Utah Connected

Final Report

January 31, 2024

USDOT FY18 ATCMTD Grant
Grant Submittal 693JJ318NF00010
UDOT Project Number F-ST99(634)
UDOT PIN 17981
Cooperative Agreement Executed: Sept 16, 2019

Acknowledgement of Support and Disclaimer

This material is based upon work supported by the Federal Highway Administration under Agreement No. 693JJ318NF00010. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the Author(s) and do not necessarily reflect the view of the Federal Highway Administration.

TABLE OF CONTENTS

UTAH CONNECTED

Introduction

The Utah Department of Transportation (UDOT) was awarded a FY 2018 Advanced Transportation and Congestion Management Technologies Deployment (ATCMTD) grant for its *Utah Connected* initiative, which is comprised of seven individual projects. This Final Report contains the description, scope, timeline, goals, performance metrics, evaluation results, lessons learned, recommendations, and conclusions for each *Utah Connected* project. Submission of this *Utah Connected* Final Report satisfies the deliverable requirement for the Final Report described in the Cooperative Agreement and specifically and collectively satisfies the 'final report deliverable' designated in individual projects within this program.

Supplemental information can also be found in the numerous Intermediate Working Papers that were submitted, UDOT's Transportation Technology website[1], and the six recorded *Utah Connected* Webinar Series outreach webinars[2].

Utah Connected Project Summary

The Utah Department of Transportation (UDOT) is dedicated to innovation and the deployment of new technologies to benefit travelers throughout the state of Utah. Leveraging the significant investments already made in Intelligent Transportation systems (ITS) deployments throughout the state is vital to achieving UDOT's vision to "*Keep Utah Moving*" by enhancing mobility, increasing safety (towards UDOT's goal of Zero Crashes, Injuries, and Fatalities), and optimizing the value of infrastructure investments. Utah's extensive ITS infrastructure and connected vehicle experience support and enable *Utah Connected* projects.

Utah Connected is an initiative with seven projects organized around three focus areas: 1) connected systems, 2) connected vehicles, and 3) connected people. Collectively, these projects help UDOT accomplish numerous goals, including increase its real-time situational awareness, improve safety, improve mobility, reduce environmental impacts, and develop lessons learned and recommendations for future deployments. *Utah Connected* is organized by focus area and project as follows:

---

[1] https://transportationtechnology.utah.gov
[2] https://www.youtube.com/@UtahDOT

- Focus Area #1: Connected Systems
    - Project 1.1 – Data Ecosystem
    - Project 1.2 – Fiber Sensing
- Focus Area #2: Connected Vehicles
    - Project 2.1 – Transit Signal Priority (TSP)
    - Project 2.2 – Snowplow Preemption
    - Project 2.3 – Curve Speed Warning (CSW)
    - Project 2.4 – Spot Weather Impact Warning (SWIW)
- Focus Area #3: Connected People
    - Project 3.1 – Lessons Learned from an Autonomous Shuttle Pilot Deployment

Figure 1 contains a map of these deployments and highlights both urban and rural deployment locations. Deployment for Project 1.2 Fiber Sensing occurred along Big Cottonwood Canyon (BCC) and Little Cottonwood Canyon (LCC); Project 2.1 TSP along State St (US-89) in Utah County; Project 2.2 Preemption along Timpanogos Hwy (SR-92), Redwood Rd (SR-68), Pioneer Crossing (SR-145), and State St (US-89); Project 2.3 CSW at five curve locations in Big Cottonwood Canyon and three locations in Salt Lake City; and Project 2.4 SWIW along SR-224, SR-248, and US-40. A major part of this grant work is the deployment and expansion of UDOT's connected vehicle, or vehicle-to-everything (V2X), system.

A map of all roadside units (RSUs) deployed under this grant are shown in Figure 2 with a tabulated list of each RSU shown in Appendix A: RSU Deployment List. In addition to these infrastructure deployments, the after-market installation of on-board units (OBUs) on 83 vehicles also took place.

