Phase 1 Performance Measurement and Evaluation Plan (PMEP)

Vehicle-to-Everything (V2X) Accelerator: Connecting the West – Utah Department of Transportation

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16. Abstract

This Performance Measurement and Evaluation Plan (PMEP) documents performance measures that will be used to evaluate the effectiveness of Utah, Colorado, and Wyoming's collaborative Connecting the West (CTW) program, part of the United States Department of Transportation's (USDOT) Saving Lives with Connectivity: Accelerating Vehicle-to-Everything (V2X) Deployment grant program. The project team will follow the plans and procedures outlined in this document to evaluate the project's effectiveness in meeting its goals and addressing the six use cases defined here. The PMEP details the methods and procedures for data collection, analysis, and reporting necessary to support the evaluation. It outlines the experimental design for the performance measures, data sources, and potential confounding factors. The PMEP was developed in alignment with the project's Concept of Operations (ConOps), System Requirements Specifications (SyRS), and Data Management Plan (DMP), ensuring that the evaluation stays consistent with defined objectives, user needs, and use cases.

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List of Acronyms and Abbreviations

ANOVA	Analysis of Variance
ATSPM	Automated Traffic Signal Performance Measures
AVL	Automatic Vehicle Location
BSM	Basic Safety Message
CAN	Controller Area Network
CDOT	Colorado Department of Transportation
CI	Connected Intersection
CIPT	Connected Intersection Preferential Treatment
ConOps	Concept of Operations
CSW	Curve Speed Warning
CTI	Connected Transportation Interoperability
CTIC	Connected Transportation Interoperability Committee
CTW	Connecting the West
CV	Connected Vehicle
DMP	Data Management Plan
DOT	Department of Transportation
DPP	Data Privacy Plan
DP	Data Plan
ERV	Emergency Response Vehicle
FCC	Federal Communications Commission
FHWA	Federal Highway Administration
GHz	Gigahertz
GM	General Motors
GNSS	Global Navigation Satellite System
HMI	Human Machine Interface
IC	Interoperability and Compatibility
IOO	Infrastructure Owner-Operator
IRB	Institutional Review Board
IRC	Interstate and Rural Corridor
ITS	Intelligent Transportation Systems
JPO	Joint Program Office
LiDAR	Light Detection and Ranging
MAP	Map Data Message
MPH	Miles Per Hour
NHS	National Highway System
NOFO	Notice of Funding Opportunity
NTP	Network Time Protocol

OBE	On-Board Equipment
OBU	On-Board Unit
OEM	Original Equipment Manufacturer
OEP	Outreach and Engagement Plan
OTP	On-Time Performance
PII	Personally Identifiable Information
PMEP	Performance Measurement and Evaluation Plan
PMP	Project Management Plan
PSM	Personal Safety Message
RLVW	Red Light Violation Warning
ROI	Return on Investment
RSE	Roadside Equipment
RSU	Roadside Unit
RTCM	Radio Technical Commission for Maritime Services
SAE	Society of Automotive Engineers
SCMS	Security Credential Management System
SDSM	Sensor Data Sharing Message
SDX	Situation Data Exchange
SI	Signalized Intersection
SPaT	Signal Phase and Timing
SRM	Signal Request Message
SSM	Signal Status Message
SWIW	Spot Weather Impact Warning
SyRS	System Requirements Specifications
TIM	Traveler Information Message
TMC	Traffic Management Center
TOC	Traffic Operations Center
TSCBM	Traffic Signal Controller Broadcast Message
TSP	Transit Signal Priority
TTC	Time to Collision
UDOT	Utah Department of Transportation
USDOT	United States Department of Transportation
UTA	Utah Transit Authority
V2X	Vehicle-to-Everything
VRU	Vulnerable Road User
VSL	Variable Speed Limit
WYDOT	Wyoming Department of Transportation

1. Introduction

This Performance Measurement and Evaluation Plan (PMEP) identifies the performance measures used to assess the impact—outcomes and outputs—of Connecting the West (CTW), a multi-state collaborative project led by the Utah Department of Transportation (UDOT) in partnership with the Colorado and Wyoming DOTs. CTW is one of three recipients of the United States Department of Transportation's (USDOT) Saving Lives with Connectivity: Accelerating Vehicle-to-Everything (V2X) Deployment grant program (often referred to as the V2X Accelerator program). In addition to defining targeted performance measures, the PMEP also describes the project's goals and objectives and explains their relationship to the project's six specific use cases. The PMEP also outlines a plan for data collection and reporting, performance evaluation and reporting, and potential risks and confounding factors.

The PMEP draws upon and was developed in conjunction with other CTW documents, including the Concept of Operations (ConOps), System Requirements Specifications (SyRS), and Data Management Plan (DMP).

1.1. Document Purpose

A PMEP is a dynamic document that guides and enables ongoing analysis of a project's impact throughout the project lifecycle. It is a tool meant to guide the project team in optimizing project design and delivery by defining key performance indicators, informing decision making, and demonstrating the effectiveness of those decisions. This PMEP is aligned with CTW goals and objectives and establishes a framework for rigorous analysis, identifies confounding factors and potential risks, and specifies techniques for mitigating those obstacles. Importantly, the PMEP also specifies the methods for data collection, analysis, and reporting, with baseline data serving as a benchmark for measuring performance. By developing and utilizing this PMEP, the project team will be better able to identify, measure, and report on the impacts of the deployed system.

1.2. Project Overview

The CTW Program is one of three V2X Accelerator sites awarded contracts by the Federal Highway Administration (FHWA) in 2024. The CTW Program is led by UDOT with partners Wyoming DOT (WYDOT) and Colorado DOT (CDOT). The CTW efforts will also include local agencies within each state, some of which will be partners in the process and others as participants.

The focus of the CTW Program is to expand the use of existing V2X applications in Utah, Wyoming, and Colorado, and to share messages among the CTW states. The V2X applications that are anticipated to be deployed are:

- Connected Intersection Preferential Treatment (CIPT) including transit priority and emergency vehicle and snowplow preemption.
- Traveler information and driver alert delivery such as curve speed warning (CSW), spot weather impact warning (SWIW), work zones, variable speed limits (VSL), road closures, chain law restrictions, and disabled vehicle alerts.
- Detection of vulnerable road users (VRUs) at intersections coupled with in-vehicle and roadside alerts to drivers about VRU presence and intersection movements.

The scope of the CTW Program includes the following deployment activities:

- Install roadside units (RSUs) at signalized intersections in Utah.
- Install RSUs at additional sites along corridors in Utah and Colorado.
- Equip additional intersections with VRU detection and warnings in Utah.
- Equip additional vehicles with on-board units (OBUs) and human machine interfaces (HMIs) where appropriate in Utah, including transit buses, snowplows, emergency vehicles (fire engines and ambulances), and general fleet vehicles including a General Motors test vehicle that will be driven by UDOT staff.
- Expand the coverage of all use cases currently being used in all CTW states.
- Establish the use of the Situation Data Exchange (SDX) across jurisdictions to make notifications uniform and interoperable across platforms in all CTW states.
- Expand the use of Connected Intersections (CI) message monitoring in Utah, to monitor ongoing compliance with established standards.
- Establish the use of security certificates and OBU certificate top-off to facilitate interoperable communications in all CTW states.

The CTW Program will also:

- Perform rigorous testing to verify that CIs meet the CTI 4501 and other standards and transmit interoperable messages in Utah and Colorado.
- Document and broadly share to create a replicable model for others and serve as a useful and meaningful reference implementation for interoperable connectivity.

The scope of this CTW Program is limited to the additional equipment, components, and functions that are expanding upon existing systems that are operating in Colorado, Utah, and Wyoming. The aforementioned activities are organized into seven projects described below:

- Project 1: Utah Signalized Intersections RSUs. This project will install RSUs at state-owned signalized intersections in Utah (i.e., over 300 signalized intersections) and some local agency-owned intersections. Intersections will be enabled with appropriate messages and applications.
- Project 2: Utah Interstate and Rural Corridor RSUs. This project will install RSUs along major interstates in Utah at appropriate intervals and along some non-interstate rural corridors to primarily support CSW and SWIW applications. Appropriate messages and applications will be enabled.

- Project 3: Utah VRU Safety at Intersections. This project will install Light Detection and Ranging (LiDAR)-based detection, Traveler Information Message (TIM) broadcasts, and electronic signs at urban intersections in Utah to issue warnings about VRU presence and collision risk.
- Project 4: Colorado Interstate 70 (I-70) Expansion and Integration. This project will install RSUs along the remaining portions of I-70 in Colorado to the Utah border without coverage. Appropriate messages and applications will be enabled.
- Project 5: Application Integration and Interoperability Testing. This project brings all the agencies together to synthesize their applications, bring their applications into uniform compliance with standards and guidelines, integrate the data into the SDX, and perform detailed testing across all the jurisdictions to identify and overcome challenges and bring systems into conformance, making them interoperable.
- Project 6: System Performance, Measurement, and Evaluation. This project includes the evaluation efforts to assess the performance of our systems, report on those metrics, and account for confounding factors. A variety of testing methods and data analyses will be engaged, including using the purpose-built General Motors (GM) vehicle to confirm interoperability and produce data about the ultimate usefulness of our system to the end user—the vehicle and its driver.
- Project 7: Project Administration, Reporting, and Outreach. This project includes all project management functions from the creation of the Project Management Plan (PMP) to the monthly reporting and participation in outreach and engagement efforts outlined in the Outreach and Engagement Plan (OEP).

1.3. Organization of the Report

This report is organized as follows:

- Section 1 – Introduction and overview
- Section 2 – Summarizes the goals and objectives of the CTW project
- Section 3 – Summarizes the use cases and describes the performance measures for the project
- Section 4 – Addresses potentially confounding factors and proposes mitigation approaches
- Section 5 – Describes baseline and deployment data in concert with the separate Data Plan (DP), which consists of the Data Management Plan (DMP) and the Data Privacy Plan (DPP)
- Section 6 – Outlines the evaluation approach, including both quantitative and qualitative data
- Section 7 – Outlines performance reporting methods and approach
- Section 8 – Measurement and evaluation schedule
- Section 9 – Identifies potential risks

2. Goals and Objectives

The CTW Program directly supports USDOT's goals to improve system safety and ensure that the benefits of connected transportation systems extend across multiple sectors. This section outlines CTW's project-specific goals and objectives, which support those larger nationwide initiatives. In addition, this section first summarizes the CTW user needs. There are 18 user needs identified, each of which correlates directly to a specific challenge as discussed in the ConOps. The goals and objectives were similarly developed in response to these same challenges in addition to stakeholder priorities and the V2X Accelerator Program goals. Defining these user needs, goals, and objectives establishes a means for measuring the project's success.

2.1. Summary of User Needs

To deliver a system that addresses the identified challenges, a key step is to identify user needs. Since the CTW Program is being built upon existing C-V2X deployments in each of the three states, many of the user needs were already understood by the CTW team. The approach taken for this effort was as follows:

- Internal CTW workshops were conducted to discuss the end user needs that drove the development and deployment of the existing C-V2X systems and to discuss where these legacy systems need to be expanded. As a result of these workshops, a long list of needs was identified (131 in total). The original set of needs captured the specific users related to each need, and these were the basis for the legacy systems that exist in Utah, Colorado, and Wyoming.
- The original user needs were combined and analyzed to develop a set of consolidated needs for the proposed system enhancements and expansions in CTW as well as to define operational policies and constraints that will need to be addressed as part of the proposed system.
- The internal CTW workshops also discussed the needs for new functionalities that do not exist in the legacy systems.

One key emphasis of the CTW Program is on expanding the existing legacy systems. Therefore, many of the user needs described in this section emphasize the expansions of existing functionalities but do not restate the original user needs that led to these.

Through the process of identifying user needs, the CTW team discussed the challenges and identified what CTW Program partners, drivers, and VRUs need from the proposed system. Details of specific needs discussed during CTW Program workshops are captured here, and the details described in these needs will be carried forward to future stages of the CTW Program. However, the more detailed user needs have been combined and analyzed to develop a set of consolidated needs for the proposed system.

It is important to note that the CTW Program is expanding existing systems with available funding, and in some of the need descriptions only one or two of the CTW states are called out. This is because those

needs are not identified as needs to be addressed by all CTW sites as part of the CTW Program—not that the need does not necessarily translate to all sites. This may be because the CTW partner already addresses the challenge or the challenge was not prioritized to be included in the CTW Program.

Each of the consolidated user needs maps to one or more challenges presented in the ConOps. The challenges represent the rationale for each of the user needs listed below.

CTW-1: Need expanded SI preferential treatment. UDOT, UTA, local agencies in Utah that operate SIs, as well as drivers, need SI preferential treatment to expand to additional intersections and vehicles. Note: Expansion of SI preferential treatment was not identified as a need for CDOT or WYDOT in the CTW Program.

