used to potentially collect trajectory data at key locations.

- To the extent possible, leverage existing systems and communications protocols to support the widespread dissemination of alerts and warning using other communications media.
- Use over-the-air updates to update device software and firmware and conduct log offloading.
- Develop a feedback mechanism to let stakeholders know that you are hearing what they have to say. Once stakeholders begin to lose confidence in the technology, that confidence is extremely difficult to regain.
- Expect challenges and issues to arise during deployments that lead to budget shortfalls. There is a high cost associated with acquisition, deployment, and management of a CV system (e.g., managing the data that are developed).
- Consider evaluation and performance measurement needs early in the concept development process. This will reduce the amount of rework that must be done at the concept development stage. Ensure that performance measures reflect the goals and objectives of the deployment. IF the CAV and exist traffic management technologies are introduced concurrently, there may be issues isolating the benefits of each individual technology. The agency must decide if they want to, as policy, always deploy both technologies concurrently. If not, the experimental design MUST have a method for isolating the benefits for each technology,

Chapter 1. Introduction

On September 14, 2015, the Connected Vehicle Pilot Deployment (CVPD) Program initiated the pilot deployments of connected vehicle (CV) applications that synergistically capture and use new forms of CV, mobile device, and infrastructure data to improve multimodal surface transportation system performance and enable enhanced performance-based systems management.[1] The focus for improved performance is not only in the area of safety but also in the areas of mobility, environment, and public agency efficiency. Figure 1 illustrates the life cycle of the CVPD.



Source: Federal Highway Administration, 2021

Figure 1. Flowchart. Three Phases of Connected Vehicle Pilot Deployment [1]

The U.S. Department of Transportation (USDOT) Intelligent Transportation Systems Joint Program Office (ITS JPO) selected three sites to service pilot deployments:

- The downtown Tampa, FL, central business district (led by the Tampa-Hillsborough Expressway Authority [THEA]).
- The New York City, NY, Manhattan area (led by the New York City Department of Transportation [NYCDOT]).
- I-80 in Wyoming (led by the Wyoming Department of Transportation [WYDOT]).

Each of these deployments completed its initial deployments.

Each pilot location measured, assessed, and reported on the performance of its deployment based on its concept of operations, site-determined goals, and site-specific evaluation plan. The Texas A&M Transportation Institute (TTI) and the Volpe National Transportation Center served as independent evaluators for each deployment. Volpe's was responsible for conducting an independent assessment of the potential safety benefits of the deployed applications at each site, while TTI's role was to perform a qualitative assessment, based on the data and evaluation results from each site, of the potential mobility, environmental, and public agency efficiency benefits resulting from CV technologies at each site. These assessments provided the foundation for this national-level synthesis.

Objective of Report

The objective of this report is to provide a synthesis of the challenges, findings, key lessons learned, and impacts from the three CV deployments and implications for future CV deployment across the Nation. Specifically, the TTI Evaluation Team performed the following for this synthesis report:

- Characterized the objectives addressed in each CVPD site, as well as attributes of the deployments (e.g., rural freeway operations subject to severe weather events).
- Assessed the extent to which these objectives, attributes, challenges, and impacts may be found elsewhere in the Nation and the extent to which insights from the deployments may be transferred elsewhere in the Nation.
- Provided a qualitative summary of the challenges and implications in measuring the safety, mobility, environmental, and public agency (SMEP) benefits of the CV technologies.
- Recommended technical approaches, and integrated deployment models derived from the site experiences with the goal of accelerating CV deployment nationwide.

Organization of Report

The organization of this report is as follows:

- Chapter 2 summarizes each of the three CVPDs: Tampa, FL, New York City, NY, and Wyoming. The summary includes the goals and objectives, applications, reported benefits, and lessons learned in each of the three CVPDs.
- Chapter 3 summarizes the characteristics, attributes, and lessons learned associated which deployment that may be transferred to other locations that may enhance the likelihood of success of these deployments.
- Chapter 4 provides a synthesis of the common deployment challenges and lessons learned across all three of the deployment sites. This chapter documents the unique challenges and issues that other sites may face doing similar types of CV deployments. This chapter also highlights how the three sites overcame those issues and challenges and summarizes the common lessons learned from the deployments.
- Chapter 5 summarizes the recommendations and guidance for future deployers at similar locations. The chapter also identifies the attributes and characteristics of the deployment that might affect/impact the transferability of the benefits and lessons learned to other sites.

Chapter 2. Summary of Connected Vehicle Pilot Deployments

This chapter summarizes the goals and objectives, applications, reported benefits, and lessons learned from each of the three CVPDs.

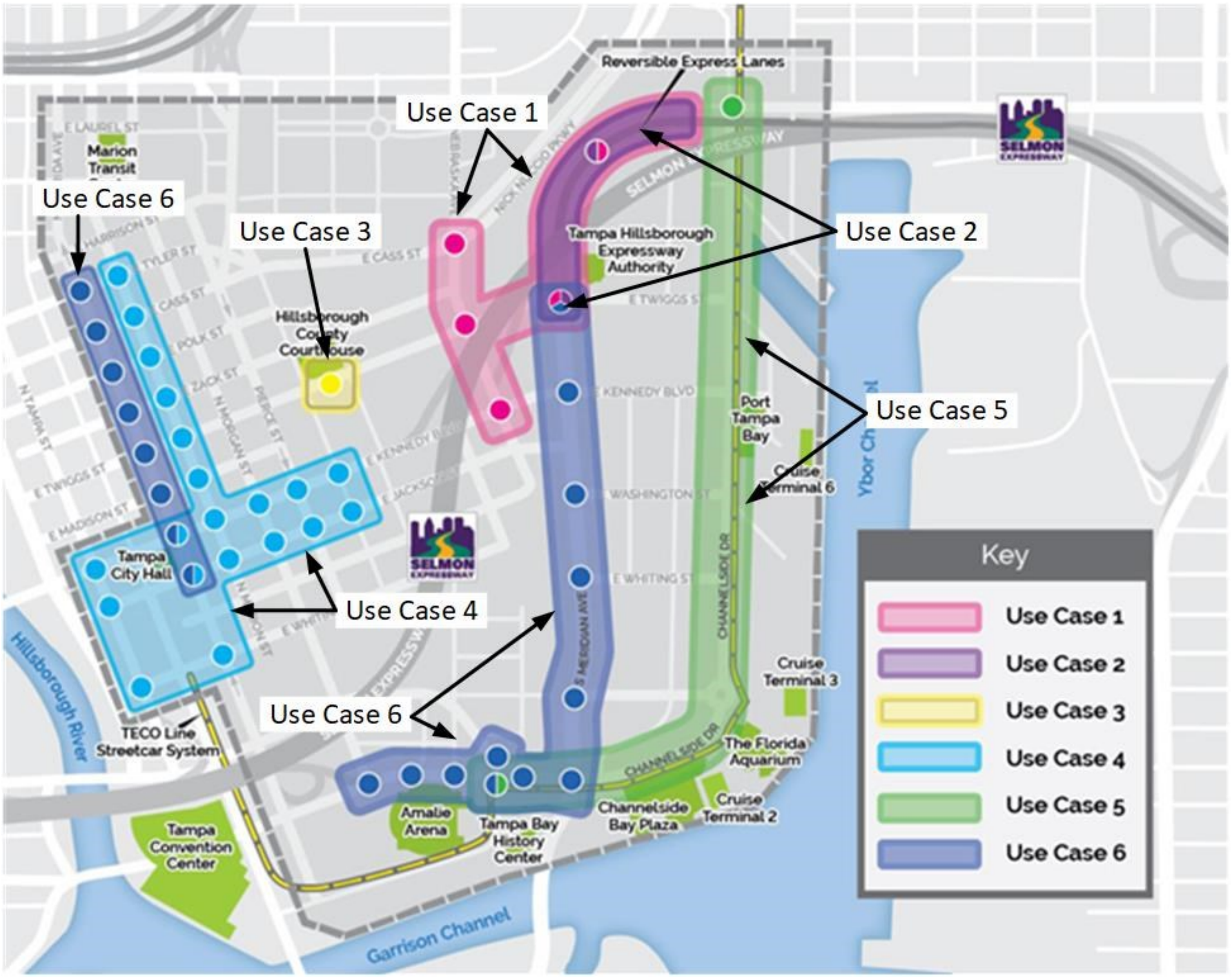
Tampa, Florida

This section summarizes the THEA CVPD in Tampa, FL. More information on the design and implementation of the THEA CVPD is available in the following documents:

- *Connected Vehicle Pilot Deployment Program Phase 1, Concept of Operations (ConOps)—Tampa (THEA).* [2]
- *Connected Vehicle Pilot Deployment Program Phase 1, System Requirements Specification (SyRS)—Tampa (THEA).* [3]
- *Connected Vehicle Pilot Deployment Program Phase 2, System Architecture Document—Tampa (THEA).* [4]
- *Connected Vehicle Pilot Deployment Program Phase 2, System Design Document—Tampa (THEA).* [5]

Description of Site

Figure 2 shows the THEA CVPD site in downtown Tampa, FL, which is bordered by the Ybor Channel (a cruise ship and commercial port channel) to the east, the Garrison Channel (a local waterway) to the south, Florida Avenue to the west, and Scott Street to the north. This area experiences several different mobility and safety issues daily. [2] For example, in the morning commute, the endpoint of the Reversible Express Lanes (REL) toll lanes is at the signalized intersection of East Twiggs Street and Meridian Avenue. East Twiggs Street and Meridian Avenue are also major routes for Hillsborough Area Rapid Transit (HART) buses into and out of downtown Tampa. Drivers experience significant delay during the morning peak, resulting in numerous rear-end crashes and red-light-running collisions. Also, Meridian Avenue and West Kennedy Boulevard experience transit signal delay, pedestrian conflicts, red-light running, and signal coordination issues. At the Hillsborough County Courthouse on East Twiggs Street, there is significant competing vehicular and pedestrian traffic during the morning peak. Similarly, commuters to MacDill Airforce Base (MAFB) who travel through the downtown area on the Simmons Expressway often encounter queues and delays where the REL exits into downtown. Also, during the morning peak, THEA is concerned with wrong-way entries into the REL in the downtown area. To improve mobility, enhance safety, mitigate the environmental impacts of queuing, and enhance agency efficiency, the THEA CVPD is deploying several CV applications and technologies to address operational issues in the deployment area.



Source: Center for Urban Transportation Research

Figure 2. Map. THEA CVPD Site [2]

Table 3 summarizes the number and types of devices that the THEA CVPD originally planned to deploy and that were deployed.

Deployment Objectives

The goal of the THEA CVPD was to improve the overall quality of life for Tampa Bay residents by creating a connected urban environment through the deployment of several CV applications. Table 4 shows the issues (in the form of Use Cases) that the THEA CVPD Team planned to address through its deployment. In a few of these Use Cases, the THEA CVPD Team planned to deploy multiple applications to address the issues. However, due to implementation delays and equipment issues, the THEA CVPD Team was unable to install all its planned applications.

Table 3. Summary of Devices for Deployment

Device Category	Tampa (THEA) Devices	Planned Number to Be Deployed	Actual Number Deployed
Infrastructure	Roadside units (RSUs) at intersections	40	49
Infrastructure	Light detection and ranging (LiDAR)–equipped pedestrian detection systems	2	2*
Vehicle	Light vehicles equipped with onboard units (OBUs)	1,600	1,020
Vehicle	HART transit buses equipped with OBUs	10	0**
Vehicle	Tampa historic streetcars equipped with OBUs	10	7
Vehicle to everything	Pedestrians equipped with the app on personal information devices (PIDs)	500+	0***

* THEA determined that the operational reliability of the LiDAR sensors was not adequate to support the Pedestrian in Crosswalk application and replaced them with video and thermal imaging sensors.
** Only deployed on a limited number of vehicles as a test.
*** During the deployment, the Pedestrian Crossing (PED-X) portion of the applications was not implemented due to issues associated with GPS accuracies in the PIDs.

Source: Texas A&M Transportation Institute based on information contained in References 6 and 7, 2022

Table 4. Summary of Use Cases Addressed by the THEA CVPD

Use Case	Condition	Description of Issues to Be Addressed	Applications
1	Morning Backup	As drivers approach the end of the Selmon Expressway REL, they enter a curve where the speed limit reduces from 70 mph to 40 mph. During morning rush hour, as vehicles exit the REL onto Meridian Avenue to make a right turn onto East Twiggs Street, the right-turn lane backs up. An additional issue is that many of these drivers then want to make a right turn onto Nebraska Avenue, which is an immediate right turn after turning onto East Twiggs Street. The combination of these issues causes the queue to back up onto the REL. This backup causes exiting vehicles turning right to use the shoulder as part of the right-turn lane. As drivers approach the REL exit, they may not be able to anticipate where the end of the queue is for the right-turn lane, potentially causing them to brake hard or attempt a rapid lane change	• End of Ramp Deceleration Warning (ERDW) • Electronic Emergency Brake Light (EEBL) • Forward Collision Warning (FCW) • Intelligent Traffic Signal System (I-SIG)
2	Wrong-Way Entry Prevention	At the exit of the REL onto East Twiggs Street, there is an easy opportunity for a driver to become confused and attempt to enter the REL going the wrong way. There are no gates or barriers at the westbound downtown terminus of the REL to prevent drivers from entering the REL going the wrong way. Drivers who are traveling on East Twiggs Street approaching the intersection where the REL ends and Meridian Avenue begins can mistakenly (or knowingly) enter the REL going the wrong way. Drivers approaching this intersection coming from downtown can inadvertently (or knowingly) make a left turn onto the REL exit. Conversely, drivers on East Twiggs Street approaching this intersection going toward downtown can inadvertently make a right turn onto the REL exit. Finally, drivers approaching the intersection on Meridian Avenue can potentially veer slightly to the left onto the REL exit. Each of these possibilities is a safety concern.	• Wrong-Way Entry (WWE) • I-SIG

Use Case	Condition	Description of Issues to Be Addressed	Applications
3	Pedestrian Conflicts	At the George E. Edgecombe Hillsborough County Courthouse, there is one primary crosswalk for pedestrian access to the main parking garage. The crosswalk is marked and has a yellow flashing beacon to warn drivers that they are approaching a crosswalk. This crosswalk is the primary route for jurors, lawyers, and other people to get to and from the courthouse. During morning rush hour, there is significant pedestrian traffic as potential jurors unfamiliar with the area attempt to arrive on time. This significant pedestrian traffic is compounded on Mondays and Tuesdays when new juror pools of up to 400 persons are required to report during rush hour. Lack of attention by drivers causes a safety concern for pedestrians trying to reach the courthouse.	• Pedestrian Collision Warning (PCW)
4	Transit Signal Priority	Two express bus routes (24LX and 25LX) use the Selmon Expressway to connect the east and west sides of the metropolitan area and exit the expressway to serve a stop in downtown. There are large residential communities in the areas of Brandon, Riverview, and Fish Hawk to the east of downtown. Aside from the employment center associated with the central business district, MAFB is situated close to the western or southern terminus of the Selmon Expressway. CV technologies were deployed to attempt to create a “virtual transit connection” between the two portions of the expressway by providing more reliable transit mobility using transit signal priority as the express buses negotiate the surface streets of downtown in the morning and evening peak hours.	• Transit Signal Priority (TSP)
5	Streetcar Conflicts	The Tampa Electric Company Streetcar runs along Channelside Drive from the Amalie Arena area, north, and past the Selmon Expressway. The streetcar is a steel-wheel-on-steel-rail fixed-guideway system in a dedicated right-of-way. An overhead catenary powers it, and the streetcar crosses intersections at grade. As a result, at various stops along the streetcar route, vehicles may have to turn right in front of a stopped or moving streetcar. As pedestrians disembark the streetcar and the streetcar prepares to depart, a vehicle may turn right in front of the streetcar. This situation occurs at signalized and non-signalized intersections, none of which have a right-turn protected movement. CV technology was used to provide information to streetcar operators and drivers to improve safety around these locations.	• Vehicle Turing Right in Front of a Transit Vehicle (VTRFTV)

Use Case	Condition	Description of Issues to Be Addressed	Applications
6	Traffic Congestion	Meridian Avenue has significant congestion and delay during morning peak-hour periods. This congestion is due to many MAFB commuters exiting the Selmon Expressway downtown and traveling through downtown arterial routes to reach the base entrance. As some of these commuters use surface roads through downtown, they interact with other traffic and pedestrians, increasing the likelihood of conflicts. In addition to Meridian Avenue, Florida Avenue (sections within the study area) experiences similar issues for downtown commuters.	• EEBL • FCW • Intersection Movement Assist (IMA) • I-SIG

Source: Texas A&M Transportation Institute based on information contained in References 6 and 7

Deployed Applications

The THEA CVPD Team originally intended to deploy 13 different CV applications in the deployment;[2] however, due to installation delays and equipment issues, the THEA CVPD Team was unable to deploy all the planned applications during Phase 3. Table 5 shows the list of final applications deployed by the THEA CVPD Team in each of the Use Cases.[7] As part of the Phase 4 activities, the THEA CVPD Team is currently working on deploying several of its planned applications (specifically, the I-SIG and TSP applications) that were not fully operational during the Phase 3 operational evaluation period.

Table 5. Applications Deployed in Each Use Case in the THEA CVPD [7]

Application						
Electronic Emergency Brake Light	Deployed	NA	NA	NA	NA	Deployed
End of Ramp Deceleration Warning	Deployed	NA	NA	NA	NA	NA
Forward Collision Warning	Deployed	NA	NA	NA	NA	Deployed
Intersection Movement Assist	NA	NA	NA	NA	NA	Deployed
Pedestrian Crossing Warning	NA	NA	Deployed	NA	NA	NA
Vehicle Turning Right in Front of a Transit Vehicle	NA	NA	NA	NA	Deployed	NA
Wrong-Way Entry	NA	Deployed	NA	NA	NA	NA
Transit Signal Priority	NA	NA	NA	Planned but not deployed	NA	NA
Intelligent Traffic Signals	Planned but not deployed	NA	NA	NA	NA	Planned but not deployed

NA = not applicable.

Source: Tampa Hillsborough Expressway Authority, 2020

The deployment was significantly impacted by several confounding factors. The long delay between when the participants were first recruited and when they first started receiving notifications appears to be a significant factor in participant retention. The high number of false alarms from some of the deployed applications may have also caused some users to stop participating in the study before the end of the evaluation period. The COVID-19 pandemic, beginning shortly after the start of the post-deployment periods, also significantly impacted evaluation results. While the evaluation period for some applications was longer, the post-deployment evaluation period for the ERDW application was only 34 days. A longer post-deployment period would be needed to better quantify mobility and environmental changes.

Safety, Mobility, Environmental, and Public Agency Efficiency Benefits

This section summarizes the SMEP benefits associated with the THEA CVPD. More detailed analysis of the benefits associated with this deployment is available in the following documents:

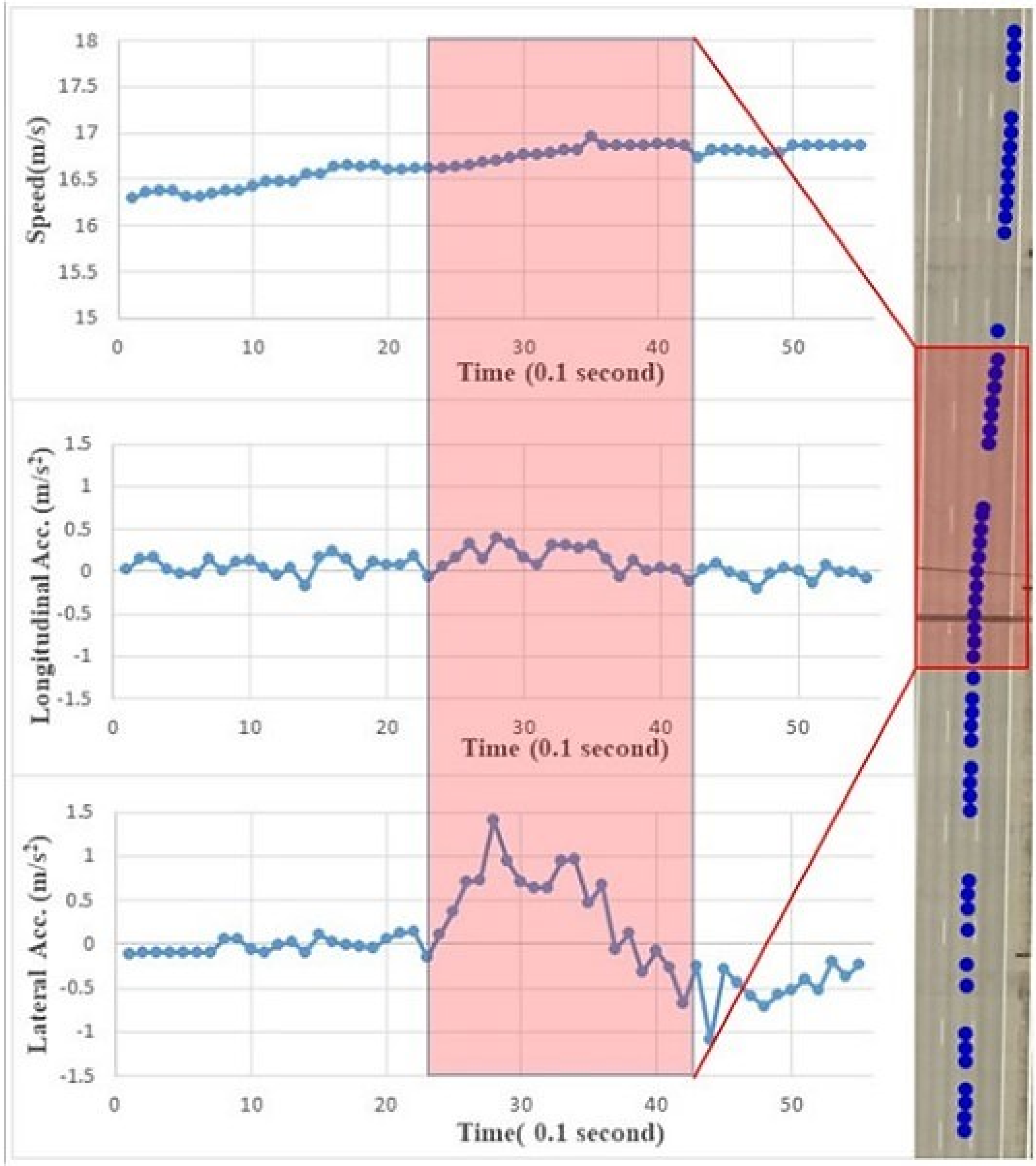
- *Connected Vehicle Pilot Deployment Program Performance Measurement and Evaluation—Tampa (THEA) CV Pilot Phase 3 Evaluation Report.* (7)
- *Safety Impact Assessment of THEA Connected Vehicle Pilot Safety Applications.* (8)
- *Connected Vehicle Pilot Deployment Program Independent Evaluation Mobility Impact Assessment—Tampa (THEA).* (9)
- *Connected Vehicle Pilot Deployment Program Independent Evaluation Environmental Impact Assessment—Tampa (THEA).* (10)
- *Connected Vehicle Pilot Deployment Program Independent Evaluation Public Agency Efficiency Impact Assessment—Tampa (THEA).* (11)

Crash Analysis

Both the THEA CVPD Team(7) and the Volpe Independent Safety Analysis Team(8) were unable to conclusively report that the safety applications resulted in reductions in crash frequencies or crash potential because vehicles equipped with CV technologies had limited interaction, THEA's analysis showed that the percentage of rear-end crashes remained similar in the before and after periods, and sideswipe crashes increased by 20 percent.(7) THEA's analysis showed, however, that the rates of conflicts per vehicle, normalized over time, decreased for the FCW (from 4.6 to 4.2) and the EEBL (from 2.2 to 1.7) applications, and increased for the IMA (from 0.1 to 0.5) application. Many of the safety applications experienced high false alarm rates and required extensive calibration, which may have prevented these applications from reaching their full crash reduction potential. Technology limitations and a limited number of interactions between equipped vehicles were also cited as reasons why safety benefits did not fully materialize. Furthermore, because crashes are rare events, the evaluation period was not long enough to determine the extent to which the applications may have produced safety benefits.

Driver Behavior Responses

The THEA CVPD Team assessed driver responses and reactions to alerts based on the vehicle's instantaneous longitudinal and lateral accelerations values. The THEA CVPD Team adopted a previously developed evaluation approach for detecting lane change behaviors to examine driver responses to the various applications used in the deployment.(7) The evaluation approach used data from Part I of the basic safety message (BSM) to generate three vehicle trajectories: travel speed over time, longitudinal accelerations over time, and lateral acceleration trajectory. Figure 3 shows an example of the trajectories for a lane change maneuver.