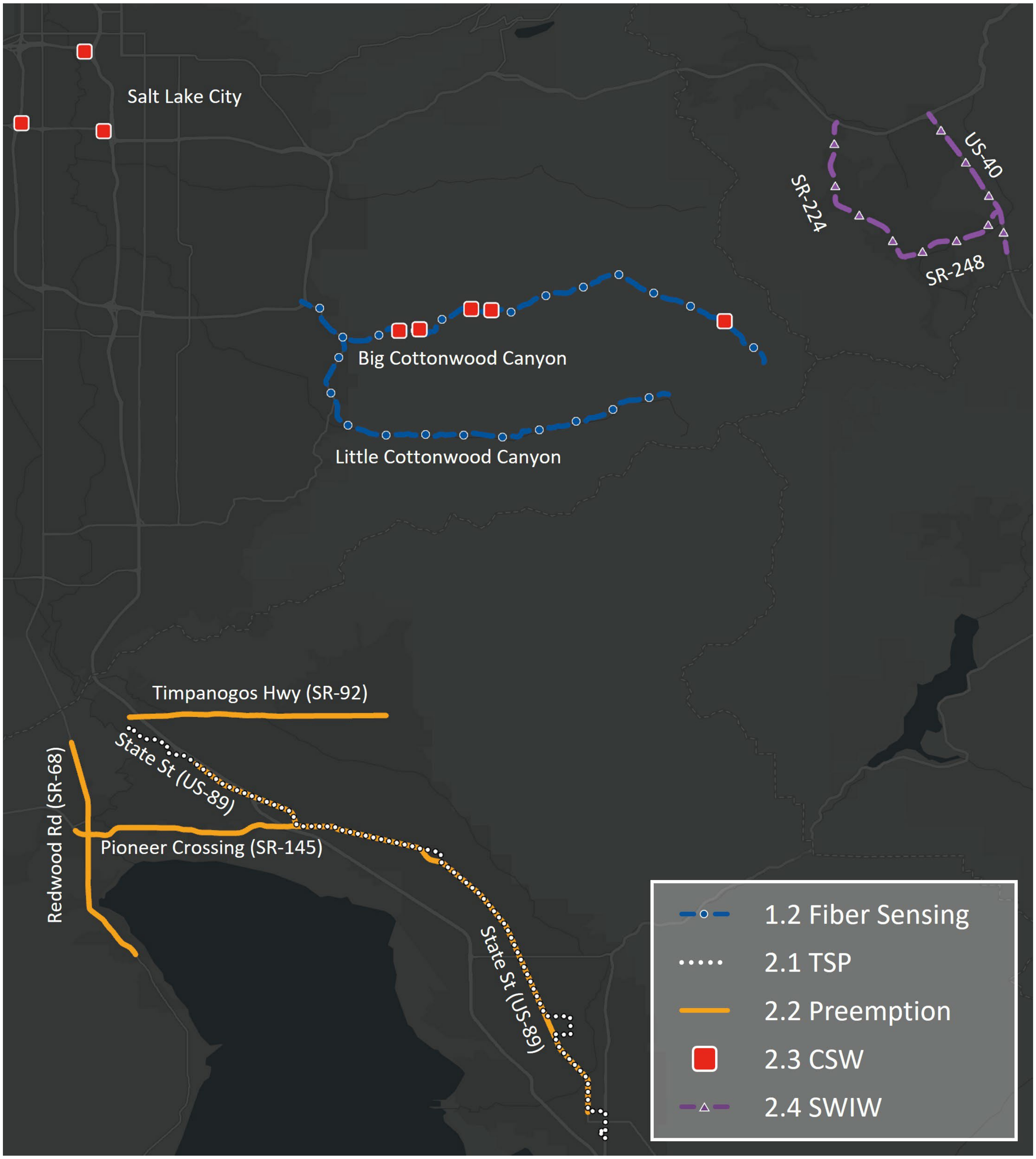

Figure 1 Utah Connected project deployment map.

Figure 2 Utah Connected RSU deployment map.

PROJECT 1.1 DATA ECOSYSTEM

1. Project Summary

Description

Project 1.1 Data Ecosystem includes the development of a cloud-based, data analytics platform, the “Data Ecosystem”, also known as “Cirrus by Panasonic”, that stores and manages all SAE J2735 V2X messages generated in projects 2.1 to 2.4, ingests all the important weather-related data needed to support Project 2.4 SWIW, and houses the CSW and SWIW applications from Projects 2.3 and 2.4, respectively.

The Data Ecosystem also includes a security credential management system (SCMS) that UDOT procured and implemented in this project for Projects 2.1, 2.2, 2.3, and 2.4. An SCMS is essential to provide secure, authentic, trusted, and private communications that are protected from misuse. Digital credentials attached to each message sent by devices along the roadside and in vehicles effectively secure the messages from misuse, enabling secure, authentic, trusted, and private communications. Messages produced by vehicles have credentials that change frequently, thus providing anonymity of the message source (with the exception of publicly-owned vehicles requesting signal priority or preemption). These credentials are part of a PKI (public key infrastructure) system, are provided by a third party, and ensure message authenticity. This effort impacts hardware selection and ecosystem design. Once installed, the SCMS has informed and enabled all other UDOT V2X deployment efforts.

More information about the Data Ecosystem can be found in Webinar #2 of the *Utah Connected* Webinar Series, titled *Connected Vehicle Data Ecosystem & Applications*.

2. Performance Metrics, Evaluation Methods, and Data Sources

This section describes the project goals that align with Section 6004 of the Fixing America’s Surface Transportation (FAST) Act (PL 114-94) and a discussion of the challenges encountered.

Goal: Increase Real-Time Full Situational Awareness

One goal of this project was to more effectively collect and provide real-time information, which was accomplished by developing a cloud-based data analytics platform and deploying C-V2X technology in the 5.9 GHz spectrum. The Data Ecosystem creates a system that works largely behind the scenes and facilitates other projects (such as TIM generation), so performance measures for Project 1.1 focus on the inputs of this system. The primary inputs that will be evaluated are absolute results based on the number of types of data sources, the number of data sources regardless of type, whether all available data are being used in the ecosystem, and the frequency at which data are being ingested. The ability to provide real-time information specific to individual vehicles will be evaluated in projects 2.3 and 2.4. System performance is evaluated through device transmission logs and project documentation is used to evaluate system compliance with national protocols and standards.

Goal: Increase Knowledge and Understanding of Emerging Technologies

Another goal was to increase knowledge and understanding of emerging technologies—the security of V2X systems, specifically—which is accomplished through the integration of a security credential management system (SCMS) into our V2X system.

For each performance measure, Table 1 contains the associated goal area, data method, data source, data collection time period, and sample size, when appropriate.

