



Enabling Trust and Deployment Through Verified Connected Intersections: Final Implementation Report

Strengthening Mobility and Revolutionizing Transportation (SMART)
Grants Program – FY2022 Award to Utah Department of Transportation
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1. Executive Summary

This document summarizes the findings of the Utah Department of Transportation (UDOT) Strengthening Mobility and Revolutionizing Transportation (SMART) Grant Stage 1 effort, supported by the United States Department of Transportation (USDOT), entitled *Enabling Trust and Deployment Through Verified Connected Intersections*. The primary objective of this effort was to establish mechanisms whereby original equipment manufacturers (OEMs) can trust that connected intersection (CI) broadcasts are accurate, consistent, reliable, and secure, based on requirements in Connected Transportation Interoperability (CTI) 4501 and processes defined by Security Credential Management System (SCMS) Manager, in order to facilitate large-scale connected vehicle (CV) deployment, by achieving the following goals:

- Complete a successful reference implementation corridor in the Salt Lake City metro area.
- Develop a process and credentialing guidance for OEMs to trust CIs to have accurate, consistent, reliable, secure messages.
- Establish ongoing collaboration between Infrastructure Owner Operators (IOOs), OEMs, and SCMS Manager and providers.
- Conduct targeted outreach and work with other deploying IOOs.
- Make test tools, procedures, validation processes, and policies publicly available and/or refer to reports and deliverables published by established standards bodies, such as SAE, and other organizations.

The project partners included UDOT, OEMs participating in the Crash Avoidance Metrics Partners Limited Liability Company (CAMP LLC) “Model Deployment of Connected and Automated Mobility” Consortium, and SCMS Manager. Overall, the testing tools and software developed in this effort to validate CIs work and demonstrated success at identifying where requirements were not met, allowing the UDOT Project Team to address issues identified. Additionally, user guides and resources were developed as a part of this effort to help users collect CI data, use the developed tools, and follow the developed CI validation approach. While stated project goals and outcomes were not entirely achieved, considerable progress was made towards validating CIs along a corridor and the project identified issues that need to be addressed to achieve a fully validated corridor. This effort successfully demonstrated that further expansion to at-scale implementation is feasible, and more agency experiences are needed to better understand the scalability and long-term impacts of operating and maintaining validated CIs. The tools, procedures, and overall data collection and analysis process developed in this effort are now available and recommended for use by other IOOs in order to further refine and enhance them based on new experiences and lessons learned as part of at-scale implementation.

2. Introduction and Project Overview

Connected vehicle (CV) technology offers the promise of fewer crashes and fatalities, increased efficiency, and environmental improvements. At signalized intersections with CV technology, referred to as Connected Intersections (CIs), infrastructure-based vehicle-to-everything (V2X) devices broadcast messages about the intersection status (i.e., Signal Phase and Timing (SPaT) message, MAP message containing intersection geometry information, and Radio Technical Commission for Maritime Services (RTCM) message for position correction information). Information broadcast by CIs is received by in-vehicle V2X devices, where applications process the information and warn drivers if warranted by the conditions. For the purposes of this effort, V2X devices are broadcasting messages within the 5.9 GHz spectrum using roadside units (RSUs) for low-latency CV safety applications; however, other applications and V2X devices may also or only use network cellular communications.

Several groups have made significant progress on CI standards in the past three years. The United States Department of Transportation (USDOT), through the Institute of Transportation Engineers (ITE) Connected Intersections effort developed the *Connected Transportation Interoperability (CTI) 4501 CI Implementation Guide*¹, and the Connected Vehicle Pooled Fund Study (CV PFS), a group of 22 Federal, State, local, and international transportation agencies has advanced a variety of CI efforts. The CI standards are based on the Red-Light Violation Warning (RLVW) application, a key safety application being prepared for early deployment in equipped vehicles. Note that USDOT is funding a CTI CI Phase 2 effort that is being led by SAE to expand on this work and update the CTI 4501 standard, which is expected to be published in 2025.

2.1 Project Description

For twenty years, CV applications have offered a promise of fewer crashes and fatalities, increased efficiency, and environmental improvements. After several years of regulatory uncertainty, the CV promise is on the brink of being brought to reality, if industry can overcome the remaining hurdles, which this effort sought to do. Specifically, this effort sought to establish mechanisms whereby original equipment manufacturers (OEMs) can trust that CI broadcasts are accurate, consistent, reliable, and secure, based on requirements in CTI 4501 and processes defined by Security Credential Management System (SCMS) Manager, in order to facilitate large-scale CV deployment.

Motivation

The motivation for this project was to set the foundation for confronting real-world challenges to be addressed by at-scale implementation of CIs. The specific challenge this project addressed was that at the completion of the aforementioned USDOT-funded CTI CI Phase 2 project, the automotive industry would still lack a mechanism to trust that Infrastructure Owner-Operator (IOO) deployed CIs are broadcasting accurate, consistent, reliable, and secured messages needed to support in-vehicle RLVW and other safety applications. Without a reproducible process to validate intersections, a coupling of this validation process to the issuance of security credentials (to inform the vehicle that the intersection has been validated), a process for detecting and reporting misbehavior and re-testing intersections, and a field deployment demonstrating validated broadcasts, production vehicles with these life-saving applications are unable to operate.

¹ Institute of Traffic Engineers. [Connected Transportation Interoperability \(CTI\) 4501 v01.01 Connected Intersections Implementation Guide](#). Last accessed September 2023.

Technologies

Deliverables this project advanced and outcomes of this project included:

- **Technologies.** Existing hardware and software at UDOT intersections that were already equipped as CIs were tested, refined, and improved, as needed, to meet requirements established by the USDOT-funded CTI 4501 Phase 2 effort and expectations of project partners;
- **Test Tools and Processes.** Test tools comprised of a combination of hardware and software were specified and developed in this project to be used to validate that CIs meet the expectations of project-participating OEMs and SCMS Manager; and
- **Validation Process.** An overall validation process and credentialing policy that utilizes the testing tools developed in this project and supporting tools developed by the CV PFS were developed by SCMS Manager and implemented in Utah during this Stage 1 effort. The creation and demonstration of this process and policy can be used to help other IOOs understand the implications (e.g., necessity, time commitment and costs) to perform validations at their locations.

Goals

The CIs completed and validated under this planning and prototype stage, as well as the CIs to be validated and trusted as a result of Stage 2 activities, will enable the eventual at-scale implementation of an underlying CI infrastructure to support in-vehicle safety applications to help reduce red-light running related crashes and other safety, mobility, and environmental applications. These impacts will benefit the entire community of drivers and riders in vehicles. The following bullets summarize the Stage 1 project goals as well as the statutory language in the Investment and Jobs Act (IIJA) (Public Law 117-58 Sec 25005) related to each:

1. Complete a successful reference implementation corridor. (IIJA: improve safety, improve reliability, increase resiliency, incentivize private-sector investments or partnerships)
2. Develop a process and credentialing guidance for OEMs to trust CIs to have accurate, consistent, reliable, secure messages. (IIJA: improve safety, improve reliability, private-sector investments or partnerships)
3. Establish ongoing collaboration between IOOs, OEMs, and SCMS Manager and providers. (IIJA: incentivize private-sector investments or partnerships)
4. Conduct targeted outreach and work with other deploying IOOs. (IIJA: improve safety, improve reliability)
5. Make test tools, procedures, validation processes, and policies publicly available and/or refer to reports and deliverables published by established standards bodies, such as SAE, and other organizations. (IIJA: improve safety, improve reliability)

Impacted Communities

Stage 1 efforts were very technically focused, so widespread public outreach and engagement was not conducted. However, limited outreach to CV PFS members and other IOOs was conducted. The ultimate safety benefits will be recognized by the entire community of the traveling public through

expanded efforts and deployment in the future. The long-term vision is that CIs will be operational at the vast majority of the approximately 300,000 state and locally operated signalized intersections, as envisioned by the 2024 USDOT National V2X Deployment Plan, *Saving Lives with Connectivity: A Plan to Accelerate V2X Deployment*.²

While the CTI 4501 efforts were focused on RLVW, the requirements for accuracy, consistency, and reliability are relatively rigid compared with what may be required for other safety and mobility applications. Therefore, while the CTI 4501 efforts did not analyze other applications, it is anticipated that other safety and mobility related applications that OEMs may consider will be supported by CIs validated against CTI 4501 requirements.