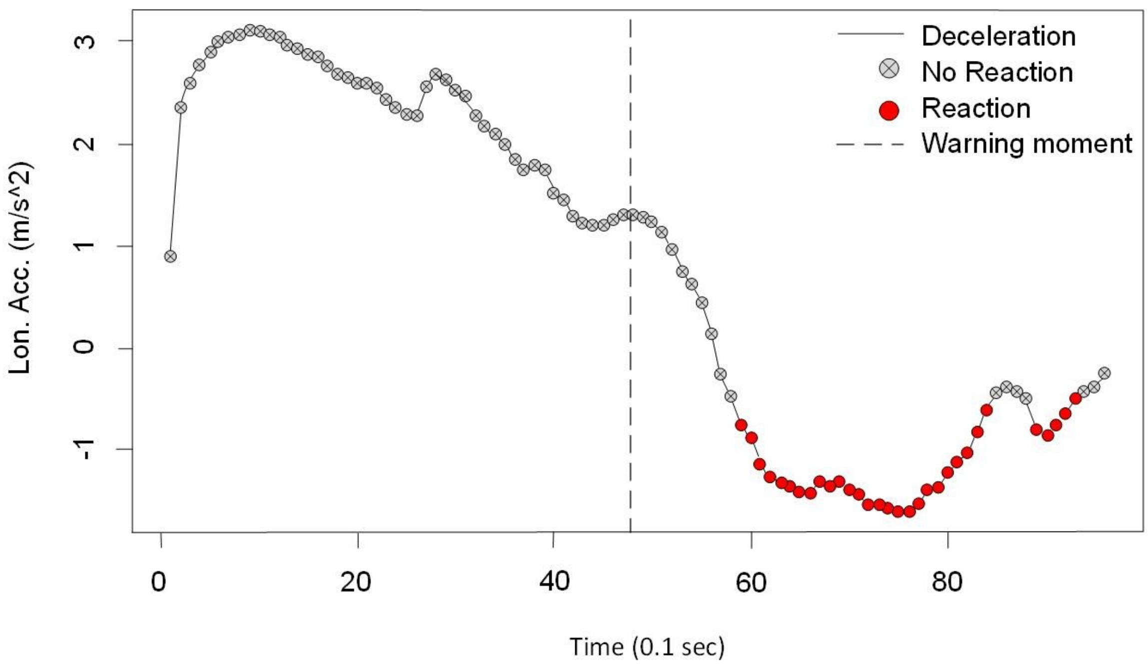


Source: Center for Urban Transportation Research, 2020

Figure 3. Graph. Example of Vehicle Speed and Accelerations Profiles during a Lane Change

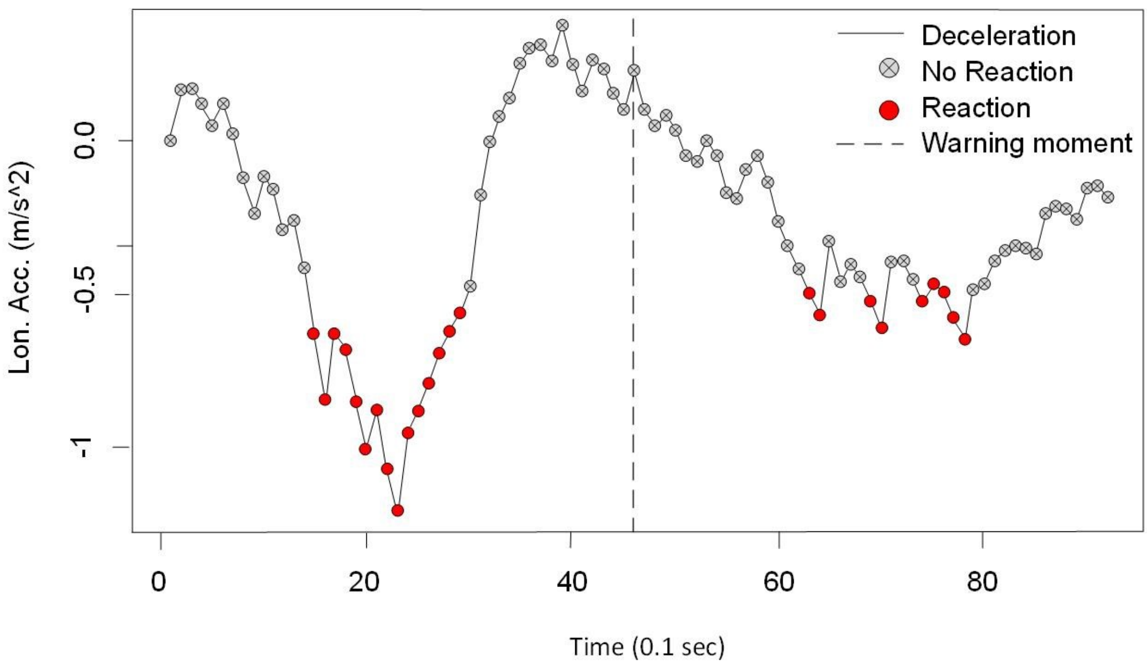
Drivers react to collision threats by engaging their brakes, changing lanes, or a combination of both. The THEA CVPD Team used longitudinal acceleration values in the OBU data logs to identify braking reactions and lateral acceleration characteristics of lane changing or swerving reactions. Because a previous analysis performed by the THEA CVPD Team revealed data gaps in the lateral acceleration values for vehicles equipped with aftermarket OBUs, the THEA CVPD Team substituted yaw rate to identify lane change maneuvers. The THEA CVPD Team conducted a calibration and validation study to confirm that substituting yaw rate for lateral acceleration was appropriate before using it to assess driver responses to the alert messages.

To analyze the participants' behavioral responses to warnings generated by vehicle-to-vehicle (V2V) applications, the THEA CVPD Team applied the conflict detection algorithm using 5- and 10-second profiles before and after the warning moment to identify true positive events. By comparing the sequence of the trajectories to when the alert was issued, the THEA CVPD Team inferred driver reactions to the alerts. Figure 4 shows a typical longitudinal trajectory for an event where the driver reacted after receiving the alert. Figure 5 shows a trajectory associated with a vehicle reacting before and after the alert was issued. Figure 6 shows an example of a trajectory where the driver did not respond to the alert, while Figure 7 shows a trajectory where the driver reacted before the alert was issued.



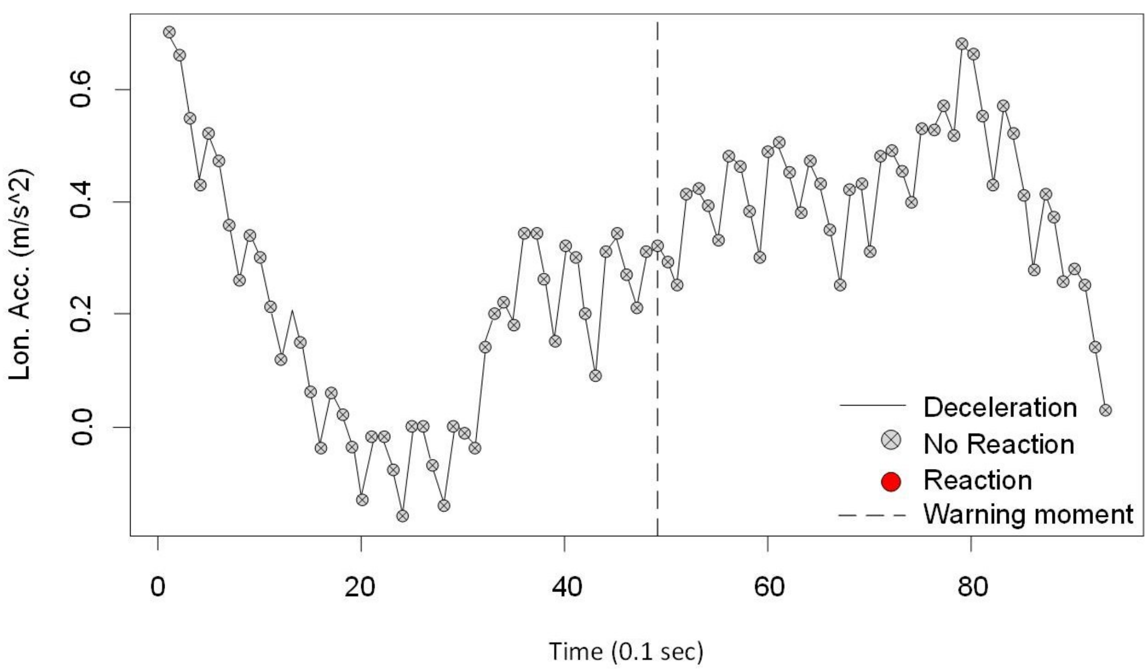
Source: Center for Urban Transportation Research, 2020

Figure 4. Graph. Example of Vehicle Profile Showing Driver Reaction to Warning Alert



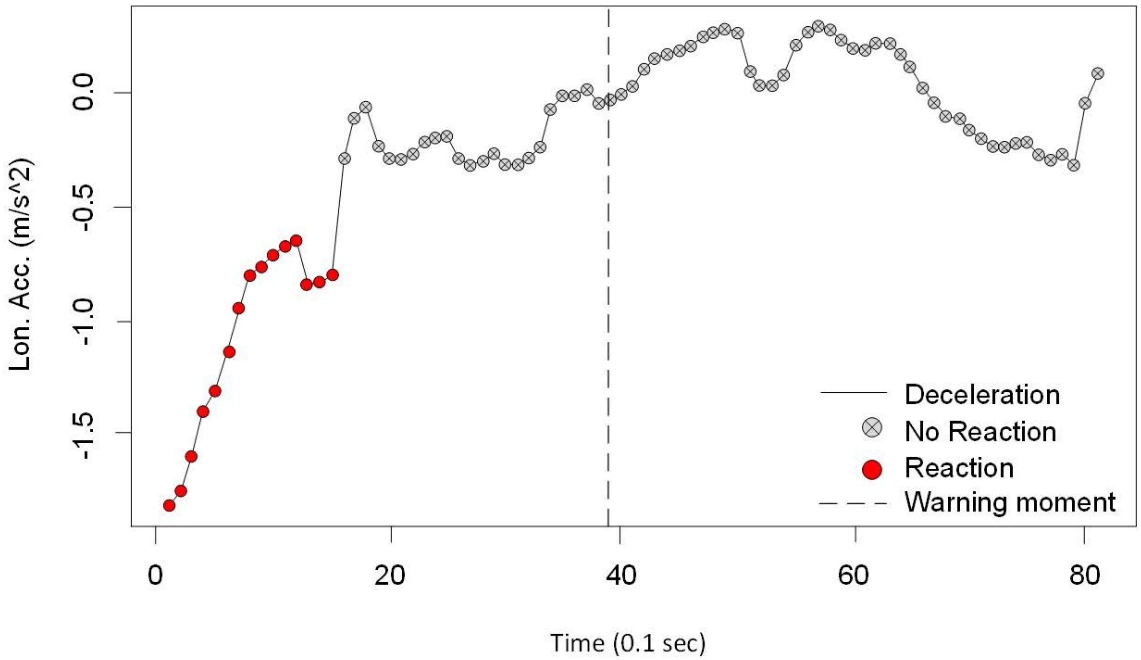
Source: Center for Urban Transportation Research, 2020

Figure 5. Graph. Example of Vehicle Profile Showing Driver Reaction before and after Warning Alert



Source: Center for Urban Transportation Research, 2020

Figure 6. Graph. Example of Vehicle Profile Showing No Driver Reaction to Warning Alert



Source: Center for Urban Transportation Research, 2020

Figure 7. Graph. Example of Vehicle Profile Showing Driver Reaction before Warning Alert

The THEA CVPD Team used this analysis technique to determine the number (and percentage) of drivers who reacted after receiving the warning.

A summary of the THEA CVPD Team's analysis of the safety applications is as follows:

- Both FCW and EEBL applications issued a substantial number of false positives (an alert when no threat was imminent). Of the 150 FCW alerts issued, 9 were true positive events, while 132 were false positive events. The EEBL issued only 4 alerts—3 of which were false positive events, and 1 was a true positive event. In evaluating Use Case 1, the two safety applications generated 10 warnings classified as true positive, but only 4 were shown to the drivers due to the evaluation's experimental design. Most of the false positive events were because the OBU could not correctly determine the lane in which the target vehicle was traveling.
- In the case of ERDW, the application must be tuned to avoid false positives, delivering warnings for a higher speed advisory when the vehicle was already traveling below that advisory. These false positives could have contributed to lowering participants' trust in the system or ignoring the warnings altogether.
- The THEA CVPD Team found that the WWE application needed considerable fine-tuning as well. Even though the WWE application was designed to trigger the "Do Not Enter" warning before drivers entered the REL ramp in the wrong way, the application tended to issue alerts even when vehicles were not actually entering the wrong way. The THEA CVPD team identified the loss of heading caused by the urban environment and overpasses as a primary cause behind the high rate of false positives.
- The initially deployed LiDAR-based PCW system faced several deployment challenges, resulting in reliability issues and failure to meet the required deployment specifications. During the operational time of the LiDAR sensors, the PCW application triggered 27 warnings that consisted of 85 percent

false positives due to the sensors' inability to correctly identify pedestrians and triggering warnings at large distances between the host vehicle and pedestrians. Because of these issues, the THEA CVPD Team replaced the LiDAR sensor with a thermal sensor to accurately detect and track pedestrians. After testing, the new system became operational on August 5, 2020; however, because of the change in travel patterns due to the COVID-19 pandemic, no PCW warning data were recorded from participant vehicles during the post-deployment evaluation period.

- During the evaluation period, the VTRFTV application generated 61 warnings that occurred in 34 unique events. The sequence of warnings varied from one warning per event to six warnings in one event. Out of those warnings, the THEA CVPD Team classified eight (13 percent) as true positive during four unique events, but only three warnings (one event) were shown to drivers due to the evaluation's experimental design.

Mobility

Table 6 summarizes the mobility benefits reported for each use case for the THEA CVPD. The THEA CVPD Team reported the following mobility-related benefits associated with its deployment:(7)

- Mean travel times on the REL decreased by 2.1 percent during the AM peak.
- Time spent idling (i.e., traveling at speeds less than 1 mph) on the REL during the AM peak reduced by 1.8 percent.
- Maximum queue length on the REL reduced by 1.8 percent.
- The travel time index (measured as peak-hour travel time divided by off-peak travel time) reduced from 2.7 to 1.9.

These mobility benefits are only for the ERDW applications deployed as part of Use Case 1. Unfortunately, the THEA CVPD Team was unable to get two applications—TSP and I-SIG—fully operational during the Phase 3 deployment period. These applications were anticipated to generate significant mobility-related benefits. THEA is currently working with its stakeholders to get these applications operational during Phase 4 of its deployment.

Respondents in the post-deployment surveys indicated being satisfied or very satisfied with overall travel time driving in downtown Tampa to a significantly greater degree than respondents in the initial survey. Eighteen percent of the after-immediate survey respondents and 26 percent of the after-final survey respondents were satisfied or very satisfied, compared to 9 percent of those in the pre-deployment survey. Levels of dissatisfaction were also higher among initial survey respondents, while significant proportions of the post-deployment survey respondents were neutral (neither satisfied nor dissatisfied). The percentage of respondents indicating that the applications deployed by THEA would lessen traffic congestion, increase fuel efficiency, and lower vehicle emissions remained the same throughout the study.

The after-final survey was conducted during summer 2020 when the COVID-19 pandemic was still very active, and the number of vehicle miles traveled (VMT) was still substantially down. Increases in the percentage of respondents reporting being satisfied or very satisfied during this period may have been impacted by the COVID-19 restriction still in place in the Tampa area.

Table 6. Summary of Mobility Benefits Reported for Each Use Case for the THEA CVPD [10]

Use Case	Deployed Applications	Reported Mobility Benefits
1: Morning Backup	• ERDW • EEBL • FCW	The ERDW contributed to: • 2.1 percent reduction in mean travel times • 1.8 percent reduction in idle time or time spent traveling at less than 1 mph • 1.8 percent reduction in queue length • A travel time index (measured as peak-hour travel time divided by off-peak travel time) reduction from 2.7 to 1.9
2: Wrong-Way Entry Prevention	• WWE	Use Case 2 did not generate quantifiable mobility measures directly attributed to the WWE application deployment
3: Pedestrian Conflicts	• PCW	THEA did not assess the impact of this application on mobility
4: Transit Signal Priority	Not deployed	The TSP application underwent a change in operations and therefore has not produced data for performance evaluation as of the date of this report
5: Streetcar Conflicts	• VTRFTV	THEA did not assess the impact of this application on mobility
6: Traffic Congestion	Not deployed	Use Case 6 only generated data conducive to establishing a baseline for a mobility assessment. THEA was unable to fully deploy the I-SIG and Multimodal Intelligent Traffic Signal System (MMITSS) applications during the evaluation period and did not generate the required data to conduct a before-after assessment.

Source: Texas A&M Transportation Institute based on information contained in Reference 7, 2022

In terms of perceived benefits, the participants believed that applications would result in fewer crashes and increased roadway safety. This opinion was especially true among participants in the final survey. There was a more positive perception that CV technology would result in less stressful driving among respondents to the initial survey than among those who were surveyed post-deployment. A significant percentage of respondents in the final survey identified lower car insurance rates as a benefit when compared with respondents in the prior two surveys.

Environmental

TTI used the reported pre- and post-deployment idle times to estimate the total fuel consumed by the idling equipped vehicle in each evaluation period (see Table 7).[10] The total number of minutes the CVs spent idling per day can then be computed by multiplying the average idle time per CV reported by the average number of CVs observed during the evaluation period (see Table 7). The total number of minutes CVs spent idling per day can then be converted into the number of hours the CVs spent idling by dividing by 60 minutes per hour.

TTI computed the average total amount of time the equipped vehicle spent idling during a typical peak period by dividing the total amount of observed idle time by the number of peak periods in each evaluation period.(10) The computation showed that, on average, equipped vehicles spent 78.4 minutes idling in the peak period in the pre-deployment period and 55.7 minutes idling per peak period in the post-deployment period.

Table 7. Average Total Idle Time per Peak Period by Equipped Vehicles on the REL (10)

Evaluation Period	Total Number of Observed Vehicles	Average Reported Idle Time (Minutes per Vehicle)	Total Amount of Observed Idle Time (Minutes)	Number of AM Peak Periods in Evaluation Period	Average Total Idle Time per Peak Period (Minutes)
Pre-deployment	18,457	1.1	20,303.7	259	78.4
Post-deployment	1,578	1.2	1,893.6	34	55.7

Source: Texas A&M Transportation Institute, 2022

After converting the average total idle time per peak period from minutes to hours and then multiplying by the average fuel consumption rate for a gasoline-powered engine under no load (as measured by the Argonne Laboratories), the TTI Evaluation Team then computed the total amount of fuel consumed while idling per peak period in both the pre- and post-deployment periods.(10) Table 8 shows the result of this computation. The computation shows that the total amount of fuel consumed by equipped vehicles idling on the REL per peak period in the pre-deployment periods was approximately 0.36 gallons and 0.26 gallons in the post-deployment period. This equates to a reduction in fuel consumption of 0.104 gallons per peak period or approximately 27 gallons per year.

Table 8. Total Fuel Consumed While Idling by CVs on the REL (10)

Evaluation Period	Average Total Idle Time per Peak Period (Minutes)	Average Total Idle Time per Peak Period (Hours)	Fuel Consumption Rate Idling (Gallons per Hour)	Total Fuel Consumed While Idling during Peak Period (Gallons)
Pre-deployment	78.38	1.30	0.275	0.36
Post-deployment	55.69	0.92	0.275	0.26

Source: Texas A&M Transportation Institute, 2022

Public Agency Efficiency

The TTI Evaluation Team conducted a qualitative assessment of the potential public agency efficiency benefits generated by the THEA CVPD. Key findings and lessons learned related to public agency efficiencies include the following:(11)

- One of the primary motivating factors for public agencies to participate in projects like the CVPD was the opportunity to work with and potentially shape emerging technologies. The experiences gained by implementing shelf-ready technology, getting it operational, and generating results was invaluable when it comes to planning, designing, deploying, and managing advanced technology projects.
- Stakeholders acknowledged that the experimental design at the beginning of the project assumed that the technology would be fully ready, out on the road, and operational. It turned out that the technology

was not fully ready as originally assumed. The deployment team had to make changes to those assumptions.

- With respect to the technology, the market in which the technology development was taking place was small-sized research and development businesses, some of which almost disappeared from the market. Regarding the deployment, the market around the technology was in rapid development, and significant growing pains were associated with the technology.
- The THEA CVPD provided the local stakeholders with valuable knowledge and experience in deploying and testing CV applications in the corridor and measuring their benefits.

One positive outcome of the deployment that proved to be valuable from a public agency efficiency standpoint was the performance monitoring tool developed to track the deployment.(11) The tool used data collected from OBUs and RSUs to monitor the status of the deployment and to provide insight into the locations and time frames where warning alerts and messages were provided to equipped vehicles. The tool, developed by the Center for Urban Transportation Research, allowed stakeholders to monitor the operational heath of the system by displaying the number of fully operational RSUs and OBUs. The tool also provides stakeholders with performance indicators that provide information on the effectiveness of the applications. The tool allowed stakeholders the ability to monitor system performance at individual intersections or on a system-wide basis. Stakeholders can aggregate performance statistics over time and by individual sites. This tool provides a solid foundation for the agencies to build upon as they enter future deployment phases.

New York City

This section summarizes the measured SMEP benefits associated with the New York City, NY, CVPD. More information on the design and implementation of the THEA CVPD deployment is available in the following documents:

- *Connected Vehicle Pilot Deployment Program Phase 1, Concept of Operations (ConOps)—New York City.* (12)
- *Connected Vehicle Pilot Deployment Program Phase 1, System Requirements Specification (SyRS)—New York City.* (13)
- *Connected Vehicle Pilot Deployment Program Phase 2, System Architecture—New York City.* (14)
- *Connected Vehicle Pilot Deployment Program, System Design—New York City.* (15)

Description of Site

ITS JPO also selected New York City (NYC) as one of three CVPDs. NYCDOT led the deployment. Located primarily in the Manhattan area and along Flatbush Avenue in Brooklyn (see Figure 8), the NYC CVPD focused on developing applications using V2V, vehicle-to-infrastructure (V2I), and infrastructure-to-pedestrian communications to improve safety as part of NYCDOT's Vision Zero goal to eliminate traffic-related fatalities and reduce crash-related injuries and damage throughout the city.(16) Originally, the NYC CVPD Team planned to deploy aftermarket safety devices (ASDs) in pay-for-hire taxicabs (yellow cabs) that traverse the midtown area, but delays in deployment due to privacy concerns and the changing pay-for-hire rideshare market in the midtown area did not make this a viable option. The NYC CVPD Team also enlisted the United Parcel Service (UPS) as an original participant in the initial stages of the project, but UPS also disengaged prior to the deployment phase. As a result, the NYC CVPD switched its deployment to city-owned fleet vehicles.

NYCDOT also installed over 450 RSUs in Manhattan and along Flatbush Avenue in Brooklyn to provide CVs with signal phase and timing (SPaT) information from the traffic signal system. The NYC CVPD Team also installed RSUs at strategic locations, such as bus depots, fleet vehicle storage facilities, river crossings, and airports, to facilitate the downloading of evaluation data and the uploading of application updates.

NYCDOT completed the Planning and Concept Development phase (Phase1) of the deployment in August 2016 and began the transition to the Design, Build, and Test phase (Phase 2) in September 2016.(16) The NYC CVPD Team started deploying RSUs in January 2019 and completed the deployment of RSUs in October 2020. Installation of the OBUs began in April 2019. NYC's COVID-19 restrictions in 2020 delayed full implementation until after the start of the Operations and Maintenance phase (Phase 3), which began January 1, 2021. At the start of 2021, the NYC CVPD Team had equipped over 2,150 vehicles. The NYC CVPD did not reach its target installations (3,000 vehicles) until August 17, 2021. (17)

Deployment Objectives

The primary goal of the NYC CVPD was to demonstrate how CV technologies and applications could potentially help NYCDOT advance its Vision Zero program to "eliminate traffic related deaths and reduce crash related injuries and damage to both vehicles and infrastructure."(16) As a result, the NYC CVPD focused on applications targeted to improve safety. The NYC CVPD Team identified mobility as a secondary but intertwined goal of the deployment. The NYC CVPD Team hypothesized that reducing the number of crashes (and their severity) and managing speeds could also improve mobility. Fewer crashes would result in less crash-related delays. Likewise, fewer stops may result in fewer crashes, particularly rear-end crashes. (17)

Source: New York City Department of Transportation, 2021

Figure 8. Map. NYC CVPD Deployment Corridors.

For this deployment, the NYC CVPD Team equipped 3,000 city-owned fleet vehicles with ASDs. (17) Various agencies use these vehicles to conduct the daily business of the city. Some equipped vehicles were pool vehicles available to agency staff on an as-needed basis, while other vehicles were assigned to individual staff members. While some could use their vehicles to commute to and from work, most participants used their vehicles for work-related trips. In most cases, drivers used the vehicles to make point-to-point, work-related trips, while other drivers were required to follow fixed routes. Table 9 shows the types of vehicles where the NYC CVPD Team deployed onboard devices.

Table 9. Agency and Vehicle Types Used in the NYC CVPD. [17]

Agency	Passenger Cars	Pickups and Trucks	Vans	Buses	Vehicle Installations
NYCDOT	Yes	Yes	Yes	No	1,238
NYC Dept. of Parks and Recreation	Yes	Yes	Yes	No	511
NYC Dept. of Corrections	Yes	Yes	Yes	Yes	259
NYC Dept. of Environmental Protection	Yes	Yes	Yes	No	159
NYC Dept. of Homeless Services	Yes	No	Yes	No	100
NYC Taxi and Limousine Commission	Yes	Yes	Yes	No	98
NYC Human Resources Administration	Yes	No	Yes	No	86
NYC Dept. of Citywide Admin. Services Fleet	Yes	No	No	No	78
NYC Dept. of Education	Yes	Yes	Yes	No	78
NYC Dept. of Buildings	Yes	No	No	No	69
NYC Administration for Children’s Services	Yes	Yes	Yes	No	65
NYC Dept. of Housing, Preservation, and Development	Yes	No	No	No	48
NYC Dept. of Health and Mental Hygiene	Yes	Yes	Yes	No	45
NYC Dept. of Design and Construction	Yes	No	No	No	38
NYC Office of Chief Medical Examiner	Yes	Yes	Yes	No	29
Metropolitan Transit Authority Bus and NYC Transit	No	No	No	Yes	14
NYC Emergency Management	Yes	No	No	No	12
NYC Dept. of Consumer Affairs	Yes	Yes	No	No	12
Anheuser-Busch InBev	No	No	Yes	No	10
NYC Dept. of Information Technology and Telecommunications	Yes	No	No	No	9
NYC Dept. of Probation	Yes	No	No	No	6
NYC CVPD Team Vehicle	No	Yes	No	No	1
Taxi Limousine Commission (Yellow Cabs)	Yes	No	No	No	1
Totals	**1,662**	**967**	**269**	**102**	**3,000**

Source: New York City Department of Transportation, 2021

Deployed Applications

The NYC CVPD Team identified seven Use Cases targeting NYCDOT's goals for the deployment. Table 10 summarizes the Use Cases identified for the NYC CVPD. Table 11 summarizes the applications deployed by NYCDOT in its deployment.