Table 1 Project 1.1 Performance Metrics

Goal Area	Performance Measure	Data Method	Data Source	Data Collection Time Period	Sample Size
Increase real-time full situational awareness	Number of types of data sources	Agency data	Project documentation	N/A	N/A
Increase real-time full situational awareness	Number of data sources	Agency data	Project documentation	N/A	N/A
Increase real-time full situational awareness	Percentage of data elements available being ingested	Agency data	Project documentation	N/A	N/A
Increase real-time full situational awareness	Frequency of data ingestion	Agency data	Project documentation	N/A	N/A
Increase knowledge and understanding of emerging technologies	Successful transmission rate	Field test	SPaT transmission logs, Device health logs	12:32:44 PM to 3:32:44 PM on July 27, 2022	n_{SPaT}=107,991 n_{MAP}=10,785 n_{TIM}=10,387
Increase knowledge and understanding of emerging technologies	Description of whether the system complies with national protocols and standards	Agency data	Project documentation	N/A	N/A

3. Evaluation Results

The Data Ecosystem records all V2X messages received by RSUs that are integrated into the system. Accordingly, J2735 messages including BSM, SRM, SSM, SPaT, MAP, TIM, and RTCM are continually being recorded and stored by the Data Ecosystem. While these messages are produced by the Data Ecosystem and deployed devices within it, other data needs to be ingested to support various applications. In addition to these J2735 messages, the Data Ecosystem also ingests six other types of data sources, which are:

- RWIS data
- Device ping status for the RSU, the signal command module (SCM), network switch, and the traffic signal controller
- RSU SNMP status
- RSU GPS status
- RSU metadata
- Mapbox maps for the Data Ecosystem's user interface (UI).

The Data Ecosystem was developed to support Utah's V2X deployments as a whole and not just the projects deployed under this grant. As such, the total number of data sources providing information to the Data Ecosystem includes devices deployed outside of this grant. In total, 199 RWIS sensors, 186 OBUs, 296 RSUs, 296 network switches, 236 SCMs, and 236 traffic signal controllers are integrated and provide data used to generate insights about current roadway conditions and device health within the Data Ecosystem. Of these devices, this grant funded the deployment of 83 OBUs, 112 RSUs, 112 network switches, and 82 SCMs.

Out of all available data elements from these data sources, 100% are being ingested into the Data Ecosystem and no data is excluded or removed. Despite its ingestion, however, not all data is being used and efforts to more fully utilize available data are underway in subsequent projects. For example, the SWIW application generates icy road alerts when an RWIS station reports a surface status of "ice" and a surface temperature between 26- and 32-degrees Fahrenheit. Some RWIS stations provide pavement surface grip data, which could alternatively be used to generate icy road alerts, but this data is not currently being used despite its ingestion.

Regarding the frequency of data ingestion, RWIS data is ingested every 10 minutes, device ping status is every second, RSU SNMP status is every 5 minutes, RSU GPS status is every 5 minutes, and RSU metadata is every 6 hours. The Mapbox data is ingested whenever users access the Data Ecosystem UI by leveraging the Mapbox APIs and ensuring the latest data is used. The J2735 messages are ingested in real-time whenever they are received by an RSU.

The Data Ecosystem's performance was evaluated through RSU packet capture (PCAP) network logs since RSU transmission is the culminating effort of many Data Ecosystem functions, like SPaT, MAP, and SWIW alerts via TIM transmission. RSU network traffic was logged and recorded in a PCAP file for a continuous three-hour time period on July 27, 2022, from 12:32:44 PM to 3:32:44 PM at the intersection of SR-224 and Meadows Drive, a location enabled for SPaT, MAP, and TIM transmission.

Message periodicity is a measure of transmission frequency and measures the elapsed time between transmissions of the same message type. Periodicity was evaluated for SPaT, MAP, and TIM messages with the results summarized in Table 2. Additionally, periodicity of the traffic signal controller broadcast message (TSCBM) was evaluated, which is generated by the controller and contains the data used to populate the J2735 SPaT. Each message type is designed to be transmitted at a certain periodicity, which is shown in the results table, along with the calculated mean, minimum, and maximum periodicity values. Additionally, the 95 percent prediction interval is shown, which demonstrates variability in the data and is a range of expected periodicity values defined by the 2.5th and 97.5th percentile values. To illustrate, SPaT messages have a designed periodicity of 0.1 seconds (100 milliseconds). The mean periodicity is 100 milliseconds while the minimum and maximum are 15.1 and 378.1 milliseconds, respectively. The 95 percent prediction interval shows that 95 percent of the SPaT messages were transmitted with a periodicity between 61.5 and 156.0 milliseconds.

Table 2 Message Periodicity Results.

Message	Designed Periodicity (seconds)	Mean Periodicity (seconds)	Minimum Periodicity (seconds)	Maximum Periodicity (seconds)	Periodicity 95% Prediction Interval (seconds)
TSCBM	0.1	0.1000	0.0918	0.1081	[0.0991, 0.1008]
SPaT	0.1	0.1000	0.0151	0.3781	[0.0615, 0.1560]
MAP	1.0	1.0012	0.8722	1.1189	[0.9425, 1.0375]
TIM	1.0	1.0398	0.9211	1.1233	[1.0067, 1.0859]

RSE latency, or process time, measures how long it takes the RSE to process and transmit a given message, which includes the time needed to apply the security certificates produced by the SCMS. The RSE deployed at signalized intersections includes two devices: a roadside processor and an RSU. For SPaT transmission, the roadside processor, or SCM, receives the TSCBM message from the traffic signal controller, converts it into J2735 SPaT, and then sends the SPaT message to the RSU. The RSU receives the SPaT, applies the security certificate, and then transmits the SPaT. RSE latency was evaluated for SPaT and MAP messages with the results summarized in Table 3.