2.2 Proof-of-Concept Overview

Scale of Stage 1 Deployment

The proof of concept assessed in this Stage 1 project was the creation of a validation process (and supporting tools and credentialing policy) that were intended to enable OEMs to trust that CIs deployed by IOOs are broadcasting accurate, consistent, reliable, and secured messages that can support in-vehicle RLVW and other CI related safety applications.

The focus of this effort for testing and validation was on a corridor that was already equipped with RSUs: SR-224 near Park City (a rural community) with Intelight controllers and Kapsch cellular-vehicle to everything (C-V2X).

Project Partners

The project partners included an IOO (i.e., UDOT), OEMs participating in the Crash Avoidance Metrics Partners Limited Liability Company (CAMP LLC) “Model Deployment of Connected and Automated Mobility” Consortium (referred to hereafter as CAMP), and SCMS Manager, however industry consensus extended beyond the project partners as part of outreach efforts to other entities for feedback, including the CV PFS for IOO inputs and participants in the USDOT-sponsored CTI Phase 2 effort for broader industry input.

Key Barriers to CV Safety Application Deployment on Production Vehicles

Initial feedback from CAMP indicated that the key barriers remaining were:

- Confidence in data coming from CIs (overcome via tools and processes developed by this Stage 1 effort).
- Number of equipped and validated CIs (progress can be made through a Stage 2 effort and unrelated efforts like the USDOT Accelerating V2X Grant Program and other grant programs).
- Release of the second FCC report and order to ensure certainty (released in November 2024).

² United States Department of Transportation. [Saving Lives with Connectivity: A Plan to Accelerate V2X Deployment](#). Last accessed May 2026.

Anticipated Scale of Stage 2 Deployment

This effort envisioned a Stage 2 “at-scale” effort that would expand the use of the validation process to more corridors in Utah, additional IOOs (at least six or more additional IOOs), and further engage OEMs and SCMS Manager to expand the validation process to accommodate increasing numbers of IOOs participating. Given the number of signalized intersections operated by local agencies, a Stage 2 at-scale deployment was envisioned to engage a number of IOOs that were local agencies, as well as state agencies (e.g., Georgia Department of Transportation (DOT), Arizona’s Maricopa County DOT, Texas Transportation Institute, University of Michigan Transportation Institute working in Ann Arbor, Ohio DOT, and Florida’s Tampa Hillsboro Expressway Authority) to facilitate the knowledge transfer and training activities from UDOT. A Stage 2 at-scale deployment would better support activities that remain new and evolving, such as the availability of a bench test environment and troubleshooting issues with signal controllers and configurations, test tools themselves, and other CV equipment as they arise. This Stage 2 “at-scale” deployment would increase IOO readiness for OEM introduction of RLVW and other safety applications in production vehicles and move the needle toward a critical mass of IOO operated intersections equipped to broadcast the data needed for lifesaving RLVW applications. One outcome of a Stage 2 deployment would be a better understanding of training needs to further expand the CI deployment, testing, and validation to other state and local IOOs around the country.

Factors impacting the scale of Stage 2 deployment include the costs to conduct testing and validation activities and the availability of products (e.g., signal controllers) that fully comply with CTI 4501 requirements for a fully validated intersection. These factors may impact the number of CIs that are able to be validated. Additionally, the November 2024 release of the Federal Communications Commission (FCC) Second Report and Order should bring additional certainty to this space and potentially expedite use of V2X technology in OEM production vehicles. In doing so, more IOOs may be willing to advance CI deployment.

Eventually, more broadly and over a longer term, deployment, testing, and validation of CIs will likely coincide with widespread deployment of in-vehicle CV safety applications by OEMs that rely upon the broadcasts of data from validated CIs. This is when the full “at-scale” benefits will be achieved.

This validation process is a key enabler for the USDOT National V2X Deployment Plan³ of having two vehicle OEMs commit to 5.9 GHz capable vehicles by the 2027 model year. Feedback from CAMP during this initiative indicated that three barriers to OEMs including V2X technologies in production vehicles are:

- Lack of trust in CI data,
- The number of validated CIs deployed, and
- The lack of a Second Report and Order from FCC (which was released in November 2024, near the conclusion of this effort).

³ Ibid ([Saving Lives with Connectivity: A Plan to Accelerate V2X Deployment](#)).

2.3 Summary of Project Activities

Milestones

The milestones for this effort fell within six categories that were tracked through the course of the project:

1. **SPaT Validation.** The four milestones were to:
 - Build and test SPaT testing and evaluation tools.
 - Define pass/fail requirements for SPaT messages compared to CTI 4501 requirements.
 - Define test scenarios that any IOO can implement.
 - Conduct SPaT validation in Utah to demonstrate functionality and feasibility.
2. **MAP Validation.** Milestones were to:
 - Create a tool and, as needed, a supporting process to evaluate MAP accuracy to support other IOOs in validating CIs.
 - Enhance the MAP accuracy processing tool created in the ITE CTI 4501 Phase 1 project.
 - Conduct an initial test of the Light Detection and Ranging (LiDAR) road scan and post-processing tool assessing affordability and industry ability to meet the specification.
 - Modify the MAP evaluation and post-processing tool as needed and conduct further validation before encouraging widespread IOO use.
3. **RTCM Research and Possible Validation.** The key milestone was to explore the impacts of RTCM accuracy on vehicle positioning, and then, if needed, create an RTCM validation tool and conduct RTCM validation in Utah.
4. **Connected Intersection Message Monitoring System (CIMMS) Assessment for Ongoing Monitoring of Validated Intersections.**⁴ Two milestones were to:
 - Determine an approach for using CIMMS, developed by the CV PFS, as an ongoing monitoring tool to continuously validate that intersections meet some critical CTI 4501 requirements.
 - To assess the sensitivity of CIMMS reports and understand other functions for CIMMS (e.g., CIMMS as a possible initial test of MAP accuracy).
5. **SCMS Manager Policies and Procedures.** The two milestones were to:
 - Develop policies and procedures that SCMS providers can require IOOs operating CIs to follow when validating intersections, and then use the validation information to indicate within the security certificate that a CI has been validated.
 - Pilot and confirm the effectiveness and practicality of these in the Utah corridors.
6. **Overall Project Management.** Milestones included creating document sharing for the project team, completing updates on the Utah corridor, and considering a Stage 2 Grant Application.

⁴ Connected Vehicle Pooled Fund Study. [Connected Intersection Message Monitoring System \(CIMMS\) Final Report](#). Last accessed July 2024.

Project Attention

This effort has been discussed among industry professionals, in particular through discussions and presentations to CV PFS members and participants in CTI 4501 Phase 2 efforts.

Deviations from Original Plan

The original plan was to develop a corridor of verified CIs, and this was not accomplished. During the last round of testing and validation, the CIs were very close to being fully validated and the roadblocks that prevented achieving validation were aspects that are out of the control of the project team. Additionally, two additional corridors (i.e., US-89 in American Fork with Econolite controllers and Kapsch C-V2X RSUs and SR-68 (Redwood Road) in Salt Lake City with Intelight controllers and Commsignia C-V2X RSUs) were initially proposed for testing, however challenges with Econolite firmware updates and a determination by the project team that testing and validation efforts would yield similar results on these corridors as the SR-224 corridor led to a decision to not conduct additional testing on these two corridors.

2.4 Document Organization

The remainder of this document is oriented around the following six sections:

- **Section 3 – [Proof-of-Concept Evaluation Findings](#)** presents the findings from the Utah proof of concept as they relate to each performance measure identified in the evaluation plan, as well as a narrative of how this effort met original expectations and demonstrated improvement in specific goal areas.
- **Section 4 – [Anticipated Costs and Benefits of At-Scale Implementation](#)** describes the anticipated impacts and costs of at-scale implementation, as well as baseline data and the methods to estimate these impacts and costs for at-scale implementation.
- **Section 5 – [Challenges, Best Practices, and Recommendations for Future Deployers](#)** describes lessons learned and insights that may assist with future deployers with fully validating CIs in their jurisdictions.
- **Section 6 – [Deployment Readiness](#)** summarizes the readiness of this effort for at-scale implementation and the remaining gaps in understanding the scalability and long-term impacts of operating and maintaining fully validated CIs.
- **Section 7 – [Wrap Up](#)** reflects on the project to discuss whether the proposed solution met expectations, possible changes to the solution that should be made for at-scale implementation, and advice for others pursuing the solution.
- **Section 8 – [Terms and Acronyms](#)** defines common items used in this document.