Because of NYC's response to the COVID-19 pandemic in 2020, the NYC CVPD Team experienced significant delays in reaching the full deployment of 3,000 vehicles. At the start of 2021, the beginning of the post-deployment evaluation period, the NYC CVPD Team had equipped over 2,150 vehicles. Installations in the remaining vehicles continued to occur well into the evaluation period. The NYC CVPD Team did not achieve full deployment until August 17, 2021. (17)

Safety, Mobility, Environmental, and Public Agency Efficiency Benefits

This section summarizes the SMEP benefits associated with the NYC CVPD. More detailed analysis of the benefits associated with this deployment is available in the following documents:

- *Connected Vehicle Pilot Deployment Program Performance Measures and Evaluation—New York City Phase 3 Evaluation Report.* (17)
- *Safety Impact Assessment of New York City Connected Vehicle Pilot Safety Applications.* (18)
- *Connected Vehicle Pilot Deployment Program Independent Evaluation Mobility Impact Assessment—New York City.* (19)
- *Connected Vehicle Pilot Deployment Program Independent Evaluation Environmental Impact Assessment—New York City.* (20)
- *Connected Vehicle Pilot Deployment Program Independent Evaluation Public Agency Efficiency Impact Assessment—New York City.* (21)

Crash Analysis

The primary objective of the NYC CVPD was to explore the potential of using CV technologies to achieve NYCDOT's Vision Zero goals.(17) The NYC CVPD team reported a total of 4,581 rear-end and 1,471 sideswipe crashes occurring between January 2021 and September 2021, after accounting for records with invalid longitude and latitude observations and missing values.(17) The NYC CVPD Team reported that no fatal rear-end collisions and two fatal sideswipe collisions occurred during the post-deployment analysis periods; therefore, the NYC CVPD Team grouped fatal collisions and injury collisions in one category for further analysis.

Table 10. Use Case Descriptions for the NYC CVPD.

Use Case Number	Use Case	Use Case Focus	Description
1	Manage Speed	Safety and mobility	Because excessive speed is a contributing factor in many crashes and fatalities, NYCDOT identified managing speeds to operate within safe limits to improve on the safe operations of the city's roadways. The NYC CVPD Team deployed three different applications aimed at managing the operating speed of equipped vehicles under different conditions: • Speed Compliance (SPDCOMP). • Curve Speed Compliance (CSPDCOMP). • Speed Compliance in Work Zones (SPDCOMPWZ).

2	Reduce V2V Crashes	Safety	The goal of NYCDOT's Vision Zero program is to reduce the number of fatalities and injuries on roadways, including V2V crashes. To reduce V2V crashes, the NYC CVPD Team deployed the following applications:
			• V2V applications including the following:
			    ○ Forward Collision Warning
			    ○ Emergency Electronic Brake Light Warning
			    ○ Blind Spot Warning (BSW)/Lane Change Warning (LCW)
			    ○ Intersection Movement Assist
			• Red-Light Violation Warning (RLVW)
			• Vehicle Turning Right in Front of Bus Warning (VTRW)

3	Reduce Vehicle-to-Pedestrian Crashes	Safety	Because of NYC's heavy pedestrian and bicycle environment and its history of frequent vehicle-to-pedestrian collisions, many of which result in fatalities, NYCDOT wanted to assess CV technologies as a potential strategy for assisting and protecting pedestrians at intersection crossings. As part of the deployment, the NYC CVPD Team deployed two different pedestrian-oriented applications: • Pedestrian in Signalized Crosswalk Warning (PEDINXWALK). • Mobile Pedestrian Signal System (PED-SIG).

Use Case Number	Use Case	Use Case Focus	Description
4	Reduce V2I Crashes	Safety	Because of the frequency and costs associated with vehicle strikes to bridges, NYCDOT identified a need to reduce the potential for V2I crashes. The NYC CVPD identified the Oversize Vehicle Compliance (OVC) application to address low-clearance issues for oversized vehicles and enforce related truck route restrictions.
5	Inform Drivers of Serious Incidents	Mobility	As the traffic manager and roadway infrastructure owner, NYCDOT needs to provide notification to drivers of areas to avoid and why. The NYC CVPD Team developed the Emergency Communication and Evacuation Information (EVAC) application to inform drivers of serious incidents.
6	Provide Mobility Information	Mobility	NYCDOT identified a need to develop reliable alternatives for providing travel time data for use in the adaptive traffic signal system. The NYC CVPD Team identified the CV Data for Intelligent Traffic Signal System (I-SIGCVDATA) application to augment NYC's existing toll tag technology for producing linked travel time information.
7	Manage System Operation		NYCDOT identified a need to manage and track the performance and operations of the deployed CV technologies. The NYC CVPD Team developed a series of system reports, databases, and management tools to support the day-to-day management and assessment of CV system operations.

Source: Texas A&M Transportation Institute based on information contained in Reference 15, 2022

Table 11. Summary Description of NYC CVPD Applications.

Application	Use Case	Description
Speed Compliance	1	This application notified drivers when their speed exceeded the posted speed limits. Using a zero-tolerance approach, any travel speed above the posted speed limit triggered a warning to the driver to reduce their speed to the posted speed limit. The speed limits were transmitted to the vehicle's ASD via map data message (MAP) messages broadcast from the system RSUs along all study corridors. The city's default regulatory speed limit was 25 mph.
Curve Speed Compliance	1	This application was deployed to inform CVs that they were approaching a sharp curve with a reduced advisory speed limit, thereby allowing the drivers to reduce vehicle speeds prior to the curve. The advisory curve speed limit was delivered to the vehicle's ASD via a traveler information message (TIM) broadcast from nearby RSUs for a predefined geofenced area approaching the curve. The application was deployed along selected on-ramps to the Franklin D. Roosevelt (FDR) Parkway in Manhattan.
Speed Compliance in Work Zone	1	This application was deployed to provide CVs that were approaching a reduced speed work zone with information on the zone's reduced speed limit and warn the drivers if their speed was above the work zone's speed limit. The geofenced work zone area and its reduced speed limit were delivered to the vehicle's ASD via TIMs broadcast from nearby RSUs. In all cases deployed in Phase 3, the defined work zone speed limit was set to 15 mph, 10 mph below the default regulatory citywide 25-mph speed limit.
Forward Collision Warning	2	This application warned the driver of the host vehicle of an impending rear-end collision with a remote vehicle ahead in traffic in the same lane and direction of travel.
Electronic Emergency Brake Light Warning	2	This application enabled equipped vehicles to broadcast a self-generated emergency brake event to other surrounding CVs. Upon receiving such event information, the host vehicle receiving that message determined the relevance of the event and provided a warning to the driver, if appropriate.
Blind Spot Warning/Lane Change Warning	2	These two related applications aimed to warn the driver of the host vehicle during a lane change attempt if the blind spot zone into which the host vehicle intended to switch was (or would soon be) occupied by another CV traveling in the same direction.
Intersection Movement Assist	2	This application warned the driver of a host vehicle when it was not safe to enter an intersection due to a high probability of collision with other remote CVs (usually at stop-sign-controlled or uncontrolled intersections).

Application	Use Case	Description
Red-Light Violation Warning	2	This application was deployed to warn drivers of potential red-light violations. The application enabled a CV approaching an RSU-equipped signalized intersection to receive information regarding the signal timing and geometry of the intersection. The application used the speed and acceleration profiles of the host vehicle along with current signal timing and geometry information to determine if it appeared likely that the vehicle would enter the intersection in violation of a red traffic signal. If the violation seemed likely to occur, the application provided a warning to the driver. The application operated on the host vehicle's ASD by processing received MAP and SPaT messages broadcast from RSUs connected to signalized intersections.
Vehicle Turning Right Warning	2	This application was deployed to determine the movement of CVs near a host transit vehicle stopped at a transit stop. The application provided an indication to the transit vehicle operator that a nearby CV was pulling in front of the transit vehicle. The application was intended to help transit vehicle operators determine if the area in front of the vehicle was occupied before it pulled away from the transit stop. (This application was deployed in limited conditions and primarily under testing conditions.)
Pedestrian in Signalized Crosswalk Warning	3	This application was deployed using pedestrian detection equipment (dedicated field-mounted infrared camera) to inform RSUs at equipped intersections of the presence of pedestrians within a defined crosswalk at signalized intersections. When pedestrians were detected, nearby CVs were notified via RSU-broadcasted SPaT (to define active pedestrian detection) and MAP messages (to define geometry and crosswalk details). Using this information, the host vehicle's ASD warned the driver of the pedestrian presence as appropriate given the vehicle's trajectory.
Mobile Pedestrian Signal System	3	This custom smartphone application provided pedestrians with information regarding the geometric conditions and active signal state of the pedestrian signals (WALK/DON'T WALK) at signalized intersections. The application functioned by receiving both MAP and SPaT messages via a cloud-based infrastructure and a location augmentation device to provide more detailed location data than that provided by the native smartphone platform.
Oversized Vehicle Compliance	4	This application was deployed to inform drivers of connected trucks and other commercial vehicles of pending low-clearance conditions based on the height of the equipped vehicle. The application functioned on the host vehicle's ASD by receiving TIMs broadcast from nearby RSUs that defined a geofenced region ahead of low-height clearance conditions and warned drivers when they entered the region of a potential bridge strike. (This application was deployed in limited conditions during the pilot.)

Application	Use Case	Description
Emergency Communications and Evacuation Information	5	This application was deployed to help transmit information from NYC's Office of Emergency Management and NYCDOT's Office of Emergency Response to CVs near or within affected areas during defined incidents and events. The vehicle's ASD warned drivers of events with a custom message upon entering a geofenced area of concern, as defined by a TIM broadcast from a nearby RSU. (This application was deployed under test conditions only with test messages during the deployment. No true emergency messages were broadcast during the evaluation period.)
CV Data for Intelligent Transportation Signal System	6	This application used data from RSUs to monitor CV movements to provide RSU-to-RSU travel time data for use in other NYCDOT systems (specifically, the Midtown in Motion adaptive traffic signal system). The intent of this application was to determine if CV technology could provide comparable travel times to existing toll tag technology used by NYCDOT's Adaptive Control Decision Support System. The RSUs monitored and reported when equipped vehicles entered defined areas (usually the intersection "box") and reported those individual sightings back to NYCDOT's traffic management center (TMC). Additional software in the TMC then matched the sightings received from different RSUs to compute RSU-to-RSU travel link travel times.

Source: Texas A&M Transportation Institute based on information contained in Reference 15, 2022

Applying a survival analysis model to both rear-end and sideswipe collisions, the NYC CVPD Team found that traffic volumes were positively correlated to rear-end and sideswipe crash frequencies in the post-deployment. The team found a 1.39 percent and a 1.24 percent increase in injury and property-damage-only (PDO) rear-end crashes, respectively, for every 1 percent increase in traffic volumes.(17) Similarly, the NYC CVPD Team found that there was a 1.93 percent and a 1.59 percent increase in injury and PDO sideswipe crashes for every 1 percent increase in traffic volumes. The NYC CVPD Team attributed this increase in raw crash records to the recovering of traffic volumes after COVID-19 and other confounding factors.

From this analysis, the NYC CVPD Team estimated the crash modification factors (CMFs) for the post-deployment periods for injury and PDO-related rear-end and sideswipe collisions, after accounting for the increases due to traffic volumes.(17) Table 12 shows the estimated CMF associated with each crash type by severity level. Because all CMFs were below 1, this implied that rear-end and sideswipe crashes in both severity levels declined during the post-deployment periods, after accounting for the increases due to traffic volumes. Although the analysis showed that injury rear-end and sideswipe crashes reduced by 5.3 percent and 1.5 percent, respectively, during the post-deployment period, these reductions were not statistically significant. The analysis also showed, however, a 9.4 percent and 15.0 percent reduction in PDO rear-end and sideswipe collisions, respectively, during the post-deployment period. The NYC CVPD Team could not to attribute these reductions solely to the introduction of CV applications but suggested the reductions were a result of “a combined treatment effect for all the potential safety-related treatments that occurred simultaneously around NYC during the NYC CVPD implementation period.” (17)

Table 12. Estimated Crash Modification Factors during Post-deployment Period for Rear-End and Sideswipe Collisions

Crash Types	Fatal and Injury	Property Damage Only
Rear-end	0.947*	0.906
Sideswipe	0.985*	0.850

* Not statistically significant at a 95 percent Bayesian credible interval (like the confidence interval in Frequentist analysis).

Source: Texas A&M Transportation Institute, 2022

Driver Behavior Responses

The NYC CVPD Team also examined time-to-collision (TTC) values using action logs and simulation for different applications.(17) The NYD CVPD Team defined TTC as the time that remained until a collision between two vehicles would have occurred if the collision course and speed difference were maintained.(17) The NYC CVPD Team reported TTC values based on both field observations and simulation. The NYC CVPD Team only examined those records with the TTC below five seconds. Table 13 shows the results of the field-based analysis of TTC, while Table 14 shows the results for the simulation-based TTC analysis. While the simulation results suggest that the applications had a positive impact in increasing the TTC values between vehicles, the field showed no significant effect on increasing TTC values. The NYC CVPD Team attributed this to the limited number of interactions between two equipped vehicles entering proximity to one another in the field.

Table 13. Change in 15th Percentile Time-to-Collision Values for Different NYC Safety Applications Based on Vehicle Logs

Application	Number of Observations	Change in 15th Percentile Time-to-Collision (Seconds)	Confidence Interval	Statistically Significant? *
FCW	632	0.198	[–0.032, 0.428]	No
EEBL	10	–0.896	[–0.138, 1.929]	No
BSW	15	–0.097	[–1.121, 0.928]	No
LCW	15	0.265	[–0.057, 0.586]	No
IMA	29	2.951	[1.780, 4.122]	Yes
RLVW**	NA	NA	NA	NA

* At a 95 percent confidence level.
** Available in simulation only.
NA = not available.

Source: Texas A&M Transportation Institute, 2022

Table 14. Change in 15th Percentile Time-to-Collision Values for Different NYC Safety Applications Based on Simulation

Application	Change in 15th Percentile Time-to-Collision (Seconds)	Confidence Interval	Statistically Significant? *
FCW	+1.60	[–0.23, 3.43]	Yes
EEBL	+1.58	[–0.5, 3.67]	Yes
BSW	+2.43	[1.8, 3.06]	Yes
LCW	+2.03	[0.88, 3.19]	Yes
IMA	+2.951	[1.780, 4.122]	Yes
RLVW	+1.22	[0.72, 1.71]	Yes

* At a 95 percent confidence level.

Source: Texas A&M Transportation Institute, 2022

The Volpe National Transportation Systems Center Team also evaluated the safety impact of the safety applications on vehicle/driver performance in the NYC CVPD.(18) Volpe's evaluation was based on data collected around 160,289 alert events (from equipped vehicles and the infrastructure during the yearlong deployment that comprised a before period from January 1 to May 19, 2021, and an after period from May 20 to December 31, 2021). The experimental design involved a vehicle control group that only received silent alerts (recorded but not observed by drivers) from the safety applications during the before and after periods, and a treatment vehicle group that experienced silent alerts during the before period and active alerts (recorded and observed by drivers) during the after period. The following is a breakdown of the total alert events by:

- Application type: 107,609 (67 percent) by V2I applications versus 52,680 (33 percent) by V2V applications.

- Alert status: 65,231 (41 percent) with silent alerts versus 95,058 (59 percent) with active alerts.
- Deployment period: 51,348 (32 percent) in the before period versus 108,941 (68 percent) in the after period.
- Vehicle group: 10,097 (6 percent) by the control group versus 150,192 (94 percent) by the treatment group.

During the NYC CVPD, the treatment group erroneously received 1,790 active alerts in the before period and 3,622 silent alerts in the after period. These alerts, while valid, were excluded from the safety impact analysis. Consequently, the number of events with silent alerts was much smaller than the number of events with active alerts for most applications (except SPDCOMP), and this inhibited the ability to perform a meaningful statistical comparison of the treatment group performance between the before and after periods. The Volpe Team then decided to assess the safety impact of all applications, other than SPDCOMP, by comparing the response between all valid events with silent alerts and all valid events with active alerts, regardless of period (before or after) or vehicle group (treatment or control). Table 15 provides key results that exhibit statistically significant differences in vehicle/driver response between events with silent and active alerts for each safety application. (18)

Table 15. Results of Volpe's Safety Impact Assessment of the NYC CVPD Applications (18)

Application	Key Finding	P Value
SPDCOMP	16% increase in speed limit compliance	0.00
RLVW	41% reduction in red-light violation rates Reduction in brake reaction time by 0.4 s	0.00 0.01
CSPDCOMP	Reduction in minimum speed by 3.6 m/s Increase in speed differential by 1.5 m/s	0.00 0.00
SPDCOMPWZ	Increase in minimum speed of 0.2 m/s Decrease in speed differential by 0.2 m/s	0.03 0.10
FCW	Reduction in brake reaction time in the Lead Vehicle Decelerating (LVD) scenario by 0.13 s 25% reduction in near-crash rate in the LVD scenario	0.08 0.07
EEBL	Reduction in brake reaction time by 0.4 s Reduction in average deceleration by 0.17 m/s^2	0.03 0.08
LCW	12% reduction in lane change rate 46% reduction in unsafe lane change rate	0.07 0.04
BSW	77% reduction in unsafe lane change rate	0.07
IMA	Reduction in brake reaction time by 1.3 s	0.02

Source: Volpe National Transportation Systems Center, 2022

Mobility

Because the NYC CVPD focused primarily on improving safety, no applications directly impacted mobility (e.g., reductions in travel time, reductions in delay, and improvements in travel time reliability). Furthermore, because of deployment issues and challenges, the NYC CVPD Team had to change the fleet of vehicles on which to deploy the applications from taxis to city fleet vehicles. Government-owned vehicles use the transportation network differently than traditional commuter-type travelers. Based on the performance measures originally planned by the NYC CVPD Team, TTI identified the following deployed applications as having the potential to impact mobility:[19]

- SPDCOMP.
- PED-SIG.
- EVAC.

Using the performance data provided by the NYC CVPD Team, the TTI Evaluation Team assessed the impacts of these applications on mobility in the deployment area and concluded the following:[19]

- While the data showed that the SPDCOMP application successfully reduced the number of speed limit violations in the deployment fleet, the NYC CVPD Team did not have sufficient data available to allow a direct assessment of this application on mobility because of limited sample sizes and the change in the deployment fleet from vehicle-for-hire to city-owned fleet vehicles.
- Field studies of the PED-SIG application showed that average wait time for sight-impaired pedestrians was 31.0 seconds, and the average crossing speed of these individuals was 3.6 feet per second, slightly above the 3.5 feet per second walking speed recommended by the *Manual on Uniform Traffic Control Devices*. The NYC CVPD Team based this finding on a limited number of sight-impaired individuals with a limited number of sample crossings. Furthermore, no pre-deployment data were available for comparison purposes.
- The NYC CVPD Team collected data from the EVAC application only for test purposes. To avoid driver confusion, the NYC CVPD never activated the application under live operating conditions. As a result, the impacts of this application on mobility remain untested.

The TTI Team also assessed the indirect impacts on mobility of some applications. [19] TTI defined indirect mobility impacts to be those produced by the application even though the primary focus of the application was to address another issue. (An example of an indirect mobility impact would be reductions in congestion due to fewer collisions.) TTI identified the following applications as having potential indirect impacts on mobility:[19]

- CSPDCOMP.
- RLVW.
- V2V safety applications (including FCW, EEBL, BSW, LCW, and IMA).

Using the data provided by the NYC CVPD Team, the TTI Evaluation Team concluded the following about the indirect impacts of the NYC CVPD on mobility:[19]

- The NYC CVPD Team indicated that compliance with curve advisory speed limits increased after fleet vehicles started issuing CSPDCOMP alerts. Better speed compliance in curves may result in smoother flow and less turbulence at curve speed entry points. Reductions in turbulence could potentially have indirect impacts on mobility.
- The NYC CVPD Team reported that likely red-light violations reduced by 152 per 1,000 events after the fleet vehicles began issuing RLVW alerts. Although the NYC CVPD Team could not link this reduction directly to actual red-light violation warnings, it does suggest that the application has some potential to indirectly impact mobility. Fewer red-light violations may contribute to fewer right-angle collisions and reduce start-up delays for cross-street traffic at signalized intersections.

- The NYC CVPD Team reported that rear-end collisions declined by approximately 5 and 9 percent after FCW and EEBL warnings, respectively, became active in the fleet vehicles. Simulation experiments conducted by the NYC CVPD Team also indicated that both applications had a positive effect on reducing conflict risks. This finding suggests that these applications might have the potential for an indirect impact on mobility if deployment fleet vehicles have the same crash exposure as the general vehicle traffic in NYC.
- The NYC CVPD Team indicated that injury and PDO sideswipe collisions reduced by 1.5 and 15 percent, respectively, after the fleet vehicles started receiving BSW and LCW alerts. While there is no evidence that these applications were solely responsible for these reductions, it does suggest that these applications could potentially generate indirect mobility benefits through reduced crash potential.
- Because of limited sample sizes, the NYC CVPD Team was unable to assess if the IMA application had an impact on potential crash experiences. Therefore, the TTI Team was unable to assess if this application had any indirect impact on mobility.

The NYC CVPD Team also deployed a mobile accessible pedestrian signal application, PED-SIG. The PED-SIG was a custom smartphone application provided to visually impaired pedestrians with information regarding the geometry conditions and active signal state of the pedestrian signals (WALK/DON'T WALK) at signalized intersections. The NYC CVPD Team tested the application using 24 individuals with various degrees of sight impairments. Each individual used the application to make multiple crossing at signalized intersections in the deployment area. The NYC CVPD Team recorded pedestrian crossing speed, crossing travel time, wait time at each intersection, and time-outs at the crosswalk. The performance evaluation was based on approximately 170 runs. No pre-deployment performance data were able for comparison, so the following results reflect only performance in the post-deployment period:

- Mean crossing speed was 1.1 meters per second (or approximately 3.6 feet per second) with a standard deviation of 0.3 meters per second (0.9 feet per second). Fifty-four percent of the participants crossed faster than the assumed 3.5 feet per second walking speed used in signal timing designs.
- Average crossing time was 9.6 seconds with a standard deviation of 2.4 seconds. Crossing time varied with the width of street being crossed.
- Average wait time per crosswalk was 31.0 seconds. Some participants started crossing right after receiving the "Walk Signal Is On" alert from application, while a few waited for a red light to begin crossing. One participant waited multiple signal cycles before crossing to ensure the crossing notification was valid before crossing.
- Sixty-three percent of the participants veered outside the crosswalk at least once during the field test.

The NYC CVPD Team conducted simulation studies to examine the potential mobility benefits associated with preventing collisions from happening in the deployment area. The NYC CVPD Team used an existing Aimsun model of Midtown Manhattan, calibrated to 2018 pre-pandemic traffic conditions, to assess the potential mobility and environmental impacts associated with preventing crashes in the Manhattan area.[(17)] The Midtown in Motion model is a microscopic simulation model of a sub-area from a larger mesoscopic dynamic traffic assignment model. The NYC CVPD Team developed four hypothetical crash scenarios (see Table 16), with each scenario simulating a 30-minute lane blockage representing a crash in the scenario.[(17)] The NYC CVPD Team modeled only one scenario at a time, with and without closure. The NYC CVPD Team then compared the results of the with and without lane closure scenario to estimate the potential delay savings associated with preventing a PDO collision on the deployment corridor. The NYC CVPD Team did not allow the model to adjust signal timings in response to crash conditions. Also, the model did not allow traveler alerts to be issued asking drivers to avoid the area of the crash. Figure 9 shows the location of the crash scenarios on the simulation network.

Source: Texas A&M Transportation Institute, 2022

Figure 9. Map. Locations of Crash Scenarios on Simulation Network (17)

The NYC CVPD Team simulated network performance with and without the lane-closing events. The team assumed that normal network performance best represented operations if the CV technology could prevent crashes from occurring.(17) Therefore, by comparing network performance with and without these collision events, the CVPD might demonstrate, in part, secondary mobility and environmental benefits of CV technology. To account for the stochastic nature of the simulation model, the NYC CVPD Team simulated each condition using five different random seeds and averaged the results from the five model runs to estimate network performance. The NYC CVPD Team used throughput, total vehicle delay, and average travel time measures of network performance. The NYC CVPD Team examined both the local-level (i.e., the area immediately at the point of the closure) and system-level (i.e., 10 blocks upstream of the crash location and on the immediate connecting side streets) impacts on roadway performance.