Table 3 RSE Latency Results.

Message	Mean RSE Latency (seconds)	Minimum RSE Latency (seconds)	Maximum RSE Latency (seconds)	RSE Latency 95% Prediction Interval (seconds)
SPaT	0.0277	0.0163	0.2947	[0.0170, 0.0797]
MAP	0.0415	0.0172	0.1672	[0.0178, 0.1036]

Although these results pertain to a specific intersection during a limited time period, additional analysis confirms that these results are representative of the performance achieved by all RSUs deployed under this grant.

The CTI 4501 v01.01 Connected Intersections Implementation Guide identifies performance requirements for V2X message transmission. Select requirements that relate to SPaT and MAP transmission are:

- **3.3.3.1.5.1 SPaT Message - Broadcast Periodicity:** A connected intersection shall broadcast SPaT messages periodically at average rate of 10 messages per second +/- 1 message over a 10-second period.
- **3.3.3.1.5.2 SPaT Message - Broadcast Latency:** A connected intersection shall broadcast SPaT messages that reflects the actual signal indications of the intersection within a latency of no more than 300 milliseconds.
- **3.3.3.1.5.3 MAP Message - Broadcast Periodicity:** A connected intersection shall broadcast MAP messages periodically at an average rate of 1 message per second +/- 1 message over a 10-second period.

However, assessing compliance to these requirements can be challenging, and in some cases, we do not believe that these metrics appropriately measure the performance of a connected intersection. For example, the requirement that SPaT be broadcast at a rate of 10 messages per second +/- 1 message over a 10-second period would be satisfied if 1 SPaT message were transmitted at t=0.0 seconds and then 9 SPaT messages transmitted at t=0.9 seconds, repeated in this manner for the entire 10-second period.

As we evaluated our system and collaborated with people from Crash Avoidance Metrics Partners LLC (CAMP), a different approach to assessing message broadcasts seemed more suitable and more aligned with the needs of applications like red light violation warning. This approach emphasizes the need for continuous SPaT broadcasts at the designed periodicity instead of confirming that the correct number of SPaT messages were broadcast over a longer period of time (i.e., 10 seconds), which is why our results measure periodicity in terms of the mean, minimum, maximum, and the 95 percent prediction interval.

In ongoing effort to modify 4501, the CTIC Phase 2 committee is considering an alternate approach to the requirements for latency and periodicity. According to the proposed language in the System Design Document (SSD) walkthrough, requirements 3.3.3.1.5.1 and 3.3.3.1.5.2 will be deprecated and the following new requirements are proposed:

- **3.3.2.1.6 TSC Signal State Periodicity:** A TSC infrastructure shall set the signal indications 10 times per second via the cabinet serial bus at 100 +/- 25 ms intervals where the duration of the 10 consecutive intervals is 1.0 seconds +/- 25 ms.
- **3.3.3.1.5.4 SPaT Message - Broadcast Latency and Accuracy - Commanded:** A connected intersection shall broadcast a SPaT message within 175 milliseconds from the time the TSC infrastructure sets the corresponding signal indications.

Based on this new language, our evaluation of TSCBM periodicity and the results in Table 2 demonstrate full compliance with 3.3.2.1.6; the minimum and maximum periodicity values of 91.8 ms and 108.1 ms fall well within the acceptable range of 100 +/- 25 ms.

However, our deployment is not always compliant with the proposed requirement on SPaT latency, requirement 3.3.3.1.5.4, which allows a latency up to 175 ms. The results in Table 3 show a maximum observed latency of 294.7 ms. Nevertheless, it is worth noting that the 97.5th percentile of SPaT periodicity is only 79.7 ms and it is the 99.994th percentile that equates to 175 ms. This means that, on average, one SPaT message in 27.8 seconds will have a periodicity that exceeds the proposed 175 ms threshold requirement. Meanwhile, a "five nines" level of service for periodicity, or the 99.999th percentile, would be attainable if one SPaT message in 166.7 seconds exceeded the 175 ms threshold.

Through work performed outside of this grant, we will continue to evaluate the periodicity, latency, and accuracy of the V2X data produced by our deployments. We will perform these evaluations to enhance the quality of our deployments, increase industry knowledge of device performance, and improve the utility of relevant standards and deployment guidance.