3. Proof-of-Concept Evaluation Findings

This section presents the findings from the Utah proof of concept. Note that this evaluation effort differed from a more traditional evaluation that focuses primarily on data analyses. While the testing and validation of the CIs conducted in this project relied on data comparisons to assess the accuracy, consistency, and reliability of the data broadcast by CIs, the primary purpose of this evaluation was not to assess the CI itself, but to assess the development, usability, and costs of implementing the validation processes and tools that key stakeholder participants (i.e., CAMP, SCMS Manager, and CV PFS IOOs) agreed were acceptable for nationwide CI deployment and V2X communications. In other words, success for this project was defined by an industry consensus and acceptance of the products that were developed, rather than specific details about the products themselves.

3.1 Findings on the Proof-of-Concept Performance

This subsection defines the performance measures from the evaluation plan, describes the data that was collected, and summarizes the findings. Note that all of the supporting resources developed as part of this effort are available on the [UDOT Transportation Technology webpage](#); it should be noted that these resources are expected to evolve in the near future as part of other efforts including the UDOT SMART Stage 2 effort. Table 1 presents the findings for specific performance measures from the evaluation plan that were assessed.

Specific findings from the proof-of-concept included:

- The developed testing tools and software work and demonstrated success at identifying where *CTI 4501* requirements were not met, allowing the UDOT Project Team to address issues identified. A reference guide of the data collection tool was developed by The Narwhal Group entitled *Traffic Signal Cabinet Logging Tool Quick Reference Guide*. The SPaT and MAP software and testing processes are respectively documented in three resources developed by CAMP entitled *Assessment of SPaT Accuracy to Support RLVW Application*, *Assessing Node Point Accuracy in the SAE J2735 MAP Message*, and *Validation Assessment & Analysis Software Toolset User Guide, Version 3.0*. Reporting expectations for test findings are documented in the *CI Test Results Report Format* resource developed by the SCMS provider Integrated Security Services (ISS) for this effort. The SPaT and MAP testing and validation tools are [available through SCMS provider ISS](#); users may [request access for free from ISS](#). Additionally, Appendix A presents the errors identified during SPaT testing for RSUs procured from two different providers.
- A new MAP validation approach was introduced and included a developed specification for LiDAR data collection to be used as an input to the MAP assessment tool. This specification is included in the CAMP *Assessing Node Point Accuracy in the SAE J2735 MAP Message* resource. This validation approach was demonstrated using both existing and new LiDAR road scan data. Assessing the relative accuracy of any given LiDAR road scan (e.g., with a field survey) is a recommended activity for Stage 2 At-Scale Deployment.

- A new MAP validation tool was developed that assesses the accuracy of the MAP message against ground truth data (LiDAR data for purposes of this project) and provides recommended adjustments to nodes within the MAP message that would allow it to be validated. This new MAP validation tool is combined with the previous MAP validation tool (a product of the CTI activities) that tested MAP messages for completeness of data and proper formatting. The MAP validation tool is [available through SCMS provider ISS](#); users may [request access for free from ISS](#).
- Feedback from OEMs in CAMP and SCMS Manager indicate that stated project goals and outcomes were not entirely achieved. The original goal was to develop a corridor of verified CIs, and this was not accomplished. However, considerable progress was made towards validating the CIs along the corridor and the project identified the issues that need to be addressed to achieve a validated corridor. During the last round of testing and validation, the intersections were very close to being fully validated and the roadblocks that prevented achieving validation were aspects that are out of the control of the project team. Specifically, the data coming out of the signal controller does not, on occasion, represent the signal controller status, and there are occasional latency issues with the RSUs. Both of these will require updates or improvements from the manufacturers before these intermittent events can be avoided entirely. A final situation that prevented full validation of the corridor was uncertainty about whether RTCM messages are needed (i.e., could not verify RTCM message requirements in the reference implementation corridor as these have not yet been completed by the CTI 4501 effort), as described in more detail below.
- The focus of this effort for testing and validation was on a corridor that was already equipped with RSUs: SR-224 near Park City (a rural community) with Intelight controllers and Kapsch C-V2X. The data and the resulting analysis reports can be found on [Zenodo's dataset archive](#) via the [UDOT Transportation Technology Verifying Connected Intersections webpage](#). Specifically, this dataset contains a series of folders for each tested CI in the reference implementation corridor, SR-224. A separate file for each tested CI contains the data collected at the CI for SPaT testing (described in the 2024 *Traffic Signal Cabinet Logging Tool Quick Reference Guide*) and the output reports from the SPaT validation tool (described in the 2024 *CAMP Assessment of SPaT Accuracy to Support RLVW Application* report), as well as the data collected at the CI for MAP testing and the output reports from the MAP validation tool (described in the 2024 *CAMP Assessing Node Point Accuracy in the SAE J2735 MAP Message* report).
- Two additional corridors (i.e., US-89 in American Fork with Econolite controllers and Kapsch C-V2X RSUs and SR-68 (Redwood Road) in Salt Lake City with Intelight controllers and Commsignia C-V2X RSUs) were initially proposed for testing, however challenges with Econolite firmware updates and a determination by the project team that testing and validation efforts would yield similar results on these corridors as the SR-224 corridor led to a decision to not conduct additional testing on these two corridors.
- Questions remain about how palatable the CI validation process and costs may be to IOOs, which was why developed validation processes were considered for affordability and palatability for not only State IOOs but also local city and county IOOs that ultimately must embrace these validation processes.

- Project activities achieved the desired outcomes specified by the project goals and analyzed per the performance measures identified in the Evaluation Plan. Project activities conducted in this proof-of-concept identified some new gaps or questions that will be explored and addressed as part of Stage 2 At-Scale Deployment activities.
- Resources developed as part of this effort are initial versions and are expected to be updated and evolve in the near future as part of other efforts, including the UDOT SMART Stage 2 effort. In particular, resources developed by SCMS Manager in this effort entitled *SCMS Manager Intersection Validation and Certificate Issuance Policy* and *SCMS Manager Intersection Validation Misbehavior Management* have not yet been implemented and future refinements are anticipated. Additional experience from the use of all resources developed in this effort will inform future updates to these documents.

Lessons learned that were identified included:

- Challenges were identified with MAP creation processes for full CTI 4501 compliance. For example, node point selection when creating a MAP message manually or with a creation tool is highly likely to result in errors that prevent a developed MAP from being accurate to CTI 4501 requirements. To address this challenge, the MAP validation tool developed in this project includes an output that identifies coordinates for alternate node points that are within the tolerance established by CTI 4501. However, refinements are needed to apply these outputs
- Challenges were identified with time sources of signal controllers that cannot be resolved by the project team without updates from the signal control manufacturer.
- Challenges were identified with some preliminary requirements in the draft update to CTI 4501 that led to the development of a profile for testing by ISS with project team input, which is documented in the *CTI 4501 Security Policy Profile* resource.
- Tools developed in this effort identified very specific issues in signal controller manufacturer firmware (note that only Kapsch signal controllers were tested in this effort), as well as different issues with devices in different configurations. This pointed to a recognized need for a process to share findings with the signal controller manufacturers.
- A preferred MAP validation data source or collection approach was not readily identified in this effort. Additional analysis and evaluation is recommended as part of the Stage 2 At-Scale Deployment, and some manual interpretation may be required in the interim period.
- Developing the SPaT data collection device (e.g., using a Cohda on-board unit) was not as straight-forward as anticipated because of some hardware and firmware constraints.

