Connected Vehicle Pilot Deployment Lessons Learned Logbook Synthesis

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16. Abstract

The Connected Vehicle Pilot Deployment (CVPD) Program seeks to spur innovation among early adopters of connected vehicle application concepts. In September 2015, Pilot deployment awards were made to three sites, New York City, Wyoming, and the Tampa Hillsborough Expressway Authority (THEA) in Tampa, FL. The pilot sites were expected to integrate connected vehicle research concepts into practical and effective elements, enhancing current operational capabilities and safety.

This report is intended to share useful solutions and lessons learned captured by the three CV sites in in their Lessons Learned Logbooks (LLLs), and to help the CV community avoid known pitfalls and expedite successful, cost-effective CV deployments.

Information in the LLLs was analzyed across all sites to generate an initial list of lessons learned. Each site reviewed the initial lessons learned synthesis for accuracy and enhancement.

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Table of Contents

List of Tables

Executive Summary

The USDOT Connected Vehicle Pilot Deployment (CVPD) Program seeks to spur innovation among early adopters of connected vehicle application concepts. In September 2015, Pilot deployment awards were made to three sites, New York City, Wyoming, and the Tampa Hillsborough Expressway Authority (THEA) in Tampa, FL. The pilot sites were expected to integrate connected vehicle research concepts into practical and effective elements, enhancing current operational capabilities and safety. Tampa (THEA) and New York City DOT (NYCDOT) CV deployment sites have completed the Phase 3 (operate and maintain) period, and Wyoming DOT (WYDOT) is actively in the third phase.

This report is intended to share successes and lessons learned captured by the three CV sites in in their Lessons Learned Logbook (LLL) with the growing early and future deployer community to help avoid potential deployment pitfalls, repetition of mistakes, and facilitate faster and cost-effective CV deployments. The lessons learned presented in this document comprise an extensive mix of experiences from all three phases of the CVPD. This report is the third in a series of sharing CVPD lessons learned with the broader ITS community.

In order to meet overall program goals of accelerating the deployment of CV technologies, pilot deployment sites were required to share insights and lessons learned with peers considering or actively deploying connected vehicle technologies. While each site developed their own LLL based on internal needs, the raw material in the LLLs have not been systematically shared outside of the sites. This report seeks to provide value by looking at the LLLs in detail across all three sites, seeking challenges and innovations common among all three sites and uniquely faced by individual sites. In this, the LLL synthesis activity augments completed and ongoing efforts to capture key CV deployment insights.

A two-step approach was used to develop the lessons learned presented in this document. First, the CVPD technical support contractor, Noblis, reviewed information captured in each site's LLL and synthesized the information across all sites to generate an initial list of lessons learned. Subsequently in the second step, initial lessons learned synthesis was reviewed by each CV site for accuracy and enhancement.

A summary of the synthesized lessons learned are presented below in Table ES-1.

Table ES-1: Summary of CVPD Lessons Learned

ID	Lessons Learned Title
1.	Reserve adequate amount of time in the schedule for contractual and paperwork issues, test planning and execution.
2.	Plan for extensive CV device procurement and vendor selection process.
3.	Assess the level of CV application maturity and stability.
4.	Use existing standards as a part of the system architecture and design process; be aware of gaps, discrepancies, and ambiguity in standards and that some standards are open to interpretation.
5.	Maintain a stable telecommunications network to minimize disruptions to/from devices/interfaces and impacts on the entire system operation.
6.	Have a tested and functioning Security Credentials Management System (SCMS) in place prior to deployment development to avoid ongoing refinements and schedule adjustments.
7.	Monitor certificate operations of CV components to allow discovery of issues, such as certificate loading problems, to occur faster, before they have an impact on the RSU and OBU operations.
8.	Use over-the-air (OTA) updates to download firmware and conduct log offloading.
9.	Test early and often in real-life settings to identify issues early and verify end-to-end system/application performance with comprehensive documentation.
10.	Test the location accuracy of CV devices with location augmentation mechanisms (e.g., dead reckoning, CAN bus integration, inertial management unit (IMU), RSU triangulation, RTCM).
11.	Develop different installation manuals/procedures for different types of participant vehicles and perform installations of equipment in a professional manner.
12.	Consider alternate installation approaches aligned with contractual/business requirements of freight partners.
13.	Give attention to antennae design, placement, and product quality. Different size trucks and buses have unique antennae configuration and wiring requirements which also differ from those for light-duty vehicles.
14.	Plan for thoroughly documenting system design & development, and equipment installation
15.	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.
16.	Design and implement appropriate data collection and privacy measures to reassure deployment stakeholders and participants that their privacy is protected.
17.	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.
18.	Maximize the impacts of CV deployment by leveraging supplementary communication protocols to disseminate traveler information messages (TIMs) beyond the geographical limits of deployment corridor/area.
19.	Communicate frequently with other deployers/partners and continue outreach efforts to recruit participants throughout the project.