Table 16. Crash Scenarios Analyzed Using Simulation by the NYC CVPD Team. [17]

Simulated Crash	Location (Network Link)	Time of Crash	Lane Blockage Duration	Lanes Blocked	Direction of Flow	Total Number of Lanes
Crash 1	1st Avenue north of 63rd Street	16:30	30 minutes	1 lane (lane #4)	Northbound	4 general-purpose lanes with parking on the left and 1 exclusive bus lane to the right
Crash 2	5th Avenue south of 55th Street	16:30	30 minutes	2 lanes (lanes #1 and #2)	Northbound	3 general-purpose lanes with 2 exclusive bus lanes to the right
Crash 3	2nd Avenue south of 23rd Street	16:30	30 minutes	1 lane (lane #4)	Southbound	4 general-purpose lanes with 1 exclusive bus lane to the left
Crash 4	6th Avenue north of 47th Street	16:30	30 minutes	2 lanes (lanes #3 and #4)	Southbound	3 general-purpose lanes with 1 exclusive bus lane to the right and parking/bike lane to the left

Source: Texas A&M Transportation Institute, 2022

Table 17 and Table 18 show the local impacts (as measured by throughput and average speeds) on the block where the crash occurred.(17) These tables show that depending on the roadways where the events occurred, a 30-minute blockage reduced throughput in the immediate vicinity of the blockage by 5 to 15 percent and speed by 2 to 41 percent. These metrics include the effects of any self-diverting drivers changing their path in response to the blockages.

Table 19, Table 20, and Table 21 show the impacts of the same 30-minute blockages on the same crashes at the system level.(17) These tables show the changes in VMT, vehicle hours traveled (VHT), and vehicle hours of delay (VHD) reported by the NYC CVPD Team. These tables show that under the crash scenarios, VMT decreased by as much as 30 percent, VHT increased by as much as 32 percent, and VHD increased by as much as 50 percent. One potential explanation for this is that the impacts of each crash scenario extended well beyond the 10 blocks upstream of the closure location and traffic that normally would have entered the network in that area diverted to alternate routes outside the data collection area. Another possibility is that the simulation ended before all the impacted vehicles had cleared the impacted area.

Table 17. Throughput at Crash Location during Crash (17)

Simulated Crash	Location (Network Link)	No Crash Scenario Section Throughput (vph)	Crash Scenario Section Throughput (vph)	Change (vph)	Percent Change
Crash 1	1st Avenue north of 63rd Street	1,217.8	1,029.8	−188.0	−15
Crash 2	5th Avenue south of 55th Street	443.3	421.5	−21.8	−5
Crash 3	2nd Avenue south of 23rd Street	874.8	834.8	−40.0	−5
Crash 4	6th Avenue north of 47th Street	718.3	685.8	−32.5	−5

Source: New York City Department of Transportation, 2022

Table 18. Average Speeds at Crash Location during Crash (17)

Simulated Crash	Location (Network Link)	No Crash Scenario Section Speed (mph)	Crash Scenario Section Speed (mph)	Change (mph)	Percent Change
Crash 1	1st Avenue north of 63rd Street	19.4	12.1	−7.3	−38
Crash 2	5th Avenue south of 55th Street	24.2	14.3	−9.9	−41
Crash 3	2nd Avenue south of 23rd Street	17.2	16.9	−0.3	−2
Crash 4	6th Avenue north of 47th Street	25.3	22.6	−2.7	−11

Source: New York City Department of Transportation, 2021

Table 19. System Impacts of Crash—Vehicle Miles Traveled [17]

Simulated Crash	Location (Network Link)	No Crash Scenario VMT (Vehicle Miles)	Crash Scenario VMT (Vehicle Miles)	Change (Vehicle Miles)	Percent Change
Crash 1	1st Avenue north of 63rd Street	988.5	788.3	−200.3	−20
Crash 2	5th Avenue south of 55th Street	550.0	541.4	−8.6	−2
Crash 3	2nd Avenue south of 23rd Street	633.4	934.2	−0.8	0
Crash 4	6th Avenue north of 47th Street	808.6	774.2	−34.4	−4

Source: New York City Department of Transportation, 2021

Table 20. System Impacts of Crash—Vehicle Hours Traveled [17]

Simulated Crash	Location (Network Link)	No Crash Scenario VHT (Vehicle Hours)	Crash Scenario VHT (Vehicle Hours)	Change (Vehicle Hours)	Percent Change
Crash 1	1st Avenue north of 63rd Street	139.9	184.5	44.5	32
Crash 2	5th Avenue south of 55th Street	78.2	81.2	3.0	4
Crash 3	2nd Avenue south of 23rd Street	64.5	63.6	−0.9	−1
Crash 4	6th Avenue north of 47th Street	88.6	102.7	14.2	16

Source: New York City Department of Transportation, 2021

Table 21. System Impacts of Crash—Vehicle Hours of Delay [17]

Simulated Crash	Location (Network Link)	No Crash Scenario VHD (Vehicle Miles)	Crash Scenario VHD (Vehicle Miles)	Change	Percent Change
Crash 1	1st Avenue north of 63rd Street	102.9	154.8	51.9	50
Crash 2	5th Avenue south of 55th Street	57.1	60.4	3.3	6
Crash 3	2nd Avenue south of 23rd Street	633.4	934.2	300.8	47
Crash 4	6th Avenue north of 47th Street	58.1	73.6	15.5	27

Source: New York City Department of Transportation, 2021

Based on the results of these simulations, the NYC CVPD Team concluded that removing crashes from the network at these locations reduced total VHD by an average of 17.5 vehicle hours and by a maximum of 51.9 vehicle hours at one location.[17] While not all these delay savings can be attributed to the CV applications directly, the NYC CVPD Team suggested that mobility benefits may be possible if it can be shown that CV technologies successfully reduce crashes in the Manhattan area. However, determining the extent to which the applications deployed by the NYC CVPD had a direct impact on crash reductions requires additional analyses.

Environmental

Because the NYC CVPD Team did not provide any quantitative or qualitative analysis of the impact of the deployment on emissions or fuel consumption, the TTI Evaluation Team used the modeling results provided by the NYC CVPD Team to estimate the potential environmental benefits. The TTI Evaluation Team assumed that the CV applications successfully prevented collisions from occurring in the deployment network.[20] Using a method developed by the Argonne National Laboratory for estimated fuel consumption while idling,[22] the TTI Evaluation Team estimated fuel consumption by assuming that estimated total system delay resulting from each incident was a close approximation of total idle time. TTI used the differences in modeled total system delay with and without the closures to estimate the delay savings associated with reducing a single incident at a modeled location in the network. Because the exact vehicle fleet composition used in the simulation was not known, the TTI Evaluation Team also assumed that all vehicles impacted by each incident used a fuel consumption rate equivalent to that of a large sedan.

The TTI Evaluation Team used the results of the NYC CVPD Team's modeling showing the effects of a 30-minute capacity reduction at select locations on total system delay to estimate the potential environmental benefits associated with the NYC applications. Table 22 shows the potential fuel saving benefits based on estimated delay savings that would occur if a crash did not occur at the identified locations.

The TTI Evaluation Team then used the Environmental Protection Agency's Greenhouse Emissions Calculator [23] to estimate the reductions in greenhouse gases because of the fuel consumption savings by eliminating a single collision at each of the four locations. Table 23 summarizes the greenhouse gas emissions reduction benefits. The TTI Evaluation Team concluded that approximately 1,287 Kg of carbon dioxide emissions could be saved by eliminating a single collision at each of the four locations in the deployment network.

Table 22. Estimated Fuel Consumption Savings Generated by a Single Reduction in Crashes

Simulated Crash	Total Vehicle Hours of Delay (without Incident)	Total Vehicle Hours of Delay (with Incident)	Delay Savings (Vehicle Hours)	Fuel Consumption Savings* (Gallon)
Crash 1	102.9	154.8	51.9	20.2
Crash 2	57.1	60.4	3.3	1.3
Crash 3	633.4	934.2	300.8	117.3
Crash 4	58.1	73.6	15.5	6.0

* Assumes that all vehicles in the traffic stream are large sedans with a fuel consumption rate of 0.39 gallons per hour of idle time.

Source: Texas A&M Transportation Institute, 2022

Table 23. Estimated Reduction of Greenhouse Gas Emissions

Simulated Crash	Fuel Consumption Savings* (Gallon)	Greenhouse Gas Equivalent (Kg of CO_2)
Crash 1	20.2	179.5
Crash 2	1.3	11.6
Crash 3	117.3	1,042.4
Crash 4	6.0	53.3

* Assumes that all vehicles in the traffic stream are large sedans with a fuel consumption rate of 0.39 gallons per hour of idle time.

Source: Texas A&M Transportation Institute, 2022

Public Agency Efficiency

The TTI Evaluation Team also examined the extent to which the NYC CVPD helped improve the efficiency of the operations agencies in the deployment area.[21] For evaluation purposes, the TTI Evaluation Team defined *public agency efficiency* as any activity or response that impacts the agency's ability to respond to changing conditions or unexpected events in the deployment area, or to improve the agency's ability to manage its infrastructure assets. TTI assessed the impacts of the deployment on the following two public agency efficiencies areas:[21]

- Improved speed and regulatory compliance.
- Improved information dissemination and situational awareness.

The NYC CVPD Team deployed four different applications aimed at achieving better compliance by the equipped vehicles:

- SPDCOMP.
- CSPDCOMP.
- SPDCOMPWZ.
- OVC.

Based on the data available, the NYC CVPD Team reported the following related to the effectiveness of these applications to achieve better speed compliance in fleet vehicles:[17]

- The SPDCOMP application was effective at achieving better speed limit compliance by fleet vehicles. The NYC CVPD Team reported that drivers receiving alerts had a reduced number of speed limit violations compared to those that did not receive alerts. Vehicles receiving SPDCOMP alerts decelerated faster and took less time to reach compliance than vehicles that did not receive alerts.
- Limited observations prevented the NYC CVPD Team from reaching a conclusive finding about the effectiveness of the CSPDCOMP and the SPDCOMPWZ applications to produce better compliance with curve speed advisories and work zone speed limits, respectively, within the deployment area.
- The NYC CVPD Team operated the OVC application in a test mode only. The NYC CVPD Team used an artificially low bridge height to generate compliance with the over-height compliance application. As

a result, the NYC CVPD Team could not form any meaningful conclusion or evaluation on the efficacies of the application's ability to change vehicle motions or driver behaviors.

The NYC CVPD included two applications that had the potential to allow NYCDOT to better manage the roadway network using CV data. These applications include EVAC and I-SIGCVDATA.

The NYC CVPD Team developed the EVAC application to help transmit information from NYC's Office of Emergency Management and NYCDOT's Office of Emergency Response to CVs near or within affected areas during defined incidents and events. The intent of this application was to provide custom TIMs to CVs when entering a geofence-defined area near an RSU. While the NYC CVPD Team never needed to implement EVAC for a true emergency condition throughout the deployment phase, they activated EVAC test messages at a handful of locations during the initial stages of the before period and at one location throughout the entire before period.(17) The NYC CVPD Team found that there was potential merit to using CV technology to issues widespread emergency traffic alerts.

The NYC CVPD Team developed the I-SIGCVDATA application to test the feasibility of using CV data to monitor CV movements as an alternative technology for producing travel time data for use with the adaptive traffic signal system.(17) The purpose of evaluating this application was to investigate whether the data produced by CVs were comparable to those produced by NYCDOT's current travel time system data, which use electronic toll collection (ETC) technology. The NYC CVPD Team compared the one-week and one-month average and median travel times, and speed estimates produced by the two systems (the ETC and the CV systems).(17) The NYC CVPD Team made the following observations about the travel times and speeds produced by these two systems:(17)

- The CVs generated similar average and median 24-hour travel time profiles, which were comparable to those produced by the ETC system.
- The CVs generated similar average speed 24-hour travel time profiles, which were comparable to those produced by the ETC system.
- There were hours of the day when the NYC CVPD Team observed significant differences in average travel times. The NYC CVPD Team attributed this finding to the few CVs traversing the network.

Based on available data, the NYC CVPD Team concluded that the availability of block-by-block CV travel time data can help NYCDOT better identify bottleneck conditions than the ETC travel time data. The CV data allowed operators to better understand the spatial and temporal evolution of traffic congestion patterns in the network.

Wyoming

This section summarizes the Wyoming CVPD. More information on the design and implementation of the Wyoming CVPD is available from the following documents:

- *Connected Vehicle Pilot Deployment Program Phase 1, Concept of Operations (ConOps)—Wyoming.* (24)
- *Connected Vehicle Pilot Deployment Program Phase 1, System Requirements Specification (SyRS)—WYDOT.* (25)

- *Connected Vehicle Pilot Deployment Program Phase 2, System Architecture Document—WYDOT CV Pilot.* [26]
- *Connected Vehicle Pilot Deployment Program, System Design Document—Wyoming.* [27]

Description of Site

WYDOT's primary goal for implementing the Wyoming CVPD was to demonstrate the potential and feasibility of using CV technologies to improve safety and mobility along 402 miles of I-80 in southern Wyoming (see Figure 10).[28] As the lead agency, WYDOT explored using CV technologies to communicate road and travel information to commercial truck drivers and fleet managers that routinely travel the I-80 corridor. The deployment built upon WYDOT's extensive road weather and traveler information systems to provide warnings and alerts about road conditions, particularly during severe winter weather and high-wind events. [28]

Source: Wyoming Department of Transportation, 2021

Figure 10. Map. Roadside Unit Locations on I-80 [24]

The scope of deployment included implementing the following:[29]

- Deploying around 76 RSUs that could receive and broadcast messages using dedicated short-range communications (DSRC) along various sections of I-80.
- Equipping a combination of WYDOT fleet vehicles (e.g., snowplows, highway patrol vehicles, and others) and commercial trucks—all regular users of I-80—with OBUs capable of receiving alerts and broadcast BSMs. A portion of the vehicles could also collect and disseminate environmental and road condition information using mobile weather sensors.
- Developing multiple V2V and V2I applications that communicate alerts and advisories to drivers about road conditions. The applications were designed to support the in-vehicle dissemination of advisories for avoiding collisions, managing speeds, implementing detours, and alerting drivers about the presence of downstream work zones and maintenance and emergency vehicles—all based on the vehicle's location in the network.

- Enabling improvements to WYDOT's TMC and traveler information practices by using data collected from CVs. Targeted improvements include better activation of WYDOT's variable speed limit (VSL) and traveler information dissemination systems (511, dynamic message signs, and others).

Deployment Objectives

WYDOT's objectives for the deployment were as follows:(29)

- Deploy and operate a set of vehicles equipped with OBUs using DSRC connectivity. These vehicles included a combination of WYDOT snowplows, WYDOT fleet vehicles, WYDOT highway patrol vehicles, and private commercial fleet vehicles to broadcast J2735 BSMs and collect vehicle weather and road condition data for use in WYDOT's TMC. These vehicles also received roadway and traffic alerts wirelessly from the TMC so that drivers would have better information about current travel conditions to make better travel decisions.
- Deploy infrastructure devices (RSUs) with DSRC connectivity to transmit advisories and alerts to equipped vehicles traveling along I-80 in Wyoming.
- Leverage data provided by the equipped vehicle to develop and demonstrate a suite of V2V and V2I applications to support a variety of wide-area travel advisories and traffic management functions, including the following:
  - Setting and removing VSLs along the I-80 corridor.
  - Supporting 511 and other traveler information.
  - Supporting road weather advisories and freight-specific travel guidance through the WYDOT Commercial Vehicle Operations Portal.

WYDOT divided the deployment fleet into two groups: friendly fleet vehicles and partner CV fleet vehicles. Friendly fleet vehicles were vehicles over which the Wyoming CVPD Team had more access and from which the team was able to collect identifiable information. Friendly fleet vehicles included WYDOT snowplows, stakeholder fleet vehicles, and WYDOT highway patrol vehicles. Because these vehicles are public or informed partner fleets, the CVPD Team could track and collect detailed information from these vehicles. Partner CV fleet vehicles included all other vehicles, namely those from private stakeholders, who could not be tracked or accurately counted due to security and privacy concerns. Table 24 provides a breakdown of the number of vehicles in the deployment fleet.

Table 24. Number of CV Devices Installed as Part of Wyoming CVPD [30]

Vehicle Type	Deployment Category	Actual
WYDOT maintenance fleet (snowplows)	Friendly	53
WYDOT highway patrol	Friendly	66
State pool fleet	Friendly	18
Medium-duty friendly fleet	Friendly	21
Heavy-duty/commercial fleet	Partner CV fleet	167
Total equipped vehicles	Not applicable	325

Source: U.S. Department of Transportation Intelligent Transportation Systems Joint Program Office, 2022

Originally, WYDOT had planned to use two types of OBUs in its deployment—one DSRC based, and the other satellite based. Both OBU types had the ability to perform the following functions:[29]

- Broadcast BSMs (including trailer information in Part 2 of the message).
- Receive and display TIMs.
- Collect and send log data to the TMC.
- Sign and validate messages using USDOT's proof-of-concept Security Credential Management System (SCMS) pseudonym certificates.
- Receive and install over-the-air updates.
- Implement the FCW application per the Society of Automotive Engineers (SAE) On-Board System Requirements for V2V Safety Communications (J2945/1) standard.

All equipped vehicles in the deployment had the following core capabilities:[29]

- The ability to share and receive information via DSRC from other connected devices (vehicle and infrastructure based).
- The ability to broadcast J2735 BSMs.
- A device (display screen) allowing drivers to disseminate alerts and advisories received by the vehicle while en-route.

While initial testing went well with both OBU devices, complications arose after WYDOT switched from USDOT's SCMS to a private SCMS provider. Because of these complications and because of the Federal Communications Commission's (FCC's) decision to reallocate the DSRC 5.9-GHz spectrum, the DSRC vendor decided in December 2020 that it would no longer support, warranty, develop, or repair its OBU and RSU devices. As a result, the Wyoming CVPD Team pivoted to using only the satellite based OBUs. With the satellite-based system, vehicles received inbound alerts while traveling anywhere in the corridor and would upload vehicle performance logs when they passed an RSU.

Deployed Applications

The Wyoming CVPD deployed four onboard applications to provide drivers with key information to help improve their safety. These applications include the following:(29)

- Forward Collision Warning.
- Stationary Vehicle Alert (SVA).
- Infrastructure-to-Vehicle Situational Awareness (I2V-SA).
- Spot Weather Impact Warning (SWIW).

The Wyoming CVPD Team deployed a fifth application, Work Zone Warning (WZW)to provide approaching drivers with information about conditions that exist in work zones. This application used a portable RSU station deployed at the work zone location to transmit alerts to approaching drivers.

Table 25 provides a brief description of each of the deployment applications.

Safety, Mobility, Environmental, and Public Agency Benefits

This section summarizes the SMEP benefits associated with the Wyoming CVPD. More detailed analysis of the benefits associated with this deployment is available in the following documents:

- *Connected Vehicle Pilot Deployment Program Phase 3, Final System Performance Measurement and Evaluation—WYDOT Connected Vehicle Pilot.* (29)
- *Safety Impact Assessment of Wyoming Connected Vehicle Pilot Safety Applications.* (31)
- *Connected Vehicle Pilot Deployment Program Independent Evaluation Mobility Impact Assessment—Wyoming.* (32)
- *Connected Vehicle Pilot Deployment Program Independent Evaluation Environmental Impact Assessment—Wyoming.* (33)
- *Connected Vehicle Pilot Deployment Program Independent Evaluation Public Agency Efficiency Impact Assessment—Wyoming.* (34)

Crash Analysis

The Wyoming CVPD Team compared crash data from the post-deployment period to that collected during the baseline period. Table 26 shows the safety-related performance measures and targets used by the Wyoming CVPD Team to assess the safety benefits of the deployment.

Table 25. Applications Included as Part of the Wyoming CVPD

Application	Description
FCW	Issues an alert if there is a threat of a front-end collision with another CV in their travel lane and direction. Forward collision warning will help drivers avoid and reduce the severity of front-to-rear vehicle collisions. The system does not take control of the vehicle to avoid a collision.
SVA	A specialized version of FCW in which a downstream vehicle is parked on the side of the road or an adjacent lane along I-80. The application alerts drivers to the situation and helps them avoid or mitigate a potential collision with the parked vehicle.
I2V-SA	Provides relevant road condition information including weather alerts, speed restrictions, vehicle restrictions, road conditions, incidents, parking, and road closures. The information is broadcast from RSUs and received by the CV.
WZW	Communicates information to approaching vehicles about conditions at a work zone ahead. Approaching vehicles receive information about work zone activities or restriction information that could present unsafe conditions, such as obstructions in a vehicle's travel lane, lane closures, lane shifts, speed reductions, or vehicles entering or exiting the work zone.
SWIW	Enables localized road condition information, such as fog or icy roads, to be broadcast from an RSU and received by a CV.

Source: Wyoming Department of Transportation Connected Vehicle Pilot Website [28]

Table 26.Wyoming CVPD Safety-Related Performance Measures

Performance Measure	Target
Number of CVs involved in a crash • Initial crashes • Secondary crashes (total and specifically rear-end crashes)	N/A
Reduction of the number of vehicles involved in a crash (compare a 5-year average before pilot to CV pilot data)	25% reduction in the number of vehicles involved in a crash

Performance Measure	Target
Reduction of total and truck crash rates within a work zone area (compare a 5-year average before pilot to CV pilot data)	10% reduction in total and truck crash rate within work zones
Reduction of total and rates of truck crash along the corridor (compare a 5-year average before pilot to CV pilot data)	10% reduction in total and truck crash rates
Reduction of critical (fatal or incapacitating) total and truck crash rates in the corridor (compare a 5-year average before pilot to CV pilot data)	10% reduction in total and truck critical crash rates

Source: Wyoming Department of Transportation, 2022

The following summarizes the Wyoming CVPD Team's analysis of crashes after the deployment of the CV technologies:

- WYDOT did not receive any reports of crashes involving a CV during the post-deployment period (December 2020 through February 2022). This performance measure requires CV fleet managers to self-report collisions involving equipped vehicles in their fleets.
- The CV pilot did not reduce the average number of vehicles involved in crashes in the post-deployment evaluation period. In fact, the average number of vehicles increased from 1.29 to 1.43 (10.3 percent) when secondary crashes were not considered and increased from 1.41 to 1.53 (8.9 percent) when secondary crashes were considered. For the truck crash data, the average number of vehicles involved in a crash increased from 1.53 to 1.56 (1.8 percent) when secondary crashes were not considered and from 1.68 to 1.70 (1.5 percent) when secondary crashes were considered.
- The percentages of work-zone-related crashes increased from 11.8 percent of total crashes to 14.6 percent, along with an increase in crash rates, from 0.88 rate per million VMT to 0.91. Truck work zone crashes also increased as a percentage (12.0 to 14.7 percent) along with a larger increase in crash rates (0.86 rate per million VMT to 1.18).
- The crash rate per million VMT decreased for all corridor segments except for the VSL segment between Laramie and Cheyenne. The overall crash rate for the corridor decreased from 0.860 to 0.700, which is an 18.6 percent reduction. The truck crash rate decreased from 0.840 to 0.762, which is a 9.2 percent reduction.
- The number and percentage of fatal and incapacitating injury crashes (both total and those involving trucks) were slightly higher in the post-deployment year compared to the baseline period.

Because these results are based on a single year of post-deployment crash data, and that equipped vehicles comprised probably less than 5 percent of the total traffic stream on I-80, the findings cannot be attributed directly to the CVPD.

Driver Behavior Responses

Based on data obtained during the installation and testing phase of the project, the Wyoming CVPD Team identified the following four driver reactions they expected to occur because the driver received an alert:

- Vehicle reduced speed—a noticeable speed reduction occurred after a driver alert was issued.
- Vehicle stopped—the speed of the vehicle came to zero after a driver alert was issued, but the driver remained on the roadway, either in the travel lane or on the shoulder.
- Vehicle exited—the vehicle exited the freeway after a driver alert was issued.
- No action—no evidence of deceleration, stopping, or exiting was observed after a driver alert was issued.

Because of the time-consuming nature of linking alert data with vehicle BSM data, the Wyoming CVPD Team used a case study approach to assess the effectiveness of the alerts on driver behavior. The Wyoming CVPD Team used data from the following three events to examine driver reactions after receiving alerts:

- A high-speed wind event on June 22, 2021.
- A work zone closure occurring during the month of June 2021.
- A winter storm event occurring on February 5, 2022.

Driver reactions to the alerts were determined based on vehicle trajectory data during the event condition. The Wyoming CVPD Team used BSM data to examine the vehicle path during the event by plotting speed and accelerations of the vehicles by time. For the weather events, the Wyoming CVPD Team also graphed event attributes data (wind speed, wind gust speed, wind direction, work zone data, etc.) from the same period. For each analysis, the Wyoming CVPD Team had to first remove the BSM associated with WYDOT maintenance and highway patrol vehicles from the event data. Because no specific thresholds for defining the above listed driver actions were set during performance measure development, the Wyoming CVPD visually analyzed the vehicle's path to infer how the driver reacted to the alerts.

This analysis approach was time consuming due to the volume of data generated by the CV pilot and the privacy-by-design nature of the data, which ensures participants' privacy. Although the Wyoming CVPD Team was only able to examine relatively few driver reactions, making it difficult to determine the effectiveness of the alerts to produce desired driver reactions, this limited analysis appears to suggest that some vehicle reacted positively to the alerts. Another complicating factor was the uncertainty in whether the driver saw the alert and whether the alert matched with real-time road conditions. Because privacy and driver anonymity were an overriding concern, the Wyoming CVPD Team could only infer driver actions at the time of the alert.