CTW-2: Need additional CIs. To encourage RLVW applications, public agencies in Utah that operate SIs need to expand the number of SIs that operate as CIs that broadcast messages for in-vehicle safety applications. Note: This need was not identified as a need for CDOT or WYDOT in the CTW Program.

CTW-3: Need accurate, reliable, and timely data broadcasts at CIs. Public agencies in Utah and Colorado that operate SIs and drivers need their existing CIs or additional CIs added through the CTW Program to deliver accurate, reliable, and timely data. Note: This need was not identified as a need for WYDOT in the CTW Program.

CTW-4: Need to expand the creation of SWIW messages. All CTW states and drivers need to increase the creation of messages to support SWIW to equipped vehicles (i.e., vehicles equipped with V2X technology).

CTW-5: Need to expand the creation of Curve Speed Warning (CSW) messages. All CTW states and drivers need to increase the creation of messages to support CSWs to equipped vehicles at selected locations.

CTW-6: Need to increase the creation of traveler information alerts and situational awareness notifications. All CTW states and drivers need to increase notifications of events and activities such as work zones, incidents, VSLs, high wind warnings, over height warnings, truck parking availability, and road or lane closures to be distributed to equipped vehicles.

CTW-7: Need to continue and expand, as appropriate, the distribution of TIMs to equipped vehicles. All CTW states need to continue to support (and expand as needed) the distribution of warnings, alerts, and situational awareness notifications (i.e., those warnings, alerts, and notifications created by addressing needs CTW-4, CTW-5, and CTW-6).

CTW-8: Need to inform third-party traveler information systems. All CTW states need a common mechanism to share alerts and warnings on Interstate and Rural Corridors (IRCs) with third-party traveler information systems.

CTW-9: Need event-sharing between CTW states. TOCs in CTW states need access to timely and accurate event reports affecting key routes in states adjacent to their jurisdiction.

CTW-10: Need to expand locations where data is collected from equipped vehicles. UDOT and CDOT need to expand the locations where they receive Basic Safety Message (BSM) data from equipped

vehicles to supplement information about vehicle movements, weather, and pavement conditions. Note: Additional coverage of RSUs in Wyoming was not identified as a need for the CTW Program.

CTW-11: Need to secure devices and data. All CTW states need to secure the physical devices and messages communicated as part of the proposed CTW system.

CTW-12: Need to expand the capability to alert drivers to possible conflicts with VRUs. UDOT and drivers need to expand the capability to detect VRUs at SIs and alert drivers as appropriate. Note: This need was not identified as a need for CDOT or WYDOT in the CTW Program.

CTW-13: Need interoperability and consistency in messages delivered. All CTW states and drivers (i.e., system end users) need systems to be deployed and operated in a consistent, interoperable, and secure manner to ensure trust.

CTW-14: Need to expand the collection, storage, and management of data for analytics to support CTW expansions. All CTW states need the capability to collect, store, and manage data in order to understand the impacts of deployed systems in the CTW Program.

CTW-15: Need to expand the capability to monitor CV2X devices health and status to support additional devices. All CTW states need to understand the status of deployed systems at any given time.

CTW-16: Need Interstate interoperability in SCMS certificates. All CTW states need the SCMS certificates broadcast to be interoperable with other states, enabling vehicles to successfully exchange messages with all three sites.

CTW-17: Need to refine and implement SCMS certificate top-off. UDOT needs to refine and implement a noncellular approach to top off security certificates in fleet vehicles. Note: This need was not identified as a need for CDOT or WYDOT in the CTW Program.

CTW-18. Need to adhere to standards and to documented best practices. All CTW states and system end users need systems to be deployed and operated using standards and documented best practices for interpreting and applying standards to facilitate interoperability with other states and systems nationally.

2.2. Deployment Goals and Objectives

This section describes the goals that drive the activities of the CTW Program and reflect the high-level needs that were the basis for initiating this effort. Improving safety, mobility, and operations effectiveness as well as advancing technology solutions are the fundamental goals of the CTW Program. Specifically, the CTW Program goals are:

- CTW Goal 1 (G1): To use interoperable V2X technologies to reduce the number of crashes and fatalities at intersections, in work zones, along rural corridors, in bad weather, and those involving VRUs.
    - Objective 1 (G1-01): [Objective SI-1] Reduced snow clearance times – Reduce the time for snowplows to complete their snow clearing along more routes than currently supported.

  - Objective 2 (G1-02): [Objective SI-3] Improved safety and reduced delays for emergency vehicles – Reduce the delays and conflicts with other vehicles that occur when emergency vehicles encounter red signal phases when traveling to active events along more routes than current.
  - Objective 3 (G1-03): [Objective SI-4] Increase the number of CIs – Increase the number of CIs to demonstrate to OEMs a commitment to operating systems to support in-vehicle safety applications.
  - Objective 4 (G1-04): [Objective IRC-2] Increase the C-V2X delivery of messages to support in-vehicle warnings and situational awareness – Expand geographic coverage and increase frequency of traveler information alerts and situational awareness messages delivered via C-V2X to private and commercial vehicles to improve mobility and safety outcomes. [See note in ConOps about this being a surrogate while the number of equipped vehicles is still statistically low.]
  - Objective 5 (G1-05): [Objective VRU-1] Demonstrate VRU Detection coupled with driver alerts – To demonstrate the coupling of VRU detection with driver alerts by expanding the number of reference implementations to be a model for widespread deployment at intersections by other IOOs nationwide.
- CTW Goal 2 (G2): To use interoperable V2X technologies to improve system operations and effectiveness of transit, emergency, and snowplow fleet vehicles to improve traveler mobility, improve safety, and reduce operating costs.
  - Objective 1 (G2-01): [Objective SI-1] Reduced snow clearance times – Reduce the time for snowplows to complete their snow clearing along additional routes through CTW RSU deployments.
  - Objective 2 (G2-02): [Objective SI-2] Increased transit on-time performance – Improve transit vehicle on-time performance (OTP) along additional transit routes through CTW RSU deployments.
  - Objective 3 (G2-03): [Objective SI-3] Improved safety and reduced delays for emergency vehicles – Reduce the delays and conflicts with other vehicles that occur when emergency vehicles encounter red signal phases when traveling to active events along additional routes through CTW RSU deployments.
  - Objective 4 (G2-04): [Objective IRC-1] Increase the creation and delivery of messages to support in-vehicle warnings and situational awareness – Increase the geographic area covered and content included in messages created to support SWIW, CSW, traveler information alerts, and situational awareness messages that will eventually reduce the number of crashes and improve mobility of travel.
  - Objective 5 (G2-05): [Objective IRC-5] Increase data collection from vehicles – To expand the number of locations where data from vehicles broadcasting BSMs are captured, and to process and store the additional data.
- CTW Goal 3 (G3) To help advance solutions to the need for national deployment of interoperable V2X systems, especially in the 5.9 GHz spectrum.

  - Objective 1 (G3-01): [Objective IRC-3] Communicate traveler information alerts to Third-Party Traveler Information Systems users – To increase the consistent delivery of information and alerts to Third-Party Traveler Information Systems.
  - Objective 2 (G3-02): [Objective IRC-4] Share event reports between CTW states – Accomplish near real-time sharing between CTW states of active event reports in each state's respective systems.
  - Objective 3 (G3-03): [Objective IC-1] Consensus on message content and structure – To reach consensus on how SAE standards-based messages are formulated and populated for delivery to C-V2X-equipped vehicles, both within CTW states and additional states.
  - Objective 4 (G3-04): [Objective IC-2] Integrate message consistency into existing CTW systems – To successfully adapt systems in each CTW state to implement agreed message consistency guidelines.
  - Objective 5 (G3-05): [Objective IC-3] Inform Industry of agreed message consistency definitions – To outreach and educate manufacturers of C-V2X equipment about the consensus reached and demonstrated success of consistent approaches to standardized messages.
  - Objective 6 (G3-06): [Objective IC-4] Demonstrate Interstate interoperability of SCMS certificates – To gain trust in multi-state interoperability of SCMS certificates by demonstrating vehicles traveling while sending and receiving SCMS certificates with RSUs in each of the CTW states.

- CTW Goal 4 (G4) To help advance solutions to the industrywide challenge that the benefits of IOO-deployed infrastructure will not be fully recognized until there is a critical mass of C-V2X equipped vehicles, and similarly that the benefits to drivers of C-V2X-equipped vehicles will not be fully recognized until there is a critical mass of C-V2X-equipped roadside infrastructure. This is often referred to as a "chicken and egg" barrier that must be overcome to expand connected vehicles (CVs) to become deployed and operational at a large scale.
  - Objective 1 (G4-01): [Objective SI-4] Increase the number of CIs – Increased the number of CIs to demonstrate to OEMs a commitment to operating systems to support in-vehicle safety applications.
  - Objective 2 (G4-02): [Objective SI-5] Improved data quality at CIs – To increase the number of Utah intersections operating accurate, reliable, and timely data that is validated against industry accepted approaches.
  - Objective 3 (G4-03): [Objective IRC-5] Increase data collection from vehicles – To expand the number of locations where data from vehicles broadcasting BSMs are captured, and to process and store the additional data.
  - Objective 4 (G4-04): [Objective IC-3] Inform Industry of agreed message consistency definitions – To outreach and educate manufacturers of C-V2X equipment about the consensus reached and demonstrated success of consistent approaches to standardized messages.
- CTW Goal 5 (G5) To help advance solutions to encourage automakers' willingness to integrate systems that will be critical for meeting safety and operational goals.

- Objective 1 (G5-01): [Objective IC-1] Consensus on message content and structure – To reach consensus on how SAE standards-based messages are formulated and populated for delivery to C-V2X-equipped vehicles, both within CTW states and additional states.
- Objective 2 (G5-02): [Objective SI-4] Increase the number of CIs – Increased the number of CIs to demonstrate to OEMs a commitment to operating systems to support in-vehicle safety applications.
- Objective 3 (G5-03): [Objective SI-7] Increase the number of CIs that support RLVW – Increase the number of CIs that broadcast accurate and reliable SPaT and MAP messages in direct support of the RLVW application.

3. Use Cases and Performance Measures

This section outlines CTW's six use cases, mirroring those also discussed in the ConOps. However, a seventh use case is added to more appropriately capture performance measures that are not tied to other specific use cases. Performance measures for each use case are then defined, along with our initial targets for each performance measure.

3.1. Use Cases

The CTW Program is focused on saving lives and improving mobility using V2X technology in the 5.9 GHz "safety spectrum" along with network communications platforms throughout Utah, Wyoming, and Colorado. The six use cases described below encompass CTW deployments. A seventh use case ("General") has been added to account for deployment efforts and performance measures that play an important role in CTW yet are not easily tied to a specific use case.

1. **UC-1: CIPT.** The CIPT use case allows authorized vehicles equipped with V2X hardware to request priority or preemption at CIs that support preferential treatment. Transit buses request priority when they are at least 5 minutes behind schedule and meet minimum occupancy thresholds, snowplows request preemption whenever the salt spreader is turned on, and emergency response vehicles (ERVs) request preemption when the vehicle is not in park and the lightbar is turned on.
2. **UC-2: RLVW**. The RLVW use case leverages a vehicle equipped with a RLVW application that has been procured directly from the OEM without any aftermarket V2X hardware or software. It describes how messages broadcast from validated CIs may be used to support in-vehicle safety applications (in this scenario, RLVW applications are used but others could be supported). RLVW applications will process messages received from CIs, in conjunction with vehicle data, to determine whether to issue a warning to the driver about the risk of running a red light based on vehicle position and trajectory and signal status.
3. **UC-3: TIM Alerts.** The TIM Alerts use case covers the utilization of many TIM alert types, including SWIW, CSW, and work zones. This use case covers intrastate operability and allows each CTW partner state (UT, CO, and WY) the discretion to determine— based on their own criteria, systems, and available information— when to generate specific TIM alerts aimed at improving roadway safety. In addition to transmitting TIM alerts to motorists using V2X, they may also be displayed to Traffic Management Center (TMC) operators.
4. **UC-4: IC.** The Interoperability and Compatibility (IC) use case is aimed at enhancing interoperability and compatibility of V2X systems and functionality among independent deployments. This use case builds upon UC-3 TIM Alerts by sharing the intrastate data collected in UC-3 with CTW partner states. With that information, the CTW partner states can determine whether to generate TIM alerts of their own, thereby establishing the interstate data sharing reflected in this use case. Raw intrastate event information is shared with CTW partner states as well as third-party partners.

5. **UC-5: VSL.** The VSL use case describes how data systems that support the issuance of VSLs through displays on VSL signs are leveraged to generate TIMs that are broadcast to equipped vehicles, providing drivers with supplemental in-vehicle messages (i.e., the in-vehicle delivery of VSLs will only accompany VSL systems with roadway signs that are external systems).
6. **UC-6: VRU.** The Driver Warning of VRU Conflict at an SI use case describes how equipment deployed at SIs is used to detect VRU presence in crosswalks and inform drivers about their potential conflict with VRUs via both roadside infrastructure and in-vehicle messaging. In-vehicle messaging to the driver will only be provided if it is determined that a vehicle is on a trajectory to conflict with the VRU. Similarly, roadside infrastructure will only activate if conditions suggest that one or more vehicle-VRU conflicts will exist.
7. **UC-7: General.** The General use case accounts for deployment efforts and performance measures that play an important role in CTW yet are not easily tied to a specific use case.