Table 1. Performance Measures and Findings of this Effort

Performance Measure from Evaluation Plan	Findings
Outcomes of testing and validation procedures and reactions from OEMs in CAMP and SCMS Manager that a fully validated corridor was achieved.	The implementation corridor was not able to consistently meet all CTI 4501 requirements for a fully validated intersection. Developed validation tools and processes worked, as expected; testing identified very specific issues in signal controller manufacturer firmware and other areas, confirming that the tools can fully validate a CI when issues beyond IOO control are resolved by manufacturers.
Feedback from UDOT and CV PFS members about whether the implementation corridor will help to reduce the time and costs to fully validate other CIs.	The implementation corridor was not able to consistently meet all CTI 4501 requirements for a fully validated intersection due to issues beyond IOO control. However, a profile (i.e., a subset of those requirements most critical to OEMs trusting intersections for RLWW application deployment) was completed and presented in the <i>SCMS Manager Intersection Validation and Certificate Issuance Policy</i> report, and can support other sites as they proceed with validating their corridors. If alternate approaches to capturing accurate lane line lat/lon values for the MAP message is identified in Stage 2, the Utah corridor can be used as a reference corridor to test these.
OEMs in CAMP can confirm they trust the process to validate CIs.	Developed validation tools and processes worked, as expected and are recognized by CAMP partners as trusted tools.
SCMS Manager confirms the testing procedures are acceptable to validate CIs.	Automated tool outputs and reports were acceptable to validate CIs.
Successful implementation by UDOT of the testing tools and procedures to test the reference implementation corridor.	Test tools and procedures were successfully used to test the reference implementation corridor.
Reactions from other IOOs about their knowledge of the project outcomes and the extent to which they are willing to perform the validation process on their CIs.	CV PFS Members were made aware of progress of this project in May 2024 and were updated in December on project outcomes. Several sites agreed to test and validate existing CIs as part of a Stage 2 At-Scale Deployment, demonstrating a willingness to perform the validation process.
Reported time and/or contractor expense performing the validation process in Stage 1.	Costs were recorded for the LiDAR data to validate MAP messages, data collection and testing per CI, and testing device equipment and assembly. (See Section 4.2)
Documentation of lessons learned and recommendations from UDOT, CAMP, and SCMS Manager to facilitate Stage 2 implementation.	Lessons learned were documented. (See Section 3.1)
Confirmation of tool availability.	Tools are available through SCMS provider ISS ; users may request access for free at ISS .
Reaction from IOOs outside the project if they are able to access and use test tools.	Tools are available through SCMS provider ISS ; users may request access for free at ISS . Other IOOs have not yet used the test tools, but will be doing so as part of the SMART Stage 2 effort.

Performance Measure from Evaluation Plan	Findings
Valid procedure to protect integrity of data by only issuing valid SCMS certificates to fully validated CIs.	SCMS Manager Intersection Validation Misbehavior Management report defines the procedure developed by this project that identifies the profile of requirements that are most critical to fully validate a CI.
Reaction and feedback from UDOT, OEMs in CAMP, and SCMS Manager, and examples of the collaboration accomplished in this project.	Feedback collected from project team members on collaboration confirmed the collaboration has led to an approach that is acceptable to the CAMP partners, SCMS Manager, and UDOT and may be expanded or evolve as part of the SMART Stage 2 effort.

3.2 How This Proof-of-Concept Met Original Expectations and Goals

As indicated in Table 1, the proof-of-concept met original expectations and goals overall. At the beginning of this effort, despite several significant testing activities in Utah, a complete set of information was still not available to IOOs about what specifically was needed to fully achieve SCMS and OEM trust in their CIs, including what the process should consist of, the tools available, and estimated costs to accomplish it. Further, OEMs had concerns over the data broadcast by CIs, which was a barrier towards implementation of RLVW applications.

For this proof-of-concept, CAMP, SCMS Manager, Narwhal, and other project team members successfully collaborated to develop test tools and procedures that they agree can be used by IOOs to validate CIs. The tools have proven sufficiently robust for validating the selected UDOT CIs but also identified previously unknown issues in the signal controllers that ultimately require signal controllers to implement a software update to address properly. As such, the reference implementation corridor only meets CTI 4501 requirements that are achievable at the end of 2024 based on available technologies; outstanding issues will remain until software updates become available. Specifically, the UDOT CIs were tested to be a reference implementation corridor for a profile or subset of CI requirements following the procedure developed as a part of this effort, as described in *SCMS Manager Intersection Validation and Certificate Issuance Policy*. However, the reference implementation corridor was not able to consistently meet all requirements for a fully validated intersection as part of these testing activities. Two key takeaways are:

1. This project produced robust validation tools and procedures that effectively identify issues and (when appropriate) validate CIs with no issues.
2. Where issues are identified, these may not be things that the IOO and supporting contractors can address and may require signal (or other equipment) manufacturers to address through new software releases. While this may introduce additional time for fully validating CIs against all CTI 4501 requirements, the software releases are expected to benefit other IOOs operating other CIs. Collectively, the industry will become more “CI friendly” over time.

3.3 How This Proof-of-Concept Demonstrated Improvement in Statutory Areas

The proof-of-concept demonstrated the following improvements in four areas identified in statutory language in the IJA (Public Law 117-58 Sec 25005):

- Improve the safety and integration of transportation facilities and systems for pedestrians, bicyclists, and the broader traveling public;

- Improve the reliability of existing transportation facilities and systems;
- Incentivize private sector investments or partnerships, including by working with mobile and fixed telecommunication service providers, to the extent practicable; and
- Increase the resiliency of the transportation system.

Improve Safety and Improve Reliability

- The automated analyses of signal controller data and resulting SPaT messages resulted in very informative outputs, identifying rare occurrences of conflicts in the data. This demonstrated several key messages:
 - The tools and procedures work, and observations by OEM participants and SCMS Manager to this process increased their confidence that robust verification tools were being produced.
 - While always anticipated, coordination with signal control manufacturers became recognized as critical to understand why these rare data conflicts occur and to enable these and other manufacturers to solve the issues properly.
 - In addition to coordination with signal controllers to ultimately reduce or eliminate conflicts in the data, the role of continuous monitoring of the intersection (and cause the CI to transition to Suspended State) is included in the *SCMS Manager Intersection Validation Misbehavior Management* report. Accomplishing this is a goal of Stage 2.
 - Establishing an industry exchange of multiple signal controller manufacturers that support IOOs at all levels is key to national safety advantages that will result from validated CIs on city, county, and state operated roadways.
- The exploration of MAP message validation identified at least two additional tools for MAP validation (e.g., new and existing LiDAR road scans and the use of CIMMS). MAP messages are critical to achieving the safety benefits of CIs; it is recognized that financial and technical resources to dedicate to MAP messages will vary for IOOs. The number of intersections made safer as CIs will increase by establishing multiple tools for MAP validation to support different budgets.
- At the onset of this project, it was recognized that a Stage 2 At-Scale Implementation would be needed to expand the UDOT reference implementation corridor to additional corridors. The Stage 2 effort will serve as an intermediary next step to help achieve a critical number of validated CIs before production vehicles with CV safety applications are released. The Stage 2 At-Scale Implementation objectives are better understood now, and the emphasis will be on advancing the collaboration with multiple signal controllers and expanded introduction of MAP validation to explore the industry support, relative accuracy, and costs for LiDAR road scan approaches.

Incentivize Private-Sector Investments or Partnerships

- The established collaboration between IOOs, OEMs, and SCMS Manager have created a mechanism for the quick resolution of challenges and barriers that occur between prototype and “at-scale” and have positively contributed to national deployment of OEM safety applications and IOO CIs.

Increase Resiliency

- The industry is expected to benefit from demonstrated integration of a transportation cybersecurity system ‘via secure over-the-air communication of data between infrastructure and vehicles owned and operated by different entities.
- The industry is expected to benefit from CIs being more consistent and interoperable based on the use of nationally available and recognized validation tools and processes.

4. Anticipated Costs and Benefits of At-Scale Implementation

This section describes the anticipated impacts and costs of at-scale implementation, as well as baseline data and the methods to estimate these impacts and costs for at-scale implementation.

4.1 Anticipated Impacts of At-Scale Implementation in the Statutory Areas

The areas identified in statutory language in the IIJA (Public Law 117-58 Sec 25005) that are anticipated to be impacted by at-scale implementation are described below.

Improve Safety and Improve Reliability

- IOOs throughout the US may benefit by modeling their CIs off the UDOT reference implementation corridor that was validated using the validation profile developed as part of this proof-of-concept in order to reduce deployment costs while achieving validated CIs.
- The test tools developed in this effort were made available to validate CIs nationally. This may help advance “at-scale” deployment quicker and encourage OEMs to hasten the use of RLWW and other safety applications in production vehicles.
- The processes developed by this effort reduced OEM concerns about CI data quality, setting a stage for having RLWW and other safety applications in production vehicles, which will lead to reductions in red-light running related crashes.
- Outreach to other IOOs made them aware of this effort, including the process for validating CIs and available testing tools, to facilitate quicker deployment of fully validated CIs.
- Test tools developed by this effort will help advance to “at-scale” deployment quicker and will encourage OEMs to hasten the use of RLWW and other safety applications in production vehicles.