The Wyoming CVPD Team also examined driver responses to V2V-type alerts. The Wyoming CVPD Team equipped vehicles to generate two V2V alerts: FCW and SVA. These applications rely on V2V communications through the system's DSRC capabilities. To produce an alert, two CVs must be within proximity of each other to allow the exchange of BSM data. Using the BSM data, each vehicle determines a TTC number based on the projected trajectories of the two vehicles to produce an alert. Given the overall small number of instrumented vehicles with DSRC capability and the large geographic extent of the project corridor, the probability of an interaction warranting an actionable FCW alert is low. Because of these factors, the Wyoming CVPD Team conducted only a limited analysis of V2V alert messages.

The Wyoming CVPD Team used a sample of FCW alerts from the first 15 days in February 2022. During this period, equipped vehicles generated 89 alerts. Five of these days (February 1, 2, 4, 5, and 12) had no FCW alerts, while February 3 had 39 alerts. All 89 alerts were mapped in Google Earth, and 36 alerts (40 percent) were found not to have occurred off the I-80 mainline. The dates and time stamps of the remaining 53 alerts were reviewed, and many of the alerts were clustered spatially and temporally, indicating they were related events where multiple alerts were given. These were combined into 10 unique events for further analysis, and geofences were constructed around them in order to spatially query the BSM data.

The Wyoming CVPD Team reviewed the BSM data files to determine the number of vehicles involved in each event and whether these vehicles had static or dynamic vehicle IDs. The Wyoming CVPD Team used static IDs to identify which events involved highway patrol or WYDOT maintenance vehicles. To reduce confounding factors associated with these vehicles, the Wyoming CVPD Team excluded these vehicles from the driver reaction analysis. For the 10 events, all but one event was found to involve highway patrol vehicles.

Mobility

Based on the data available at the time this report was prepared, there was no conclusive evidence to indicate the Wyoming CVPD had any impact on mobility on I-80, either directly or indirectly.[29,32].. Case study analysis indicated that under certain situations, drivers of CVs took appropriate action after receiving alerts. However, because no data were available from a control group, it was not possible to conclude that the action the drivers took was in direct response to receiving the alert as opposed to their normal reactions to the circumstances. However, neither the Wyoming CVPD Team nor the TTI Evaluation Team expected to have much change in daily mobility measures for the following reasons:[29,32]

- The focus of the deployment was on improving safety and demonstrating the feasibility and applicability of using CV technology to improve information dissemination during severe weather events. In most cases, the weather itself was responsible for the degradation in mobility, and WYDOT's emphasis is preventing collisions during these situations.
- The level of market penetration was extremely low (325 vehicles were equipped with CV technologies)—almost half of which were friendly fleet partners such as WYDOT snowplows, maintenance vehicles, and highway patrol vehicles. During severe weather conditions, the mission of these vehicles is to ensure the safety of other travelers, not optimize their mobility.

Another key success of the project was demonstrating the value of using satellite communications for disseminating traveler information. Through the CVPD, WYDOT was able to develop a partnership with a major vehicle satellite communication provider. After resolving several technical issues, WYDOT made it possible for CV drivers to receive TIMs while traveling on any State or Federal highway instead of just I-80. This function has allowed WYDOT to gather additional interest from fleet partners to receive weather and travel alert messages statewide.

Environmental

Unfortunately, no data were provided that would allow the TTI Evaluation Team to estimate the amount of delay savings or reduction in idle times resulting from the deployment.[29] The TTI Evaluation Team conducted an analysis of the potential fuel consumption reduction benefits using a simple input-output analysis and hypothetical closures in different sections of I-80.[33] The input-output analysis used capacity and demand to estimate the total amount of delay associated with closing portions of I-80. TTI estimated demand using annual average daily traffic (AADT) values reported by the Wyoming CVPD Team. Peak-hour demand was assumed to be 10 percent of the measured AADT for the section of roadway. The analysis also assumed that the closure would last one hour. The analysis shows the potential fuel consumption benefits *if* the CV technology could successfully prevent this hypothetical closure from occurring. This analysis was intended to provide order-of-magnitude estimates of the potential fuel consumption benefits.

The input-output analysis showed the following:[33]

- On average, preventing a one-hour closure within the corridor could generate potential fuel consumption savings of approximately 23.8 gallons of gasoline from passenger cars and 46.5 gallons of diesel from trucks, assuming a 50-50 vehicle mix.
- For a one-hour closure, fuel consumption due to idling was estimated to range from 19.3 to 67.3 gallons of gasoline for passenger cars and 19.4 to 67.3 gallons of diesel for trucks for different sections of roadway. This also assumes a 50-50 mix of passenger cars and trucks. Currently, the percentage of truck on I-80 ranges from 27 percent to 65 percent of the total traffic stream.

- Potential fuel consumption benefits are greater on the west end of the corridor, where AADT values tend to be higher compared to the east end of the corridor.
- Potential fuel savings are highly dependent on the locations of the incident, the total duration of the incident, input demands at the time of the collision, and many other factors.
- Intuitively, as the portion of vehicle mix changes, so does the amount of fuel consumed by the different vehicle classes. Trucks consume fuel at approximately twice the rate of automobiles.
- The results are highly dependent on the duration of closures. This analysis showed that an exponential relationship exists between fuel consumption and the total duration of closure.

One could also potentially infer environmental benefits based on adherence and conformity to posted regulatory speeds. Better speed compliance and conformity around the speed limit would imply fewer accelerations, producing a smoother trip. Fewer acceleration cycles might result in improved fuel consumption and fewer emissions. [(33)] The Wyoming CVPD Team had two measures associated with speed limit compliance:

- The percentage of vehicles traveling no faster than 5 mph over the posted speed limit.
- The percentage of vehicles traveling within (+/–) 10 mph of the posted speed limit.

WYDOT's analysis of speed compliance by all vehicles showed the following:[(29)]

- While the overall percentage of drivers traveling no more than 5 mph above the speed limit improved in the later months of the post-deployment period during all weather conditions, there was only a slight improvement (3 percent) in adherence during the mixed weather category—one of the conditions targeted by the deployment. In all other weather categories, the percentage of vehicles traveling no more than 5 mph over the speed limit declined in the post-deployment period. These speed adherence values are for all vehicles (including both equipped and unequipped vehicles), and the market penetration of CVs in the overall traffic stream was small.
- In terms of the percentage of vehicles traveling within a 10-mph buffer around the posted speed limit (a measure of variability of speed), the data showed a general trend for more uniform speeds around the posted speed limit during all weather conditions; however, as noted by the CVPD Team, this source of improvement may be "coming from the absence of storm conditions that resulted in particularly low speed buffer results in the baseline period."[(29)]

Public Agency Efficiency

The Wyoming CVPD was successful, however, at demonstrating how data from CV technologies could be integrated with other WYDOT systems to improve situational awareness. WYDOT hypothesized that the quantity of road reports and the coverage would increase during the CVPD and that the latency between reports would decrease. Using records for 499 weather events from January 2021 to April 2022, the Wyoming CVPD Team examined the extent to which the CVPD improved the quantity, coverage, and latency of road condition reports during the deployment. The following summarizes the Wyoming CVPD Team's findings:[(34)]

- The quantity of road condition reports coming into the TMC increased from 4.3 reports per section of I-80 per day during weather events in the baseline conditions to 16.9 reports per section per day in the post-deployment. An increase in the number of road condition reports will allow WYDOT operators to be more responsive to changing travel conditions.

- The coverage of the network with road condition reports per hour during weather events increased from 5.0 in the baseline condition to 6.4 in the post-deployment period. An increase in the coverage of the network using CV technologies would eliminate the need for maintenance vehicles to generate road condition reports and allow WYDOT to focus on keeping the roadway open during weather events.
- The latency of road condition reports per section during weather events dropped from 3.9 hours to 3.2 hours. Reducing the frequency between updates helps TMC operators better match traffic management strategies to changing operational and weather conditions.

WYDOT also hypothesized that CV technologies would improve its ability to disseminate changing road conditions.[29,34] In the deployment, all the equipped vehicles had the ability to receive TIM alerts and warnings via both DSRC and satellite communications. Both technologies were shown to have comparable performance in disseminating alerts and warnings to equipped vehicles.

Throughout the deployment, it become clear that significant improvements to the database were necessary to generate reliable and timely work zone TIMs. [29]

As a result of the deployment, WYDOT has expanded its ability to provide traveler information not only in the corridor but throughout the State. Using the data structures, data exchanges, and processes developed in the CVPD, WYDOT extended its ability to disseminate TIMs via satellite to include all State and Federal highways throughout the State. WYDOT extended its information dissemination capabilities by developing an Alexa Skill that can also produce alerts and warnings using the data provided by WYDOT's Situational Awareness applications.

Chapter 3. Characterization of CVPD Sites

This chapter summarizes the characteristics and attributes of the three CVPD locations. These attributes likely impact the *transferability* of deployment site lessons, approaches, and benefits to any other jurisdiction nationwide. As more locations consider deploying CV technologies, the characterization of these sites may guide future deployments and increase the likelihood of success for other CV deployments as the state of the practice matures.

Table 27 summarizes the attributes associated with each deployment site. This matrix was intended to help other locations looking to deploy CV technologies identify which pilot sites approximate their deployments.

Target Users

Target users refers to the different segments of the driving population which were the target of the deployment. Each deployment targeted a different segment of the traveling population. This section provides a brief description of the attributes of the target users associated with each deployment.

Tampa

For the THEA CVPD, the target users were traditional commuter drivers entering or traveling through downtown Tampa via the REL of the Selmon Expressway. The THEA CVPD Team recruited these drivers from its database of toll tag users in the area. THEA incentivized individuals to participate in the study by providing toll reduction incentives for a year. Participants were required to use their personal vehicle to participate in the deployment. Perspective participants in the THEA CVPD came primarily from THEA's existing customer pool. Other attributes of the Tampa participants included the following:(7)

- 43.5 percent of the users identified themselves as female, while 54.3 percent identified themselves as male.
- 54.8 percent of the users were between the ages of 36 and 55 years old.
- 61.9 percent of the users reported having obtained a bachelor's degree or higher in terms of education.
- 49 percent of the users reported traveling less than 100 miles in a typical work week.

Table 27. Summary of CVPD Site Attributes

Category	Tampa	New York City	Wyoming
Target users	• Daily commuters • Transit operators • Moderate population core • Pedestrians and other vulnerable road users	• Operators of NYCDOT fleet vehicles (professional) • Transit operators • Commercial truck operators • Fleet operators (snowplows, sanitation vehicles, etc.) • Dense population core • Vulnerable road users	• Freight operators: ○ Long-distance trips • Familiar with advanced technology in the cab
Vehicle population	• Personal vehicles • Transit buses (express) • Fixed-route transit: ○ Express buses ○ Trolleys	• Auto-oriented fleet vehicles with high fleet turnover • Buses • Trucks • Maintenance fleet vehicles (sanitation, snowplows, etc.)	• Long-distance interstate trucks (data consumer) • A high proportion of trucks and/or recreational vehicles (RVs)
Network characteristics (road types and geometries)	• Urban grid • Moderate driveway density • Moderate operating speeds • Exclusive transit ways • Moderate intersection spacing	• Urban grid • Corridor oriented • Low operating speeds • Tight intersection spacing • One-way pairs • Urban canyons	• Rural interstate • Linear corridor • High operating speeds (during ideal conditions) • Roadway vertical/ horizontal alignment
Operational conditions—weather	• (No CV applications were designed to operate only under specific weather conditions)	• (No CV applications were designed to operate only under specific weather conditions)	• Snow and rain events • High-wind events • Frequent closures due to hazardous travel conditions
Operational conditions—demand	• Moderate traffic demands • Moderate pedestrian traffic • Peak period (particularly AM) • Pass-through to a major trip generator (e.g., Air Force base) • Regional VMT • Vehicle travel and delay	• High traffic demands • High pedestrian traffic • Non-peak period (midday/shoulder of peaks) • Regional VMT • Vehicle travel and delay	• Low traffic demands • A high proportion of truck traffic • Consistent demand levels (limited peaking) • Regional VMT • Vehicle travel and delay

Category	Tampa	New York City	Wyoming
Issues to be addressed	• Point-specific safety issues: ○ Intersection oriented • Congestion-oriented issues: ○ Queuing ○ Improved signal progression • Conflicts between user populations: ○ Vehicle/pedestrian ○ Vehicle/trolley	• Individual driver safety/ performance • V2V conflicts • Corridor-level performance (secondary)	• Crashes during severe weather events: ○ Multi-vehicle collisions • Single-vehicle rollover (wind)

Source: Federal Highway Administration, 2022

New York City

The NYC CVPD focused on two different target users: one-vehicle based and the other pedestrian-based with vision-impaired pedestrians. Originally, the NYC CVPD planned to install the vehicle-based applications in privately-owned taxicabs; however, because of equipment delays, changes in the vehicle-for-hire marketplace, and privacy concerns by the taxicab operators, the NYC CVPD team changed the target users to be public fleet vehicle operators from different departments of the City of New York. Therefore, users in the NYC CVPD were all city employees that used their vehicles to conduct their normal daily work tasks. Because the NYC CVPD developed the CV technology in pool vehicles, many vehicles may have had numerous drivers that used the vehicles on an as-needed basis to perform different types of work-related activities (e.g., field inspections, maintenance, general operations of the city's roads, signals, buildings, parks, and other infrastructure). Other vehicles were assigned to a single user, some of whom had the authority to use their vehicle for commuting purposes. Some users could be considered as professional drivers (e.g., transit operators, sanitation vehicle operators) that travel using fixed routes; however, most were not professional drivers, but traversed the deployment area regularly in conducting their normal work activities. Most of the trips performed by these target users occurred on weekdays between the hours of 8:00 AM and 3:00 PM.

The NYC CVP Team also tested the PED-SIG application using 24 pedestrians with different levels of visual impairment. Most of these users (83 percent) were between 25 and 44 years old. Twenty-nine percent of these users identified themselves as partially sighted or low vision, while 71 percent of these users self-identified as being blind or totally bind. Fifty-eight percent of the users indicated that they used a long or white cane to assist with their mobility needs, while 21 percent indicated that they used a guide dog to assist them in their daily travels. Half of the users indicated that they traveled through six or more intersections daily.

Wyoming

The Wyoming CVPD targeted two sets of professional fleet operators: one set being primarily operators of government fleet vehicles and the other being heavy-duty commercial fleet operators. Both target population had considerable experience driving long distances under different operating conditions. The government fleet operators were primarily WYDOT maintenance vehicle operators (primarily snowplow operators and WYDOT highway patrol vehicles). Their trips generally consisted of traveling fixed portions of the deployment corridor multiple times during inclement weather conditions. Their primary trip purpose was to assess roadway conditions, clear incidents, and provide snow and ice accumulation removal during winter storms. These group of deployment users provided data input into the system about roadway travel conditions. This user group drove a mixture of high-performance light-duty vehicles and heavy-duty maintenance vehicles.

The second set of users were private, heavy-duty commercial fleet vehicle operators. This user population was selected because they tend to travel long stretches of the corridor on a regular basis. This user segment desires information about roadways and travel conditions to assist them in making travel decisions (e.g., changes in departure time, taking alternate routes, and sheltering in place). The users generally have considerable experience driving in all types of travel conditions. They also tend to be used to having technology in their vehicles to assist them with making travel decisions.

Vehicle Fleets

Each pilot site also had a different type of target vehicle as the focus of its deployment. The *vehicle fleet* refers to the types of vehicles on which the CV technology was deployed. This section provides a brief description of the vehicle fleets used at each deployment.

Tampa

The THEA CVPD vehicle fleet consisted of primarily personal vehicles. Between March 2018 and December 2018, THEA equipped 1,020 private vehicles with aftermarket OBUs. The applications were developed and deployed by aftermarket vendors using SAE standards and application specifications. Installations were performed by certified technicians from a local community college. The deployment fleet consisted of light-duty vehicles (primarily of passenger vehicles), a few HART buses (seven total buses), and eight steel-wheeled electric streetcars.

Although THEA equipped 1,020 vehicles with devices, the maximum number of active participants was 964, which occurred around December 2018. From this high point, the number of active participant vehicles declined steadily throughout the post-deployment period. On September 30, 2020, at the end of the post-deployment period, the number of active participant vehicles had decreased to 651 vehicles. Participants left the deployment for several reasons including lack of incentive, moving out of the Tampa Bay area, changing commuter routes, changing vehicle owners, mechanical issues with the vehicle, and other reasons.

New York City

The NYC CVPD Team equipped 3,000 vehicles with ASDs as part of the deployment. As previously mentioned, the NYC CVPD Team had planned to deploy the applications in privately-owned taxicabs; however, changes in market conditions, privacy concerns, and equipped delays forced the NYC CVPD Team to change target deployment fleet. In the final deployment, the NYC CVPD Team ended up equipping primarily government fleet vehicles from various departments within the City of New York. The breakdown of the vehicles by type included 3 percent buses (including transit and non-transit buses), 32 percent pickups or work trucks, 9 percent vans, and 55 percent passenger cars and sport utility vehicles. Typically, these vehicles travel between 100 and 120 miles per week and are active on the network between 7 to 10 hours per week.

The NYC CVPD Team deployed devices in 13 different makes and numerous different models of vehicles. The numerous different makes and models proved to be a complicating factor for the NYC CVPD Team because of the different antenna configurations and connections to the vehicles' onboard diagnostic ports. Due to the travel restrictions in place in NYC during the COVID-19 pandemic during 2020, the NYC CVPD Team did not reach full deployment in 3,000 vehicles until August 17, 2021. The NYC CVPD team began the post-evaluation period (January 2021) with a total of 2,150 completed vehicle installations.

Wyoming

The Wyoming CVPD fleet consisted of two main vehicle groups: friendly fleet vehicles and partner fleet vehicles. The friendly fleet was composed of vehicles from WYDOT's maintenance fleet, WYDOT's highway patrol, and other fleet vehicles. Because the vehicles were primarily from WYDOT, the Wyoming

CVPD was able to exercise a little more control over the friendly fleet vehicles compared to the partner fleet vehicles. The friendly fleet vehicles had fixed identification numbers, allowing their movements to be tracked through the deployment corridor.

Commercial fleet operators composed the partner vehicle fleet. Because privacy and security were a major concern for these vehicles, the Wyoming CVPD Team used dynamic identification numbers with these vehicles so their movements could not be tracked during the deployment.

Network Characteristics

Each deployment site differed in terms of the roadway network on which the CV technologies were deployed. This section provides a brief comparison of the roadway network characteristics of each deployment site.

Tampa

The Tampa deployment was representative of a deployment that might occur in a typical small- to medium-sized urban area. While the Tampa Bay area is quite heavily populated, the deployment was focused on the downtown area. The deployment area consisted of multiple one-way pairs traveling in the general east-west direction bisected by similar one-way pairs traveling north-south. The roadways in the deployment area were typically two lanes wide and contained parking on either one or both sides of the roadway. Roadway generally had moderate driveway densities that serve adjacent properties. Speed limits in the network were 30 mph, with several major arterials having higher posted speed limits (N. Florida and N. Tampa Streets had a speed limit of 35 mph and E. Jackson Street had a posted speed limit of 40 mph). The roads with the higher speed limits were the primary entry routes for traffic entering the downtown area. Most intersections were controlled by a traffic signal system operated by the City of Tampa, managed through its TMC.

Given that the THEA CVPD Team was unable to get the I-SIG and TSP applications fully deployed during the evaluation period, the deployment became focused on the following transportation interfaces:

- The transition at a high-speed expressway facility onto the downtown urban grid through a series of signalized intersection.
- The intersection between arterial streets and pedestrians near a heavy pedestrian generator.
- The interaction between a transit line that operated in a dedicated right-of-way and the automobiles that cross that line.

For the first transition, drivers approached the end of the Selmon Expressway REL where the speed limit reduced from 70 mph to 40 mph on a curve. During the morning rush hour, a queue forms in the right lane as vehicles exit the REL onto Meridian Avenue to make a right onto East Twiggs Street. Traffic turning right on the next downstream intersection creates queue spillback, which exacerbates the queue on the REL. High-speed traffic approaching the queue cannot anticipate where the queue for the right lane ends, causing them to hard brake or attempt a rapid lane change to enter the queue. Because this terminus is reversible (inbound during the AM peak and outbound during the PM peak), uninformed or unaware drivers approaching this terminal may inadvertently turn the wrong way into ongoing exiting traffic, creating the potential for head-on or sideswipe collisions due to a wrong-way movement. The ERDW, EEBL, WWE, and FCW applications were all intended to alleviate issues associated with this interface point.

Another interface issue addressed by the Tampa team was the interface between pedestrian movement at a heavily used unsignalized intersection and vehicle traffic traveling on the arterial. In this case, pedestrians must cross East Twiggs Street to access a major pedestrian generator (the county courthouse) from the parking garage. During specific times of day and days of week, a substantial number of pedestrians may be crossing the street through the crosswalk, and inattentive drivers can cause safety concerns for pedestrians trying to access these facilities.

The last interface issue addressed as part of this THEA CVPD was between the streetcar line and turning vehicular traffic. The Tampa Electric Company Streetcar provides a streetcar service along Channelside Drive from the Amalie Arena area north past the Selmon Expressway. The streetcar operates on a fixed-rail guideway in a dedicated right-of-way and crosses several streets at grade. At various stops along the route, it is common for vehicles to turn right in front of a stopped or moving streetcar. As part of the deployment, the CVPD Team equipped eight streetcars with CV technology to improve safety and operations at the interface points.

New York City

The NYC CVPD could be considered to represent the type of deployments that would occur along corridors in a heavily populated metropolitan area. The NYC CVPD area encompassed three district areas in the boroughs of Manhattan and Brooklyn. The first area was a 4-mile segment of FDR Drive from 50th Street to 90th Street in the Upper East Side and East Harlem neighborhoods of Manhattan. FDR Drive is a two-way, north-south limited-access highway with six travel lanes, three in each direction, on the east side of Manhattan. Its challenges include short-radius curves, a weight limit of 8,000 pounds, and minimum bridge clearance of 9 feet 6 inches. FDR Drive also runs through two tunnels underneath the New York Presbyterian Hospital from 68th Street to 71st Street and Carl Schurz Park from 81st Street to 90th Street. Commercial vehicles, trucks, and tractor trailers are prohibited on all parts of the corridor, and buses cannot access FDR Drive north of 23rd Street.

The primary deployment area included four one-way arterial roadways: 1st Avenue, 2nd Avenue, and 5th Avenue from 14th Street to 67th Street, and 6th Avenue from 14th Street to 59th Street. The 1st, 2nd, and 5th Avenue corridors were 2.6 miles long, while the 6th Avenue deployment area was 2.2 miles. These arterials are bisected by a series of streets creating a uniform grid pattern. The block lengths on the avenues range from about 650 feet between 1st and 2nd Avenue to about 920 feet between 3rd and 6th Avenues, and the typical distance between streets is approximately 270 feet. On-street parking is permitted along most of the deployment corridors in one or both directions of travel. Frequently, one or more lanes operate as a bus lane by time of day. Dedicated bicycle lanes exist on both the deployment avenue and street. The regulatory speed limit on all these facilities is 25 mph. The major intersections in this deployment area are all signalized.

The NYC CVPD also included Flatbush Avenue, located across the East River in Brooklyn. Flatbush Avenue could be considered to be more consistent with a typical urban arterial. It is bi-directional, running north-south with eight total lanes, four in each direction. Flatbush Avenue has a median from Tillary Street to Fulton Street and six total lanes, three in each direction, from Fulton Street to Grand Army Plaza. There is one parking lane on each side and no bike lanes.

Wyoming

The Wyoming CVPD represented a typical type of deployment expected to occur along a rural highway or interstate facility. I-80 is a four-lane, access-controlled facility that traverses the entire State of Wyoming and is one of the Nation’s major east-west freight corridors. This deployment covered all 402 miles of I-80. The corridor consists of long stretches (ranging from 60 to 115 miles exist between towns) of rural interstate. The elevation of I-80 in Wyoming is all above 6,000 feet, with the highest point reaching 8,640 feet (2,633 m) above sea level at Sherman Summit, near Buford, which is the highest community on I-80. The high altitude along the corridor increases the frequency of severe weather events (e.g., ice- and snow-covered road surfaces, poor visibility from fog and blowing snow, and high-wind events), especially during the winter season—between October 1 and May 1 of a given year. Because of I-80’s geographic position, with high elevation, combined with its daily freight traffic, WYDOT has provided truck parking and rest areas in between towns to aid freight traffic in complying with hours-of-service regulations and weather and road closure delays, but heavy vehicle operators frequently have difficulty finding available parking. The long distances between reasonable stop locations also become an issue when dealing with fast-changing weather systems where the roadway conditions can be substantially different at the end of a 60-mile road segment than at the beginning.

The lack of suitable and available routes to I-80 also created another challenge to the deployment. In Wyoming, the highway system beyond the interstates consists primarily of two-lane rural highways. These highways are not suitable for accommodating truck volumes beyond the local freight movement. During extended road closures, these two-lane highways are also typically closed to prevent large-scale diversion of freight traffic. Also, these alternate routes are not always built to the same geometric standards as the interstate, increasing the hazards during severe weather events. This leaves the available interstate system to absorb diverted traffic on either I-90, approximately 250 miles to the north, or I-70, approximately 100 miles to the south, both of which have their own challenges of mountainous terrain and severe weather events. Most freight traffic on I-80 is destined for the middle portion of the west (California, Nevada, or Utah), as opposed to the northwestern States, so diversion to I-90 through South Dakota and Montana adds considerable travel time to their routes. Diversion to I-70 is better with respect to travel distance but is in most mountainous terrain and can become severely congested due to urban traffic in Denver, tourist travel to the Colorado mountain towns, and oil and gas development on the western slope of Colorado. The undesirability of diversion to the other interstates can be observed by the willingness of freight trucks to park and wait out the I-80 closures.