Chapter 1. Introduction

The USDOT Connected Vehicle Pilot Deployment (CVPD) Program seeks to spur innovation among early adopters of connected vehicle application concepts. In September 2015, Pilot deployment awards were made to three sites, New York City, Wyoming, and the Tampa Hillsborough Expressway Authority (THEA) in Tampa, FL. The pilot sites were expected to integrate connected vehicle research concepts into practical and effective elements, enhancing current operational capabilities and safety. The CV Pilot is a three-phase deployment and all three sites have completed Phases 1 (12-month period of concept development) and 2 (a period of design/build/test). While the Tampa (THEA) and New York City DOT (NYCDOT) CV deployment sites have completed the Phase 3 (operate and maintain) period, as of December 2021, Wyoming DOT (WYDOT) is actively in the third phase. THEA is actively in a Phase 4 (June 1, 2020 to September 30, 2022) deployment with light vehicle Original Equipment Manufacturers (OEMs) to further the work completed in the previous phases; however, this synthesis does not include lessons learned from that effort. THEA is documenting lesson learned in a logbook; however, these will not be available until the end of Phase 4. For more information on the CVPD Program, please visit the program's webpage (https://www.its.dot.gov/pilots/).

CV technology deployment is an example of a large "system of systems" that encompasses both technical (e.g., complex design, procurement, requirements specification, build, integration, testing, etc.) and non-technical (e.g., forming partnerships, contracting, addressing legal issues, etc.) activities. Consequently, it is imperative that agencies considering future CV deployments equip themselves with requisite expertise (both technical and non-technical) to be successful. In addition, future CV deployers should learn from the experiences of pioneer deployers such as the CVPD sites. These experiences may be success stories (e.g., how to successfully install antennas on trucks) or lessons learned (e.g., not building adequate testing period into project schedule leading to project delays, rigorous application of the systems engineering). Notwithstanding, the combined insights from these experiences provide valuable observations that can be utilized by future CV deployers to facilitate desirable outcomes while minimizing or eliminating undesirable outcomes.

What is consistent among the experiences of all three sites is that the maturity of the various devices and applications was not what was expected. While there had been numerous "demonstrations", "trials", "proof of concept", and "sample" systems during the prior phases of connected vehicle technology experimentation which included such efforts as the Safety Pilot[1], the practical, main-stream deployment, and integration into the ITS environment brought forth new challenges. Further, the scale of the deployment for such systems as New York City with over 450 roadside units and thousands of fully equipped vehicles uncovered many new challenges to the equipment suppliers and system deployment.

[1] Intelligent Transportation Systems - Connected Vehicle Safety Pilot (dot.gov)

It is hoped that the lessons learned presented here lead to more consistent, interoperable, and robust implementations supporting the deployment of a national program supporting compatible operation. While the technology has moved from Dedicated Short-Range Communications (DSRC) to Cellular Vehicle-to-Everything (V2X), the deployment lessons for specific applications are expected to be similar when deploying C-V2X and satellite technology, however there may be additional challenges if C-V2X devices will have to operate with only 30 MHz of dedicated spectrum instead of 75 MHz.

Purpose

The purpose of this document is to share useful solutions and lessons learned captured by the three CV sites in in their Lessons Learned Logbooks (LLLs), and to help the CV community avoid known pitfalls and expedite successful, cost-effective CV deployments.

Background

In order to meet overall program goals of accelerating the deployment of CV technologies, pilot deployment sites were required to share insights and lessons learned with peers considering or actively deploying connected vehicle technologies. This included the accommodation of site visits and development/maintenance of the LLLs, as well as outreach events (webinars and conferences) where sites shared these insights. While each site developed their own LLL based on internal needs, the raw material in the LLLs have not been systematically shared outside of the sites. This report seeks to provide value by looking at the LLLs in detail across all three sites seeking challenges and innovations common among all three sites and uniquely faced by individual sites. In this, the LLL synthesis activity augments completed and ongoing efforts to capture key CV deployment insights.

The Intelligent Transportation System Joint Program Office (ITS JPO) has published two (2) Lessons Learned reports for Phase 1 and Phase 2 respectively.[2,3] These earlier Lessons Learned publications were based on either interviews with CVPD sites and USDOT staff or review of presentation materials used by the sites at the Institute of Transportation Engineers (ITE) Annual Meeting 2018. The publications are limited in scope as they capture CV deployment experiences specific to either Phase 1 or Phase 2. In contrast, this Lessons Learned synthesis document presents experiences captured in all three Phases of the CVPD and provides a broad range of information including program level lessons learned. Most critically, this document synthesizes the detailed lessons learned information across all three sites as captured by each site's LLL.