Incentivize Private-Sector Investments or Partnerships

- Reduced OEM costs of testing or demonstrating safety applications by having access to or using the UDOT reference corridor.
- The process developed by this effort through SCMS Manager collaboration with OEMs and UDOT reduced OEM concerns about CI data quality that set a stage for having RLWW and other safety applications in production vehicles, which will lead to reductions in red-light running related crashes.
- The established collaboration between IOOs, OEMs, and SCMS Manager have created a mechanism for the quick resolution of challenges and barriers that occur between prototype and “at-scale” will have positively contributed to national deployment of OEM safety applications and IOO CIs.

Increase Resiliency

- The industry benefits from the demonstrated integration of a transportation cybersecurity system via secure over-the-air communication of data between infrastructure and vehicles owned and operated by different entities.
- Interoperability will enhance resiliency of CIs that follow a consistent validation process using nationally available and recognized validation tools.

4.2 Anticipated Costs of At-Scale Implementation

An overarching objective of this proof-of-concept was to understand what is needed (and how much it can be expected to cost) to accomplish fully validated CIs and to make that process reasonable and manageable for individual IOOs. The costs of this proof-of-concept effort were \$1.8M, however this included significant resource allocation for the development of testing tools and procedures for CI validation. Specific costs for testing CIs in Utah were tracked as they occurred in order to anticipate costs of at-scale implementation for validating CIs per intersection, including the equipment and labor hours and procurement costs. Engagement with other IOOs via the CV PFS and their testing/sampling of the tools and processes will allow for more perspectives and better estimates of IOO time and costs to implement “at-scale” as part of the Stage 2 effort. In this effort, estimated costs to validate CIs were:

- \$3000 per CI for LiDAR data to validate the MAP message.
- \$350-\$450 per CI to collect and analyze data per test. (Note that additional data collection and analysis may be needed if the results do not validate the CI.)
- \$5000-\$5800 per TSCLT (i.e., data collection tool).

At this time, a key cost driver relates to the validation profile determined by SCMS Manager, understanding that the full suite of requirements presented in *CTI 4501 version 2* is not feasible to examine for every CI. That is, there was a recognition that trust in the CI implementation could be established based on testing a subset of requirements and confirming the accuracy of how that subset was implemented. Additional key cost drivers include:

- IOO staff time to prepare CIs for testing and validation. Even after deployment, significant time may be needed at a CI to troubleshoot identified issues both before and as a result of testing.
- Validation tools and data collection, with specific considerations regarding additional training needed, and how user friendly and time consuming the processes are. As one example, a comprehensive understanding of costs is not available for all data collection alternatives for executing the developed MAP validation approach, as it may conceivably be done via a new LiDAR road scan process, using existing LiDAR road scan data, a survey, using the CIMMS monitoring tool, or by some other means.
- Other party costs to operate and maintain a fully validated CI (e.g., SCMS provider).

Moving forward, as additional CIs are validated there is a potential for costs to go down over time given the increased IOO staff familiarity and experiences with validation processes and tools, availability of improved hardware and software products from vendors and signal control manufacturers, development of more streamlined testing tools, and availability of SCMS providers equipped to perform and support validation.

Sources of uncertainty at this time relate to the timeline for releasing updated available hardware and software (i.e., from signal controller manufacturers) required to fully validate a CI, as well as access to and maintenance of testing and validation tools, specific data collection tools and approaches that will be ultimately required for validating CIs, and the development and availability of streamlined processes and tools that may reduce the costs to test and validate CIs in the future.

4.3 Methods to Estimate Anticipated Benefits and Costs Associated with At-Scale Implementation

The safety risks to pedestrians and drivers of all vehicles when red-light running events occur are recognized industry wide. RLVW applications have long been identified as an approach to reduce the occurrence of red light running. Additionally, the developed testing tools and validation processes provide a foundation for expanding them to support testing activities needed to validate CIs for the use of other applications. Since the focus of this project and evaluation was on assessing the extent to which the tools and processes developed were accepted by the industry, the evaluation did not attempt to estimate the quantitative safety benefits (i.e., no estimate of the number of crashes to be prevented were developed). Rather, the benefits were assessed by the extent to which OEMs and IOOs have increased knowledge about and trust in the processes and tools developed. As substantial gains were achieved in these areas, there are inferred benefits in coming years when RLVW and other safety applications are deployed and supported by IOO operated CIs.

The costs of at-scale implementation of the tools and processes were estimated by the time and effort expended by Utah in utilizing the resources developed to validate their CIs. Specifically, the estimated time to conduct specific testing activities at a CI are:

- Configuring the TSCLT (i.e., the data collection tool for testing) to match a given traffic signal cabinet: 15 minutes.
- Install TSCLT in cabinet, including both the physical install and testing to ensure messages are being received: 30 minutes.
- TSP and preemption during testing, including watching the traffic signal controller to ensure a timing plan change takes place, then priority on two approaches and preemption on two approaches with a delay between each priority or preemption for the traffic signal to return to coordination for two cycles: about 45 minutes.
- Remove TSCLT from cabinet: 15 minutes.

In total, this results in about 1 hours and 45 minutes of staff time to conduct validation testing at each CI. From this, a reasonable estimated range for the cost to test each CI a single time is about \$350-\$450. However, many variables will affect the ultimate total cost to validate a CI that will likely cause this estimate to rise. These variables include:

- Staff experience with testing tools and related activities to conduct testing in a timely manner. (Note that these processes are described in the *2024 Traffic Signal Cabinet Logging Tool Quick Reference Guide*.)
- Staff experience in terms of years of experience and seniority (i.e., senior staff versus junior staff).
- Driving time from the office site to a CI and between each CI being tested.

- Potentially significant time to conduct preliminary testing activities to ensure the CI meets requirements prior to conducting formal validation testing.
- Additional time to make adjustments to the CI and repeat formal validation testing each time the CI does not pass the validation test.

Additionally, LiDAR data was procured at a cost of \$3000 per CI to validate the MAP message; in this effort, LiDAR data was procured for 11 CIs at a cost of \$33,000.

Finally, the equipment cost for each TSCLT logging tool built in this effort was \$3800, plus 6-8 hours of staff time to assemble and test the tool for an additional \$1200-\$2000; this yields an estimated cost of \$5000-\$5800 per TSCLT. The OBU represented the most significant equipment cost at \$3618, while other equipment components for the TSCLT included a protective case, a 5-port managed switch, 12 Volts Direct Current power supply, power inlet and switch, power cords, and ethernet cables. As above, the amount of time required to assemble and test the tool may vary based on staff experience.

Engagement with other IOOs via the CV PFS and their testing/sampling of the tools and processes with CAMP through the UDOT SMART Grant Stage 2 activities in other locations will allow for more perspectives and better estimates of IOO time and costs to implement “at-scale.”

4.4 Baseline Data for At-Scale Implementation

Baseline data collected during this Stage 1 effort for at-scale implementation was:

- **Baseline status of CIs nationwide.** No CI deployments were proven to meet the full spectrum of requirements outlined in CTI 4501 version 02, and no CI deployments were recognized by OEMs or SCMS Manager as fully validated. Testing activities conducted at CIs in Utah identified minor issues that were not completely addressed by the end of the Stage 1 effort to be considered fully validated by OEMs or SCMS Manager. Note there is an understanding by OEMs and SCMS Manager that a CI may be considered fully validated in the near term until some outstanding issues preventing full compliance with CTI 4501 version 02 are addressed by traffic signal controller manufacturers.
- **Baseline status of UDOT Connected Corridor(s) including gaps.** Based on testing and validation activities conducted as a part of the SMART Stage 1 effort, gaps were identified to understand remaining needs to achieve validated CIs meeting the validation profile, which testing tools and procedures are able to detect and confirm.
- **Baseline status of knowledge of CI validation processes.** Testing tools and procedures are available to validate CIs against the validation profile. Additional experience is required to better understand the costs and potential efficiencies of validating CIs at scale.
- **Baseline status of OEM concerns the quality and consistency of CI data.** To date, OEMs are gaining trust in the data broadcast by CIs that are able to be validated against the validation profile based on the testing tools and procedures developed by this effort, which has helped to reduce this barrier towards implementation of RLVW applications.