4. Lessons Learned, Recommendations, and Conclusions

The Data Ecosystem has proven to be a valuable tool for collecting and processing all the J2735 and related data necessary to operate UDOT's V2X system. Since the data volumes are large, hosting this system in the cloud is essential to its efficient operation. Some of the lessons learned from development of this system are as follows:

- Access to the data is not intuitive or straightforward. With other funding, we continue to improve the ability of the system to share and disseminate the recorded data, including for outside parties.
- Hosting of V2X data in the cloud yields on-going costs for transmission and storage. At the outset of this project, we had no tangible estimate of these costs. Considerations need to be given to how much data is stored and for how long. Long-term off-line storage should be considered as an alternative for data that no longer justifies cloud storage but might be useful for research.
- SCMS System
    - Certificate policies are still maturing and changes to those policies or nuances in hardware configurations sometimes cause glitches in the system. When certificates are expired or are non-existent, receiving devices will ignore the messages.
    - Original certificates on some of our older OBUs had a 3-year expiration date and could not effectively be replaced without "re-enrolling" the device. We replaced these older OBUs because that was easier than re-enrolling the devices. The new expiration date on the devices is 10 years. We believe that a remote re-enrollment procedure will be in place by the time these devices expire.
    - Each message type requires certificates with specific Provider Service Identifiers (PSID) for those messages. In addition, the RSU needs to be programmed using SNMP commands to handle each type of message. In some cases, RSUs were installed with a limited set of PSIDs, and we later decided that additional message types (such as a TIM) should be enabled at those RSUs. This requires a

    significant effort but front-loading an RSU with PSIDs that may not be used poses a security risk and additional cost. Planning for future deployments should carefully consider the message types that will be broadcast at given locations.
    - Security certificates have expiration dates and need to be replenished at periodic intervals. Those intervals are longer for OBU certificates than for RSU certificates. Connections to the internet are needed for these certificates to be replenished. There are on-going costs for security certificate replenishment and for tools that allow the status of certificates to be monitored.
- Message transmission periodicity and latency are impacted by a variety of factors, including the volume of message traffic, delays for signing the messages with certificates, signal controller capabilities and firmware versions, and hardware constraints. All these issues need to be considered when installing and maintaining V2X systems.
- The project team worked closely with UDOT's Weather Group to access pertinent data from RWIS stations around the state. The API used for those RWIS stations was well constructed and easy to use.

PROJECT 1.2 FIBER SENSING

1. Project Summary

Description

UDOT has one of the most robust, DOT-owned fiber optic networks in the nation. Achieved through public private partnership and trade, the network has been expanded greatly in the last decade to include 3400 miles of fiber in both urban and rural areas. The UDOT fiber network extends to some very remote corners of the state and contributes to our “connected system.” Fiber sensing, also known as Distributed Acoustic Sensing (DAS), uses fiber optic cable to monitor roadways in real time by detecting acoustic events in the vicinity of the fiber. This is a well-used technology in some industries (pipelines and security) but is new in the transportation industry.

UDOT deployed this DAS system in the 14-mile long Big Cottonwood Canyon (BCC) and the 12-mile long LCC, two heavily used recreational corridors near Salt Lake City. The roads in these canyons have significant challenges resulting from traffic volumes, grades, winding mountainous terrain, and winter avalanches. Traditional ITS technologies exist along this roadway but, because of the terrain, do not provide full coverage. UDOT has fiber next to the pavement surface with a few locations where the fiber crosses the road, both of which are ideal for traffic and event detection using DAS. Installing DAS involved placing an interrogator unit and a processing unit in the fiber hub building that serves these two canyons, followed by system calibration and integration. The goal was to detect vehicle speed, travel time, direction, and incidents, such as crashes, avalanches, and rockfalls along the corridor.

While the fiber location in the roadway was correctly identified as ideal, the installation techniques, which occurred several years before this grant was awarded, was not conducive to DAS and resulted in poor detection capabilities along certain stretches of the roadway. Consequently, a temporary installation occurred in American Fork Canyon where the fiber was optimally installed—fiber location near travel lanes and installation techniques that don’t dampen the acoustic signals—to compare differences in system performance. Figure 3 shows a map of the three corridors along which the fiber sensing was installed with the permanent installations in BCC and LCC and the temporary installation in American Fork Canyon.