[2] Connected Vehicle Pilot Deployment Program Phase 1 Lessons Learned. https://rosap.ntl.bts.gov/view/dot/31937.

[3] Driving Towards Deployment: Lessons Learned from the Design/Build/Test Phase. https://rosap.ntl.bts.gov/view/dot/37681.

A two-step approach was used to develop the lessons learned presented in this document. First, the CVPD technical support contractor, Noblis, reviewed information captured in each site's LLL and synthesized the information across all sites to generate an initial list of lessons learned. Subsequently in the second step, initial lessons learned synthesis was reviewed by each CV site for accuracy and enhancement.

Note: The examples provided in the Lessons Learned section below are meant for illustration of actions taken by sites in support of corresponding lessons learned. They are intended to further enhance the meaning of lessons learned presented in this document. For each lesson learned, examples are not always provided for all three sites. Lack of examples from a CVPD site for a particular lesson learned does not imply that an action wasn't taken and could be due to that a site did not experience a specific issue.

CV Technology Deployment

It is important to note that CV Pilot technologies deployed in the CVPD project were from aftermarket suppliers. So, all participating vehicles had to be retro-fitted with CV devices as opposed to vehicles pre-equipped with CV technology from OEMs. To ensure the security of aftermarket CV technology, originally USDOT partnered with the Crash Avoidance Metrics Partnership (CAMP) to design and develop a Proof-of-Concept (POC) security solution for vehicle-to-vehicle (V2V) and vehicle-to infrastructure (V2I) communications. The POC Security Credential Management System (SCMS) development occurred in parallel with the site deployments; however, eventually the CAMP POC SCMS was replaced with a commercial solution capable of providing a SCMS solution for all three CVPD sites. A SCMS uses Public Key Infrastructure (PKI) for encryption and certificate management to ensure trusted communications and operations in a secure environment. While the SCMS keys can be used for encryption, the CVPD sites used the SCMS only for message signing and certificate management.

Chapter 2. Lessons Learned

In general, the lessons learned synthesis presented in this report has both technical and non-technical focus. Technical lessons learned are those that pertain to safely deploying CV technology in the field in accordance with specified functional and performance requirements (e.g., CV technology and devices testing, telecommunication, standards and interoperability). The non-technical lessons learned are those from deployment activities that provide an enabling institutional, legal, and social environment for CV technology deployment to be successful (e.g., preparation activities, contracts and partnership agreements, scheduling)

For each lessons learned presented, the following information is provided:

- **Title** – This is the subject of a lesson learned. The title provides the central theme associated with a lesson learned.
- **Summary** – Provides concise information about challenges encountered by CVPD sites that resulted in a lesson learned, their impacts on CV deployment, and the general approach used by the CVPD sites to address these challenges.
- **Key Actions Taken/Impacts** – This is a bullet list of specific actions taken by CVPD sites to address challenges encountered, and their resulting impacts on CVPD.

The lessons learned are presented below. Please note that the ordering of the lessons learned is just for identification and does not in any way suggest the level of significance.

1. **Reserve adequate amount of time in the schedule for contractual and paperwork issues, test planning and execution.**

Building adequate time into project schedule ensures enough time to address contractual and paperwork issues which typically takes longer than expected time to execute. Also, adequate amount of time is needed to enable thorough testing of individual CV devices and the CV system as a whole. Incorporating adequate amount of time in the schedule ensures adherence to deployment schedule and avoidance of extended project delays.

- Significant amount of time was spent on finalizing contracts with CV device contractors, coordination and execution of MOUs with multiple fleet owners and agencies.
- Significant amount of time (beyond what was originally planned) was spent on test planning, execution, and required re-testing activities. For example, due to lack of time, testing activities at some of the sites had to be scaled down to only safety critical requirements.
- It is also important to note that there was a lack of test equipment and procedures even for the fundamental technology. Precise measurements of such parameters as SPaT accuracy, latency, and error checking for the MAP messages were not available and had to be developed by the vendors and the pilot sites. This proved to be a major challenge as well and required considerable time just to develop and proof the test tools. Subsequently, USDOT made some test equipment available, but precise measurement of the SPaT content is still lacking.

2. Plan for extensive CV device procurement and vendor selection process.

The CVPD sites found early sourcing of suppliers and vendors is key to creating a collaborative environment to understand how system requirements are implemented in the design, to source suppliers who are willing to participate in developing open specifications, and to source suppliers who can meet aggressive schedules with quality. Working with the vendors on the approach for practical at scale data collection was necessary.