5. Challenges, Best Practices, and Recommendations for Future Deployers

This section describes some considerations, lessons learned, and insights that arose over the course of this SMART Stage 1 effort that may assist future deployers with fully validating CIs in their jurisdictions. Solutions have not yet been identified for all challenges or unknowns, some of which remain unknown due to the limited nature of this Stage 1 effort. Future efforts, including a Stage 2 effort, will help practitioners better understand the costs, operations and maintenance considerations, the ability to streamline developed processes, and level of effort and needs for expanding workforce capability.

- **Procurement and budget.**
 - *Challenge:* If LiDAR services or datasets are selected for MAP validation, the cost and timing to procure and schedule these services may be a challenge for agencies. For instance, while these services are already used by agencies for asset management purposes, adjusting contracts or specifications to gather the very specific data that are needed to validate the MAP message (particularly for intersecting roadways that are within a different jurisdiction beyond what is typically procured by the agency) may add extra time and cost.
 - *Challenge:* The support services required to conduct preliminary testing and prepare a CI for validation is an additional budget consideration that could vary based on workforce capability.
- **Technology sustainability / integration with incumbent systems.**
 - *Challenge:* The preparations to achieve a fully validated CI may encounter several challenges as it relates to incumbent systems and processes. Updates may be required if signal controllers used in the field are not able to provide accurate and complete SPaT data needed to support a fully validated CI, for example.
 - *Challenge:* Issues identified at CIs that have already been tested will need to be addressed and, depending on the mechanism for addressing them, could in some ways be a bigger challenge than untested CIs (e.g., given a heightened urgency to maintain existing functionalities in an accurate, safe, and secure manner).
 - *Recommendation:* The *SCMS Manager Intersection Validation Misbehavior Management* report considers the impact of misbehavior information provided by the CIMMS process.
 - *Challenge:* Work is still underway to understand the need for RTCM validation. More broadly, the specific need and value of RTCM is not yet fully understood for various circumstances, specifically where it may be needed via what sources and in what locations. The CTI 4501 Requirements regarding RTCM are not as specific as other requirements regarding performance and part of the research of this project is to explore whether additional clarification about RTCM performance can be captured.

- *Recommendation:* Agencies may consider whether it is possible to validate a MAP message with LiDAR services as part of the same process that an agency already uses for asset management purposes.
- *Challenge:* The CTI Connected Intersections Implementation Guide 4501 v01.01 provides the RTCM message user needs, requirements, and design. An updated version of CTI 4501 expected to be released in 2025 will contain just the user needs while the requirements, design, validation test cases and procedures will be included in the SAE J3258 report. While not in the scope of the Utah SMART Grant project, the project team decided to attempt to approach this as an initial pilot site for validating that broadcast RTCM corrections messages were consistent with the updated CTI 4501 requirements. This included not only providing CIs that supported the requirements but also supporting the hardware and software validation tool efforts and executing the documented CTI 4501 validation test procedures. In advance of a final validation test tool, a prototype test tool was developed to evaluate corrections performance for a variety of Global Navigation Satellite Systems (GNSS) configurations and test environments including some in the Salt Lake City area. The results of these efforts will be documented in SAE J3258. A challenge in completing these activities was that, as of the writing of this report, the requirements and design for the RTCM corrections messages were not complete, thus the validation test tool and testing activities described above were not able to be performed during stage one. The SAE J3258 requirements and corresponding validation test cases and procedures are anticipated to be completed within the second quarter of 2025. The primary changes will address which GNSSs, messages, and frequencies are to be supported as well as how this information is incorporated into the SAE J2735 message.
- *Recommendation:* Needed RTCM test tool and validation activities (which are proposed to be undertaken in stage two SMART Grant activities in Utah), include:
 - Upgrading the CI to support the SAE J3258 requirements.
 - Developing the validation test tool hardware including adding a mobile ground truth system to the prototype test tool to support performing mobile positioning accuracy analysis.
 - Developing the validation test tool analysis software.
 - Running the validation test procedures as defined in SAE J3258 and generating validation reports.
 - Provide feedback on gaps, issues, and / or improvements for SAE J3258.
 - Consider adding real-time monitoring to detect anomalies in the provided RTCM corrections data.
 - Packaging the hardware validation tool in a format that can be easily shared with other pilot sites for performing RTCM validation at their CI.

- **Data governance.**
 - *Challenge:* CIMMS data storage needs currently can incur relatively high costs for a single CI that is not sustainable for scalability in the long term. Determining what and how much data for testing is “good enough” remains a challenge that has not yet been addressed.

- **Cybersecurity.**
 - *Challenge:* Threats to critical infrastructure are abundant, however a true understanding of the different types of potential risks associated with fully validated CIs remains elusive. The proposed security requirements in *CTI 4501 version 02* do not appear to be testable or realistically achievable by IOOs in the near term, and so it will be necessary to identify an acceptable approach to security.
 - *Recommendation:* The ISS *CTI 4501 Security Policy Profile* resource developed by this effort provides a recommended solution for applying the CTI 4501 v02 requirements to securely deploy CIs.

- **Workforce capability.**
 - *Challenge:* The processes needed to prepare and conduct CI testing and validation, as well as address the variety of technical issues that may arise in the meantime, are not well understood by many agencies.
 - *Recommendation:* Training and knowledge transfer will be needed to prepare others in the workforce for at-scale deployment; UDOT is prepared to support this through engagement of neighboring state and local agencies.

- **Partnerships.**
 - *Best practice:* This effort demonstrated a successful collaboration between IOOs, OEMs, and SCMS Manager that is a model for moving forward as testing tools and procedures are further refined and implemented by additional deployers.
 - *Recommendation:* Other IOOs intending to fully validate CIs is possible and encouraged as part of the partnerships created in this effort.

6. Deployment Readiness

The SMART Stage 1 effort has certainly advanced the state of the practice for achieving fully validated CIs, and this section summarizes the readiness of this effort for at-scale implementation. More agency experiences are needed to better understand the scalability and long-term impacts of operating and maintaining validated CIs, which is also described below.

6.1 Project Readiness for At-Scale Implementation

The proof-of-concept successfully demonstrated that further expansion to at-scale implementation is feasible, as described below.

Requirements for Successful At-Scale Implementation

Feedback from CAMP's involvement in this initiative has indicated that remaining barriers to OEMs including V2X technologies in production vehicles are: lack of trust in CI data and the number of validated CIs deployed (note that the November 2024 release of the Second Report and Order from FCC removes a third previously identified barrier). There are several things this effort has influenced:

- Completion of the CI validation tools and approaches for both SPaT and MAP validation.
- Finalizing SCMS Manager Processes and Policies for validating CIs.
- Encouraging agency deployment and validation of CIs by introducing the process and tools to CV PFS member agencies, which expressed interest in using the testing tools and procedures developed as part of this effort.

Note that there is an understanding that developed tools, procedures, and overall data collection and analysis process, which are now available to other IOOs and described in Appendix B, are expected to be refined and enhanced in the future based on experiences and lessons learned, especially as additional state and local agencies expand their use of these tools and procedures.

Strategies or Demonstrated Progress

The progress for achieving goals for this effort include:

- The testing tools and software worked and were successful at identifying where *CTI 4501* requirements were not met. The CIs identified for this effort were validated using the developed tools and validation processes.
- Feedback from OEMs in CAMP and SCMS Manager indicated that stated project goals and outcomes were achieved.
- Project activities achieved desired outcomes per the performance measures identified in the Evaluation Plan. While challenges arose, the project team identified alternatives that still accomplished the overall trust in the CI data, as needed by OEMs, CAMP, and SCMS Manager.

Key Obstacles to Scaling this Project

Several issues arose over the course of this effort related to technology sustainability, workforce capability, and procurement and budget, and could impact the feasibility of fully validating CIs:

- CIMMS data storage needs remain uncertain and currently incur costs that are not feasible for at-scale deployment. However, efforts are currently underway to streamline data processing that would reduce data storage requirements, and associated costs.
- Signal controller variations and issues may hinder at-scale deployment. The testing and validation tools developed as part of this effort identified previously unknown issues; while this is a sign that the tools work as intended, it also means that additional issues could be identified while testing other signal controller types and configurations in Stage 2. Some of these issues require updates from the signal controller manufacturers themselves, and as such may not be quickly resolved to allow for validation of all CTI 4501 requirements.
- Costs are a potential obstacle for agencies to scale CI validation more broadly. For instance, if the developed test tools and validation processes are too complex for IOOs to achieve with the available workforce, there is a risk that agencies will not see the benefit of dedicating resources to validate CIs, particularly without OEM production vehicles that support V2X safety applications.
- Agency preparation for CI validation requires workforce capabilities that may exceed some agency resources. Specifically, UDOT has worked for years to deploy and test CIs, resulting in staff and contractor experiences with V2X equipment to support troubleshooting and resolving identified issues; while the barriers to testing and validating CIs are now lower as a result of this effort, a learning curve will still exist for agencies that have less deployment experience.