3.2. Performance Measures and Targets

This section provides details on the hypothesis for each use case, associated performance measures, and targets for each performance measure. Although the hypotheses provide insight into the reason for implementation and the expected impact of each use case, some performance measures are not intended to test the stated hypothesis. Instead, they aim to answer important research questions identified by the project team.

To illustrate why a hypothesis may not be tested by the associated performance measures, consider the hypothesis of UC-3: TIM Alerts—that dissemination of information that affects highway and travel conditions in real-time will improve safety. One example of a TIM alert deployed in CTW is an icy-road alert. A typical experiment design might randomly assign participants into two groups: one group will receive the icy-road alert and the other will not. The experiment would then recruit drivers to drive around during snowstorms. The null hypothesis would be that icy road alerts do not affect safety and an alternative hypothesis might be that vehicle operators that received the icy-road alert were involved in fewer crashes during snowstorms. The ethical concerns with asking drivers to intentionally drive in hazardous conditions are clear.

If all vehicles on the highway were capable of displaying the icy-road alert, the experiment would be inherently different; the crash rate during icy conditions could hypothetically be compared between geographic areas with the alert enabled and areas with it disabled, although intentionally withholding information that may reduce crashes is a separate ethical issue that would still remain.

To avoid these ethical concerns, surrogate, safety-oriented performance measures have been identified to answer research questions that support many of the CTW deployments designed to improve safety. Many of these surrogate safety measures are assigned to the Situational Awareness category.

To conclude this illustration, one of the surrogate safety performance measures for the icy-road TIM alert is the number of alerts transmitted by CTW deployments. Measuring the number of transmitted alerts, coupled with a geographic deployment footprint, demonstrates the readiness of our IOO-deployed infrastructure to disseminate safety-related information in real time to vehicle operators on our highways. Our ability to disseminate this information will provide more direct and measurable safety benefits as

OEM adoption of V2X increases the penetration rate of V2X-equipped vehicles capable of receiving and displaying these alerts.

Including and setting performance measure targets is a valuable step in the planning process for any project and facilitates the determination of project success. In many cases, however, baseline performance data is necessary to inform what might be an achievable target. Only some baseline data has been collected, and targets have been set using the information available at this time. In other cases, relevant targets will represent confirmation that the deployed V2X alerting system is functioning as designed instead of a targeted number of alerts. For example, we will report the number of ERV at Incident Scene Alerts (PM-1-15) to confirm that our deployment generates alerts informing motorists that they are approaching an incident where emergency responders are present at the scene. It is relevant that the alert is generated as designed, not that a certain number of alerts were generated. These targets also represent the fact that there are significant data availability challenges that limit what can actually be measured.

In the subsections that follow, the hypothesis, performance measures, and targets are grouped by the following categories are listed for each use case:

- Safety
- Mobility & Efficiency
- System Operational
- Agency ROI
- Situational Awareness

3.2.1. UC-1: CIPT

The hypothesis for CIPT is that providing preferential treatment improves mobility for requesting vehicles. The associated performance measures are listed below, followed by Table 1 that details each performance measure, its target, and its relationship with the project goals and objectives.

Mobility & Efficiency

- **PM-1-01: Transit On-Time Performance –** The percent of on-time timepoint departures, where “on-time” is considered 0-5 minutes behind schedule.
- **PM-1-02: Transit Travel Time –** Travel time (minutes) between two points, typically the beginning and end of the route but also between two timepoints.
- **PM-1-03: Plow Speed –** Snowplow speed (mph).
- **PM-1-04: Time to Plow Corridor –** Time (minutes) that it takes a snowplow to travel between two points.
- **PM-1-05: ERV Speed –** Emergency response vehicle speed (mph).

System Operational

- **PM-1-06: Number of TSP Requests –** Number of TSP requests (a bus approaching an intersection sending multiple SRMs constitutes one TSP request).
- **PM-1-07: Number of TSP Requests Granted –** Number of TSP requests granted, which is indicated by ATSPM logs, SPaT, SSM, or a combination thereof.
- **PM-1-08: Number of Preemption Requests –** Number of preemption requests (a vehicle approaching an intersection sending multiple SRMs constitutes one preemption request).
- **PM-1-09: Number of Preemption Requests Granted –** Number of preemption requests granted, which is indicated by ATSPM logs, SPaT, SSM, or a combination thereof.
- **PM-1-10: Number of SRMs Received –** Count of SRMs received.

Agency ROI

- **PM-1-11: Estimated Transit Fuel Savings –** Estimated reduction in fuel costs due to TSP, which is expected to result in improved mobility and less idling.
- **PM-1-12: Reduced Transit Passenger Delay –** Passenger delay (person-minutes).
- **PM-1-13: Reduced Plow Operating Costs –** Estimated reduction in plow operating costs, which is expected to be a combination of fuel savings and labor costs.

Situational Awareness

- **PM-1-14: Number of ERV Responding to Incident Alerts –** Count of ERV Responding to Incident TIMs. When an ERV is responding to an incident, a TIM alert will be generated and transmitted by nearby RSUs to inform road users that an ERV responding to an incident is nearby.
- **PM-1-15: Number of ERV at Incident Scene Alerts –** Count of ERV at Incident Scene TIMs. When an ERV is at an incident scene, a TIM alert will be generated and transmitted by nearby RSUs to inform road users of the ERV's presence and location at an incident scene.

Table 1. Performance Measures and Targets – UC-1: CIPT
Source: Crest Solutions, July 2026

Performance Measure	Target	Goals	Objectives
PM-1-01: Transit On-Time Performance	10% of "1 - OTP" (e.g., if OTP is 85% then 1 - 0.85 = 0.15, or 15%, so the target is a 1.5% improvement)	G2	G2-02, G2-04
PM-1-02: Transit Travel Time	2.5% reduction	G2	G2-02, G2-04
PM-1-03: Plow Speed	5% increase	G1, G2	G1-01, G1-04, G2-01
PM-1-04: Time to Plow Corridor	5% reduction	G1, G2	G1-01, G1-04, G2-01

Performance Measure	Target	Goals	Objectives
PM-1-05: ERV Speed	5% increase	G1, G2	G1-02, G1-04, G2-03
PM-1-06: Number of TSP Requests	More than 1	G1, G2	G1-04, G2-02, G2-05
PM-1-07: Number of TSP Requests Granted	More than 1	G2	G2-02, G2-05
PM-1-08: Number of Preemption Requests	More than 1	G1, G2	G1-01, G1-02, G1-04, G2-01, G2-03, G2-05
PM-1-09: Number of Preemption Requests Granted	More than 1	G1, G2	G1-01, G1-02, G2-01, G2-03, G2-05
PM-1-10: Number of SRMs Received	More than 1	G1, G2	G1-04, G2-05
PM-1-11: Estimated Transit Fuel Savings	1% savings	G2	G2-02
PM-1-12: Reduced Transit Passenger Delay	2.5% reduction	G2	G2-02, G2-04
PM-1-13: Reduced Plow Operating Costs	1% savings	G1, G2	G1-01, G2-01
PM-1-14: Number of ERV Responding to Incident Alerts	More than 1	G1, G2	G1-02, G2-03
PM-1-15: Number of ERV at Incident Scene Alerts	More than 1	G1, G2	G1-02, G2-03

3.2.2. UC-2: RLVW

The hypothesis for RLVW is that the accurate, consistent, reliable, and timely provision of SPaT and MAP enable vehicular applications to generate relevant alerts for human operators to prevent red light running. The associated performance measures are listed below, followed by Table 2 that details each performance measure, its target, and its relationship with the project goals and objectives.

System Operational

- **PM-2-01: SPaT Transmission Periodicity –** Time interval between consecutive SPaT messages (milliseconds).
- **PM-2-02: MAP Transmission Periodicity –** Time interval between consecutive MAP messages (seconds).
- **PM-2-03: SPaT Transmission Latency –** Duration of time (milliseconds) from when the traffic signal controller sets the signal indications to when the corresponding SPaT message is broadcast by the RSU.

- **PM-2-04: SPaT Accuracy –** Number and percent of SPaT data fields that pass the CI validation test.
- **PM-2-05: MAP Accuracy –** Number and percent of MAP nodes that pass the CI validation test.
- **PM-2-06: Number of RLVW-Supported CIs –** Number of CIs that broadcast accurate and reliable SPaT and MAP messages according to CTI 4501 requirements for performance and message content.
- **PM-2-07: RLVW Display Latency –** Duration of time (milliseconds) from when the RLVW criteria are met to when the RLVW alert is displayed on the HMI.

Situational Awareness

- **PM-2-08: Number of RLVW Alerts Displayed –** Count of RLVW alerts displayed on the HMI.
- **PM-2-09: Number and Rate of False Positives –** Number and rate of RLVW alerts displayed when the RLVW criteria were not met.
- **PM-2-10: Number and Rate of False Negatives –** Number and rate of RLVW alerts not displayed when the RLVW criteria were met.
- **PM-2-11: Distance from Stop Bar when RLVW is Displayed –** Distance (meters) from the vehicle to the stop bar when the RLVW is displayed on the HMI.

Table 2. Performance Measures and Targets – UC-2: RLVW
Source: Crest Solutions, July 2026

Performance Measure	Target	Goals	Objectives
PM-2-01: SPaT Transmission Periodicity	75—125 ms at 90% compliance	G1, G2, G3, G5	G1-04, G2-04, G2-05, G3-01, G3-04, G5-03
PM-2-02: MAP Transmission Periodicity	975—1025 ms at 90% compliance	G1, G2, G3, G5	G1-04, G2-04, G2-05, G3-01, G3-04, G5-03
PM-2-03: SPaT Transmission Latency	Less than 175 ms at 90% compliance	G1, G2, G3, G5	G1-04, G2-04, G2-05, G3-01, G3-04, G5-03
PM-2-04: SPaT Accuracy	95% pass rate	G3, G5	G3-01, G3-03, G3-04, G5-03
PM-2-05: MAP Accuracy	99% pass rate	G3, G5	G3-01, G3-03, G3-04, G5-03
PM-2-06: Number of RLVW-Supported CIs	95% of CIs	G1, G3, G4, G5	G1-03, G1-04, G3-04, G4-01, G4-02, G5-02, G5-03
PM-2-07: RLVW Display Latency	Less than 175 ms at 90% compliance	G2, G3	G2-05, G3-01, G3-04

Performance Measure	Target	Goals	Objectives
PM-2-08: Number of RLVW Alerts Displayed	More than 1	G1, G2, G3, G4, G5	G1-04, G2-04, G2-05, G3-01, G4-03, G5-03
PM-2-09: Number and Rate of False Positives	Zero and 0%	G1, G2, G3, G4, G5	G1-04, G2-04, G3-01, G3-03, G3-04, G4-02, G4-03, G5-03
PM-2-10: Number and Rate of False Negatives	Zero and 0%	G1, G2, G3, G4, G5	G1-04, G2-04, G3-01, G3-03, G3-04, G4-02, G4-03, G5-03
PM-2-11: Distance from Stop Bar when RLVW is Displayed	Less than or equal to the alert distance and greater than the warning distance	G3, G4	G3-01, G4-02

3.2.3. UC-3: TIM Alerts

The hypothesis for TIM Alerts is that dissemination of information that affects highway and travel conditions in real time will improve safety. The associated performance measures are listed below, followed by Table 3 that details each performance measure, its target, and its relationship with the project goals and objectives.

System Operational

- **PM-3-01: TIM Transmission Periodicity –** Time interval between consecutive TIM messages (seconds).
- **PM-3-02: TIM Transmission Latency –** Duration of time (milliseconds) from when the traffic event is created to when the corresponding TIM message is broadcast by the RSU.
- **PM-3-03: TMC Alert Latency –** Duration of time (milliseconds) from when the traffic event is created to when the corresponding alert is provided to TMC operators.

Situational Awareness

- **PM-3-04: Number of Unique TIMs transmitted –** Number of unique TIMs transmitted by CTW sites.
- **PM-3-05: Number of CSW locations –** Number of dangerous curves with corresponding CSW TIMs.
- **PM-3-06: TMC Operator Perceived Usefulness of V2X Alerts –** Likert survey of TMC operators on perceived usefulness of alerts generated by the V2X central system where a score of 1 means strong disagreement that they are useful, 3 is neutral, and 5 is strong agreement that they are useful.