- Utilized the systems engineering process (e.g., user needs, requirements, specifications, traceability) throughout the project lifecycle. In addition, NYC CV deployment relied on NYCDOT's Request for Expression of Interest and Proposal (RFEIP) process and leveraged existing device vendor experience.
- Tampa (THEA) deployment conducted multiple scans using RFPs (with on-the-road testing) to identify promising suppliers who could meet system, cost, and project timing requirements. The team found it critical to scrutinize and select the best suppliers for the CV Deployment.
- WYDOT CVPD team conducted pre-delivery device testing to ensure devices provided required functionality and were not missing files.
- During design and procurement stages, the NYCDOT team conducted a rigorous analysis of the CV deployment vendors and their sub-suppliers/sub-vendors that contribute to the proposed CV system. The vendor has had to rely on its sub-vendor to adjust software for location accuracy and security. The OBUs had software from various sources, which increased the time necessary to accommodate issues discovered.
- Obtained RF tools (interference detection, protocol analyzers, GPS repeaters, etc.) early to support testing of the different NYCDOT deployment vehicle fleets. WYDOT did same for bench and initial device delivery testing.
- The three CVPD sites concluded it would have been useful to accurately assess the CV hardware, primarily the OBUs and RSUs as to where they were on the Technology Readiness Level (TRL) scale. This assessment would have indicated the larger scope and cost of testing that the WYDOT CVPD encountered.

3. Assess the level of CV application maturity and stability.

At the beginning of the CVPD program, CV applications were not at the maturity level expected to allow for deployment. Better knowledge of applications (e.g., open source, individual vendors) facilitates deployment and reduces additional resources required to test and address the application's maturity.

- Optimized CV applications during integration and testing, and for the CVPD all-site interoperability testing at Turner Fairbank Highway Research Center. Need to understand that onboard applications for the pilots will need to function without optimization in other locations. For example, Tampa (THEA) worked with vendors to debug the V2V applications and made them deployment ready.
- Developed a threat arbitration mechanism to develop a clear protocol for warning priority when multiple applications could cause priority confusion to the driver [e.g., Forward Collision Warning (FCW), Emergency Electronic Brake Light (EEBL), and End of Ramp Deceleration Warning (ERDW)]. NYCDOT team noted when multiple warnings are triggered, a clear protocol for warning priority is needed to avoid driver confusion.

4. Use existing standards as a part of the system architecture and design process; be aware of gaps, discrepancies, and ambiguity in standards and that some standards are open to interpretation.

The use of standards helped create a solid deployment effort for the three CVPDs in Phase 2, simplified systems engineering/technical documentation, and assisted with interoperability. THEA participated as Working Group Voting Members and Subject Matter Experts to fill two identified gaps in the US standards: 1) Successful THEA deployment of the international OCIT communications standard led to the creation of the NTCIP 1218 standard, 2) Successful use of the USDOT V2X Hub publication led to the creation of NTCIP 1202v3 and the RSU Standard.

- The three CVPD sites identified a set of common messages and relevant standards.
- Worked with standards committees and developers to add compatibility with older standards. For example, NYCDOT CV site employed draft NTCIP 1202v3 standard that may be considered for interoperability with other future CV deployments.
- Avoided, where possible, using unpublished standards. Tampa (THEA) CVPD used the following process: design using standards published on January 1, 2017; if a USA standard does not exist, design using international standards; and if no standard exists, refer to the USDOT V2X Hub publication.
- Identify common requirements that affect interoperability, as the Tampa (THEA) and NYCDOT CVPD sites did for crosswalks, before design starts.
- Work with Standards Development Organizations (SDOs) to address and incorporate heavy vehicle trailer into BSM Part II in SAE Standard J2945/2. The WYDOT team was not able to include tractrix with the pilot, due to current maturity of the ecosystem; however, they will use the BSM Part II to define trailers and pivot points.
- It also became obvious to the three CVPD sites that ambiguities within the standards can cause issues with interoperability; it is important to remain involved with the standards program to increase the probability of interoperable solutions.

5. Maintain a stable telecommunications network to minimize disruptions to/from devices/interfaces and impacts on the entire system operation.

Conducting network testing, working with equipment vendors and service providers in real-time, and establishing a network monitoring process (as done by WYDOT and NYCDOT) supports reliable and secure CV communications and can prevent and minimize CV system operations downtime.

- Established network monitoring of IPv4 and IPv6 networks to test for reliability issues on the backhaul system from the OBUs to the RSUs to the TMC and to the internet for SCMS updates. The WYDOT CVPD team worked with the WYDOT Enterprise Technology Services team to address IPv6 challenges on the backhaul. THEA central software constantly monitored network reliability, with daily automated push reports to stakeholders.
- Coordinated with vendors (network and equipment) to test and troubleshoot for connectivity and security issues between the RSU and the traffic controller. NYCDOT CV deployment continued discussions with vendors to collaborate on testing to resolve these issues.
- Tested the network connection from different service providers. For example, NYCDOT deployment found that SNMPv3 was not supported for some of the devices hence the project had to rely on SNMPv1 to some devices using DTLS/TLS for the network security.
- Generated and maintained a checklist for each source-destination communication pair to confirm full connectivity. NYCDOT deployment found that to confirm full connectivity, the recipient side may have to be checked in addition to the transmitter side.
- Using DSRC sniffers, Tampa (THEA) CVPD scanned periodically to verify radio interference and unauthorized broadcasts.