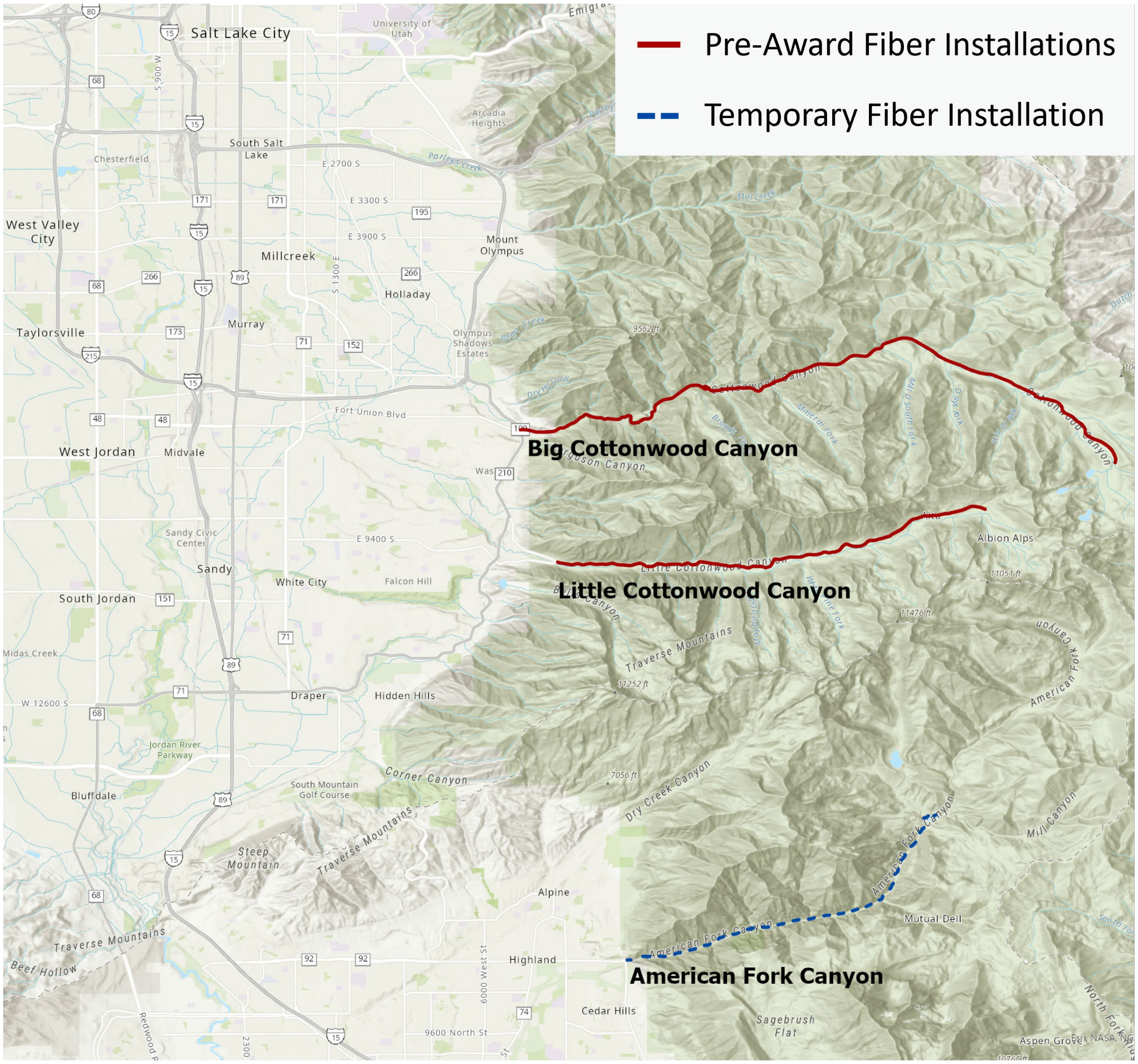

Figure 3 Project 1.2 fiber sensing deployment map.

2. Performance Metrics, Evaluation Methods, and Data Sources

This section describes the project goals that align with Section 6004 of the Fixing America's Surface Transportation (FAST) Act (PL 114-94) and a discussion of the challenges encountered.

Goal: Increase Real-Time Full Situational Awareness

Fiber Sensing fills a literal gap wherein certain segments of the roadway in BCC and LCC are not currently being monitored, which enables UDOT to increase its real-time full situational awareness of these canyons. Traditional traffic monitoring sensors are deployed periodically along highways to provide the traffic volume and vehicle classification data and comply with federal Highway Performance Monitoring System (HPMS) requirements. The data are also used as an input to UDOT's travel demand model and many other decision frameworks that utilize segment AADT and volumes by vehicle classification.

Table 4 summarizes each performance metric for this project and the associated goal areas, data methods, data sources, data collection time periods, and sample size.

Table 4 Project 1.2 Performance Metrics

Goal Area	Performance Measure	Data Method	Data Source	Data Collection Time Period	Sample Size
Increase real-time full situational awareness	Miles being monitored	Agency data	Project documentation	N/A	N/A
Increase real-time full situational awareness	Percentage of corridor being monitored	Quantitative data comparison	Project documentation	N/A	N/A
Increase real-time full situational awareness	Number of vehicles sensed through DAS compared to traditional methods	Quantitative data comparison	Acoustic sensors, continuous count station vehicular counts	May 30, 2023	91
Increase real-time full situational awareness	Percentage of crash incidents that are detected	Quantitative data comparison	Acoustic sensors, crash reports	2019 to 2023	4
Increase real-time full situational awareness	Number of non-traffic detectable events	Quantitative data comparison	Acoustic sensors, event reports	2019 to 2023	7

Project and Data Challenges

This project utilized fiber sensing technologies in a new way to monitor highway traffic and other acoustic events affecting the roadway, such as crashes, avalanches, mudslides, and rock falls. Although this technology has been successfully deployed in other industries, a variety of factors were discovered that affected the performance of this system.

First, the fiber's ability to effectively monitor traffic and non-traffic events is highly sensitive to fiber installation methods. Fiber installed more than 14 meters from the highway and/or encased in concrete or flowable fill limits detection capabilities. Several portions of BCC and LCC did not have ideal fiber conditions and detection capabilities were limited.

Additionally, considerable time tuning the algorithms that interpret the acoustic signals was needed since crashes, mudslides, and avalanches were "new" event types that this technology has not been used to measure. Accordingly, interpreting the data and converting it from its raw form into actual events takes exceptional skill.

3. Evaluation Results

In BCC, 14 miles of fiber was being used to monitor vehicular traffic and other events affecting the highway. In LCC, 12 miles of fiber was used. However, we were surprised to discover that certain fiber installation techniques would so strongly limit detection capabilities. In BCC, only 3.3 percent, or about 0.5 miles, could effectively monitor vehicular traffic. Other events, such as crashes and avalanches, have a much great acoustic signal and could be detected where traffic monitoring was not possible. LCC had improved fiber placement and vehicular traffic could be monitored along 75 percent, or about 9 miles of the canyon.