Operational Conditions—Weather

Weather can have a significant impact on traffic performance and safety. Rain, snow, ice, and poor visibility are often major contributing factors to vehicle crashes. The Federal Highway Administration (FHWA) reports that motorists can waste about 1 billion hours stuck in traffic related to adverse weather. [36] This section provides a brief characterization of the weather attributes associated with each deployment site.

Tampa

Weather was not a significant factor in the Tampa deployment. Tampa is in a subtropical climate with hot and humid conditions from mid-May through mid-October. During this period, mid-afternoon thunderstorms are common, particularly from June through September. These thunderstorms are typically sporadic and localized and may last anywhere from a few moments to a few hours. During the summer, the average monthly rainfall is about 7.5 inches, compared to 2.5 inches per month during the wintertime. These localized storms can have a heterogeneous effect on travel behavior in the deployment area, impacting travel speeds and pedestrian trip patterns.

Tampa is subject to hurricanes; however, no hurricanes impacted travel in the Tampa area during the deployment phase.

New York City

Weather was also not a significant consideration in the NYC CVPD. Because of the potential impact weather could have on the performance of the applications, the NYC CVPD Team appended weather data to all collected event data to provide context to the warning messages and driver responses. The weather data came from the National Weather Service's Meteorological Aerodrome Report weather stations deployed near the corridor.

The NYC CVPD Team reported several significant weather events occurring during the post-deployment evaluation period, including the following:

- Winter Storm Orlena, which produced heavy snowfall and extended winter weather and clean-up conditions from January 31 to February 2, 2021.
- Winter weather conditions that produced heavy snow, sleet, and icy conditions on February 7 and February 18–19, 2022.
- Remnants of Tropical Storm Henri, which caused very heavy rainfall and limited flash flooding (August 21–23, 2022).
- Remnants of Hurricane Ida, which caused record rainfall and flash flooding.

The NYC CVPD team reported that fleet activity declined sharply because of changes in travel patterns and activities during these events.

Wyoming

The Wyoming deployment was designed specifically to provide information to alert and inform commercial fleet vehicles equipped with CV technology about weather conditions in the corridor, specifically winter weather and high-wind events. During the post-deployment period, the Wyoming CVPD Team reported a total of 499 weather-related events lasting a total of 5,807 hours.[29] While not all of these events were severe, these events all represent periods where travel on I-80 was impacted. Table 28 highlights some of the major weather events that occurred in the corridor during the evaluation. Most of these events impacted at least 200 miles of the corridor.

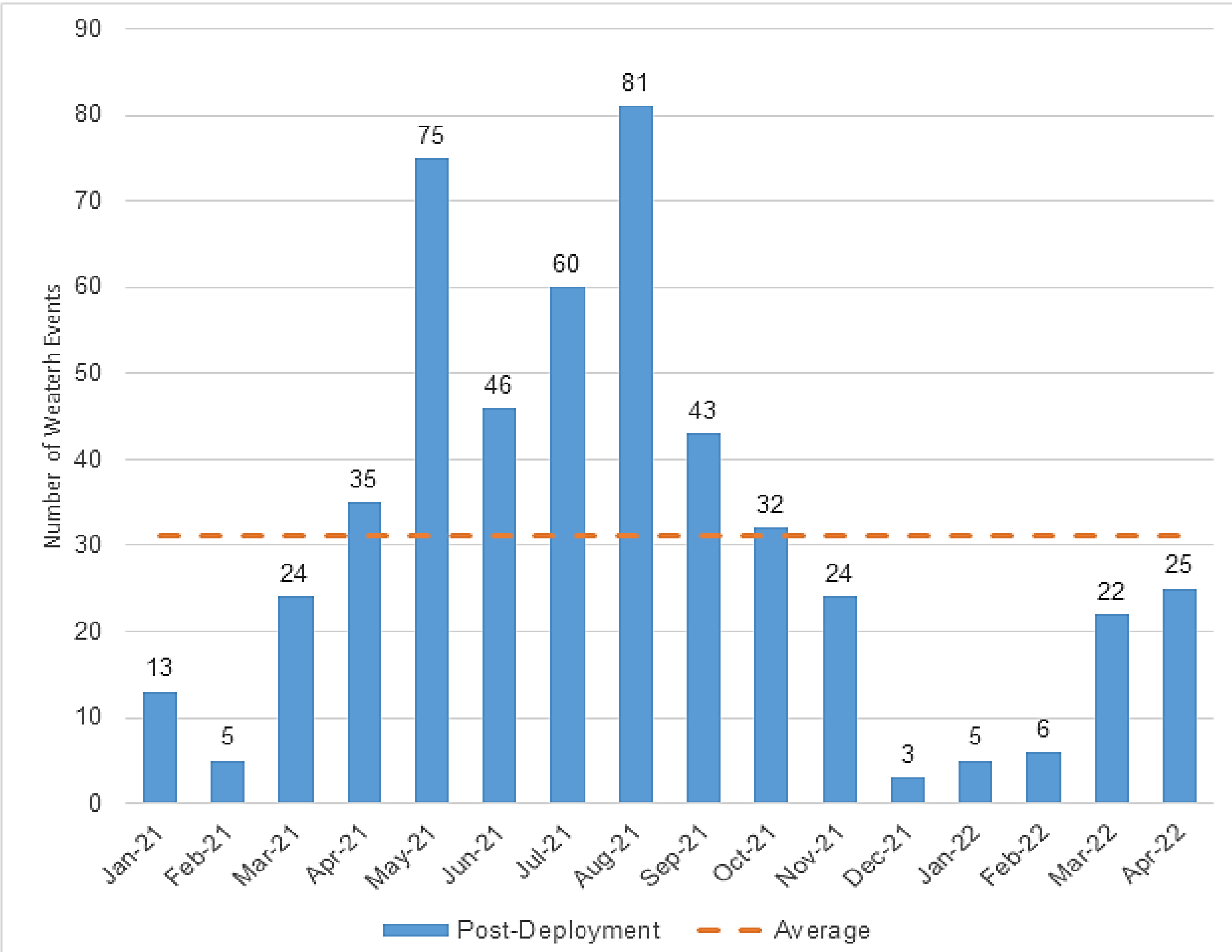
Figure 11 shows the average number of storms per month, while Figure 12 shows the average duration of these storms. While the frequency of events was less, the severity, complexity, duration, and coverage of storms are higher during winter months than during summer. For example, the Wyoming CVPD Team reported only five events occurring in February 2011 and in January 2022, but each of these events lasted over 100 hours and impacted nearly the entire deployment corridor. In contrast, during the summer months, the number of weather events per month increased substantially (between 45 and 80 events per month), but their duration ranged only from 2.5 to 5 hours.

Table 28. Significant Weather Events on I-80 in Wyoming CVPD, January 2021 to April 2022[29]

Date of Event	Hours of Storm	Number of Unique Reporting Sections	Event Conditions Listed in the Reports
Jan. 4–7, 2021	49	64 (entire I-80 corridor)	Slick, slick in spots, strong wind, blowing snow, extreme blow-over risk, closed to light high-profile vehicles
Feb. 2–16, 2021	293	64 (entire I-80 corridor)	Slick, slick in spots, closed, strong wind, blowing snow, extreme blow-over risk, closed to light high-profile vehicles
March 12–17, 2021	83	64 (entire I-80 corridor)	Slick, slick in spots, drifted snow, closed, fog, blowing snow, reduced visibility, black ice
April 12–17, 2021	104	64 (entire I-80 corridor)	Slick, slick in spots, drifted snow, closed, strong wind, fog, blowing snow, reduced visibility, black ice
May 28, 2021	6	34 (covering 215 miles of I-80)	Strong wind
June 10–11, 2021	16	58 (covering 355 miles of I-80)	Strong wind
July 5, 2021	6	42 (covering 280 miles of I-80)	Strong wind
Aug. 20, 2021	12	34 (covering 195 miles of I-80)	Strong wind, extreme blow-over risk, closed to light high-profile vehicles
Sept. 18–20, 2021	49	62 (almost entire I-80 corridor)	Slick, slick in spots, strong wind, fog
Oct. 11–16, 2021	92	64 (entire I-80 corridor)	Slick in spots, strong wind, blowing snow, black ice, extreme blow-over risk, closed to light high-profile vehicles, fog, reduced visibility
Nov. 8–17, 2021	142	60 (almost entire I-80 corridor)	Fog, reduced visibility, drifted snow, slick in spots, strong wind, extreme blow-over risk, closed to light high-profile vehicles
Dec. 4–5, 2021	33	58 (covering 355 miles of I-80)	Strong wind, extreme blow-over risk, closed to light high-profile vehicles
Dec. 6, 2021–Jan. 10, 2022	197	64 (entire I-80 corridor)	Slick, slick in spots, strong wind, fog, blowing snow, reduced visibility, black ice, no unnecessary travel, extreme blow-over risk, closed to light high-profile vehicles
Feb. 1–14, 2022	248	62 (almost entire I-80 corridor)	Slick, slick in spots, drifted snow, blowing snow, reduced visibility, black ice, fog, strong wind, extreme blow-over risk, closed to light high-profile vehicles

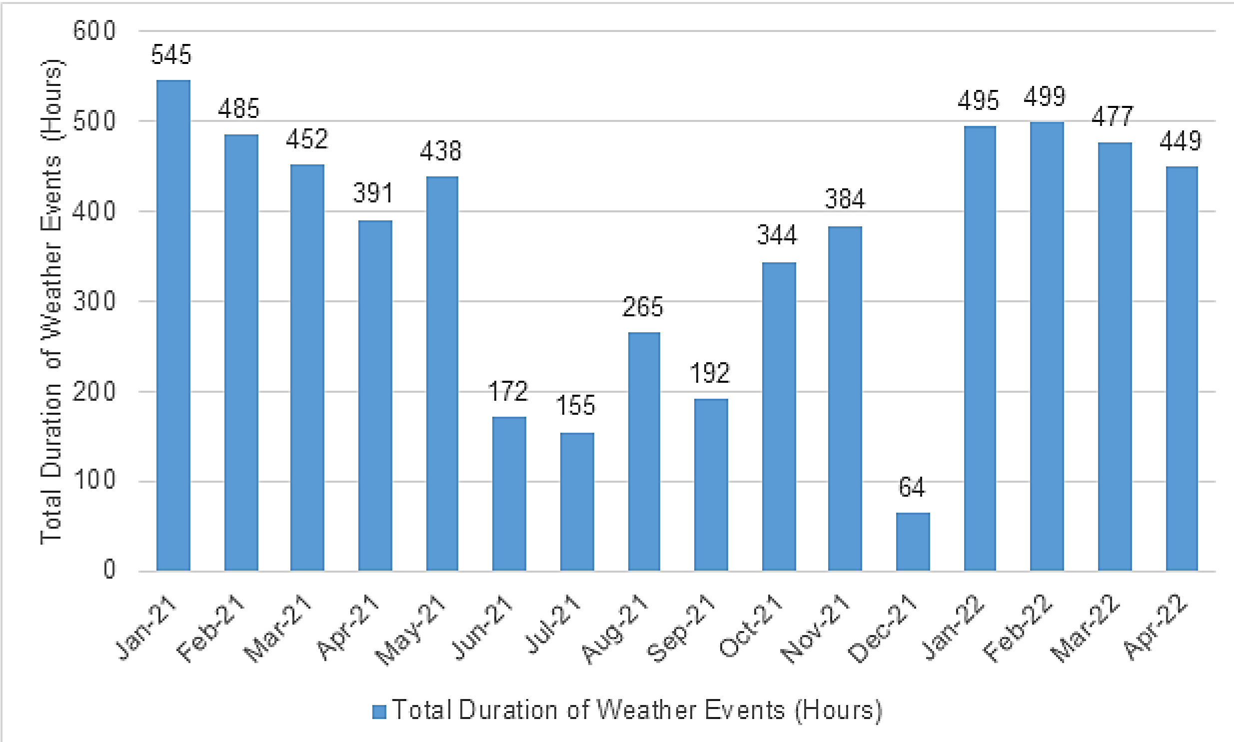
Date of Event	Hours of Storm	Number of Unique Reporting Sections	Event Conditions Listed in the Reports
March 4–14, 2022	204	64 (entire I-80 corridor)	Slick, slick in spots, closed, strong wind, blowing snow, black ice, extreme blow-over risk, closed to light high-profile vehicles
April 4–6, 2022	45	64 (entire I-80 corridor)	Strong wind, extreme blow-over risk, closed to light high-profile vehicles, slick, slick in spots, blowing snow, closed to light

Source: Wyoming Department of Transportation, 2022



Source: Wyoming Department of Transportation, 2022

Figure 11. Bar Chart. Number of Weather Events in I-80 Deployment Corridor [29]



Source: Texas A&M Transportation Institute based on data contained in Reference 29

Figure 12. Bar Chart. Total Duration of Severe Weather Storms in I-80 Deployment Corridor

Because of the frequency, severity, duration, and impact of weather events on traffic operations in the corridor, WYDOT has implemented several traffic management strategies to manage operations in the corridor during weather events. These strategies include weather-responsive VSLs, closure gates, and weather-related traveler information system (both pre-trip and en route). WYDOT has also developed a Commercial Vehicle Operator Portal, a free service where commercial fleet vehicle operators can receive information about current and forecasted road weather impact information. The forecasts are updated daily by WYDOT meteorologists and are tailored to provide specific information important to freight operators. The information includes 72-hour forecasts, in 12-hour increments for visibility and road surface conditions and in 3-hour increments for wind conditions. Each forecast includes a predicted impact level (low, moderate, or high) and is provided on a section. Commercial fleet operators can also customize forecasts to specific roadways (including I-80) commonly used by commercial fleets. The Wyoming CVPD is intended to supplement these strategies and improve the potential to provide real-time weather alerts and updates directly to commercial fleet operators in their vehicles.

Operational Conditions—Travel Demands

Each of the deployment areas exhibit different operating environments in terms of background traffic demands and operating characteristics. This section highlights some of the major differences in the travel demands exhibited by each of the deployment sites.

Tampa

Traffic demands in the downtown area are moderate with AADT volumes around 16,000 vehicles per day. The intersection of Twiggs Street and Meridian Avenue at the entrance/exit to the Selmon Expressway REL has long queues during the morning rush hour due to poor signal progression and right turns onto Twiggs Street immediately followed by a second right turn onto Nebraska Avenue. This causes the queue to back up onto the Selmon Expressway REL exit and into the curve, where rear-end crashes and other incidents are occurring. The area of downtown Tampa from the Selmon Expressway along Twiggs Street to Marion Street and along Meridian Avenue to Channelside Drive had a significant amount of queuing and congestion during the morning peak periods and special events.

The Tampa deployment area also experienced moderate pedestrian demands. One objective of the deployment focused on addressing driver safety at the Hillsborough County Courthouse on Twiggs Street. This area was characterized by significant competing vehicular and pedestrian traffic during the morning peak hours (7:00–10:00 AM).

New York City

The NYC driving environment is extraordinarily complex. Narrow roadways with high traffic demand and high parking demands make the operating environment especially complex. The deployment area exhibits a significant mixture of roadway users including transit, vehicles, bicycles, and pedestrians—all of which place heavy traffic demands at intersections particularly during peak hours. Each roadway in the deployment area exhibits high AADT volumes, ranging from over 30,000 vehicles per day to around 17,000 vehicles per day. Significant congestion exists on many of the roadways in the deployment area, especially during the morning and evening peaks. Traffic demands also remain high during the shoulder periods of the peaks.

The NYC CVPD Team reported the deployment experienced major special events that impacted travel in the deployment corridors. For example, the NYC CVPD Team reported that the annual meeting of the United National General Assembly created substantial disruptions to traffic flows on the east side of Manhattan September 21–27, 2021.

Because the deployment fleet consisted of city service vehicles, the impacts of national holidays and other special days reduced fleet activities on those days.

Wyoming

Of all the sites, the Wyoming site had the least amount of traffic demand. AADT demands are less than 15,000 vehicles per day. The site exhibits a high percentage of commercial truck use—with the percentage of trucks averaging about 49 percent of the vehicle mix. Because I-80 serves as a major truck route across the United States, traffic demands on I-80 are constant, except around some of the major metropolitan areas where traffic volumes increase slightly during normal peak hours. Peaking at these locations is short lived, and recurring congestion is not a significant issue along the corridor.

Issues Addressed

The issues addressed by each deployment was different. This section provides a brief synopsis of the types of issued targeted by each deployment.

Tampa

The THEA CVPD was based on traffic studies within the pilot area that identified six issues that can potentially be mitigated using CV technology. These issues were chosen based on historic data demonstrating current untreated needs in downtown Tampa, their impact to the community, and the ability to measure the performance of the applied technology versus the current, untreated conditions. Although THEA had originally planned to address transit travel time reliability and traffic signal timing issues as part of its deployment, THEA was forced to scale back its deployment due to time constraints, changes in the communications spectrum allocations at the Federal level, and resource and equipment availability issues. In the end, THEA deployed technologies to address the following four issues:

- Long queues during the morning rush hour backed up onto the Selmon Expressway REL exit and into the curve, where rear-end crashes and other incidents were occurring. THEA hypothesized that this was caused by poor signal progression and right turns in the vicinity of the exit.
- The entrance/exit point of the REL onto the downtown street network was a potential site for wrong-way entries. Wrong-way drivers were (and continue to be) a significant problem in the Tampa Bay area and elsewhere in the State.
- A mid-block pedestrian crossing combined with no protected left turn into a parking garage for the county courthouse created safety issues for pedestrians traversing Twiggs Street. Additionally, pedestrians were crossing at unmarked locations, further complicating the pedestrian safety concern.
- Downtown Tampa is a tourist destination and the home to several events. The streetcar line runs parallel to vehicle lanes with a common approach to traffic control signals. Often unaware of the trolley's presence, vehicles turn right into the trolley's path.

THEA's expectation for its deployment included the following: [6]

- The combination of the ERDW, EEBL, and FCW applications would provide drivers with better knowledge about the location of the end of queue to avoid the need for a hard brake or rapid lane change as they approached the REL exit in the right lane during the morning peak.
- The WWE application would alert drivers from mistakenly entering the REL going the wrong direction from E. Twiggs Street during both the morning and evening peaks
- The PCW application would alert drivers of pedestrians using the primary crosswalk from the main parking garage to George E. Edgecombe Hillsborough County Courthouse.
- The VTRFTV application would provide streetcar operators with information about vehicles turning right in front of the streetcar as they prepared to depart after letting pedestrians board or disembark from the streetcar at signalized and unsignalized intersections.

New York City

The NYC CVPD focused on safety improvements for both motorists and non-motorists. Crash risks increased during nighttime hours when vehicle speeds tend to be higher, pedestrian crossing the roadway are more difficult to see. The issues NYCDOT addressed through the deployment included the following:

- Managing travel speed in the network by improving the compliance of equipped vehicles with regulatory and advisory speed limits.
- Reducing the potential for head-on, sideswipe, and right-angle collisions between two equipped vehicles.
- Reducing the potential for red-light violations by equipped vehicles at signalized intersections.
- Reducing the potential for vehicle-pedestrian collision by providing generalized warnings to drivers of pedestrian presence in a crosswalk and supporting visually impaired pedestrians at signalized intersections.
- Reducing V2I collisions by alerting drivers of pending low-clearance conditions and the height of equipped vehicles.
- Informing drivers of serious incidents and emergencies.
- Providing mobility information to potentially support infrastructure-based mobility applications.

A key concept for the NYC CVPD project was to equip a large fleet of vehicles with CV technology to advance toward the Vision Zero goal of eliminating injuries and fatalities from traffic crashes. NYCDOT viewed CV technology as one component in a systematic approach in alerting vehicles of unsafe roadway conditions and preventing collisions with other vehicles and pedestrians.

Only a small portion of the NYC roadway network was included in NYC's evaluation area. Some applications, such as V2I applications like RLVW and CSPDCOMP, were only supported in the deployment area (i.e., where the RSUs were deployed). However, the geographic reach of the CV technology was much broader. Vehicles equipped were designed to function anywhere two equipped vehicles were within range of one another. As a result, equipped vehicle encounters occurred on many different surface streets. The fleet size meant that there were many opportunities for the applications to activate over a large geographic area and diverse roadway environments.

The NYCDOT expected the following benefits from applications in its deployment: (17)

- The SPDCOMP application would discourage speeding by improving speed limit adherence and reduce speed variable by vehicle fleets on given study roadway segments during certain travel periods.
- The CSPDCOMP application would improve truck safety by reducing the number of curve speed violations at applicable roadway segments.
- The SPDCOMPWX application would improve safety in work zones by reducing the number of work-zone speed limit violations of applicable study roadways.
- The FCW, EEBL, BSW, LCW, and IMA applications would reduce vehicle-to-vehicle crashes.
- The RLVW application would reduce the number and severity of red-light violations at studied intersections.

- The VTRW would reduce the number of bus /right-turning vehicle crashes at studied intersections.
- The PEDINXWALK application would improve pedestrian safety on heavily traveled bus routes, by reducing the number of pedestrian-related crashes at crosswalks.
- The PED-SIG application would improve safety for visually and audibly impaired pedestrians when crossing signalized intersections.
- The OVW applications would address bridge low clearance issues and increase enforcement of truck route restrictions by reducing the number of low clearance violations.
- The EVAC application had the potential to inform drivers of emergency conditions in the Manhattan area.
- The I-SIGCVDATA application had the potential to replace and provide better information than NYCDOT's legacy travel time detection systems.

Wyoming

For the Wyoming CVPD, the issues addressed by the deployment centered around improving safety and public agency efficiencies associated with weather and, to a lesser degree, construction events. WYDOT indicated the following occurred during the 2016–2017 winter: (37)

- Over 1,300 crashes were reported on I-80. An analysis of weather conditions at the time of these crashes showed that over 50 percent occurred when the road conditions were classified as icy/frosty (39 percent) or snowy (15 percent).
- About 25 percent of these crashes were multi-vehicle crashes, some including more than 10 vehicles total. These crashes can be the reason sections of I-80 are closed. During the pre-deployment period, WYDOT reported a cumulative total of 515 hours of closures on 52 road closure segments.
- 4.4 percent of the 12,641 crashes occurring during that period were reported as critical, involving a fatality or severe injury.
- About 40 percent of vehicles were traveling 5 mph or more above the posted speed, and a little over half of the vehicles were traveling outside a +/–10 mph buffer around the speed limit.

WYDOT's expectation for its deployment included the following: (37)

- The implementation of CV applications such as FCW, WZW, and in-vehicle TIM messages has the potential to reduce the number of vehicles in a crash by warning the drivers of a crash ahead and the total number of crashes in all conditions.
- Because of the information provided by the CVs, the quantity and coverage of road condition information would increase and the latency (the time between updates) of road condition information would decrease.
- The successful integration of CV systems and technologies (including the generation, transmission, and receipt of V2V and V2I messages) will improve back-office processes, helping to identify areas of improvements.
- By improving situational awareness regarding posted speeds limits, especially in VSL areas, WYDOT could improve speed limit compliance and speed variability in the deployment corridor.

Chapter 4. Deployment Issues and Challenges

This chapter provides a synthesis of the common deployment issues and challenges across all three of the deployment sites. This chapter also highlights how the three sites overcame those issues and challenges.

Systems and Technologies

In interviews following each deployment, all the deployment sites indicated that the maturity level of the technology and applications was overstated. Several site stakeholders indicated that they thought being "deployment ready" meant that the technology and the applications were well vetted, hardened, and readily available on the market. Several sites reported some of the applications and devices to be more in the prototype/early deployment stages and not commonplace on the market. Several of the sites reported spending a considerable amount of time (beyond what they had originally planned) planning, executing, and re-testing applications. The lack of available test equipment and procedures, even for the most fundamental technology, also was an issue for most sites.

The sites also found the many of the CV standards were immature. The sites noted that many of the standards had gaps, discrepancies, and ambiguities and were open for interpretation. The sites worked with multiple standard development organizations and committees to clarify and fill-in some of the holes in the standards to promote interoperability. For example, the NYC and THEA CVPD Teams worked together to identify common requirements for defining crosswalks. The three sites worked together to identity a set of common messages and relevant standards to promote interoperability between the sites. The Wyoming CVPD TEAM worked with the Society of Automotive Engineers (SAE) to address and incorporate heavy vehicle trailers into BSM, Part II specifications. The solutions that several sites developed to address their issues and challenges later led the development and refinements of several new and existing standards and specifications including the following:

- Requirements for Road Weather Applications (SAE J2945/3).
- Object Definitions for Roadside Units (NTCIP 1218 v01).
- Object Definitions for Actuated Signal Control (ASC) Interface (NTCIP 1202 V3)
- Dedicated Short Range Communication (DSRC) Performance Requirements for V2v Safety Awareness (SAE J2945/2).

Another significant issue encountered by all the sites was the amount of effort needed to fine-tune the applications. All three sites cited significant issues with false alerts during the initial stages of deployment. All three sites also reported spending considerable time and personnel resources tracking down the sources of errors. These errors were caused by many factors including errors in the MAP, transmission errors, processing requirements associated with the technologies, incorrect operation assumptions, incorrect threshold requirements, etc. Because of the complexities associated with finding errors in the applications, all sites reported underestimating the time and resources required for fine-tuning and calibration. Unless automated tools are available to assist, the time and personnel resources required to calibrate and validate more than one or two applications at multiple locations was arduous. At sites like Wyoming where significant travel distances exist between RSU locations, multiple trips to device locations to perform maintenance or calibration can result in significant travel requirements.