6. **Have a tested and functioning Security Credentials Management System (SCMS) in place prior to deployment development to avoid ongoing refinements and schedule adjustments.**

Although not as timely as preferred by site deployers, collaborative efforts across USDOT, CV Pilot sites, and vendors resulted in a successful, functioning SCMS solution and lessons learned. The three CVPD teams spent significant time working with the evolving SCMS. Unfortunately, as features were implemented within the SCMS it sometimes had a negative impact on the operation that required rollback to an earlier version of the SCMS; had the full SCMS been operational sooner in the project then the security libraries would have been stable and well tested; changes to the security software within the OBU is costly.

- During Phase 1, the three CV Pilot sites worked with the USDOT SCMS developer and other security vendors (e.g., hardware security solution providers) and participated in USDOT-sponsored Plugfest events to refine requirements needed for a SCMS solution that worked for the three deployments and would support a national SCMS.
- Addressed security in all aspects of the NYCDOT site deployment to include physical security of the NYCDOT Transportation Management Center (TMC), devices and network security, and system access needs. It is important to note that THEA lost almost 75% of its original participants because of the SCMS delay. This was a primary driver in THEA pushing forward to utilize a commercial SCMS.

7. **Monitor certificate operations of CV components to allow discovery of issues, such as certificate loading problems, to occur faster, before they have an impact on the RSU and OBU operations.**

Persistent issues with certificate downloads and failure of certificate top off processing caused high rate of error message logging and rapid growth of log file impacting RSU and OBU operation and performance.

- Installed a firmware release on Lear RSUs to reduce error logging and slow log file size growth so that RSUs could resume normal processing of CV messages and other functions of the WYDOT CVPD.
- The NYCDOT deployment site implemented a weekly CV device monitoring and reporting mechanism for certificate top off success or failure and detection of issues or error with SCMS interface.
- Implemented an active SCMS certificate update mechanism for tracking the cause of any unsuccessful certificate update in the NYCDOT CVPD.
- During design, THEA made the decision to download 3 years' worth of certificates to avoid having to periodically download certificates to vehicles.

8. Use over-the-air (OTA) updates to download firmware and conduct log offloading.

Calculating and testing OTA download speeds early in the design helped to identify issues and allow site teams time to work with vendors on solutions to ensure timely downloads of certs, software updates, and uploads of log files. Once an update is ready, begin by deploying to only test groups for verification so that update does not expose new, significant issues to every entity.

- Deployed additional RSUs to enable partial downloads. Without these extra RSUs a complete full firmware download was not possible for Tampa (THEA) CVPD OBU firmware updates. NYCDOT deployed approximately 130 RSUs to support uploading, downloading, and V2XLocate2.
- Important to test the log offloading at highway speed, as this can be unreliable. WYDOT CVPD worked with the vendor to test the speed of a 100k-sized file to offload to an RSU as well as use a restartable SCP connection to allow for uploads and downloads to OBUs to work over multiple RSUs.
- WYDOT CVPD updated configuration instructions and provided them to fleet installers after the team was made aware of an error and confirmed how to resolve issue. Over the air updates are essential for firmware, configurations, and applications on the human-machine interface (HMI); the cost to physically touch the vehicles is prohibitive due to challenges associated with scheduling trucks at warehouses and logistic hubs.
- NYCDOT CV deployment used this technique to optimize and conserve the device's processing power when handling multiple WAVE Service Announcements (WSA) for OTA uploads and downloads. It is likely to be necessary to map out a strategy for optimal use of the spectrum by limiting both the power levels and channel usage. OBUs can receive from 30-50 or more RSUs simultaneously in RSU dense areas. Note that this will be more challenging if the amount of spectrum is reduced to 30 MHz.

9. Test early and often in real-life settings to identify issues early and verify end-to-end system/application performance with comprehensive documentation.

The CVPD sites were able to identify technical issues through early and consistent testing in real-life settings and worked with vendors to resolve them. Frequent tests also ensured that CV performance reliability was acceptable prior to deployment in Phase 3. In addition, testing in real-life environment under different operational conditions and scenarios enabled the CVPDs at all three sites to identify issues that were previously not detected in limited controlled system tests as well as individual component tests. Testing activities and results were well documented in various documents.