Table 3. Performance Measures and Targets – UC-3: TIM Alerts
Source: Crest Solutions, July 2026

Performance Measure	Target	Goals	Objectives
PM-3-01: TIM Transmission Periodicity	975—1025 ms at 90% compliance	G1, G2, G3	G1-04, G2-04, G2-05, G3-01, G3-04
PM-3-02: TIM Transmission Latency	Less than 1 second	G1, G2, G3	G1-04, G2-04, G2-05, G3-01, G3-04
PM-3-03: TMC Alert Latency	Less than 1 second	G1, G2, G3	G1-04, G2-04, G2-05, G3-01, G3-04
PM-3-04: Number of Unique TIMs transmitted	More than 34	G1, G2, G3, G4	G1-04, G2-04, G2-05, G3-01, G3-04
PM-3-05: Number of CSW locations	25	G3, G4	G3-01, G4-03
PM-3-06: TMC Operator Perceived Usefulness of V2X Alerts	Average rating greater than 4	G1, G2, G3	G1-04, G2-04, G3-01, G3-03

3.2.4. UC-4: IC

The operational hypothesis for IC is that sharing information in a standardized format will improve real-time situational awareness, enhance alert dissemination to motorists, and improve safety. The associated performance measures are listed below, followed by Table 4 that details each performance measure, its target, and its relationship with the project goals and objectives.

System Operational

- **PM-4-01: Event Report Sharing Latency –** Duration of time (seconds) from when the traffic event is created to when the corresponding Event Report is received by the SDX.
- **PM-4-02: TIM Sharing Latency –** Duration of time (seconds) from when the TIM is created to it is received by the SDX.
- **PM-4-03: SDX Percent Uptime –** Percentage of time that the SDX is operational.

Situational Awareness

- **PM-4-04: Number of Event Reports Ingested by the SDX –** Count of unique Event Reports ingested by the SDX.
- **PM-4-05: Number of TIMs Ingested by the SDX –** Count of unique TIMs ingested by the SDX.
- **PM-4-06: Number of Third-Party Recipients of SDX Data –** Count of third-party users that ingest SDX data.

- **PM-4-07: Number of Drives Influenced by SDX Data –** Count of drives, or vehicle trips, that are influenced by SDX data as determined by Waze.

Table 4. Performance Measures and Targets – UC-4: IC
Source: Crest Solutions, July 2026

Performance Measure	Target	Goals	Objectives
PM-4-01: Event Report Sharing Latency	Less than 1 second	G1, G2, G3	G1-04, G2-04, G2-05, G3-01, G3-02, G3-04
PME-4-02: TIM Sharing Latency	Less than 1 second	G1, G2, G3	G1-04, G2-04, G2-05, G3-01, G3-02, G3-04
PM-4-03: SDX Percent Uptime	99%	G2, G3	G2-05, G3-01, G3-02, G3-04
PM-4-04: Number of Event Reports Ingested by the SDX	More than 1	G2, G3, G4, G5	G2-05, G3-01, G3-02, G3-04, G4-03, G5-01
PM-4-05: Number of TIMs Ingested by the SDX	More than 1	G1, G2, G3, G4, G5	G1-04, G2-04, G2-05, G3-01, G3-02, G3-04, G4-03, G5-01
PM-4-06: Number of Third-Party Recipients of SDX Data	More than 1	G2, G3	G2-05, G3-01, G3-02, G3-04
PM-4-07: Number of Drives Influenced by SDX Data	More than 1	G2, G3, G4	G2-05, G3-01, G3-02, G3-04, G4-03

3.2.5. UC-5: VSL

The hypothesis for VSL is that in-vehicle VSL notifications will improve speed limit adherence and safety. The associated performance measures are listed below, followed by Table 5 that details each performance measure, its target, and its relationship with the project goals and objectives.

Safety

- **PM-5-01: Speed Differential –** Difference between vehicle speed and speed limit.

System Operational

- **PM-5-02: RSU's TIM Reception Latency –** Duration of time (seconds) from when the VSL system changes the speed limit to when the corresponding TIM message is received by the RSU.
- **PM-5-03: TIM Transmission Latency –** Duration of time (seconds) from when the VSL system changes the speed limit to when the corresponding TIM message is broadcast by the RSU.

- **PM-5-04: TIM Display Latency –** Duration of time (milliseconds) from when the VSL TIM display criteria is met to when the VSL TIM is displayed on the HMI.

Situational Awareness

- **PM-5-05: Number of VSL Corridors with VSL TIM Alerts –** Count of VSL corridors for which VSL TIMs are broadcast.
- **PM-5-06: Total Length of VSL Corridors with VSL TIM Alerts –** Length (miles) of VSL corridors for which VSL TIMs are broadcast.
- **PM-5-07: Number of Unique VSL TIMs transmitted –** Number of unique VSL TIMs transmitted by CTW sites.

Table 5. Performance Measures and Targets – UC-5: VSL
Source: Crest Solutions, July 2026

Performance Measure	Target	Goals	Objectives
PM-5-01: Speed Differential	50% reduction	G1	G1-04
PM-5-02: RSU's TIM Reception Latency	Less than 1 second	G2, G3	G2-05, G3-01, G3-04
PM-5-03: TIM Transmission Latency	Less than 1 second	G1, G2, G3	G1-04, G2-04, G2-05, G3-01, G3-04
PM-5-04: TIM Display Latency	Less than 175 ms	G1, G2, G3	G1-04, G2-04, G2-05, G3-01, G3-04
PM-5-05: Number of VSL Corridors with VSL TIM Alerts	2 corridors	G2, G3, G4	G2-05, G3-01, G4-03
PM-5-06: Total Length of VSL Corridors with VSL TIM Alerts	20 miles	G2, G3, G4	G2-05, G3-01, G4-03
PM-5-07: Number of Unique VSL TIMs Transmitted	More than 1	G1, G2, G3, G4	G1-04, G2-04, G2-05, G3-01, G4-03

3.2.6. UC-6: VRU

The hypothesis for VRU is that data from the timely detection and classification of vehicles and VRUs at signalized intersections can be used to generate alerts of potential conflicts to improve safety. The associated performance measures are listed below, followed by Table 6 that details each performance measure, its target, and its relationship with the project goals and objectives.

Safety

- **PM-6-01: Distance between Vehicle and VRU –** Distance (meters) between vehicles and VRUs.
- **PM-6-02: Speed of Vehicle Approaching VRU –** Vehicle speed (meters per second).

- **PM-6-03: Deceleration Rate of Vehicle Approaching VRU –** Vehicle acceleration rate (meters per second squared).
- **PM-6-04: Frequency of Hard Braking Events –** Frequency of right-turn traversals that exceed the hard braking thresholds identified in SAE J2735.

System Operational

- **PM-6-05: SDSM Transmission Periodicity –** Time interval between consecutive SDSM messages (seconds).
- **PM-6-06: SDSM Transmission Latency –** Duration of time (milliseconds) from when the LiDAR object data record is created to when the corresponding SDSM message is broadcast by the RSU.
- **PM-6-07: Positional Accuracy of LiDAR-Detected V2X-Equipped Vehicles –** Distance (centimeters) from the LiDAR-reported center of vehicle to the BSM-reported center of vehicle.

Situational Awareness

- **PM-6-08: Number of In-Vehicle VRU Alerts Displayed –** Count of VRU alerts displayed on the HMI.
- **PM-6-09: Number and Rate of In-Vehicle False Positives –** Number and rate of VRU alerts displayed when the VRU alerting criteria were not met.
- **PM-6-10: Number and Rate of In-Vehicle False Negatives –** Number and rate of VRU alerts not displayed when the VRU alerting criteria were met.
- **PM-6-11: Number of Times Blank-Out sign is Illuminated –** Count of VRU blank-out sign illuminations.
- **PM-6-12: Number and Rate of Blank-Out Illumination False Positives –** Number and rate of blank-out sign illuminations when the VRU alerting criteria were not met.
- **PM-6-13: Number and Rate of Blank-Out Illumination False Negatives –** Number and rate of blank-out sign illuminations not activated when the VRU alerting criteria were met.

Table 6. Performance Measures and Targets – UC-6: VRU
Source: Crest Solutions, July 2026

Performance Measure	Target	Goals	Objectives
PM-6-01: Distance between Vehicle and VRU	Minimum distance is 50% greater with all records greater than 0 meters	G1, G4	G1-05, G4-02
PM-6-02: Speed of Vehicle Approaching VRU	25% reduction	G1, G4	G1-05, G4-02
PM-6-03: Deceleration Rate of Vehicle Approaching VRU	25% reduction	G1, G4	G1-05, G4-02

Performance Measure	Target	Goals	Objectives
PM-6-04: Frequency of Hard Braking Events	0%	G1, G4	G1-05, G4-02
PM-6-05: SDSM Transmission Periodicity	75—125 ms at 90% compliance	G1, G2, G3, G4	G1-04, G1-05, G2-04, G3-01, G3-04, G4-03
PM-6-06: SDSM Transmission Latency	Less than 175 ms	G1, G2, G3, G4	G1-04, G1-05, G2-04, G3-01, G3-04, G4-03
PM-6-07: Positional Accuracy of LiDAR-Detected V2X-Equipped Vehicles	50 cm	G1, G2, G3, G4	G1-04, G1-05, G2-04, G2-05, G3-01, G3-04, G4-02, G4-03
PM-6-08: Number of In-Vehicle VRU Alerts Displayed	More than 1	G1, G2, G3, G4	G1-04, G1-05, G2-04, G2-05, G3-01, G3-04, G4-02, G4-03
PM-6-09: Number and Rate of In-Vehicle False Positives	Zero and 0%	G1, G2, G3, G4	G1-04, G1-05, G2-04, G3-01, G3-04, G4-03
PM-6-10: Number and Rate of In-Vehicle False Negatives	Zero and 0%	G1, G2, G3, G4	G1-04, G1-05, G2-04, G3-01, G3-04, G4-03
PM-6-11: Number of Times Blank-Out sign is Illuminated	More than 1 per approach	G1, G2, G3, G4	G1-04, G1-05, G2-04, G2-05, G3-01, G3-04, G4-02, G4-03
PM-6-12: Number and Rate of Blank-Out Illumination False Positives	Zero and 0%	G1, G2, G3, G4	G1-04, G1-05, G2-04, G3-01, G3-04, G4-03
PM-6-13: Number and Rate of Blank-Out Illumination False Negatives	Zero and 0%	G1, G2, G3, G4	G1-04, G1-05, G2-04, G3-01, G3-04, G4-03

3.2.7. UC-7: General

In addition to the performance measures associated with the six CTW use cases, there are performance measures that relate more broadly to CTW as a whole and the overarching vision of national V2X interoperability. Furthermore, performance measures with the category of *Other* exist only for this use case.

Many of the performance measures for this use case are based on goals identified in *ITS America National V2X Deployment Plan: An Infrastructure & Automaker Collaboration* dated April 2023 and help determine the influence of CTW on achieving these goals. The associated performance measures are

listed below, followed by Table 7 that details each performance measure, its target, and its relationship with the project goals and objectives.

System Operational

- **PM-7-01: BSM Transmission Periodicity –** Time interval between consecutive BSM messages (seconds).

Situational Awareness

- **PM-7-02: Percent of NHS Routes with an RSU –** Percentage of NHS routes in Utah, Colorado, and Wyoming that have at least one RSU deployed on it.
- **PM-7-03: Percent of NHS within Range of an RSU –** Percentage of NHS miles in Utah, Colorado, and Wyoming within range of an RSU.
- **PM-7-04: Percent of Signalized Intersections with V2X –** Percentage of signalized intersections with an RSU broadcasting the associated SPaT and MAP.

Other

- **PM-7-05: Number of Non-State Public Agencies with V2X-Equipped Vehicles –** Number of non-state public agencies with V2X-equipped vehicles.
- **PM-7-06: Number of SCMS Providers Using Interoperable Security Credentials –** Number of SCMS providers using interoperable security credentials.
- **PM-7-07: Number of Automotive Supplier or OEM Partners Supporting CAN Decoding for BSMs –** Number of automotive supplier or OEM partners that provide CAN decoding information used by the deployment team to populate data in the BSM.
- **PM-7-08: Number of V2X Applications or Use Cases Utilizing 5.9 GHz –** Number of V2X applications (or use cases) utilizing 5.9 GHz.