Other issues and challenges related to deployed systems and technologies include the following:

- Location accuracy was a challenge, particularly in the urban environment. Two of the sites indicated that their applications required greater location accuracy than what is available through normal GPS technologies. GPS signal drift can lead to false warnings and improper placement of the vehicle in the roadway network. Some applications may benefit from agencies providing position correction information as part of their deployments.
- Grade separations were also a challenge in dealing with the elevation element of location accuracy. Elevation is an essential component of the safety applications in the urban environment. Information about roadway elevations is important for helping vehicles locate themselves appropriately on the network, particularly on elevated or overlapping roadway segments.
- Agencies need to be aware of the data reception ranges of their OBU and RSU devices. Where device densities are high, the proximity of devices can place a loading burden on OBUs and RSUs. For example, in the NYC deployment, a single vehicle received 24 different MAP messages in 17 seconds.
- Estimating the trajectory of the vehicle correctly can be particularly challenging. Loss of vehicle heading while stopped causes applications to wrongly issue false warnings. Roadway curvature and map inaccuracies can also lead to a high number of false alerts due to inability to correctly determine relative position between vehicles.

Security Credentialing and Management

The SCMS is a public key infrastructure system that provided credentials and certificates to CV devices to enable trusted communications. CV devices, such as OBUs in vehicles and RSUs within the infrastructure, sign their messages with the certificates received from the SCMS. The primary purpose of the SCMS was to ensure that message exchanges in the deployments did the following: [38]

- Maintained integrity—the message was not modified between the sender and receiver.
- Assured authenticity—the message originated from a trustworthy and legitimate source.
- Ensured privacy—the message appropriately protected the privacy of the sender.

When other devices receive these messages, they can validate those signatures and ensure they are coming from a trusted source so that applications within the device can act on those messages. An OBU validates messages from other OBUs to ensure they can provide the safety of live warnings such as forward collision warnings. RSUs validate signal request messages from vehicles, such as buses, to enable transit signal priority applications. The SCMS provides the back-end systems for OBUs and RSUs to request and download certificates over the devices' lifetimes because these certificates are typically only valid for one-week increments and need to be updated over time. [39]

The three CVPD sites were required to use the SCMS Proof of Concept (POC) to assist USDOT in obtaining a better understanding of the policy framework, scalability, tools and requirements, and technical challenges in ensuring general deployment communications security. The goals of this effort were to demonstrate that the key concepts of the SCMS were feasible and that there were SCMS providers capable of meeting the certificate needs of deployed CV devices.[40] The temporary proof-of-concept security system enabled USDOT's CV projects to address unanswered questions regarding the exchange of information among vehicles, roadway infrastructures, TMCs, and wireless mobile devices. Because of limited funding, the SCMS POC ended its services in December 2020, requiring two of the sites to transition to a private provider to provide security credentialing to support their post-deployment operations. [40]

Other issues and challenges related to use the SCMS include the following:[41]

- The number of certificates needed on a weekly basis depends on the anticipated number of hours and distances traveled by the deployment fleet. Through initial SCMS efforts, USDOT recommended that 20 certificates per vehicle were sufficient to maintain the anonymity of vehicles to provide two hours' travel per day. However, because some of the deployments included vehicles that traveled more than two hours a day, additional certificates were needed. The NYC CVPD negotiated with its SCMS vendor to obtain 60 certificates per validity period for its vehicles.
- At the time of the deployment, the SAE J2945/1 Certificate Change requirement called for certificates to be changed every five minutes but contained an exception involving the "absolute distance" from the previous certificate change location. Under the absolute distance assumption, a vehicle traveling within an urban grid network (such as in NYC) may not trigger the certificate change mechanism. Because it was still possible for vehicles to operate in a large area for an extended period and not be required to change its certificate, the NYC CVPD Team decided to implement a change mechanism that required certificates to change every 2 km traveled or every five minutes, whichever comes first.
- The validity period for RSU application certificates is one week, which required RSUs to contact the SCMS on a weekly basis. Some entities have equipment installed in the field that does not have access to the internet, making it more difficult to support certificate refresh. It is important to consider how many devices will be installed in locations without cellular connection or access to backhaul. Another consideration is whether the RSUs can directly communicate with the SCMS or whether these communications must be proxied through the TMC.
- In deployments with limited RSU installations (e.g., rural areas), OBUs may not encounter RSUs often enough to receive certificate updates. This may prevent some vehicles, especially in rural areas, from receiving, sending, and propagating messages correctly because their certificate may expire before reaching the next RSU.
- Before agencies procure services for a private SCMS, they should complete their project planning and have an idea of the number of OBUs, RSUs, and TMC/back-end systems that will need to be enrolled with the SCMS. Agencies need reasonable estimates of the number of devices supported by their deployment to get an accurate quote for obtaining the appropriate number of certificates.
- As entities set up their devices, it is possible that the devices could run out of valid certificates because the certificates expire during transport from the device vendor to the deployer. Devices that only store a few certificates may stop transmitting because they run out of valid certificates. When this occurs, devices may have to be restarted to enable the download of new certificates.
- Prior to procuring a SCMS vendor, entities should know what applications their devices will be supporting. When deploying secure CV devices that are signing messages with certificates from a SCMS, knowing the applications the devices will support—and the messages used by those applications—is extremely important. As part of the initialization/set-up process for these CV devices,

the agencies will need to enroll specific Public Safety Identification (PSID) and Software Security Practitioners (SSPs) with SCMS (if necessary). If these devices are deployed without enrolling with the proper PSIDs and SSPs, agencies may be required to reinitialize those devices, which could entail removing RSUs from the field or removing OBUs from vehicles and bringing them back to a depot.

- While certificates can be downloaded while a vehicle is in motion, devices must be returned to a secure environment for re-enrollment in the SCMS infrastructure. Ideally, enrollment should occur in the same environment where maintenance is being performed. Another option is to have a process in place to have the devices removed for suspected improper operation sent back to the vendor for repair and validation or replacement of the enrollment certificates.
- It is necessary to implement a credential management misbehavior detection feature to address vulnerabilities to cyber-attacks, spoofing, and malfunctioning equipment. These can be performed with misbehavior detection software and the use of a certificate revocation list distribution mechanism, both of which are essential to maintain the security of the CV infrastructures.
- To support SCMS functionality, CV devices require processing signatures and validations of certificates. Early deployers need to ensure that their device hardware can support the load to handle the number of signatures and validations that need to be processed every 10th of a second (the rate at which BSMs are broadcast). Deployers should have a good understanding of the load requirements on their CV devices and ensure that their hardware is not underpowered

Business Practices and Policies

Except for procurement practices, all the sites reported that their existing business policies and practices were sufficient to sustain current and expanded operations into the future. Business processes included formal scoping, planning, programming, and budgeting.

Procurement was the biggest issue among the sites. Because the technologies were not readily available off the shelf, a couple of the sites had to use non-traditional means of procuring the devices. For example, the NYCDOT used a Request for Expression of Interest and Proposal (RFEIP) to leverage the experiences of existing device vendors. THEA conducted multiple scans using RFPs (with on-the-road-testing) to identify promising suppliers who could meet system, cost, and project timing requirements. WYDOT conducted pre-delivery testing to ensure devices provided the required functionality. Most agency procurement policies were not designed to support “bleeding edge” technologies needed for a pilot. At least one site indicated that implementing special procurement policies delayed the deployment because procurement specialists from outside the agency had to be consulted to address the complexities associated with procuring developing technologies.

The contractual process also impacted the schedule and the project implementation, in general. Several sites spent a considerable amount of time finalizing contracts with CV device contractors, and coordinating and executing Memoranda of Understanding with multiple fleet owners and agencies. An interviewee from one site indicated that contracts were delayed by more than 18 months because additional approval in the procurement process was needed.

Making sure that the procurements were cost effective and, at the same time, that the units would work in a large-scale deployment took a lot of time and effort. For example, one site reported challenges in getting the contract for RSUs after they learned that the existing units on the market were not up to what was needed. This site had to find a new RSU vendor, and then there were challenges in getting that vendor under contract.

Financial and institutional issues, particularly those related to long-term operations and maintenance, were considered early in the deployment. All three sites engaged relevant stakeholders (e.g., USDOT, site, state and local DOTs, transportation associations, etc.) early in the process to define performance measures, assessment approaches, and other evaluation needs. The sites identified the need for flexible and realistic deployment schedules that could be adjusted as new, unforeseen circumstances developed. This was deemed critical because of the lack of experience with emerging technology and the technology's maturity level.

Collaborations

Collaboration with internal and external stakeholders was essential to the success of each pilot deployment. Each deployment had a core level of stakeholders consisting of the deployment management, the deployment developers and integrators, and the general operating staff of the host agency. This core team often brought in external stakeholders or representatives of the user group to assist in the decision-making process. The core stakeholders were at the mid-level of their respective organizations and consisted of individuals who would be responsible for the daily operation of the systems once deployed. The core stakeholders meet on a regular basis (at least monthly) through roundtables to discuss issues and identify solutions.

The sites reported that collaboration required a strong champion. Each site had a public agency leader that provided strong leadership in guiding the deployment. Because other stakeholders often had their own priorities and goals for the deployment, the champion was needed to build consensus and keep the deployment targeted toward its goal. In the end, the project champion was responsible for setting the priorities and was responsible for being the final decision maker for the deployment.

In addition to the collaboration specific to each deployment, collaboration was encouraged (and facilitated by FHWA) between deployment sites. Project teams from all the sites would meet with FHWA on a regular basis (at least monthly) in a series of roundtables. These roundtables were designed to allow deployment teams from each site to share issues and challenges encountered across all the deployment sites, conduct peer exchanges, and identify solutions common across sites such as the following:

- Interpreting communications standards and specifications.
- Developing testing procedures for conducting verification and validation testing of select applications.
- Addressing security credentialing issues and challenges.
- Developing over-the-air update capabilities for applications deployed on vehicles.
- Developing processes for uploading evaluation data into the SDC.

Inter-site collaboration was also a critical part of the interoperability testing conducted by the pilots and USDOT. (42)

Other common issues and challenges that stakeholders reported throughout the deployment included the following:

- The need to continually educate new stakeholders and decision makers on the potential benefits offered by the CV technologies throughout the life cycle of the deployment.
- Priorities among the stakeholders can change, especially when it takes a long time to operationalize systems.
- There is often a need to involve stakeholders beyond the boundary of the systems. It was important to ensure inoperability with other CV deployments occurring elsewhere in the State and region. Road operators in different States need to be on the same page (standardized) to deploy in a reasonable amount of time. A nationwide decision must be made on what baseline CV technology should be deployed so that everyone has the same understanding of how to implement it and can purchase that technology at a reasonable price.

Data Management and Retention

Privacy and the protection of personally identifiable information (PII) was a critical issue for all three sites which drove the designs of many of the data management and retention decisions. Each site dedicated significant resources to implement workable solutions to ensuring confidentiality and integrity of the data. The sites used different methods and techniques for ensuring privacy. For example, the NYC CVPD developed a process for obfuscating their data by aggregating data into “bins” that could not be disaggregated for alternative uses The Wyoming CVPD Team used dynamic identification numbers which continuously changed to make it difficult to track any single participant’s trips. THEA developed process that removed PII through their central software before data before it was retained.

One issue encountered by the sites was the tradeoff between need for privacy protection and the data needed for a robust evaluation. In some cases, the need for protecting participant privacy can conflict with the collection of robust evaluation data, particularly that used to assess driver responses to specific situations or specific alerts. Agencies may need to make special accommodations (such as using an Institutional Review Board) to review and monitor the collection of data from deployment participants.

The Secure Data Commons (SDC) is a cloud-based analytics platform developed by USDOT to provide a secure location for traffic engineers, researchers, and data scientists to share and collaborate on research, tools, algorithms, and analysis. Each deployment site was required to upload all the data generated through the deployment into the SDC. The data to be uploaded included not only CV data but also any ancillary data collected through the deployment, including weather conditions data and metadata describing the data input. Each site was responsible for developing, formatting, and uploading data into the SDC.

The development of the SDC lagged slightly behind the deployments at each site. The SDC was not fully operational until late in the deployment process. Therefore, uploading processes and data structures were not fully known until the sites were well within their deployment planning. Through the interview process, several sites identified that having prior knowledge of the type and structure of the data to be included in the SDC would have changed the way they collected and managed their data.

Each site was responsible for processing and uploading information into the SDC. The sites performed significant processing on the data before uploading it into the SDC. Of particular concern was the removal of PII. Each site had its own processes for removing PII including:

- Using cordon boundaries to limit the data to a specific geographic area.
- Aggregating data into time- or location-based bins.
- Using dynamic vehicle identification numbers or altering vehicle identification numbers to prevent vehicles from being uniquely identified at each RSU.

All these processes had an impact on the types of analyses and the interpretation of the evaluation results. While the protection of PII is critical in these types of evaluations, too much obfuscation of the data may limit a site's ability to use the data for traffic management and evaluation purposes, particularly when investigating the interaction between two vehicles (e.g., investigating how alerts changed driver behavior). Agencies need to carefully consider how they plan to use the data collected by these types of deployments and structure the data collection processes.

Testing and Interoperability

Testing and validation of applications turned out to be a significant challenge associated with all three deployments. All three sites reported spending considerable time planning and executing tests to confirm the functionality of the applications. The sites noted a general lack of test equipment and procedures to conduct the necessary testing. As a result, all three sites developed extensive documentation for testing including test plans, test cases, test procedures, test results, and observations. The sites found that tests needed to be repeated after each major firmware or software upgrade to ensure that performance and functionality was not compromised.

The teams also found that testing in a real-life environment under different operating conditions and scenarios was extremely valuable. Testing in these conditions enabled the sites to identify issues that were not previously detected in limited controlled system testing or laboratory testing. Several sites maintained a small fleet of test vehicles that they would use to test applications and upgrades before deploying updates to the larger vehicle fleet. This also allowed the CVPD Teams the ability to test the applications in different locations and operating environments (i.e., around tall buildings, different times of day) to ensures reliability and consistency of performance.

Another major concern heading into the deployment was the level of interoperability between the deployments. While not every site deployed the same applications, one issue facing the FHWA and deployers was to prove that interoperability between the deployments was possible using standards-based technologies. For the CVPDs, USDOT and the sites agreed on the following definition for interoperability:(42)

> *A vehicle with an onboard unit (OBU) from one of the three CV Pilot sites is able to interact with OBUs and/or roadside units (RSUs) from other sites in accordance with the key connected vehicle interfaces and standards*.

To address the concerns associated with interoperability, the three deployment sites and FHWA conducted a series of interoperability tests using a closed course at the Turner Fairbank Highway

Research Center in McLean, VA. in June 2018, [42] The purpose of the test was to demonstrate RSUs and OBUs from each of the three sites were able to exchange properly formatted messages. OBUs used at each site were expected to accomplish the following:[42]

- Receive BSMs transmitted by each of the other sites' OBUs.
- Authenticate messages as needed (i.e., when acting on the data or hearing a device for the first time).
- Parse messages (i.e., decode messages to the individual data elements).
- Process messages (i.e., use the data as an input to applications, triggering responses according to the device's own application).

The testing leveraged four V2V applications to demonstrate interoperability: FCW, EEBL, IMA, and RLVW. The tests also included examining the ability for an OBU from one of the sites receiving SPaT and MAP information from another site (via an RSU). These applications were selected because they were common across the three sites and interoperability was a critical requirement for these to function as designed.

The results of this interoperability testing indicated vehicles from each of the deployments could exchange messages with vehicles from other deployments. The test also showed that these same vehicles could exchange information with the infrastructure through an OBU. While this test was conducted in a controlled field environment, it demonstrated that interoperability across multiple devices was achievable.

Confounding Factors

Confounding factors are those factors that are beyond the control of the agency to measure, predict, or control, but their effects can influence the overall performance of the system. All three CVPDs were significantly impacted by the following confounding factors outside their ability to control.

Failure of NHTSA to Issue Proposed Rulemaking on V2V Technologies

Coming on the heels of the Safety Pilot Model Deployment, all three sites were expecting the National Highway Traffic Administration (NHTSA) to implement rulemaking requiring all new light vehicles in the United States to be equipped with DSRC to support safety applications. NHTSA had suggested that V2V capabilities would not develop without government interventions, and that the effectiveness of the technology would depend on reaching critical mass in the marketplace and proving the interoperability between manufacturers' equipment. The industry expected NHSTA to issue this proposed rulemaking in 2016 during the initial stages of the CVPD, opening the marketplace for new technology developers; however, NHTSA never released the proposed rulemaking. The sites were counting on this rulemaking to gradually increase market penetration of CV for sustaining future operations.

Changes in DSRC Spectrum Allocation

In December 2019, FCC unanimously approved a proposal to transition the spectrum previously reserved to support DSRC to a spectrum-sharing model. Under the revised spectrum allocation, FCC reallocated the lower 45 megahertz of the spectrum to be unlicensed, making it available for Wi-Fi and other purposes. This change in allocation significantly disrupted the CV marketplace, causing several technology suppliers to abandon the marketplace or adjust their product lines. This marketplace shift left several sites without any support for their product suppliers as they approached the final stages of their deployments.

Originally, all the sites remained committed to continuing development of CV technologies into the future. However, on November 28, 2020, FCC adopted new rules for the 5.9-GHz band (the bandwidth on which DSRC resides), designating the lower 45 megahertz for Wi-Fi and other unlicensed uses and the upper 30 megahertz for enhanced automobile safety using cellular vehicle-to-everything (C-V2X) technologies. Under the new rules, all intelligent transportation system services supported in the lower 45 megahertz were required to vacate the band within one year (approximately the time frame the post-deployment evaluation ended for each of the sites). Because of this ruling, all sites have terminated their use of DSRC, and two sites are exploring other communications operations for continuing their deployments. For example, the THEA CVPD is looking to complete its Phase 3 deployment to implement TSP and I-SIG applications using a C-V2X platform. The Wyoming CVPD plans to continue to make TIM alerts and warnings available to private fleet vehicles through satellite communications and is exploring options to replace its DSRC-based RSUs with C-V2X technologies.

COVID-19 Pandemic

The final issue reported by all three sites was the COVID-19 pandemic. COVID-19 reached the pandemic stage in the United States during March 2020. The pandemic altered travel patterns, lessened demand, and changed trip making in all the deployment corridors. The pandemic also significantly impacted the availability of devices and the personnel resources to install equipment in two of their three sites, pushing their post-evaluation period to the beginning of 2021. The pandemic also significantly compressed the period over which the safety and mobility benefits could be evaluated at the sites. Original evaluation plans called for one year of pre- and post-deployment data. Evaluation periods were significantly shorter in Tampa (approximately 1.5 months of post-deployment evaluation data) and NYC (approximately 4 months of post-deployment data).

Chapter 5. Performance Measurement Issues and Challenges

This section is a compilation of the issues and challenges that the sites reported in planning and measuring the SMEP agency benefits associated with their deployments.

Experimental Design

Each deployment site used a slightly different approach for assessing the safety and mobility benefits associated with its deployment. The THEA CVPD Team used a randomized experimental design to assess driver responses to warning and alerts. The THEA CVPD Team randomly assigned study participants to treatment and control groups. Individuals assigned to the treatment group were provided with alerts and warning produced by the applications, while individuals assigned to the control group did not receive alerts and warning produced by the applications. Participants were assigned to either treatment or control using a randomized two-to-one matching criteria (two treatment to one control) stratified by gender, age, income, and education. The team conducted pre-assignment and post-assignment checks to ensure a balanced stratified sample split between the treatment and control groups. However, as the deployment progressed, issues occurred that required the THEA CVPD Team to reclassify the participants groups. One of the over-the-air updates to the vehicle onboard firmware inadvertently corrupted the treatment and control group assignments, causing some participants to no longer align with their original assessment groups. As a result, the THEA CVPD Team ended up with three analysis groups: one where the participants did not receive alerts for the entire post-deployment period, one where the participants received alerts or the entire duration of the post-period, and one where the participants initially did not receive alerts and then received alerts after an initial period. As a result, the experimental design used to assess driver responses changed from a before and after comparison with a control group to a with and without comparison with participates in the treatment group being the “with” group and the individuals in the control group being the “without” group. Limited number interactions between equipped vehicles and issues with false-positive alerts (alerts being issued when no hazard existed) further complicated the THEA CVPD Team’s experimental design.

To assess the mobility impacts of the deployment, the THEA CVPD Team used an interrupted time series approach to assess changes in performance measure over the duration of the evaluation period. This approach does not rely on the direct identification of treatment and control groups, but instead assesses if a shift (or change) in the baseline performance trend occurred after the CV technology was deployed. This approach requires sufficient data to be collected in both the before and after periods to ensure that performance trends are observable in the data. Unfortunately, the COVID-19 pandemic significantly restricted the collection of adequate performance data in the post-deployment period, making it difficult to establish the long-term performance trends of the applications. Interrupted time series approach also works well when a clear distinction exists between the before and after periods. Because the transition from pre- to post-deployment occurred over several months, a clear boundary between the before and after period is not readily observable in the Tampa deployment.

The NYC CVPD used separate experimental designs to evaluate the driver behavior impacts using vehicle-based CV applications and the pedestrian's behavior impacts resulting from the PID CV application. To assess the driver behavior impacts, the NYC CVPD Team used a driver experiment design consisting of both a before and after model and a control and treatment model. The experimental plan dividing the before and after periods relied on the NYC CVPD Team to be able to operate in-vehicle devices in either a silent warning mode or an active warning mode. In the silent mode, the applications deployed in the vehicle were fully operational, but did not provide warnings or alerts to the driver. In the active mode, the applications were also fully operational and provided warning and alerts to drivers. In addition to the before and after components of the experimental design, the NYC CVPD Team used treatment and control groups to help isolate the impacts of confounding factors.

The use of pool fleet vehicles in the NYC CVPD provided additional complications to the NYCDOT's experimental design. Because drivers could use different vehicles on a day-to-day basis, drivers might experience inconsistent CV application behaviors on a day-to-day basis by receiving warnings if they used a treatment vehicle and no warnings if they used a control vehicle. To lessen the possibility of this occurring, the NYC CVPD Team used only NYCDOT vehicles as control group vehicles. The number of vehicles in the control group was also small (150 vehicles or 5 percent of the total number of equipped vehicles) compared to the overall number of equipped vehicles. Also, because the group assignment could not realistically be adjusted after the devices were installed, the assignment of control group vehicles as part of new installations lagged the installations of treatment group vehicles during the initial stages of the deployment before period.

The NYC CVPD Team used a separate experimental design to assess the pedestrian information devices (PID) developed for the deployment. The approach involved recruiting volunteers with vision disabilities to participate in the field tests. Testing was conducted under specifically defined test conditions, albeit in the real-world operating environment of NYC city streets. At least one IRB-certified NYC CVPD team member accompanied each participant to ensure their safety. However, because of testing requirements, NYC CVPD Team tested the PID application using only a limited number of pedestrians (24 individuals).

Because of delays in getting the commercial fleet vehicles equipped with the technology, the Wyoming CVPD had to use a non-experimental approach for assessing driver responses to the messages and alerts produced. The approached used by the Wyoming CVPD Team compared data collected under baseline conditions (representing the "before" condition) with data collected before and after the full deployment of the CV technology. The Wyoming CVPD did not include a control group, making it difficult to assess what could have happened in the absence of the improvements. Because the baseline data were collected several years before the CV technology was deployed, it is difficult to account for confounding factors.

Performance Measures

Each site tailored their applications to address specific local issues. The sites were expected to demonstrate improved performance in one or more of the following areas: safety, mobility, environment, and public agency efficiency. USDOT expected that improved performance would cause widespread adoption of CV applications by transportation agencies.

As part of their agreement with USDOT, each site was required to assess their deployment against their planned operational objectives. Each site identified performance measure that linked their concept development activity to the evaluation effort. Performance measures needed to be well aligned with the deployment concept. The plans for the pilot's impact assessment were a major driver of concept development. The sites found it helpful to have a Performance Measurement Plan tailored to identify data flows that would support the evaluation effort.

The sites used a combination of output and outcome-based performance measures. *Output measures* relate to the physical quantities of items, levels of effort expended, scope of activities, and efficiencies in converting resources to product. *Outcome measures* are used to quantify quality of service. Outcome measures are used to answer questions like "what impact did the deployment have on traffic performance?" Both output and outcome measures are quantitative. Quantitative performance measures present numerical evidence about how well a system is performing. These numerical values can be compared to established performance targets to determine progress toward attaining a specific objective. Qualitative performance measures provide a subjective perception of the effectiveness of the deployment from a user's perspective.

Table 29 summarizes the measures used to assess the mobility, safety, and public agency benefits associated with the deployment. One common issue that existed throughout each of the deployment was having adequate market penetration to cause these performance measures to change, particularly those related to mobility. Even in those sites where a larger number of vehicles were equipped (e.g., NYC, and Tampa), the deployment team found that very few vehicles used enough of the network to provide adequate sampling of travel conditions for all times of the day. Several of the sites found that the low quantity of post-cleansed events data limited their ability to definitely assess safety and mobility benefits in their evaluation.

Table 29. Summary of Performance Measures Used to Evaluate CVPDs.