- The three CVPD sites began testing early in Phase 2 and conducted numerous tests to check if performance and functional requirements are being met. In addition, testing was done frequently to check CV device software updates.
- For example, WYDOT team members conducted bench testing whenever they received a new shipment of devices or firmware updates. In addition, Tampa (THEA) team realized that testing in the laboratory was not adequate to verify that the applications were integrated and functional, so they worked with the vendors as a team to perform integration testing in Tampa during Phase 2. For firmware updates, Tampa (THEA) created a small group of vehicles termed “friends of the pilot”. These vehicles received the updated firmware first. The Tampa (THEA) team would then test firmware prior to its release to all participants. Also, NYCDOT repeatedly tested CV applications and devices in different locations/environments (e.g., around tall buildings in Manhattan, peak and off-peak periods, etc.) to ensure reliable and consistent performance.
- The three CVPD sites developed extensive documentation for testing including test plans, test cases, test procedures, test results and observations. For example, documented test plans/results enabled NYC CV deployment to quickly identify root causes of issues during the Operational Readiness Demonstration (ORD) and develop solutions. In addition to the required test documents, Tampa (THEA) kept a testing issues log spreadsheet during the installation/operation phases that detailed the dates, issues and the actions taken to resolve the issues. All three CVPD sites used traceability matrix to track each Requirement from Needs to Design and Verification.

10. Test the location accuracy of CV devices with location augmentation mechanisms (e.g., dead reckoning, CAN bus integration, inertial management unit (IMU), RSU triangulation, RTCM).

Without location accuracy, CV applications will not function correctly. Tampa (THEA) found that smart phone GPS was not suitable for those safety applications requiring a high degree of location accuracy for intended operational functionality (e.g., pedestrian signal system (PED SIG)). NYCDOT found that the V2XLocate improved the location accuracy sufficient for operation of many of the V2V and V2I safety applications in many locations, but the success was not universal.

- Verified the GPS timing accuracy and synchronization in CV devices. The GPS timing and synchronization in NYCDOT CV deployment OBUs and RSUs at times were found to be inaccurate and shaky.
- Used multiple sensors to enhance GPS location accuracy and enable auto-switch of the location augmentation method from V2XLocate[4] to GPS. The NYCDOT CVPD team tested GPS location accuracy using data from CAN bus at 10 Hz, inertial navigation, and RSU trilateration/triangulation in urban canyon and open-sky conditions.
- Used laser light (target) to establish vehicle's location reference during OBU location accuracy testing to address location challenges due to urban canyons and scaffolding in the NYCDOT CVPD site area.

[4] This is a proprietary solution offered by Cohda using time of flight from RSU transmissions.

11. Develop different installation manuals/procedures for different types of participant vehicles and perform installations of equipment in a professional manner.

Recognizing the differences in participating vehicle types and developing different installation procedures helped minimize installation errors, damage to vehicles, and amount of time required for installation. In addition, installing CV equipment with professionalism and caution helps minimize participant complaints, damage to vehicles, maintenance issues and repeat visits to installers.

- Each type of vehicle participating in the deployment (e.g., light-duty sedan, light-duty truck, semi-trailers, etc.) is different in size, configuration, and use. Hence, NYCDOT developed different versions of the installation manual/procedures for each vehicle type.
- Participants and vehicle dealers tend to blame vehicle maintenance issues on CV equipment installations. Hence, Tampa (THEA) technicians often tested vehicles before and after installation of CV equipment to ensure that no new mechanical or electrical issues are introduced as a result of installations. Tampa (THEA) team partnered with a professional OBU integration/installation vendor to perform the installation task.
- Installation of some CV equipment required drilling into various parts of vehicles which led to incidents such as damaging vehicle gas lines and EV batteries, water damage to vehicles due to improper installation of drip loops, larger drill holes, etc. NYCDOT used lessons learned from these initial installations to ensure that subsequent drilling activities were done in the right place in vehicles, screws used for drilling were of the correct size, drip loops were properly installed, and alternative approach to drilling was used when necessary/possible (e.g., use of adhesives).
- NYCDOT thoroughly inspected the vehicles prior to installation; any vehicle with pre-existing diagnostic warnings or issues were not touched to avoid becoming responsible for unrelated problems.
- NYCDOT thoroughly inspected vehicles after installation to ensure that there are no exposed wires, CV equipment is firmly held to the vehicle, and CV equipment is functioning as expected.

12. Consider alternate installation approaches aligned with contractual/business requirements of freight partners.

Installations on freight fleets may be different from other vehicle types due to contractual and business requirements. Therefore, it is important to engage freight partners and understand their contractual and business obligations prior to equipment installations.