A temporary installation was implemented in American Fork Canyon, where fiber placement was confirmed to be ideal and conducive to traffic monitoring. Camera footage was used to count traffic volumes at a T-intersection along the highway. Out of the 91 vehicles seen by the camera, the fiber sensing system detected 96 percent of them.

Determining how much of a corridor can be monitored using fiber depends on the strength of the signal produced. A snowplow, for instance, will produce an enormous signal as it travels with the blade down on the pavement compared to a passenger vehicle. Particularly strong signals, such as those from crashes, avalanches, and rockfalls, were detected on segments where typical vehicular travel could not be detected. Figure 4 contains sample waterfall plots for each of the deployed canyons that act as time-space diagram with the angled lines representing vehicle trajectories.

The crisscrossing lines of the American Fork Canyon plot, representing vehicles traveling both up the canyon and down the canyon, demonstrate the clarity with which traffic can be detected when the fiber is optimally installed. The fiber detection in American Fork Canyon was so good that even bicyclists produced a discernible signal that the system could detect.

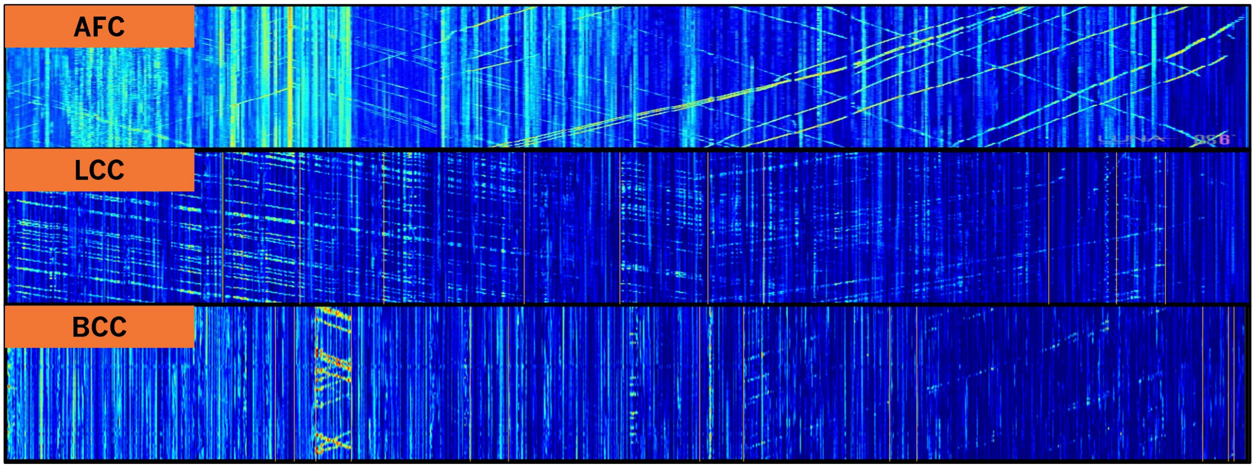

Figure 4 Sample waterfall plots for American Fork, Little Cottonwood, and Big Cottonwood Canyons.

Given the strong signal produced by vehicle crashes, all four crashes were successfully detected by the fiber sensing system. Construction efforts that cut the fiber, one mudslide, one flooding incident, and four avalanches were also detected and constituted 100 percent of non-traffic monitoring events. Algorithms for detecting these events are still being refined and all false-positive events are being considered in this effort.

The existence of false positives is primarily due to two reasons: (1) DAS monitoring of events such as avalanches, rock falls, mudslides, and crashes is a novel use case for this technology and we are still understanding how to distinguish these events based on the detectable signatures, and (2) variations in fiber installation and pavement conditions exist along the fiber line means that the exact same event would likely produce different signatures at different locations along the fiber line. While the data is recorded and available in real-time, understanding of many of these events was not obtained until after the fact. An increased sample size of known events and more uniform fiber conditions will help further refinement of these algorithms to support real-time alerts and any subsequent incident response.

4. Lessons Learned, Recommendations, and Conclusions

The Fiber Sensing / DAS tool shows great promise for continuous detection of events along highway corridors, especially those in rural areas or challenging terrain where traditional ITS sensors are challenged to provide coverage. Improved situational awareness along these corridors can improve response time for incidents, enhancing safety. Some of the lessons learned from development of this system are as follows:

- Fiber placement, fiber type, and backfill methods are critical to facilitating traffic and event monitoring using fiber optic cables.

- Site-specific customization is needed to establish appropriate algorithms for interpreting the data, which requires a specific skillset and significant ground-truth data for calibration.
- Fiber sensing is not anticipated to replace cameras or radar sensors, but can augment and enhance highway monitoring and provide much greater coverage than traditional point detectors.

PROJECT 2.1 TRANSIT SIGNAL PRIORITY

1. Project Summary

Description

The Utah Smart Transit Signal Priority (TSP) project was first deployed in 2017 on Redwood Road, an urban corridor in Salt Lake County on which Utah Transit Authority (UTA) Route 217 runs, and along the Utah Valley Express (UVX) corridor in 2019, a bus rapid transit line in the Provo-Orem area of Utah County. The system allows buses that are behind schedule by a given threshold to request priority at a signalized intersection by sending an SRM message over the V2X system to the signal controller through the RSU. When it was operationalized on Redwood Road in November 2017, it was the first Vehicle to Infrastructure (V2I) system in the United States to be fully operational in a functioning transportation system, executed in cooperation with the UTA.