Table 7. Performance Measures and Targets – UC-7: General
Source: Crest Solutions, July 2026

Performance Measure	Target	Goals	Objectives
PM-7-01: BSM Transmission Periodicity	75—125 ms at 90% compliance	G2, G4	G2-05, G4-03
PM-7-02: Percent of NHS Routes with an RSU	50%	G2, G3, G4, G5	G2-05, G3-01, G4-03, G5-02
PM-7-03: Percent of NHS within Range of an RSU	5%	G2, G3, G4, G5	G2-05, G3-01, G4-03, G5-02
PM-7-04: Percent of Signalized Intersections with V2X	25%	G1, G2, G3, G4, G5	G1-03, G2-05, G3-01, G4-01, G4-03, G5-02, G5-03

Performance Measure	Target	Goals	Objectives
PM-7-05: Number of non-state public agencies with V2X-equipped vehicles	10 agencies	G2, G3, G4	G2-05, G3-01, G4-03
PM-7-06: Number of SCMS providers using interoperable security credentials	More than 1	G2, G3, G4	G2-05, G3-01, G3-06, G4-03
PM-7-07: Number of automotive supplier or OEM partners supporting CAN decoding for BSMs	More than 1	G1, G2, G3, G4	G1-04, G2-05, G3-01, G4-03
PM-7-08: Number of V2X applications (or use cases) utilizing 5.9 GHz	15	G1, G2, G3, G4	G1-04, G2-05, G3-01, G4-03

4. Confounding Factors and Mitigation Techniques

This section identifies and discusses specific factors that may influence the results of the performance evaluation. Mitigation techniques are also discussed so that observed impacts are accurately attributed to the deployments rather than external influences. The confounding factors listed here in Table 8 are partially drawn from the preconditions identified in the ConOps for each operational scenario, or use case.

Table 8. Confounding Factors and Mitigation Techniques
Source: Crest Solutions, July 2026

Confounding Factor	Description	Mitigation Techniques
V2X Hardware Performance	V2X hardware performance issues have been observed in existing deployments and are expected to occur in CTW as well. The frequency and magnitude of these performance issues is not well known and some of our proposed metrics are aimed at better understanding their impact. These issues are commonly manifest by degraded transmission periodicity and latency, skipped messages, and periods of time where no messages are transmitted.	We have eight years of deployment testing and experience. During this time, we have established relationships with hardware vendors and actively worked with them to solve observed performance issues. Some devices were unable to satisfy our performance expectations, and we will not deploy them in CTW. Additionally, hardware will be intently observed and monitored to identify and quantify performance issues. Hardware models and/or vendors with known performance issues will not be deployed.
OBE Monitoring Limitations	Many CTW Use Cases involve the transmission of a TIM alert, the OBU's reception of the TIM, and then the display of TIM alert content on an in-vehicle screen, or HMI. Detailed verification of this data flow may be hindered if OBE monitoring limitations exist.	If these monitoring capabilities are not native to OBE, software may need to be developed to record the needed data. However, some hardware platforms are "closed" and do not allow third-party software development. If this is encountered, in-vehicle cameras could be installed to record the HMI screen itself without capturing any personally identifiable information (PII) and be linked to a GNSS device for timestamp consistency.
Variations in Transit Operations	Many components of transit operations are outside the control of this study, including schedule quality, ridership patterns, and traffic congestion. Unusual events may cause outliers in the data and temporary or seasonal trends may indicate a correlation that doesn't typically exist.	A large sample size and lengthy data collection period will be the primary method to mitigate this issue. This will normalize the collected data and facilitate the identification of outliers. Stratification by season and time-of-day may also be used to control for this confounding factor.
Susceptibility of Transit Operations to Serial and Cluster Effects	Transit operations are particularly susceptible to serial and cluster effects, which directly influence schedule deviation and OTP. These effects are the result of nonindependence, add uncertainty to the evaluation, and may influence the results of the evaluation if not properly controlled.	To control for the confounding factors due to lack of independence in the transit AVL data, the statistical practices of blocking, using covariates, and a time-series analysis will be utilized.

Confounding Factor	Description	Mitigation Techniques
Winter Storm Variations	Unlike transit operations whose routes have the same travel path and start and end points, plow routes can often vary according to the geographic intensity of the storm, pre-treatment effectiveness, and the number of plows in operation. Accordingly, plow performance during a given storm may not be comparable to its performance during a subsequent storm simply because its travel path was different. Furthermore, differences in storm intensity, time of day, and traffic conditions may prevent inter-storm comparisons even if the plow's travel path is identical.	To minimize the impact of these potentially confounding factors, the statistical technique of blocking will be utilized. If this proves insufficient to control for this confounding factor, multiple regression or an analysis of variance (ANOVA) F-test may be used.
Time Synchronization	Significant time synchronization issues have been observed among ITS devices if a uniform time source is not used. If clocks on devices are not synchronized, comparing the recorded timestamps will yield inconsistent and erroneous results.	Internal clocks will not be used on deployed devices. Ideally, GNSS time will be used among all devices because this is the only time source available to OBUs. Traffic Signal Controllers and other RSE have utilized Network Time Protocol (NTP) since they are connected to UDOT's network, but small differences between NTP and GNSS time exist. Measuring the difference between these two time sources is necessary to confirm that any difference is no more than a few milliseconds. If large discrepancies are observed (e.g., greater than 100 ms), a GNSS receiver may be installed and used as the time source for affected RSE.

5. Data Collection, Reporting, and Sharing

This section describes the data collected for baseline and post-deployment performance evaluations, how results and insights will be reported, and how the data will be shared.

5.1. Data Collection

The baseline data collection period varies widely depending on the performance measure and available data. For most performance measures, baseline data collection will occur post-deployment with the V2X applications disabled. For example, in UC-6: VRU, the LiDAR will be deployed and baseline data collected to evaluate PM-6-01: Distance between Vehicle and VRU. Then, the in-vehicle and roadside alerting mechanisms will be turned on and PM-6-01 will be assessed again to determine deployment impacts. In accordance with the anticipated deployment timeline, most baseline data will be collected from mid-2026 to March 2027. A notable exception is the transit and plow AVL data, which is collected by their respective fleet management systems outside of CTW, and is expected to cover the 12 months immediately before deployment is complete.

Although all V2X data will be collected and stored post-deployment and throughout Phase 2, not all of it will be used in the evaluation. Using a subset of the data by applying a geographic or timeframe filter, or through random selection, will be appropriate in many cases. Defining this subset will be accomplished later in the project as vehicle deployments and experiment designs are finalized. Generally, performance measures with a before-after design will utilize data collected through the first half of Phase 2, metrics associated with a descriptive study design will be assessed near the end of Phase 2, and those with a descriptive statistics design will have a customized time frame based on a statistical determination of the required sample size.

As described in the Data Plan, the frequency of data collection varies based on the data type, as well as system capabilities and operational constraints. Collection intervals may range from continuous, real-time data streams to data captured on an as-needed basis.

For each use case, a table provides summary information about the following:

- Performance measures
- Data sources used in the evaluation
- Whether the performance measure is used to establish baseline performance, evaluate post-deployment performance, or both
- Expected aggregation levels for analysis and reporting
- Responsible party, or the owner/supplier of the data
- Description of the performance measure

5.1.1. UC-1: CIPT

Table 9. Performance Measure Descriptions and Data – UC-1: CIPT
Source: Crest Solutions, July 2026

Performance Measure	Data Source	Evaluation	Aggregation	Responsible Party	Description
PM-1-01: Transit On-Time Performance	Transit AVL	Baseline and Post-Deployment	Route, Direction, Timepoint, Trip	UTA	The percent of on-time timepoint departures, where “on-time” is considered 0-5 minutes behind schedule.
PM-1-02: Transit Travel Time	Transit AVL	Baseline and Post-Deployment	Route, Direction, Timepoint, Trip	UTA	Travel time (minutes) between two points, typically the beginning and end of the route but also between two timepoints.
PM-1-03: Plow Speed	Plow AVL, BSM	Baseline and Post-Deployment	Corridor, Corridor Segment, Intersection	Plow Operations	Snowplow speed (mph).
PM-1-04: Time to Plow Corridor	Plow AVL, BSM	Baseline and Post-Deployment	Corridor, Corridor Segment, Intersection	Plow Operations	Time (minutes) that it takes a snowplow to travel between two points.
PM-1-05: ERV Speed	BSM	Baseline and Post-Deployment	Corridor, Corridor Segment, Intersection	Project Team	Emergency response vehicle speed (mph).
PM-1-06: Number of TSP Requests	SRM, ATSPM	Post-Deployment	Route, Intersection, Day	Project Team	Number of TSP requests (a bus approaching an intersection sending multiple SRMs constitutes one TSP request).
PM-1-07: Number of TSP Requests Granted	ATSPM, SPaT, SSM	Post-Deployment	Route, Intersection, Day	Project Team	Number of TSP requests granted, which is indicated by ATSPM logs, SPaT, SSM, or a combination thereof.

Performance Measure	Data Source	Evaluation	Aggregation	Responsible Party	Description
PM-1-08: Number of Preemption Requests	SRM, ATSPM	Post-Deployment	Vehicle Role, Corridor, Intersection	Project Team	Number of preemption requests (a vehicle approaching an intersection sending multiple SRMs constitutes one preemption request).
PM-1-09: Number of Preemption Requests Granted	ATSPM, SPaT, SSM	Post-Deployment	Vehicle Role, Corridor, Intersection	Project Team	Number of preemption requests granted, which is indicated by ATSPM logs, SPaT, SSM, or a combination thereof.
PM-1-10: Number of SRMs Received	SRM	Post-Deployment	Vehicle Role, Route, Corridor, Intersection	Project Team	Count of SRMs received.
PM-1-11: Estimated Transit Fuel Savings	Transit AVL, SRM, BSM	Baseline and Post-Deployment	Route, Corridor, Intersection	UTA, Project Team	Estimated reduction in fuel costs due to TSP, which is expected to result in improved mobility and less idling.
PM-1-12: Reduced Transit Passenger Delay	Transit AVL, Transit APC, SRM, BSM	Baseline and Post-Deployment	Route, Corridor, Intersection	UTA, Project Team	Passenger delay (person-minutes).
PM-1-13: Reduced Plow Operating Costs	Plow AVL, Survey	Baseline and Post-Deployment	Corridor, Intersection	Plow Operations	Estimated reduction in plow operating costs, which is expected to be a combination of fuel savings and labor costs.
PM-1-14: Number of ERV Responding to Incident Alerts	TIM, SRM	Post-Deployment	ERV Trip	Project Team	Count of ERV Responding to Incident TIMs.
PM-1-15: Number of ERV at Incident Scene Alerts	TIM, SRM	Post-Deployment	ERV Trip	Project Team	Count of ERV at Incident Scene TIMs.

5.1.2. UC-2: RLVW

Table 10. Performance Measure Descriptions and Data – UC-2: RLVW
Source: Crest Solutions, July 2026

Performance Measure	Data Source	Evaluation	Aggregation	Responsible Party	Description
PM-2-01: SPaT Transmission Periodicity	RSU_Tx Log	Post-Deployment	Intersection, Signal Timing Plan, CIPT Events, RSU Load	Project Team	Time interval between consecutive SPaT messages (milliseconds).
PM-2-02: MAP Transmission Periodicity	RSU_Tx Log	Post-Deployment	Intersection, Signal Timing Plan, CIPT Events, RSU Load	Project Team	Time interval between consecutive MAP messages (seconds).
PM-2-03: SPaT Transmission Latency	TSCBM, ATSPM, SPaT	Post-Deployment	Intersection, Signal Timing Plan, CIPT Events, RSU Load	Project Team	Duration of time (milliseconds) from when the traffic signal controller sets the signal indications to when the corresponding SPaT message is broadcast by the RSU.
PM-2-04: SPaT Accuracy	TSCBM, ATSPM, SPaT, CI Validation Report	Baseline and Post-Deployment	Intersection, Signal Timing Plan, CIPT Events, RSU Load	Project Team	Number and percent of SPaT data fields that pass the CI validation test.
PM-2-05: MAP Accuracy	MAP, CI Validation Report	Baseline and Post-Deployment	Intersection	Project Team	Number and percent of MAP nodes that pass the CI validation test.
PM-2-06: Number of RLVW-Supported CIs	CI Validation Report	Baseline and Post-Deployment	N/A	Project Team	Number of CIs that broadcast accurate and reliable SPaT and MAP messages according to CTI 4501 requirements for performance and message content.

Performance Measure	Data Source	Evaluation	Aggregation	Responsible Party	Description
PM-2-07: RLVW Display Latency	RSU_Tx Log, OBE Log	Post-Deployment	Intersection, Approach	Project Team, GM	Duration of time (milliseconds) from when the RLVW criteria are met to when the RLVW alert is displayed on the HMI.
PM-2-08: Number of RLVW Alerts Displayed	OBE Log	Post-Deployment	Intersection, Approach	GM	Count of RLVW alerts displayed on the HMI.
PM-2-09: Number and Rate of False Positives	SPaT, BSM, OBE Log	Post-Deployment	Intersection, Approach	Project Team, GM	Number and rate of RLVW alerts displayed when the RLVW criteria were not met.
PM-2-10: Number and Rate of False Negatives	SPaT, BSM, OBE Log	Post-Deployment	Intersection, Approach	Project Team, GM	Number and rate of RLVW alerts not displayed when the RLVW criteria were met.
PM-2-11: Distance from Stop Bar when RLVW is Displayed	BSM, OBE Log	Post-Deployment	Intersection, Approach	Project Team, GM	Distance (meters) from the vehicle to the stop bar when the RLVW is displayed on the HMI.