- Freight partners usually have their own equipment installation team. Hence, WYDOT conducted installation training for these teams based on their schedule and continued to provide technical support to ensure installations were done correctly. Notwithstanding, there were still issues of faulty installations by freight partners, leading to some CV equipment not functioning properly.
- WYDOT engaged freight partners in numerous discussions to clarify requirements of participating in the pilot (e.g., the need to drill holes in trucks) as well as understand freight partner contractual obligations that must be adhered to (e.g., some truck leasing contracts do not permit holes to be drilled in the truck).

13. Give attention to antennae design, placement, and product quality. Different size trucks and buses have unique antennae configuration and wiring requirements which also differ from those for light-duty vehicles.

Assess truck and bus (NYC CV site) configurations early in the process to ensure the vendor can provide solutions for gaps in their current products. For custom installations, WYDOT CVPD followed the following process: develop a prototype mounting design and wiring, install on a first vehicle, conduct tests, then machine, or tool/develop based on results. Note that the NYCDOT vendor developed a through the glass antenna mount for the transit vehicles which proved successful – although it took several iterations to perfect the mechanical design and select the proper adhesive.

- WYDOT CVPD worked with one of the vendors, but reliability and durability of components was not consistent.
- Often required custom approaches to wiring and mounting. For example, low-volume antennae mounting kits were machined by WYDOT team members because the components were not available off-the-shelf. Otherwise, retrofitting in large-scale would have been resource intensive and resource prohibitive.
- The CVPD sites tested and calibrated DSRC antennae after OBU installation to ensure proper configuration for broadcast reception. NYCDOT CV deployment used a standalone DSRC antennae at the installation lot/bay to assist in each vehicle's antennae calibration. WYDOT CVPD tested all available antennas (e.g., pole, Sharkfin) and on all configurations of vehicles to determine if data results were those expected.

14. Plan for thoroughly documenting system design & development, and equipment installation.

Early in the project, the maturity of the CV ecosystem was not well defined or tested. WYDOT CVPD team found system documentation is critical to fall back on to ensure the project meets the user needs. Lack of vendor user and admin documentation presented challenges for troubleshooting, training, and operations.

- USDOT and support contractor documentation reviews, document updates by site staff, and discussion with vendors to nail down concept and detailed design content required resources, hence WYDOT CVPD team learned to plan a significant amount of time for these activities.
- Updated pre-delivery testing checklist to confirm fixes for known errors functioned correctly. WYDOT team members developed a plan and documentation for WYDOT installers to update map files in OBUs on equipped WY Highway Patrol vehicles.
- Developed plan, and documentation for installers and installation kits for fleet partners to ensure proper installation of OBUs and other equipment. For example, NYC CV team generated an installation guide for ensuring proper installation of RSUs on mast arms. THEA CV team conducted a site survey of every infrastructure installation location, including an inventory of existing signal controllers, communications, cable conduit, optimum location for RSU antennas and lane marking geometry for MAP file creation.
- Active participation and "group" sharing of design issues among the sites were of significant value to each site as well as the CVPD Program.

15. 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.

Defining data needs earlier in the project ensured that the sites developed their CV systems to generate quality and appropriate data needed to support their performance measurement and evaluation goals. In addition, the cost of communications, data storage, and processing was minimized as a result of collecting the right amount of needed data.

- The three CVPD sites defined their data needs early in the planning phase (i.e., Phase 1). This ensured that data considerations were factored into the development of their CV system requirements and design, vendor selection, CV applications development, data processing approach, privacy considerations, and other critical decisions.
- The three CVPD sites engaged relevant stakeholders (e.g., USDOT, sites state and local DOTs, transportation associations, etc.) to define performance measures, performance measure estimation approach, and other evaluation needs early in the planning phase (i.e., Phase 1).
- Based on performance measurement and evaluation needs, the three sites defined appropriate mechanisms for collecting, storing, and processing data. For example, WYDOT and NYCDOT decided to reduce the size of BSM data collected by using an event-based approach where BSM data is collected within a pre-defined time window before and after the occurrence of an event.

16. Design and implement appropriate data collection and privacy measures to reassure deployment stakeholders and participants that their privacy is protected.

The CVPD sites dedicated adequate time to figure out and implement workable solutions to ensure that the confidentiality, integrity, and availability of data is guaranteed. In designing privacy controls for the CVPD, the sites considered both current and future legal ramifications of collecting and storing participant data.

- To protect the privacy of CV deployment participants, NYCDOT obfuscated their CV data by transforming into another coordinate system. This ensured that deployment participants actual movements in the real-world cannot be obtained. It also aggregated the data into “bins” such that it could not be disaggregated for alternative uses.
- Similarly, WYDOT used dynamic vehicle IDs for private trucks participating in the pilot. As a result, participants movements are difficult to be tracked since vehicle IDs change frequently.
- Tampa (THEA) encrypted all PII data in transit or at rest and ensured that all individuals with access to PII have received the necessary training in protecting PII. The THEA Central software removed PII for individuals granted research access to the data, but without access to PII.