Site	Mobility	Safety	Public Agency Efficiency
Tampa (7)	• Travel Time • Travel time reliability • Queue length • Excess time spent in idle	• Crash comparison • Types of crashes • Severity of crashes • Types of conflicts • Number of alerts	• NA
New York City (17)	• Vehicles speeds at curve entry • Lateral acceleration in the curve • Pedestrian qualitative feedback • Pedestrian crossing speed and crossing travel time • Time out of the crosswalk • Wait time at intersection for crossing	• Fatal crash counts • Injury crash counts • Property damage only crash counts • Time to collision (vehicle to vehicle) • Pedestrian-related conflicts/hard braking events • Time to collision (vehicle to pedestrian)	• Number of curve speed violations • Number of vehicle speed limit violations • Red-light violation counts • Number of over-height vehicle clearance warning generated • Number of vehicles receiving emergency evacuation information when generated
Wyoming (29)	• Total vehicle traveling no more than 5 mph over posted speed • Total vehicles traveling within +/- 10 mph of posted speed • CVs speed compliance compared to non-CVs	• CVs involved initial or secondary crash • Number of vehicles involved in crash • Total and truck crash rates within a work zone area • Total and truck crashes along the corridor • Critical total and truck crash rates in the corridor • CVs that likely took action following receipt of an alert • CVs that likely took action following receipt of V2V alert	• Number of road condition reports • Number of road sections with at least one report • Average refresh time of road reports • Percentage of TIMs received by at least one RSU • Percentage of TIMs received by at least one OBU on I-80 through satellite • Percentage of TIMs receive by at least one "Friendly" vehicle from RSUs • Percentage of TIMs received by at least one OBU through either satellite or RSU

Source: Texas A&M Transportation Institute, 2022.

Assessing Driver Responses to Alert/Warning Messages

All three sites cited improving safety as a primary objective of their deployments. Improvements in safety are typically measured through changes in crash frequencies and severity; however, crashes are rare and random events represent only a very small proportion of the total number of events and vehicle interactions that can occur on the transportation system. Furthermore, the applications developed by the sites were designed to alert drivers of potential vehicle interactions which may lead to a crash, if not responded to by the driver. As a results, the sites used driver responses to alerts as a surrogate safety performance measure. According to the *Highway Safety Manual* (43), two important factors must be considered when using surrogate safety measures:

- The events upon which the surrogate measure is based need to proximate and usually precede a crash event.
- The causal line is presumed to exist between the surrogate measure and expected crash frequency.

The sites used BSM data from equipped vehicles to infer how drivers responded to the different alerts and warning produced by each site. Table 30 shows the vehicles actions each site used in assessing driver responses.

The sites found these analyses to be time consuming due to the volume of data generated by the CVs and the privacy-by-design nature of the data, which ensures participant's privacy. Because the driver alert data did not contain vehicle identification information, it is a time-consuming process to link alert data with vehicle BSM data to determine the likely action taken by the driver after receiving the alert.

The sites also had to implement extensive data processing and data cleaning rules to facilitate these analyses and to help identify true positive events (i.e., events where conditions warranted an alert) from false positive events (events where conditions did not warrant an alert, but one was issued).

Another complicating factor was the uncertainty in whether the driver saw the alert and whether the alert matched with real-time road conditions. Privacy of the system was the overriding concern, so vehicles were not instrumented with in-vehicle or external cameras. The sites had to use additional data from other sources (e.g., nearby weather sensors, notes from construction personnel) to obtain insight into what the driver might have been experiencing at the time of the alert. System data was not always available to confirm if the driver had the system turned on at the time of the alert, so driver actions at the time of the alert could only be inferred.

Table 30. Performance Measures Used to Assess Driver Responses to Warnings and Alerts

Tampa [7]	New York City [17]	Wyoming [29]
• **Longitudinal acceleration** of host vehicle sent BSMs around the anchor point of a warning event. • **Lateral acceleration** values (yaw rates) by the host vehicle BSM around the anchor point of a warning event.	• **Deceleration Difference**—The difference between maximum deceleration after a warning is given and the deceleration when the warning is given. • **Time Duration to Slow Down to Speed Limit After Warning** —The time duration between the time when a warning is issued to the first time the observed speed is below the corresponding speed limit. • **Time Duration to First Deceleration After Warning**—The time duration between the time when a warning is issued to the first time the driver decelerates.	• **Vehicle Reduced Speed** was assigned to events where a notable speed reduction was witnessed after the driver alert was given. • **Vehicle Stopped** was assigned for events where the analyst found the vehicle speed came to zero after the driver alert was given but the driver remained on the roadway, either in the lane or shoulder areas. • **Vehicle Exited** was assigned for events where the analyst found the vehicle exited after the driver alert was given. • **No Action** taken was assigned for events where the analyst found no evidence of deceleration, stopping, or exiting.

Source: Texas A&M Transportation Institute, 2022.

Setting Performance Targets

Performance targets are values of specific performance measures that an agency is targeting or expects to achieve over a defined period through some action or activity that it undertakes (e.g., a 10 percent reduction in crashes during the deployment period). Agencies can use performance targets as a way of measuring progress toward attaining a goal or objective ("how well are we doing?") or as a threshold for when a specific action should occur. In both cases, a priori knowledge of the effectiveness of the strategy, tactic, or activity is needed to set effective performance targets.

Because the technology was still emerging, the sites found it difficult to identify specific performance targets for their deployment. Because this was the first time that many of the applications were tested in a deployment setting, the sites had limited knowledge about the extent to which applications would impact safety and mobility. More information was needed to assess to what extent performance of the applications was impacted by different operating scenarios and environments. Little was known about the long-term sustainability of performance by some of the applications.

Setting performance targets also requires the establishment of a solid baseline of performance over time. Before performance targets can be set, agencies need to understand where they are in terms of network performance. Most deployers have a general understanding or idea of performance, but many do not have good baseline data or a performance monitoring system from which to build a performance baseline. Establishing a good baseline requires extensive data collection over an extended period (usually several years).

Participant Recruitment and Retention

Each deployment used a different segment of the driving population as study participants. The THEA CVPD recruited existing THEA toll tags users who normally travel to the downtown area as part of their normal commute. Technology was installed in their personal vehicle. Therefore, there is a strong likelihood that the same driver performed each trip (or data collection session). The NYC CVPD equipped city-owned vehicles with CV technologies, some of which were assigned to a single user while others operated as a shared resource for different operators out of a vehicle pool. For the vehicles operating out of a pool, there was a strong likelihood that each vehicle had a new or different driver each trip. Furthermore, drivers of public fleet vehicles may not be good surrogates for private vehicle operators. Public fleet operations tend to spend more hours during the day driving than regular commuter drivers. Public fleet drivers use their vehicle for work purposes (as opposed to for commuting), which have different operating characteristics than commute trips. Furthermore, public fleet drivers may tend to drive less aggressively than they would in their personal vehicles. All these factors can confound the analyses of some performance measures, especially those being used to gauge drivers' reactions to diverse types of alerts.

Likewise, it is difficult to extrapolate findings for commercial fleet vehicle operators to general passenger car drivers. Commercial fleet vehicles have entirely different operating behaviors than passenger vehicles. Commercial fleet vehicles accelerate slower, require greater stopping distances, and are less maneuverable than private vehicles. Commercial fleet vehicle operators, particularly long-haul freight operators, are used to having advanced technologies as part of their vehicle configuration and therefore may be more receptive to being assisted by advanced technologies. All these factors should be considered when determining a deployment fleet.

Retention can also be an issue. The THEA CVPD experienced a considerable delay between when the technology was installed in the vehicles and when alerts were issued to the drivers. While this delay may not have caused participants to leave the study, it may have reduced their trust in the system to provide them with good alerts. WYDOT also experienced issues with recruitment and retention due to delays in getting the CV applications to work. Because of these delays, most of the commercial fleet vehicles used in the deployment were only active during the last two months of the project.

Use of Control Groups

The differences in perspective between the research/evaluation and deployment were an ongoing dilemma at most sites. The need for research-oriented performance measures caused the sites to review several decisions made as the project progressed, primarily centered around data collection and privacy protection. One site suggested that data collection processes needed to include more detailed information about locations and site-specific factors that may have impacted driver decisions (while still retaining privacy protection measures).

The use of a control group was an issue across all sites. The use of control groups is a common method used to establish causality (i.e., a cause-and-effect relationship). A control group in an experiment is a group of subjects that do not receive the treatments (in the CVPD, i.e., the alerts produced by the technology). Control groups serve as a comparison point to gauge the magnitude and significance of a treatment on the population. Control groups are generally used in experiments in which the effect of the treatment is known.

From a public agency perspective, some agencies were hesitant to withhold a treatment from a portion of the population to serve as a control group especially when the treatment involves actions or treatments that may have the potential to prevent a collision or enhance safety. Agencies often take the position that if there is a reasonable expectation that applications will have a positive performance impact, then all participants should receive those benefits.

Field Measurement versus Simulation

In some cases, it was extremely difficult to directly measure some performance measures in the field (e.g., changes in vehicle emissions). Field measurements are often impacted by the operating environment that exists at the time of the measurement. These factors may include weather and road operating conditions; the presence of events; time of day, day of week, and seasonal impacts of travel demand; the composition of the traffic stream; etc. Sometimes, these factors can be external to the experiment (e.g., confounding factors) and cannot be monitored or anticipated. In addition, some performance measures can be overly sensitive to these factors, while others remain relatively unaffected by these factors.

Furthermore, it is often difficult to isolate the effects of one treatment from another in field-measured data. For example, drivers may receive alerts from different applications simultaneously, and it is difficult to isolate the extent to which the alert contributed to a particular observed effect. This may result in erroneous conclusions on the benefits of some treatments. A substantial amount of data from multiple sources may need to be collected, managed, and retained to understand the efficacy of a treatment. Often, agencies may not have the resources or capabilities to support this effort.

Modeling and simulation represent an analysis approach that can overcome many of the shortcomings associated with direct field observations. A properly developed and calibrated simulation model allows agencies to quantify the system-wide mobility and environmental impacts related to deploying CV technologies in a deployment area. Furthermore, the model allows agencies to answer questions and provide insight into conditions and situations that affect the mobility and environmental benefits associated with deploying CV technologies. Modeling and simulation allow agencies to examine how changes in market penetration, both from a vehicle perspective and an infrastructure perspective, impact the benefits associated with deploying CV technologies in the deployment areas. Simulation and modeling also allow agencies to translate safety impacts (e.g., the prevention of crashes) into secondary mobility benefits.

Those looking to assess surrogate safety performance measures for their own locations should review the following FHWA documents:

- ***Active Transportation and Demand Management*** **(website) (available at https://ops.fhwa.dot.gov/atdm/research/index.htm).**
- ***Active Transportation and Demand Management (ATDM) Trajectory-Level Validation State of the Practice Review*** **(available at https://rosap.ntl.bts.gov/view/dot/32715).**
- ***A Framework for Validating Traffic Simulation Models at the Vehicle Trajectory Level*** **(available at https://rosap.ntl.bts.gov/view/dot/34271).**
- ***Proof of Concept for Trajectory-Level Validation Framework for Traffic Simulation Models*** **(available at https://rosap.ntl.bts.gov/view/dot/34397).**
- ***Trajectory Investigation for Enhanced Calibration of Microsimulation Models*** **(available at https://www.fhwa.dot.gov/publications/research/operations/21071/index.cfm).**

These documents discuss and evaluate the trajectories output from some microsimulation models and how some microsimulation models may not reflect realistic vehicle performance in near-crash conditions. Obtaining actual vehicle trajectories will more than likely be needed to validate whether the trajectories produced by the models reflect the actual real-world performance.

Confounding and Exogenous Factors

Confounding and exogenous factors external to the evaluation process can also impact the transferability of the benefits. An *exogenous factor* is a variable that completely or partially accounts for the apparent association between an outcome and a treatment. [44] Examples of common exogenous factors that might influence performance include the following:

- Daily or seasonal variations in traffic demands,
- Changes in the operating environment (fog, rain, snow, high winds, etc.)
- Planned disruptions such as work zones or special events.

- Unplanned disruptions such incidents, stalled vehicles, etc.

Confounding factors are those factors that can influence traffic performance that are beyond the control of the agency to measure, predict, or control. Example of significant confounding factors might include the following:

- Changes in economic conditions between evaluation periods.
- Radical changes in fuel prices impacting travel demands.
- Global or regional conflicts that impact availability of resources and equipment.
- Changes in legislation or regulatory conditions.
- Changes or shifts in population.

The sites implemented processes and procedures for collecting and correlating non-CV data with capture CV data logs. Much of the non-CV data was used to track identified exogenous factors and to provide the sites with additional context to the operational condition in which the CV application warnings were occurring. These data were either fused with event data produced by the system or stored as supplemental data in the SDC. Other supplemental data collected stored by the sites include the following:

- Weather data from National Weather Service weather reporting stations or from agency operated weather stations.
- Traffic volume data.
- Loop detector or speed data
- Work zone and incident log data.

The effects of confounding factors can be subdued or eliminated by using an appropriate experimental design that accounts for these external factors. [(44)] Since confounding factors are external to the experiment, they are usually not monitored during the experimental period. As a result, changes in these factors during the experimental period may bias eventual findings. The sites had to deal with several significant external events impacting the project. These events include the following:

- The economic impacts of for-hire-vehicles (FHV) on the original NYC taxi fleet.
- A global COVID-19 pandemic that changed travel patterns over the time span of the project and had a tremendous impact on fleet installations and testing.
- Changes to regulations governing the connected vehicle radio communications technology.
- Initial full-scale deployment of the security infrastructure ensuring trusted communications.

Chapter 6. Lessons Learned and Recommendations for Future Deployments

This chapter summarizes the key lessons learned by the sites throughout the course of their deployment. These lessons learned may provide valuable insight for agencies performing their own CV deployments. Other information on lessons learned is available in the following references:

- *Connected Vehicle Pilot Deployment Program Phase 1 Lessons Learned*. (46)
- *Connected Vehicle Pilot Deployment—Lessons Learned Logbook Synthesis.* (47)

Key Lesson Learned

The following highlights some of the key lessons learned from the deployments. These lessons learned are not listed in any particular order of importance.

- From inception to deployment, the process of planning, designing, deploying, testing, and operating a CV deployment was long. The sites found that having dedicated champions for the deployment was essential to the success of the deployment. Without clear and strong champions, interest in deployment waned and commitments faltered. Each of the sites had a core group of champions dedicated to achieving the deployments goals and objectives.
- Each deployment had significant obstacles and uncertainties that had to be overcome. Deployment teams were able to overcome many of these impediments through strong cooperation and collaborations.
- The systems engineering processes proved to be a valuable tool for the sites. The sites found that using the system engineering process helped flesh out issues and provided solutions associated with technology and kept the deployment on-track.
- The CV applications were not at the level of maturity expected to allow for off-the-shelf deployment. Each site devoted a considerable amount of time and resources to making the applications function in their deployment. Better knowledge of the functional and operational requirements of the applications is needed, including system documentation.
- The sites found that documented installation procedures and manuals were needed for each type of participant vehicle used in the deployment. The sites customized the installation procedures to each vehicle type. The site found that proper installation procedures minimized installation errors and damage to vehicles, and reduced the time needed for installation. The sites also found that installations needed to be performed in a professional manner. The sites found they needed to inspect each vehicle to ensure that installation procedures were followed precisely.

- Adequate system documentation of applications was critical for ensuring the applications met user needs. Lack of vendor user and administrative documentation presented challenges for troubleshooting, training, and operations.
- The sites found considerable gaps, discrepancies, and ambiguities existed in many of the CV applications standards, and that some standards were open to interpretation. The sites had to develop verifiable system requirements that worked with evolving standards. The critical part of this process was to have a solid set of user needs and well-formed concept of operations.
- Without position correction, many of the CV applications did not function correctly. Two of the sites found that without position correction, the device's GPS were not suitable for applications requiring a high degree of location accuracy to operate properly. Inclusion of vertical elevation in MAP messages was also needed to allow vehicles to properly locate themselves in the network.
- Collaborations with both internal and external stakeholders were critical for a successful deployment. Each CVPD site benefited from sharing information about issues and solutions from the other sites. Other sites were used as sounding boards for developing solutions promoted interoperability between deployments.
- Equipment design and placement were not the same for every vehicle. The same antenna placement used with automobiles cannot be used with commercial heavy-duty trucks. The installation of OBUs and antenna testing were unique to each truck type. Truck antennae placement needed additional testing to make sure that the range of coverage was maintained. Antenna testing documentation was useful to other deployers as well
- Substantial time was needed to appropriately address contractual issues, testing planning, and execution. All three deployment sites spent a considerable amount of time finalizing contracts with device contractors and coordinating and executing memoranda of understanding with multiple user groups. They also spent a considerable amount of time developing test plans and processes, and then testing (and re-testing)
- Interoperability did not happen by accident. The sites were cognizant of the elevated risk of non-interoperability associated with several different applications being deployed and took steps to ensure that applications resulted in consistent alerting and messages across multiple platforms.
- Data sharing needs and requirements were incorporated into the planning stages of the architecture. Requirements related to data storage and retention, isolation of computer resources, and data security protocols were addressed early in the planning phase. It can be extremely difficult and time consuming to retrofit data-sharing capabilities once the system has been developed.
- Over-the-air (OTA) updating of application software, device firmware, and configuration parameters was essential for keeping the system up to date, correct and error free.
- The sites found that applications should be tested with the security credentialing service active. Much of the testing and fine-tuning of the applications was performed without the security credential management service active. After the credentialing services were engaged, several of the sites reported issues and challenges with applications not performing as intended. All sites agreed that conducting testing with security credentialing engaged was needed to ensure that the applications performed as originally intended and without delays.
- The sites needed to develop systems and tools to monitor the operational status of the RSU. Because of the critical nature of the data to support safety applications, agencies need to be able to rapidly detect and correct malfunctioning RSUs, especially in remote locations. The tools were needed to perform remote diagnostics and alert the agency when the RSU has gone off-line. The sites noted challenges with RSU certificates having a cascading effect that caused the RSUs to malfunction. Some sites also had challenges getting initial OBU certificates to download via RSU.

- Many freight fleets lease vehicles. Therefore, equipment installations that impacted the vehicle's original condition (e.g., making holes to install antennae) is something that needs to be discussed early on to make sure the fleet owner/operator understood and approved these modifications.
- Several techniques were used for protecting the privacy of applications users; however, a tradeoff existed between preserving privacy and data availability for evaluation. The sites found that agreements needed for a robust evaluation conflicted with some of their privacy policies. The sites engaged Institutional Review Boards to ensure that data collection requirements did not violate privacy protection requirements.
- Defining evaluation and performance assessment data needs early in the process allowed the sites to design appropriate strategies and mechanisms for collecting, storing, and processing data. Incorporating data needs early in the process allowed the sites to ensure that data considerations were appropriately factored into their system requirements and communications architectures, vendor selection, data processing approaches, privacy considerations, and other crucial design decisions.
- Without significant market penetration, the sites found it difficult to effectively assess the safety, mobility, environmental, and public agency benefits of the technology. The amount of data generated by equipped vehicles to support deployed applications depended on CV penetration rates. Without sufficient deployment numbers, is the sites found it difficult to identify and assess the benefits of the technologies.
- Leveraging existing traffic management systems and technologies and traveler information systems helped extend the benefits of the deployment and provided a pathway for future expansion for two of the sites; however, it can be difficult to isolate benefits if the technologies are introduced concurrently. Proper the experimental designs are required for isolating the benefits for each technology.

Recommendations for Future CV Deployments

The following provides some recommendations for agencies when considering future CV deployments.

Planning and Design

The following summarizes recommendations targeted at sites and site developers in the planning and design of their deployments:

- Ensure that the deployment addresses identifiable needs based on an assessment of current and forecasted operating conditions. The needs assessment should consider current challenges, solutions, practices, limitations, gaps, and improvement potential. The needs assessment should include projected conditions at opening day as well as project long-term conditions.
- Understand the level of maturity of the applications and technologies supporting the deployment. Thoroughly test and verify the functionality of equipment before committing to full-scale procurement, especially with new and unproven technologies.
- Ensure that the systems being planned and procured do not extend beyond the capabilities of the agency to support or maintain it. Agencies should ensure that operations and maintenance personnel have adequate knowledge, skills, ability, and resources to support the deployment. Additionally, agencies may want to ensure the rapid repair and replacement of critical system components.
- Keep deployment simple and implementable. Focus on getting one or two applications working well and leave more complex applications until after gaining an understanding of the limitations of technologies. Keep the scope of the deployment relevant and implementable.

- Develop approaches for integrating the CV technologies with existing transportation systems' management and operations. Think about how to use CV technologies to expand existing capabilities as opposed to introducing new functionality to existing programs. Insist on the release of fundamental operating requirements for existing applications, including test procedures.
- Avoid building a system that can only be supported by a single vendor. Agencies should consider how they plan to recover from poor equipment and maturity issues of applications. If possible, an agency may want to include a second vendor or technology that can be turned to in case vendor-related issues with original device vendors arise**.**
- Communicate frequently with other deployers/partners and continue outreach efforts to recruit participants throughout the project.
- Make sure that procurement practices can meet the needs of the deployment. Most government agency processes are not designed to meet the unique challenges encountered during the CVPDs. For new technologies, agencies should consider procuring equipment/devices as a vendor contract. Because of the amount of probable troubleshooting that will be needed, this should be procured as professional or engineering services.
- Engender consensus on the goals of the deployment among the various stakeholders early in the deployment planning. Maintain consensus throughout the deployment through regularly scheduled stakeholder meetings and phone calls that keep all team members up to date regarding the progress of the deployment.
- Strong documentation is needed to safeguard against this risk. Agencies should consider using living documentation methods to ensure that information about the system is current, accurate, and easy to understand. Agencies need to develop accurate project assumption logs and concepts of operations documentation early in the development process. These documents need to be review and updated on a regular basis. The use of metadata to describe processes and data elements is also important critical for removing ambiguities on logged data. As part of the initial project development, agencies should also develop a maintenance plan for ensuring that the system continues to function within its design elements.
- Much of the technology used in these kinds of project is in the early development stages and cannot be procured off the shelf using normal procurement practices. Engage procurement and contracting personnel early in the procurement process to ensure conformance with the existing procurement practices. Because of the uncertainties associated with developing CV technologies, agencies early establishment of a contingency fund/budget line item to address unanticipated issues
- The number and type of deployment vehicles is predicated of the specific issues to the addressed. Agencies should deploy the systems to have a meaningful impact of system performance. Agencies may want to consider using microscopic simulation models to explore what levels of market penetration are needed to produce measurable benefits.
- Agencies need to consider data use rights and privacy when using data from equipped vehicles and infrastructure for the evaluation effort, under certain constraints. Agency need to be aware of legal requirements related to the collection and use of data collected from human subjects. Obtaining the data needed for a robust evaluation may have some conflicts with a robust privacy policy. Consideration of agreements to allow robust data collection may be needed to obtain the data to permit a robust evaluation. The use of an opt-in agreement/contract like those already in use with many cell phone apps where individuals agree to share their data might be a viable method of obtaining user data. Agencies should engage an Institutional Review Board to ensure adequate privacy protection for human use subjects are in place.
- Deployments can be long and people in decision-making/influential positions within an organization will leave. Their replacements may not be as committed to the deployment as their predecessor.

Agencies may want to consider developing a succession plan as part of the project planning documentation to ensure continuity of personnel throughout the deployment.

Installation and Testing

The following summarizes several recommendations related to installation and testing of CV technologies:

- Much of the technology used in these kinds of projects is in the early development stages and cannot be procured off the shelf using normal procurement practices. Engage procurement and contracting personnel early in the procurement process to ensure conformance with the existing procurement practices.
- Test early and test often. Develop an appropriate test plan to test the functionality of the system end to end and at different stages of development. Detailed testing is required for OBU and RSU software, and in most cases, every aspect of the tests must be re-tested after each modification and firmware update to ensure that end-to-end functionality is not affected by any firmware upgrades.
- Reserve ample time in the schedule to account for testing, both test planning and test execution. Do not underestimate the time required to fine-tune and calibrate applications. Accurate delivery of alerts and messages can be compromised by configuration issues.
- Agencies need to develop strategies for conducting upgrades and enhancements of applications using over-the-air messaging.
- Define data and performance measurement/evaluation needs early in the project so that decisions regarding data, CV system design, back-office processing strategy, CV vendor selection, and others would be better informed.
- Have a tested and functioning SCMS in place prior to deployment to avoid ongoing refinements and schedule adjustments. Add in the SCMS from the beginning when the CV system is being built. Testing done without the security turned on slows down the deployment.

Operations and Maintenance

The following summarizes the recommendations based on the lessons learned by the sites and the USDOT development team related to operations and maintenance associated with a development:

- Maintain the accuracy and quality of information used to produce alerts. Incorrect or erroneous information can erode user acceptance and trust in the system.
- Minimize time between user recruitment/installation and going live. If the lag time is too great, users will forget about their commitment and/or lose interest.
- Be prepared to spend considerable time configuring application parameters. Agencies need to establish performance standards and thresholds to ensure that high quality data is available.
- Develop a clear protocol for prioritizing warning alerts to drivers when multiple applications could produce simultaneous alerts. The sites noted that a clear protocol for prioritizing alerts was needed to avoid driver confusion.
- Supplement CV device penetration rates with non-CV sensor data to generate timely and adequate information to support relevant CV application operations that rely on such data to operate and meet functional and performance objectives. Non-CV sensor data as well as third-party data or crowd-

sourced data could be used to support operation and evaluation of deployments, including calibration. These systems could also be used to potentially collect trajectory data at key locations.

- To the extent possible, leverage existing systems and communications protocols to support the widespread dissemination of alerts and warning using other communications media.
- Use over-the-air updates to update device software and firmware and conduct log offloading.
- Develop a feedback mechanism to let stakeholders know that you are hearing them. Once stakeholders begin to lose confidence in the technology, that confidence is extremely difficult to regain.
- Expect challenges and issues to arise during deployments that lead to budget shortfalls. There is a high cost associated with acquisition, deployment, and management of a CV system (e.g., managing the data that are developed).
- Consider evaluation and performance measurement needs early in the concept development process. This will reduce the amount of rework that must be done at the concept development stage. Ensure that performance measures reflect the goals and objectives of the deployment.

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