5.1.3. UC-3: TIM Alerts

Table 11. Performance Measure Descriptions and Data – UC-3: TIM Alerts
Source: Crest Solutions, July 2026

Performance Measure	Data Source	Evaluation	Aggregation	Responsible Party	Description
PM-3-01: TIM Transmission Periodicity	RSU_Tx Log	Post-Deployment	RSU, RSU Load	Project Team	Time interval between consecutive TIM messages (seconds).

Performance Measure	Data Source	Evaluation	Aggregation	Responsible Party	Description
PM-3-02: TIM Transmission Latency	Event Reports, RSU_Tx Log	Post-Deployment	Event Type, RSU, RSU Load	Project Team	Duration of time (milliseconds) from when the traffic event is created to when the corresponding TIM message is broadcast by the RSU.
PM-3-03: TMC Alert Latency	Event Reports, TMC System Log	Post-Deployment	Event Type	Project Team, TMC	Duration of time (milliseconds) from when the traffic event is created to when the corresponding alert is provided to TMC operators.
PM-3-04: Number of Unique TIMs transmitted	TIM	Post-Deployment	Event Type	Project Team	Number of unique TIMs transmitted by CTW sites.
PM-3-05: Number of CSW locations	Project Documentation	Baseline and Post-Deployment	Highway Classification Level	Project Team	Number of dangerous curves with corresponding CSW TIMs.
PM-3-06: TMC Operator Perceived Usefulness of V2X Alerts	Survey	Post-Deployment	Event Type	Project Team	Likert survey of TMC operators on perceived usefulness of alerts generated by the V2X central system.

5.1.4. UC-4: IC

Table 12. Performance Measure Descriptions and Data – UC-4: IC
Source: Crest Solutions, July 2026

Performance Measure	Data Source	Evaluation	Aggregation	Responsible Party	Description
PM-4-01: Event Report Sharing Latency	IOO Data Exchange Log, SDX	Post-Deployment	Event Type, IOO	Project Team, Trihydro	Duration of time (seconds) from when the traffic event is created to when the corresponding Event Report is received by the SDX.

Performance Measure	Data Source	Evaluation	Aggregation	Responsible Party	Description
PME-4-02: TIM Sharing Latency	IOO Data Exchange Log, SDX	Post-Deployment	Event Type, IOO	Project Team, Trihydro	Duration of time (seconds) from when the TIM is created to it is received by the SDX.
PM-4-03: SDX Percent Uptime	SDX	Post-Deployment	N/A	Trihydro	Percentage of time that the SDX is operational.
PM-4-04: Number of Event Reports Ingested by the SDX	SDX	Post-Deployment	Event Type, IOO	Trihydro	Count of unique Event Reports ingested by the SDX.
PM-4-05: Number of TIMs Ingested by the SDX	SDX	Post-Deployment	Event Type, IOO	Trihydro	Count of unique TIMs ingested by the SDX.
PM-4-06: Number of Third-Party Recipients of SDX Data	Project Documentation	Post-Deployment	N/A	Trihydro	Count of third-party users that ingest SDX data.
PM-4-07: Number of Drives Influenced by SDX Data	Waze	Post-Deployment	IOO	Trihydro	Count of drives, or vehicle trips, that are influenced by SDX data as determined by Waze.

5.1.5. UC-5: VSL

Table 13. Performance Measure Descriptions and Data – UC-5: VSL
Source: Crest Solutions, July 2026

Performance Measure	Data Source	Evaluation	Aggregation	Responsible Party	Description
PM-5-01: Speed Differential	BSM	Post-Deployment	Hour of Day, Corridor	Project Team	Difference between vehicle speed and speed limit.

Performance Measure	Data Source	Evaluation	Aggregation	Responsible Party	Description
PM-5-02: RSU's TIM Reception Latency	VSL System Log, RSU_Rx Log	Post-Deployment	RSU	Project Team	Duration of time (milliseconds) from when the VSL system changes the speed limit to when the corresponding TIM message is received by the RSU.
PM-5-03: TIM Transmission Latency	VSL System Log, RSU_Tx Log	Post-Deployment	RSU	Project Team	Duration of time (milliseconds) from when the VSL system changes the speed limit to when the corresponding TIM message is broadcast by the RSU.
PM-5-04: TIM Display Latency	OBE Log	Post-Deployment	Corridor, Vehicle	Project Team	Duration of time (milliseconds) from when the VSL TIM display criteria is met to when the VSL TIM is displayed on the HMI.
PM-5-05: Number of VSL Corridors with VSL TIM Alerts	Project Documentation	Baseline and Post-Deployment	N/A	Project Team	Count of VSL corridors for which VSL TIMs are broadcast.
PM-5-06: Total Length of VSL Corridors with VSL TIM Alerts	Project Documentation	Baseline and Post-Deployment	N/A	Project Team	Length (miles) of VSL corridors for which VSL TIMs are broadcast.
PM-5-07: Number of Unique VSL TIMs Transmitted	TIM	Post-Deployment	Corridor	Project Team	Number of unique VSL TIMs transmitted by CTW sites.

5.1.6. UC-6: VRU

Table 14. Performance Measure Descriptions and Data – UC-6: VRU
Source: Crest Solutions, July 2026

Performance Measure	Data Source	Evaluation	Aggregation	Responsible Party	Description
PM-6-01: Distance between Vehicle and VRU	LiDAR, BSM	Baseline and Post-Deployment	Intersection, Approach, Hour of Day, VRU Type	Ouster, Project Team	Distance (meters) between vehicles and VRUs.
PM-6-02: Speed of Vehicle Approaching VRU	LiDAR, BSM	Baseline and Post-Deployment	Intersection, Approach, Hour of Day, VRU Type	Ouster, Project Team	Vehicle speed (meters per second).
PM-6-03: Deceleration Rate of Vehicle Approaching VRU	LiDAR, BSM	Baseline and Post-Deployment	Intersection, Approach, Hour of Day, VRU Type	Ouster, Project Team	Vehicle acceleration rate (meters per second squared).
PM-6-04: Frequency of Hard Braking Events	LiDAR, BSM	Baseline and Post-Deployment	Intersection, Approach, Hour of Day, VRU Type	Ouster, Project Team	Frequency of right-turn traversals that exceed the hard braking thresholds identified in SAE J2735.
PM-6-05: SDSM Transmission Periodicity	RSU_Tx Log	Post-Deployment	RSU	Project Team	Time interval between consecutive SDSM messages (seconds).
PM-6-06: SDSM Transmission Latency	LiDAR, RSU_Tx Log	Post-Deployment	RSU	Ouster, Project Team	Duration of time (milliseconds) from when the LiDAR object data record is created to when the corresponding SDSM message is broadcast by the RSU.

Performance Measure	Data Source	Evaluation	Aggregation	Responsible Party	Description
PM-6-07: Positional Accuracy of LiDAR-Detected V2X-Equipped Vehicles	LiDAR, BSM	Baseline and Post-Deployment	Intersection, Hour of Day, OBU Vendor	Ouster, Project Team	Distance (centimeters) from the LiDAR-reported center of vehicle to the BSM-reported center of vehicle.
PM-6-08: Number of In-Vehicle VRU Alerts Displayed	OBE Log	Baseline and Post-Deployment	Intersection, Approach	Project Team	Count of VRU alerts displayed on the HMI.
PM-6-09: Number and Rate of In-Vehicle False Positives	LiDAR, OBE Log	Baseline and Post-Deployment	Intersection, Approach	Ouster, Project Team	Number and rate of VRU alerts displayed when the VRU alerting criteria were not met.
PM-6-10: Number and Rate of In-Vehicle False Negatives	LiDAR, OBE Log	Baseline and Post-Deployment	Intersection, Approach	Ouster, Project Team	Number and rate of VRU alerts not displayed when the VRU alerting criteria were met.
PM-6-11: Number of Times Blank-Out sign is Illuminated	VRU System Log	Baseline and Post-Deployment	Intersection, Approach	Project Team	Count of VRU blank-out sign illuminations.
PM-6-12: Number and Rate of Blank-Out Illumination False Positives	LiDAR, VRU System Log	Baseline and Post-Deployment	Intersection, Approach	Ouster, Project Team	Number and rate of blank-out sign illuminations when the VRU alerting criteria were not met.
PM-6-13: Number and Rate of Blank-Out Illumination False Negatives	LiDAR, VRU System Log	Baseline and Post-Deployment	Intersection, Approach	Ouster, Project Team	Number and rate of blank-out sign illuminations not activated when the VRU alerting criteria were met.

5.1.7. UC-7: General

Table 15. Performance Measure Descriptions and Data – UC-7: General
Source: Crest Solutions, July 2026

Performance Measure	Data Source	Evaluation	Aggregation	Responsible Party	Description
PM-7-01: BSM Transmission Periodicity	BSM	Post-Deployment	OBU Vendor	Project Team	Time interval between consecutive BSM messages (seconds).
PM-7-02: Percent of NHS Routes with an RSU	NHS Shapefile, Project Documentation	Post-Deployment	IOO, Highway Classification Level	Project Team	Percentage of NHS routes that have at least one RSU deployed on it.
PM-7-03: Percent of NHS within Range of an RSU	NHS Shapefile, Project Documentation	Post-Deployment	IOO, Highway Classification Level	Project Team	Percentage of NHS within range of an RSU.
PM-7-04: Percent of Signalized Intersections with V2X	Project Documentation	Post-Deployment	IOO, Metro Area	Project Team	Percentage of signalized intersections with an RSU broadcasting the associated SPaT and MAP.
PM-7-05: Number of non-state public agencies with V2X-equipped vehicles	Project Documentation	Post-Deployment	N/A	Project Team	Number of non-state public agencies with V2X-equipped vehicles.
PM-7-06: Number of SCMS providers using interoperable security credentials	Project Documentation	Post-Deployment	N/A	Project Team	Number of SCMS providers using interoperable security credentials.

Performance Measure	Data Source	Evaluation	Aggregation	Responsible Party	Description
PM-7-07: Number of automotive supplier or OEM partners supporting CAN decoding for BSMs	Project Documentation	Post-Deployment	N/A	Project Team	Number of automotive supplier or OEM partners that provide CAN decoding information used by the deployment team to populate data in the BSM.
PM-7-08: Number of V2X applications (or use cases) utilizing 5.9 GHz	Project Documentation	Post-Deployment	N/A	Project Team	Number of V2X applications (or use cases) utilizing 5.9 GHz.

6. Performance Evaluation

This section outlines the approach and methodologies for measuring the baseline, computing operational performance, and assessing system impacts. It reviews the data sources and collection processes, the types of data analysis to be conducted, and how performance measures will be assessed. It also includes an evaluation framework that responds to the confounding factors discussed in Section 4.

6.1. Evaluation Design Approach

The CTW evaluation will measure a variety of deployment impacts through outputs and outcomes. Output performance measures address how well the deployment performed its intended functions while outcome performance measures assess benefits or changes in behavior that result from the deployment. Outcome-based performance measures are sought after whenever possible, but the nature of the V2X environment (low penetration rate of equipped vehicles and the rare occurrence of events that V2X is designed to address) make outcome-based impacts difficult to measure. As a result, many output-based performance measures are utilized to evaluate technical performance and demonstrate IOO V2X readiness, a primary goal of CTW.

A variety of quasi-experimental design approaches, including before-after, control vs treatment, and time series analysis will be used to evaluate deployment impacts and test use case hypotheses. Current understanding of confounding factors, data limitations, and use case characteristics helped identify which approach should be used for each performance measure and which statistical methods should be applied.

For some output-based performance measures, a descriptive study will be used to report characteristics of the deployment, such as the number of icy-road TIMs that were transmitted by the deployment. Experiment design principles will be followed whenever possible to demonstrate how CTW deployments changed outputs (e.g., the increase in number of transmitted icy-road TIMs due to the expanded deployment of CTW activities). Other output-based performance measures will use descriptive statistics to report deployment characteristics, such as metrics associated with V2X transmission periodicity and latency.

Anticipated statistical tests for outcome and output performance measures include one-sample one-sided t-test, one-sample two-sided t-test, ANOVA F-test, and multiple regression. Other statistical practices such as blocking, covariates, the Tukey-Kramer procedure, and rank transformations are also expected to be used as the data are analyzed.

For certain performance measures, baseline performance data is needed to set reasonable targets. Furthermore, setting targets for some performance measures may not be appropriate as the magnitude of the desired outcome is uncontrollable in the experiment. In some cases, however, the target is clear, such as PM-2-02: MAP Transmission Periodicity where “an average rate of 1 message per second ± 1 message over a 10-second period” is the standard identified in CTI 4501. Performance measure targets are also included in the following subsections where appropriate and when they are identifiable at this

stage in the project. The dynamic nature of this document and the evaluation process will result in the addition or modification of performance measure targets.

6.2. Performance Measurements and Evaluation Methodology

This subsection describes the evaluation design approach and methodologies for each use case. Where appropriate, performance targets are also identified in the evaluation methodology column.