17. **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.**

The amount of data generated by equipped CVs to support deployed applications depends on CV penetration rate. Consequently, there are instances where CV data alone would not be enough to support the functional and performance objectives of some deployed CV applications due to low penetration rates. CVPD sites that experienced this situation supplemented CV data with traditional data to ensure deployed applications operated as expected.

- Due to low CV device penetration rates, the Tampa (THEA) CV deployment supplemented data generated by the limited CV devices with data from non-CV sensors (e.g., camera, speed radar) to support the operation of deployed CV applications (e.g., supplementing CV data with video detection data to support a MMITSS application at signalized intersections).

18. **Maximize the impacts of CV deployment by leveraging supplementary communication protocols to disseminate traveler information messages (TIMs) beyond the geographical limits of deployment corridor/area.**

Due to limited number of deployed RSUs, transmission of traveler information messages tends to be geographically restricted to only the deployment corridors. The choice of OBUs and communication strategy can project the impacts of CV deployment beyond the pre-defined geographical limits .

- The three CVPD sites relied on DSRC communication to relay TIMs to equipped vehicles.
- The transmission of TIMs through DSRC communication is limited to only the geographical limits of the deployment corridor/area in NYCDOT and Tampa (THEA) CV deployments where RSUs are located.
- WYDOT used OBUs with dual communication media (i.e., DSRC and satellite communication). In areas where DSRC communication was nonexistent, transmission of TIMs was achieved through satellite communications.

19. Communicate frequently with other deployers/partners and continue outreach efforts to recruit participants throughout the project.

Sustained engagements between a CVPD site and other deployers, partner agencies and the general public was critical to the success of the CVPDs. These engagements aided the CVPD sites in addressing a lot of technical and operational challenges and ensured that mistakes were not repeated and solutions to common problems were identified.

- The CVPD sites communicated among themselves and with other deployers through multiple engagements to learn from each other and discuss solutions to common technical and institutional challenges. For example, the three CVPD sites participated in Monthly Technical Roundtables to discuss common technical issues and work out solutions.
- The CVPD sites engaged partner agencies to understand the impacts of any changes in partners' activities on the CVP deployment and plan accordingly to mitigate any potential issues. For example, NYCDOT constantly engaged with Metropolitan Transportation Authority (MTA) to learn about availability of buses for deployment and to plan for contingencies should the buses become unavailable.
- Some participants who showed initial interest and signed up for the deployment backed out later due to multiple reasons (e.g., partner fleet not having availability required to support deployment, lack of continuous interest, etc.). However, WYDOT's continued outreach activities at workshops, conferences, and other events mitigated against the loss of participants. Similarly, Tampa (THEA) recruited more participants than originally estimated to make up for the attrition rate.
- Taxi participation in NYCDOT's deployment didn't happen due to external factors such as competition from ridesharing companies. NYCDOT had to adjust for the drop in vehicle count by equipping some public vehicles for the deployment.

Appendix A. Lessons Learned Examples from Connected Vehicle Pilot Sites

LL ID	CV Pilot Site	Date Identified	Contact Person	Task ID(s)	Task Name(s)	Lesson Learned Title	Description or Observed/Predicted Result	Actions Taken
WY-1	Wyoming	3/15/2017	Tony English	2-B	System Architecture and Design	Utilize existing standards as a part of the system architecture and design process.	The use of standards helped create a solid deployment effort in Phase 2, simplified technical documentation, and assisted with interoperability.	Pilot sites identified a set of common messages and relevant standards.
THEA-22	Tampa	9/30/2019	Rafal Ignatowicz	2-B	System Architecture and Design	RSUs for over-the-air updates.	We calculated the length of time needed for participants to download firmware updates and realized the average user might not be within reach of the existing RSUs long enough for successful download.	Added RSUs for over-the-air updates.
NYC-3	New York City	2/1/2017	Sam Sim	2-J	Stakeholder Outreach	Obtain stakeholder feedback early for determining the details of the devices and the system.	Based on stakeholder feedback, NYCDOT chose to utilize an audio-only HMI for the OBU instead of visual display as observed in other CV pilot sites. The audio-only HMI provides words and tones associated with particular threats.	Meetings with stakeholders were held in early part of NYC CV pilot to gain insight on the participants' needs in developing the ConOps, SyRS, SAD, SDD, etc.

U.S. Department of Transportation
ITS Joint Program Office-HOIT
1200 New Jersey Avenue, SE
Washington, DC 20590

Toll-Free "Help Line" 866-367-7487
www.its.dot.gov

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