6.2 Gaps in Understanding Maintenance and Operating Requirements

Given the limited experiences nationally with CIs, and remaining unknowns about requirements for ongoing monitoring of a validated CI, a number of gaps remain in understanding the maintenance and operating requirements for a fully validated CI. These gaps include the following:

- Enabling technologies and software are still being developed, resulting in a limited understanding of long-term maintenance needs, and are yet to be operated or deployed at scale.
- The process for monitoring and ongoing validation requirements is likely to evolve, and the tools for monitoring and validation, such as CIMMS are still being refined and expanded to be more robust.
- There is limited to no data available to help IOOs understand the long-term costs of maintaining CIs and the associated supporting systems and processes.
- Unforeseen cybersecurity challenges exist, and the requirements for ensuring security at a fully validated CI have not yet been determined.

6.3 Assessment of At-Scale Implementation: Harnessing Benefits and Mitigating Negative Impacts

There are no identified negative impacts of new technologies associated with fully validated CIs on the availability of good-paying jobs with the choice to join a union.

7. Wrap Up

Overall, the solution that was developed and demonstrated as a part of the UDOT Stage 1 SMART Grant effort met expectations. The tests and procedures developed are sufficiently robust to validate CIs. One key finding was that the tools and preliminary testing identified previously unknown issues in the signal controllers that the project team continues to work to address with the signal control manufacturers but were not able to be resolved during the project period. A description of supporting resources for the tools and processes developed as a part of this effort are presented in Appendix B.

Given the consensus and confidence in the test tools and procedures for CI validation by OEMs and CAMP, as well as the experiences and input from UDOT and other IOOs, the proof-of-concept was successful in achieving its goals and objectives.

Any IOO considering plans to validate CIs should bear several things in mind:

- Some issues identified as part of this UDOT effort still require updates from signal controller manufacturers to be a fully validated CI. However, the testing tools and validation processes developed as part of this effort are available to validate CIs against a profile or subset of CI requirements as defined by SCMS Manager.
- CI technologies and monitoring tools, as well as the test tools and validation procedures developed as part of this effort, are all in the early stages of deployment. As such, continued evolution is expected to occur as other issues are identified; however, efficiencies are anticipated over time. For example, agency staff may be able to conduct testing activities faster given increased experience with tools and troubleshooting, and technology solutions may be streamlined to hasten data collection and analysis.
- While OEM production vehicles are not yet equipped with RLVW and other safety applications, IOO commitments to deploy and validate CIs and other V2X solutions are needed to encourage OEM commitments.

8. Terms and Acronyms

8.1 Terms

Connected Intersections (CIs) are signalized intersections with connected vehicle (CV) technology, specifically infrastructure-based vehicle-to-everything (V2X) devices that broadcast messages about the intersection status (i.e., Signal Phase and Timing (SPaT) message, MAP message containing intersection geometry information, and Radio Technical Commission for Maritime Services (RTCM) message for position correction information). For the purposes of this effort, V2X devices are broadcasting messages within the 5.9 GHz spectrum using roadside units for low-latency CV safety applications; however, other applications and V2X devices may also or only use network cellular communications.

Red-Light Violation Warning (RLVW) is a key connected vehicle (CV) safety application being prepared for early deployment in equipped vehicles, which provides an in-vehicle warning to drivers that they are about to enter an intersection during a red light.

Validation and **verification** are two related terms that for the purposes of Connected Intersections (CIs) are used interchangeably to describe the process (and supporting tools) that will enable OEMs to trust that CIs deployed by IOOs are broadcasting accurate, consistent, reliable, and secured messages that can support in-vehicle Red-Light Violation Warning (RLVW) and other CI related safety applications.

8.2 Acronyms

C-V2X	Cellular-vehicle-to-everything
CAMP	Crash Avoidance Metrics Partners, LLC
CI	Connected intersection
CIMMS	Connected Intersection Message Monitoring System
CTI	Connected Transportation Interoperability
CV	Connected vehicle
CV PFS	Connected Vehicle Pooled Fund Study
DOT	Department of Transportation
FCC	Federal Communications Commission
IIJA	Investment and Jobs Act
IOO	Infrastructure owner operator
ISS	Integrated Security Services
ITE	Institute of Transportation Engineers
LiDAR	Light Detection and Ranging
OEM	Original equipment manufacturer
RLVW	Red-Light Violation Warning

RSU	Roadside unit
RTCM	Radio Technical Commission for Maritime Services
SAE	Society of Automotive Engineers International
SCMS	Security Credential Management System
SMART	Strengthening Mobility and Revolutionizing Transportation
SPaT	Signal phase and timing
TSCLT	Traffic Signal Cabinet Logging Tool
UDOT	Utah Department of Transportation
USDOT	United States Department of Transportation
V2X	Vehicle-to-everything

Appendix A: Signal Phase and Timing Testing Error Summary

Introduction

To evaluate the accuracy, consistency, and reliability of SPaT transmitted by CIs, the Traffic Signal Cabinet Logging Tool (TSCLT) was developed to serve several critical purposes. Briefly, the TSCLT:

- Collects serial data from the signal cabinet load switches – These load switches control the signal head and serve as ground truth for the status of each signal indication (e.g., red, yellow, green, flashing yellow arrow, etc.). This data is called the Signal Phase Event Log (SPEL) and is patterned after the Indiana Traffic Signal Hi Resolution Data Logger Enumerations.
- Receives OTA V2X messages – The embedded OBU receives the J2735 messages transmitted by the RSU.
- Logs the TSCBM message produced by the controller – This helps troubleshoot any issues encountered with the data since the TSCBM is the upstream source of SPaT.
- Logs the immediate forward messages (IFM) sent by the ECLA to the RSU – This helps troubleshoot any issues with the data and enables individual packets to be monitored at this intermediate step.
- Uses GNSS to acquire UTC time – A timestamp is applied to each data packet so that a single time source is used for all messages. This eliminates the challenge of comparing timestamps produced by devices with different time sources.

The CAMP data analysis software currently only uses the SPEL and the OTA datasets. The additional data collected by the TSCLT are used to troubleshoot discovered problems, track individual data packets, assess device performance, and determine the source of errors or poor OTA performance.

The TSCLT and CAMP's data analysis software successfully identified when SPaT was accurate, consistent, and reliable, and when it was not. The CAMP software processes and analyzes SPaT for accuracy, latency, and periodicity, and produces summary reports that provide results and whether the requirements in CTI 4501 were met.

However, a simple pass/fail determination does not fully capture the frequency, nor the magnitude, with which a requirement was not met. The results help fill this knowledge gap and provide more granularity into the accuracy, consistency, and reliability of SPaT.

Metrics

This section describes what information is included in the results and its significance.

- SIG # – A unique identifier for signalized intersections.
- Date – Date when the data was collected (yymmdd).
- RSU – Identifies the RSU vendor whose device was used during the test. Distinct differences were observed between the two RSU vendors that impacted CTI 4501 compliance.
- MSGs – Lists the J2735 messages transmitted during the test.