6.2.1. UC-1: CIPT

Table 16. Evaluation Methodology – UC-1: CIPT
Source: Crest Solutions, July 2026

Performance Measure	Design Approach	Evaluation Methodology
PM-1-01: Transit On-Time Performance	Before-After, Control vs Treatment, Time Series	A before-after comparison of OTP will be used to evaluate transit performance after TSP is enabled, a control vs treatment study will compare non-TSP and TSP-enabled routes, and a time series analysis will control for lack of independence and susceptibility to serial effects in transit operations.
PM-1-02: Transit Travel Time	Before-After, Control vs Treatment, Time Series	A before-after comparison of travel time will be used to evaluate transit performance after TSP is enabled, a control vs treatment study will compare non-TSP and TSP-enabled routes, and a time series analysis will control for lack of independence and susceptibility to serial effects in transit operations.
PM-1-03: Plow Speed	Before-After, Control vs Treatment	A before-after comparison of plow speed will be used to evaluate plow performance after preemption is enabled, a control vs treatment study will compare non-preemption and preemption-enabled corridors.
PM-1-04: Time to Plow Corridor	Before-After, Control vs Treatment	A before-after comparison of corridor plow times will be used to evaluate plow performance after preemption is enabled, a control vs treatment study will compare non-preemption and preemption-enabled corridors.
PM-1-05: ERV Speed	Before-After	A before-after comparison of ERV speed will be used to evaluate ERV performance after preemption is enabled.
PM-1-06: Number of TSP Requests	Descriptive Study	A descriptive study will report how many TSP requests were made at CTW RSUs deployed at signalized intersections
PM-1-07: Number of TSP Requests Granted	Descriptive Study	A descriptive study will report the number of TSP requests that were granted.

Performance Measure	Design Approach	Evaluation Methodology
PM-1-08: Number of Preemption Requests	Descriptive Study	A descriptive study will report the number of preemption requests made at CTW RSUs deployed at signalized intersections.
PM-1-09: Number of Preemption Requests Granted	Descriptive Study	A descriptive study will report the number of preemption requests that were granted.
PM-1-10: Number of SRMs Received	Descriptive Study	A descriptive study will report the number of SRMs received.
PM-1-11: Estimated Transit Fuel Savings	Before-After	A before-after comparison of bus trajectory data will use speed and acceleration data to estimate fuel consumption.
PM-1-12: Reduced Transit Passenger Delay	Before-After, Control vs Treatment	A before-after study will evaluate passenger delay. A control vs treatment study will assess regional or system-wide ridership patterns to control for changes in ridership during the study period.
PM-1-13: Reduced Plow Operating Costs	Before-After, Control vs Treatment	A before-after comparison of snowplow trajectory data will use speed and acceleration data to estimate fuel consumption and reduced fuel costs. Reduced labor costs as a result of faster plow times will also be added to obtain the reduced plow operating cost from preemption.
PM-1-14: Number of ERV Responding to Incident Alerts	Descriptive Study	A descriptive study will report the number of ERV Responding to Incident TIMs.
PM-1-15: Number of ERV at Incident Scene Alerts	Descriptive Study	A descriptive study will report the number of ERV at Incident Scene TIMs.

6.2.2. UC-2: RLVW

Table 17. Evaluation Methodology – UC-2: RLVW
Source: Crest Solutions, July 2026

Performance Measure	Design Approach	Evaluation Methodology
PM-2-01: SPaT Transmission Periodicity	Descriptive Statistics	A one-sample two-sided t-test will be used to test whether SPaT periodicity differs from the target of 100 ms according to CTI 4501v02.
PM-2-02: MAP Transmission Periodicity	Descriptive Statistics	A one-sample two-sided t-test will be used to test whether MAP periodicity differs from the target of 1 sec according to CTI 4501v02.

Performance Measure	Design Approach	Evaluation Methodology
PM-2-03: SPaT Transmission Latency	Descriptive Statistics	A one-sample one-sided t-test will be used to test whether SPaT transmission latency is less than the target of 175 ms according to CTI 4501v02.
PM-2-04: SPaT Accuracy	Descriptive Study	A descriptive study will report the results produced by the CI Validation Test report pertaining to SPaT accuracy.
PM-2-05: MAP Accuracy	Descriptive Study	A descriptive study will report the results produced by the CI Validation Test report pertaining to MAP node accuracy.
PM-2-06: Number of RLVW-Supported CIs	Descriptive Study	A descriptive study will report the results produced by the CI Validation Test report and determine how many intersections satisfy the performance and message content requirements set forth in CTI 4501.
PM-2-07: RLVW Display Latency	Descriptive Statistics	A one-sample one-sided t-test will be used to test whether RLVW transmission latency is less than the target of 175 ms, an upper limit that has not yet been established by the project team.
PM-2-08: Number of RLVW Alerts Displayed	Descriptive Study	A descriptive study will report the number of RLVW alerts displayed.
PM-2-09: Number and Rate of False Positives	Descriptive Study	A descriptive study will report the number and rate of RLVW false positives.
PM-2-10: Number and Rate of False Negatives	Descriptive Study	A descriptive study will report the number and rate of RLVW false negatives.
PM-2-11: Distance from Stop Bar when RLVW is Displayed	Descriptive Statistics	Two distances from the stop bar are relevant in this test to properly notify the driver of a potential a red light running violation: (1) the distance from the stop bar when above average braking is required, the alert distance; and (2) the distance when aggressive braking is required, the warning distance. In this evaluation, two one-sample one-sided t-tests will be used to test whether the distance from the stop bar when the RLVW alert is displayed is (1) less than or equal to the alert distance and (2) greater than the warning distance.

6.2.3. UC-3: TIM Alerts

Table 18. Evaluation Methodology – UC-3: TIM Alerts
Source: Crest Solutions, July 2026

Performance Measure	Design Approach	Evaluation Methodology
PM-3-01: TIM Transmission Periodicity	Descriptive Statistics	A one-sample two-sided t-test will be used to test whether TIM periodicity differs from the target of 1 sec.
PM-3-02: TIM Transmission Latency	Descriptive Statistics	A one-sample one-sided t-test will be used to test whether TIM transmission latency is less than the target of 1 second, an upper limit that has not yet been established by the project team.
PM-3-03: TMC Alert Latency	Descriptive Statistics	A one-sample one-sided t-test will be used to test whether TMC alert latency is less than the target of 1 second, an upper limit that has not yet been established by the project team.
PM-3-04: Number of Unique TIMs transmitted	Descriptive Study	A descriptive study will report the number of unique TIMs transmitted by CTW sites.
PM-3-05: Number of CSW locations	Descriptive Study	A descriptive study will report the number of dangerous curves with corresponding CSW TIMs.
PM-3-06: TMC Operator Perceived Usefulness of V2X Alerts	Survey	A survey will be issued to TMC operators to assess the perceived usefulness of the alerts generated by the V2X central system.

6.2.4. UC-4: IC

Table 19. Evaluation Methodology – UC-4: IC
Source: Crest Solutions, July 2026

Performance Measure	Design Approach	Evaluation Methodology
PM-4-01: Event Report Sharing Latency	Descriptive Statistics	A one-sample one-sided t-test will be used to test whether Event Report sharing latency is less than the target of 60 seconds, an upper limit that has not yet been established by the project team.
PME-4-02: TIM Sharing Latency	Descriptive Statistics	A one-sample one-sided t-test will be used to test whether TIM sharing latency is less than the target of 60 seconds, an upper limit that has not yet been established by the project team.
PM-4-03: SDX Percent Uptime	Descriptive Study	A descriptive study will report the percent uptime of the SDX

Performance Measure	Design Approach	Evaluation Methodology
PM-4-04: Number of Event Reports Ingested by the SDX	Descriptive Study	A descriptive study will report the number of event reports ingested by the SDX.
PM-4-05: Number of TIMs Ingested by the SDX	Descriptive Study	A descriptive study will report the number of TIMs ingested by the SDX.
PM-4-06: Number of Third-Party Recipients of SDX Data	Descriptive Study	A descriptive study will report the number of third-party users that ingest SDX data.
PM-4-07: Number of Drives Influenced by SDX Data	Descriptive Study	A descriptive study will report the number of drives, or vehicle trips, that are influenced by SDX data as determined by Waze.

6.2.5. UC-5: VSL

Table 20. Evaluation Methodology – UC-5: VSL
Source: Crest Solutions, July 2026

Performance Measure	Design Approach	Evaluation Methodology
PM-5-01: Speed Differential	Before-After, Control vs Treatment	A before-after comparison of speed differential will be used to evaluate changes in driver behavior after the in-vehicle VSL alerting mechanism is activated. A control vs treatment study may be used to compare driver behavior for different corridors or direction to control for potential cluster effects.
PM-5-02: RSU's TIM Reception Latency	Descriptive Statistics	A one-sample one-sided t-test will be used to test whether RSU TIM reception latency is less than the target of 1 second, an upper limit that has not yet been established by the project team.
PM-5-03: TIM Transmission Latency	Descriptive Statistics	A one-sample one-sided t-test will be used to test whether VSL TIM transmission latency is less than the target of 1 second, an upper limit that has not yet been established by the project team.
PM-5-04: TIM Display Latency	Descriptive Statistics	A one-sample one-sided t-test will be used to test whether VSL TIM display latency is less than the target of 175 ms, an upper limit that has not yet been established by the project team.
PM-5-05: Number of VSL Corridors with VSL TIM Alerts	Descriptive Study	A descriptive study will report the number of VSL corridors for which VSL TIMs are broadcast.

Performance Measure	Design Approach	Evaluation Methodology
PM-5-06: Total Length of VSL Corridors with VSL TIM Alerts	Descriptive Study	A descriptive study will report the length of VSL corridors for which VSL TIMs are broadcast.
PM-5-06: Number of Unique VSL TIMs Transmitted	Descriptive Study	A descriptive study will report the number of unique VSL TIMs transmitted by CTW sites.

6.2.6. UC-6: VRU

Table 21. Evaluation Methodology – UC-6: VRU
Source: Crest Solutions, July 2026

Performance Measure	Design Approach	Evaluation Methodology
PM-6-01: Distance between Vehicle and VRU	Before-After, Control vs Treatment, Time Series	A before-after comparison of distance between vehicle and VRU will be used to evaluate changes in driver behavior after the VRU alerting and blank-out signs are activated, a control vs treatment study may be used to compare driver behavior for different approaches at the same intersection to control for potential cluster effects, and a time series analysis will control for lack of independence as vehicles get closer and closer to the point of potential conflict.
PM-6-02: Speed of Vehicle Approaching VRU	Before-After, Control vs Treatment, Time Series	A before-after comparison of vehicle speed will be used to evaluate changes in driver behavior after the VRU alerting and blank-out signs are activated, a control vs treatment study may be used to compare driver behavior for different approaches at the same intersection to control for potential cluster effects, and a time series analysis will control for lack of independence as vehicles get closer and closer to the point of potential conflict.
PM-6-03: Deceleration Rate of Vehicle Approaching VRU	Before-After, Control vs Treatment, Time Series	A before-after comparison of deceleration rate will be used to evaluate changes in driver behavior after the VRU alerting and blank-out signs are activated, a control vs treatment study may be used to compare driver behavior for different approaches at the same intersection to control for potential cluster effects, and a time series analysis will control for lack of independence as vehicles get closer and closer to the point of potential conflict.

Performance Measure	Design Approach	Evaluation Methodology
PM-6-04: Frequency of Hard Braking Events	Before-After, Control vs Treatment, Time Series	A before-after comparison of frequency of hard braking events will be used to evaluate changes in driver behavior after the VRU alerting and blank-out signs are activated, a control vs treatment study may be used to compare driver behavior for different approaches at the same intersection to control for potential cluster effects, and a time series analysis will control for lack of independence as vehicles get closer and closer to the point of potential conflict.
PM-6-05: SDSM Transmission Periodicity	Descriptive Statistics	A one-sample two-sided t-test will be used to test whether TIM periodicity differs from the target of 100 ms.
PM-6-06: SDSM Transmission Latency	Descriptive Statistics	A one-sample one-sided t-test will be used to test whether SDSM transmission latency is less than the target of 175 ms, a value patterned after the SPaT latency requirement in CTI 4501v02.
PM-6-07: Positional Accuracy of LiDAR-Detected V2X-Equipped Vehicles	Descriptive Statistics	A one-sample one-sided t-test will be used to test whether the positional difference is greater than the target of 50 cm, a lower limit that has not yet been established by the project team.
PM-6-08: Number of In-Vehicle VRU Alerts Displayed	Descriptive Study	A descriptive study will report the number of VRU alerts displayed on the HMI.
PM-6-09: Number and Rate of In-Vehicle False Positives	Descriptive Study	A descriptive study will report the number and rate of VRU alerts displayed when the VRU alerting criteria were not met.
PM-6-10: Number and Rate of In-Vehicle False Negatives	Descriptive Study	A descriptive study will report the number and rate of VRU alerts not displayed when the VRU alerting criteria were met.
PM-6-11: Number of Times Blank-Out sign is Illuminated	Descriptive Study	A descriptive study will report the number of VRU blank-out sign illuminations.
PM-6-12: Number and Rate of Blank-Out Illumination False Positives	Descriptive Study	A descriptive study will report the number and rate of blank-out sign illuminations when the VRU alerting criteria were not met.
PM-6-13: Number and Rate of Blank-Out Illumination False Negatives	Descriptive Study	A descriptive study will report the number and rate of blank-out sign illuminations not activated when the VRU alerting criteria were met.

6.2.7. UC-7: General

Table 22. Evaluation Methodology – UC-7: General
Source: Crest Solutions, July 2026

Performance Measure	Design Approach	Evaluation Methodology
PM-7-01: BSM Transmission Periodicity	Descriptive Statistics	A one-sample two-sided t-test will be used to test whether BSM periodicity differs from the target of 100 ms.
PM-7-02: Percent of NHS Routes with an RSU	Descriptive Study	A descriptive study will report the percentage of NHS routes that have at least one RSU deployed on it.
PM-7-03: Percent of NHS within Range of an RSU	Descriptive Study	A descriptive study will report the percentage of NHS within range of an RSU.
PM-7-04: Percent of Signalized Intersections with V2X	Descriptive Study	A descriptive study will report the percentage of signalized intersections with an RSU broadcasting the associated SPaT and MAP.
PM-7-05: Number of non-state public agencies with V2X-equipped vehicles	Descriptive Study	A descriptive study will report the number of non-state public agencies with V2X-equipped vehicles.
PM-7-06: Number of SCMS providers using interoperable security credentials	Descriptive Study	A descriptive study will report the number of SCMS providers using interoperable security credentials.
PM-7-07: Number of automotive supplier or OEM partners supporting CAN decoding for BSMs	Descriptive Study	A descriptive study will report the number of automotive supplier or OEM partners that provide CAN decoding information used by the deployment team to populate data in the BSM.
PM-7-08: Number of V2X applications (or use cases) utilizing 5.9 GHz	Descriptive Study	A descriptive study will report the number of V2X applications (or use cases) utilizing 5.9 GHz.

6.3. Qualitative Feedback Plan

Collecting qualitative feedback from stakeholders involved in or impacted by the deployment is expected for two of the project's six use cases. Participants will be recruited through emails and phone calls and qualitative data will be collected by administering surveys and/or conducting interviews. Both methods will generate feedback regarding the effectiveness, timeliness, and impact of project deployments for each specific use case. Survey questions will follow a Likert scale format. For example, if a question asks how

plow speed was affected by signal preemption, answers might be much slower, slower, no change in speed, faster, or much faster. Qualitative data will be constructed and analyzed in terms that are comparable to the quantitative analysis. This will allow for a more comprehensive analysis and impact measurement that takes into account direct user experience. Table 23 summarizes the qualitative data collection details.

Table 23. Qualitative Data Collection Summary
Source: Crest Solutions, July 2026

Use Case	Stakeholders	Target Responses	Recruitment	Collection Method	Frequency	Sample Questions
UC-1: CIPT	Plow operators, Maintenance shed foremen	20, 5	Email and phone	Surveys and/or interviews	End of Phase 2	• How often did you receive signal preemption when plowing? • How was plow speed affected by preemption? • How was plow travel time affected by preemption? • How timely was preemption provided?
UC-3: TIM Alerts	Control Room operators	10	Email and phone	Surveys and/or interviews	End of Phase 2	• How often did you receive alerts generated by the V2X system? • How often did you use information from the V2X system alerts? • How accurate was the information from the V2X system alerts? • How timely was the information from the V2X system alerts?

The federal regulations that govern Institutional Review Board (IRB) oversight define research as "a systematic investigation...designed to develop or contribute to generalizable knowledge" (US Dept of Health and Human Services, 45 CFR 46). Our qualitative feedback plan is an internal program evaluation not designed to develop or contribute to generalizable knowledge as defined in 45 CFR 46.102(l). Therefore, we will pursue an IRB exemption as we believe it does not meet the federal regulatory definition of human-subjects research.

7. Performance Measurement Reporting Plan

Baseline and post-deployment performance measure reporting will be available on a public-facing dashboard. Initially, this dashboard will be used primarily by the project team and will go through several iterations as baseline data is collected, analyzed, presented, and discussed by the project team. In addition to the dashboard, periodic reporting to the project team will occur at regularly scheduled team meetings in the form of presentations, memorandums, or dashboard demonstrations. Similar communication with project stakeholders will also occur as stakeholder insights and input from the Project Team are critical to identifying key metrics and ensuring that the data are analyzed and presented in a useful way.

The dashboard will be interactive so users can navigate between tabs or screens and adapt the charts, maps, and other visualizations according to their needs. The collage of screenshots in Figure 1 includes examples of dashboards, charts, and other visualizations currently used by members of the project team to provide insights into UDOT's existing V2X deployments.

Data will be added at least monthly so that trends and insights continually represent the most recent data collected.

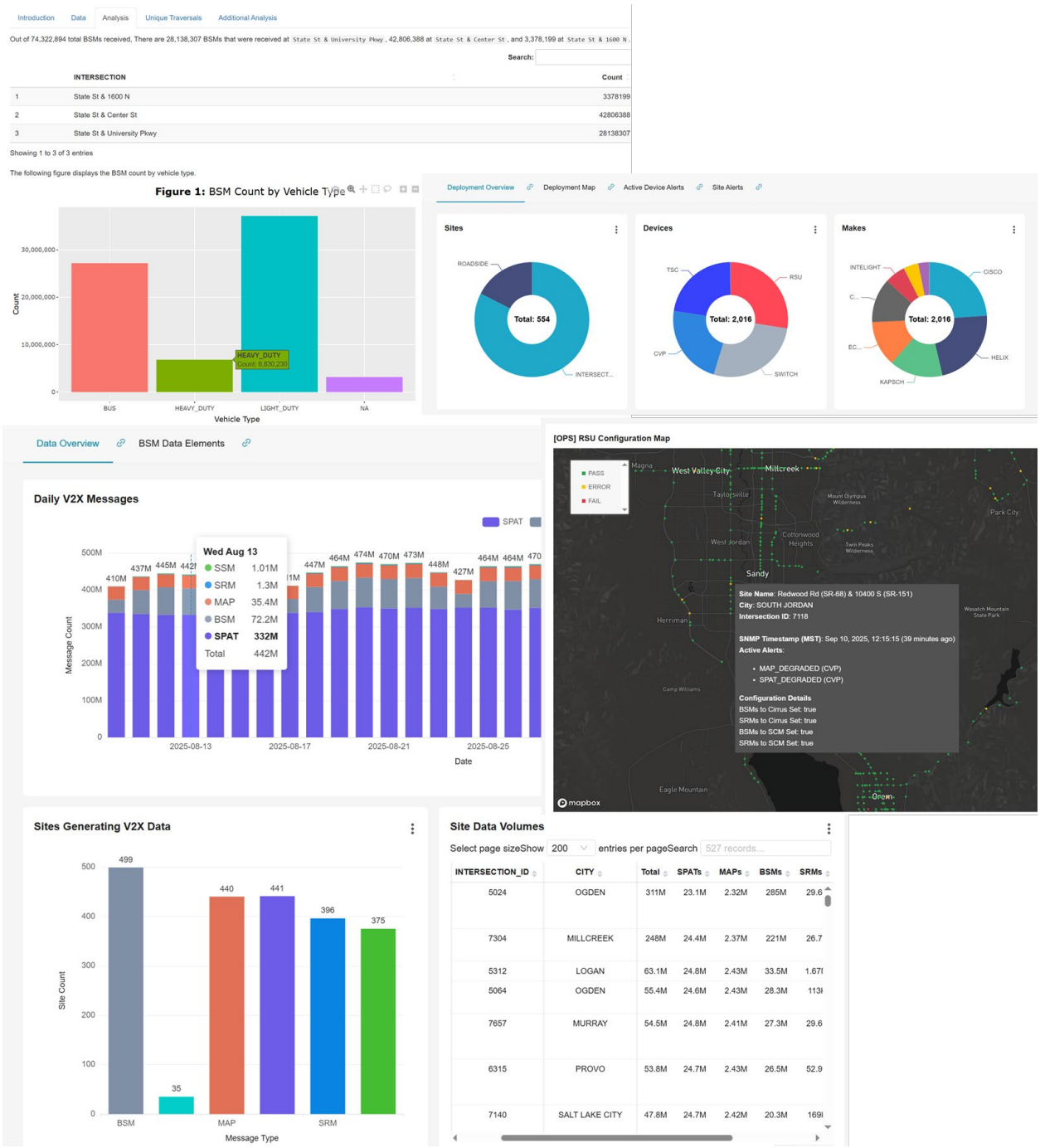

Figure 1. Sample Dashboard Charts and Performance Measure Visualizations
Source: Crest Solutions, July 2026

8. Performance Measurement and Evaluation Schedule

This section provides a timeline for all performance measurements and evaluation activities, outlining the schedule for the assessment of various impacts (Table 24). It specifies the frequency of evaluations and indicates when specific impacts will be assessed. The timeline also defines key milestones, including the start and end dates of data collection, timelines for analysis, and the due dates for submitting evaluation reports.

Table 24. Evaluation Schedule
Source: Crest Solutions, July 2026

Activity	Description	Beginning Date	Ending Date
Draft PMEP development	Generate initial draft of the PMEP, then complete multiple rounds of revision.	07/2025	10/2025
Final PMEP submission	Submit the final PMEP report to USDOT.	10/2025	07/2026
Baseline data collection	Collect pre-deployment data to establish a threshold from which to measure deployment performance indicators.	10/2024	03/2027
Periodic baseline performance reporting	Produce reports addressing baseline performance measures and update the performance measurement dashboard at least monthly.	06/2026	06/2027
Deployment data collection	Continuous collection of data during deployment phase.	09/2026	06/2027
Periodic performance measure calculation	Update dashboards with new data at least monthly, analyze data, and communicate insights to key stakeholders.	09/2026	06/2027
Qualitative feedback data collection and analysis	Develop and administer surveys to gather feedback from specific categories of stakeholders and users; analyze responses to augment quantitative data insights and analysis.	12/2026	06/2027
Draft System Performance Report	Generate initial draft of System Performance Report, synthesizing findings from deployment performance measures; complete multiple rounds of revisions.	04/2027	07/2027
Final data analysis	A careful review of the data to ensure accuracy of reported findings.	06/2027	08/2027

Activity	Description	Beginning Date	Ending Date
Final System Performance Report	Submit final System Performance Report to USDOT.	07/2027	09/2027

9. Potential Risks

This section identifies several potential risks and challenges that may affect performance evaluation throughout the CTW project lifecycle. Potential risks and corresponding mitigation efforts include the following:

1. **Regulation uncertainty, such as the FCC revoking C-V2X licenses or offering remaining spectrum to unlicensed Wi-Fi.** UDOT and CTW partners are active proponents of V2X and regularly participate in conferences, webinars, workshops, and a variety of presentations to advocate for V2X and the critical role it needs to play in our transportation system. Continuing these efforts will help reduce the likelihood of this risk being realized, which would be fatal to the project.
2. **USDOT does not proceed with Phase 2 or does not approve UDOT for Phase 2.** Either of these events would obviously halt the project and remove the need for continued performance evaluation. The CTW project team can take action to mitigate against the second of these scenarios, where they are not approved for Phase 2. To do this, the project team will ensure that all Phase 1 requirements are met and that preparations for Phase 2 are complete.
3. **Degraded OBU performance or poor OBU integration with the vehicle.** This would prevent the population of critical BSM data fields that are needed for application functionality and performance evaluation. To mitigate the effects of degraded performance, some post-processing can be performed to calculate certain fields, but there may be a need to rely on RWIS data alone to generate SWIWs. As discussed in the ConOps, degraded functionality and performance can occur because of cybersecurity incidents. Because CTW operations only include fleet vehicles at this time, risks of cybersecurity incidents are minimal. However, as the CTW Program advances, the topic of identifying the roles and responsibilities for cybersecurity events will continue to be reviewed and incorporated. To guard against such incidents, the program incorporates the following measures:
    a. The Connected Transportation Interoperability Committee (CTIC) Program is progressing towards a definitive set of CI security requirements that operators of CIs agree to implement.
    b. The CTW Program is leveraging existing vendor products that have inherent safeguards toward detecting and mitigating cybersecurity incidents.
    c. The SCMS architecture includes trusted root certificates operated by authorized vendors.
4. **Inability to install HMIs in partnering fleets.** To mitigate, HMIs will be installed in UDOT vehicles. This will result in a smaller geographic area for the evaluation given the travel patterns of UDOT fleet vehicles.
5. **IRB processes.** IRB approval or exemption may impact how and whether our qualitative feedback plan is executed.

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