- SPaT Collection – Identifies the SPaT collection method (OTA or IFM). OTA means the over-the-air SPaT transmitted by the RSU and received by the TSCLT. IFM means the immediate forward messages sent by the ECLA to the RSU for broadcast
- Timestamp – Identifies what timestamp is evaluated.
 - SPaT MSG – Timestamp found within the SPaT message itself (a combination of the MinuteOfTheYear and DSecond data elements).
 - TSCLT Rx – Timestamp when the OTA SPaT is received by the TSCLT.
 - IFM – Timestamp when the ECLA sends SPaT to the RSU for broadcast.
- n – The number of SPaT messages collected.
- Single Message SPaT Periodicity – These metrics assess the consistency of SPaT according to the designed single message periodicity of one message every 100 +/- 25 ms.
 - Min – Minimum observed single message periodicity.
 - Percentile 75 ms – Percent of SPaT with a periodicity ≤ 75 ms. This is the acceptable lower limit for all timestamps.
 - Percentile 125 ms – Percent of SPaT with a periodicity ≤ 125 ms. This is the acceptable upper limit for the SPaT MSG and IFM timestamps.
 - Percentile 175 ms – Percent of SPaT with a periodicity ≤ 175 ms. This is the acceptable upper limit for the TSCLT Rx timestamp because the RSU is afforded 50 ms to process (encode and apply security credentials) and broadcast each SPaT message.
 - Max – Maximum observed single message periodicity.
 - Single IPR – Single InterPercentile Range, which measures the percent of observations that fall within the acceptable upper and lower limits for periodicity.
- Cumulative SPaT Periodicity – These metrics assess the consistency of SPaT over a 10-consecutive message interval with the designed cumulative periodicity of 10 messages every 1.0 second +/- 25 ms.
 - Min – Minimum observed cumulative periodicity for 10 consecutive SPaT.
 - Percentile 975 ms – Percent of 10 consecutive SPaT with a cumulative periodicity ≤ 975 ms. This is the acceptable lower limit for all timestamps.
 - Percentile 1025 ms – Percent of 10 consecutive SPaT with a cumulative periodicity ≤ 1025 ms. This is the acceptable upper limit for the SPaT MSG and IFM timestamps.
 - Percentile 1075 ms – Percent of 10 consecutive SPaT with a cumulative periodicity ≤ 1075 ms. This is the acceptable upper limit for the TSCLT Rx timestamp because the RSU is afforded 50 ms to process (encode and apply security credentials) and broadcast each SPaT message.
 - Max – Maximum observed cumulative periodicity for 10 consecutive SPaT.

- Cumulative IPR – Cumulative InterPercentile Range, which measures the percent of 10 consecutive SPaT message intervals that fall within the acceptable upper and lower limits for cumulative periodicity.
- SPaT Broadcast Latency – These metrics assess the reliability of SPaT to be broadcasted within 175 ms from the time the signal controller sets the corresponding signal indications. This is the calculated difference in the TSCLT-applied timestamps from the SPEL and the OTA datasets. For each phase, the first SPaT message indicating yellow is compared to the analogous yellow record in the SPEL. Since the emphasis of the RLVW application is thru movements, these results only include yellow phases for thru movements.
 - Min – Minimum observed latency
 - Max – Maximum observed latency
- Minimum End Time Accuracy – These metrics assess the accuracy of the minEndTime value in SPaT for yellow phases. For each phase, the minEndTime value in the first SPaT message indicating yellow is compared to duration of yellow in the SPEL. The requirement is that the minEndTime accuracy be within 100 ms of the actual duration of yellow. Since the emphasis of the RLVW application is thru movements, these results only include minEndTime accuracy for thru movement yellow phases. It should be noted that minEndTime accuracy was worse for left turn phases.
 - Min – Minimum observed accuracy
 - Max – Maximum observed accuracy

Results

The results for the metrics previously described highlight a variety of issues and challenges to address in the Stage 2 effort. For example, various issues include:

- Regarding cumulative SPaT periodicity, issues that were noted in four RSUs included no OTA SPaT for up to 18.4 seconds, although the IFM log confirms ECLA sent all SPaT to the RSU; instances of skipped OTA SPaT; and instances where duplicate SPaT messages were transmitted to the RSU; IFM log confirms that the ECLA sent the duplicated SPaT messages to the RSU.
- Regarding SPaT broadcast latency, in addition to the skipped SPaT, there was an approximate 6-second delay in SPaT transmission that occurred completely within the RSU. During a preemption event, an extra yellow phase is recorded in SPaT but it is not found in the TSCBM SPEL or the actual ATSPM log. This results in erroneous calculations by the analysis software that attempts to pair non-matching yellow events and results in extremely large values (i.e., a maximum SPaT broadcast latency of 526,640 ms).
- Regarding minimum end time latency, one RSU showed extremely high and incorrect values for minEndTime in the TSCBM message during preemption events, which mimics behavior observed at other intersections. Another RSU had 114 yellows for thru movements, all of which failed minEndTime accuracy and all minEndTime errors were also incorrect in the TSCBM message.

Appendix B: Supporting Resources Developed in this Effort

A series of documents were developed as part of this effort by the project team partners at the Crash Avoidance Metrics Partners Limited Liability Company (CAMP LLC) Consortium (i.e., CAMP), Security Credential Management System (SCMS) Manager, and INTEGRITY Security Services (ISS). While these documents are available on the Utah Department of Transportation (UDOT) [Transportation Technology webpage](#), readers are encouraged to directly check the webpages of these organizations for updated versions of these documents. That is, the documents developed as part of this effort, described below, and available on the UDOT webpage are version one resources that are expected to evolve in the near future as part of other efforts. These resources are described below.

Assessment of SPaT Accuracy to Support RLVW Application (CAMP, December 2024). This report describes the development of data acquisition and analysis tool for verification of requirements specified in CTI 4501v01 and v02 for analysis of signal phase status and the corresponding timing information generated by the traffic signal controller infrastructure and broadcast of SPaT message by the RSU of a CI.

Assessing Node Point Accuracy in the SAE J2735 MAP Message (CAMP, August 2024). This paper describes the use of mobile LiDAR scan data to assess node point accuracy for three CIs located in southeast lower Michigan. Specifically, CTI 4501 establishes requirements for SAE J2735 MAP Message node point accuracy supporting in-vehicle RLVW applications. These requirements are specified in relation to pavement markings defining ingress and egress lane boundaries for mapped intersections. Commercial Mobile Mapping services typically use a combination of scanning LiDAR technology in conjunction with high accuracy positioning (GNSS / GPS) and multi-axis high-resolution photography to create 3D models of roadways which include the locations of lane markings, curbs, stop bars and crosswalks. This information can be used to verify that the node point accuracy requirements established in CTI 4501 are satisfied by the MAP message developed for a CI.

Validation Assessment & Analysis Software Toolset User Guide, Version 3.0 (CAMP, August 2025). This document serves as the user guide for a software toolset created for the CI Program developed under the Vehicle-to-Infrastructure 5 (V2I-5) Consortium of Ford, GM, and Nissan. This initiative was conducted to facilitate the deployment of CIs that provide Red Light Violation Warning (RLVW). This version of the guide was updated under the UDOT SMART Grant. The toolset contains six modules (software tools) that are designed to validate over-the-air transmission of SPaT and MAP messages to facilitate CI deployment for RLVW.

Traffic Signal Cabinet Logging Tool Quick Reference Guide (UDOT and The Narwhal Group, December 2024). The Traffic Signal Cabinet Logging Tool (TSCLT) is a device used to collect data from a CI, which can then be analyzed by various CAMP applications to determine whether those messages meet the CTI 4501 specification. This guide is meant to inform practitioners who will be deploying the TSCLT in (or near) a traffic signal cabinet for a CI.

SCMS Manager Intersection Validation and Certificate Issuance Policy (SCMS Manager, September 19, 2024). This document describes the role of the SCMS Manager in the implementation and enforcement of validated intersections. SCMS Providers which are authorized by the SCMS Manager to issue certificates to V2X stations must support the intersection validation procedures defined in this policy if they intend to issue credentials for validated intersections.

SCMS Manager Intersection Validation Misbehavior Management (SCMS Manager, December 23, 2024). This report considers the impact of misbehavior information provided by the Connected Intersections Message Monitoring System (CIMMS) process. This application collects data broadcast from a CI (in the form of SPaT and MAP data) along with BSM data from vehicles that drive through the intersection. It then performs analysis to compare the movement of vehicles (as reported in the BSM data) against the intersection status (as indicated in the SPaT and MAP data). Statistical data on misbehavior events is tracked against threshold values.

CI Test Results Report Format (ISS, May 31, 2024). This report outlines a recommended format for traffic organizations to use when providing cybersecurity test results for CIs to SCMS providers. This machine-readable format is crucial for maintaining accurate and up-to-date cybersecurity information throughout the lifecycle of the CI. By adopting this standardized format, SCMS providers can automate the certification process, ensuring continuous compliance and security monitoring, and enhancing the overall efficiency and effectiveness of the cybersecurity management for CIs.

CTI 4501 Security Policy Profile (ISS, August 20, 2024). This document specifically delineates requirements that either (a) apply exclusively to RSUs or (b) involve additional security controls necessitated by the installation of an RSU. By focusing on these specific scenarios, the document provides targeted guidance to ensure that RSUs are deployed and managed securely, minimizing potential vulnerabilities.