Previous evaluations of UTA Route 217 utilize bus automatic vehicle location (AVL) data, high-resolution automated traffic signal performance measures (ATSPM) data, and V2X data. These evaluations indicate that schedule reliability for equipped buses achieve up to a 6 percent improvement in schedule reliability and up to a 34 percent reduction in schedule deviation variability with minimal impacts to general traffic.

In Project 2.1, UDOT and UTA expanded this system to UTA Route 850 along Utah County State Street from the Lehi Frontrunner Station to 300 South in Provo (see Figure 5) by deploying 48 C-V2X RSUs along the corridor and equipping 30 UTA buses with OBUs. A tabulated list of each RSU shown in Appendix A: RSU Deployment List. This deployment further leverages the investment and collaboration of the Pooled Fund Study states and FHWA, who built the Multi-Modal Intelligent Traffic Signal Systems (MMITSS) software that this TSP system was based on, and builds on UDOT's earlier TSP deployments. UDOT and UTA selected Route 850 after considering route importance, schedule adherence challenges, and traffic characteristics.

More information about the deployment and operation of transit signal priority in this project can be found in Webinars #3 and #4 of the *Utah Connected* Webinar Series, titled *Deploying Connected Vehicle Technology* and *Connected Vehicles Technology for Transit Signal Priority and Preemption*.

Figure 5 Project 2.1 TSP deployment map.

2. Performance Metrics, Evaluation Methods, and Data Sources

This section describes the project goals that align with Section 6004 of the Fixing America's Surface Transportation (FAST) Act (PL 114-94) and a discussion of the challenges encountered.

Goal: Improved System Performance

The primary goal of this project was improving the performance of transit operations for Route 850 through V2X-enabled TSP. Many V2X safety benefits require increased penetration rates but improved transit operations is a significant and measurable Day 1 benefit when deploying this technology.

Route 850 AVL data from January 2, 2022, to June 30, 2023, were used to evaluate the impact of TSP on bus performance. AVL data were recorded for each bus by timepoint. A pre-post analysis was executed to compare how bus performance was impacted by TSP. The "before" time period was January 2, 2022 to December 31, 2022 and the "after" time period was January

1, 2023 to June 30, 2023. Table 5 lists the performance measures of on-time performance (OTP) and travel time, along with their associated goal areas, data methods, data sources, data collection time periods, and sample size.

Table 5 Project 2.1 Performance Metrics

Goal Area	Performance Measure	Data Method	Data Source	Data Collection Time Period	Sample Size
Improved System performance (including optimized multimodal system performance)	Transit on-time performance	Field test, Quantitative data comparison	AVL data	1/2/2022–6/30/2023	362,689
Improved System performance (including optimized multimodal system performance)	Transit travel time	Field test, Quantitative data comparison	AVL data	1/2/2022–6/30/2023	362,689

Project and Data Challenges

This project encountered challenges coordinating with individuals unfamiliar with previous TSP deployment efforts and best practices by their predecessor. This led to the understanding that clearly documenting roles, responsibilities, and step-by-step instructions was needed to ensure that deployed technology meets the functional requirements and that device configurations are done properly. All these challenges were ultimately overcome.

3. Evaluation Results

Some deployment challenges prevented TSP from functioning at 24 of the 49 intersections during the data collection time period. A map of Route 850 RSUs colored by classification category is shown in Figure 6. The 14 intersections with Q-Free (formerly Intelight) controllers were not properly configured, an error which was corrected after data collection ended. TSP is now functioning at these intersections. The 5 intersections with incomplete MAPs were due to major road construction that prevented the creation of accurate MAPs until construction was completed. The 5 intersections owned by Orem did not allow TSP due to signal timing disruption concerns when TSP is granted. The 25 intersections with Econolite traffic signal controllers were the only intersections during the data collection time period where TSP was functioning properly. Thus, the reported benefits were realized with only a portion of the intersections properly acknowledging and granting the TSP requests. Consequently, it is expected that bus performance will improve even more now that these 14 Q-Free controllers are granting TSP.

Figure 6 Route 850 RSU classification.

A pre-post evaluation was executed and compared bus performance during the study period. The pre-deployment timeframe was during 2022 and post-deployment was during 2023. However, not all buses running on Route 850 were equipped so the evaluation was also able to compare the performance of equipped and non-equipped buses during the same post-deployment time period during 2023. This post-deployment comparison of equipped and non-equipped buses was critical to understand differences in bus performance during the similar operating conditions in 2023.

On-Time Performance (OTP) Results

Figure 7 shows that equipped buses on Route 850 experienced improved schedule adherence with TSP. Equipped bus OTP improved from 86.8 percent pre-deployment to 88.1 percent, an increase of 1.3 percentage points. UTA has indicated that a 1.0 percentage point increase in OTP is meaningful, and this 1.3 percentage point improvement was obtained during a time when TSP was only functioning at half of the intersections along the route. While OTP improved for equipped buses in 2023, it worsened for non-equipped buses with OTP decreasing from 86.8 percent in 2022 to 85.4 percent in 2023.

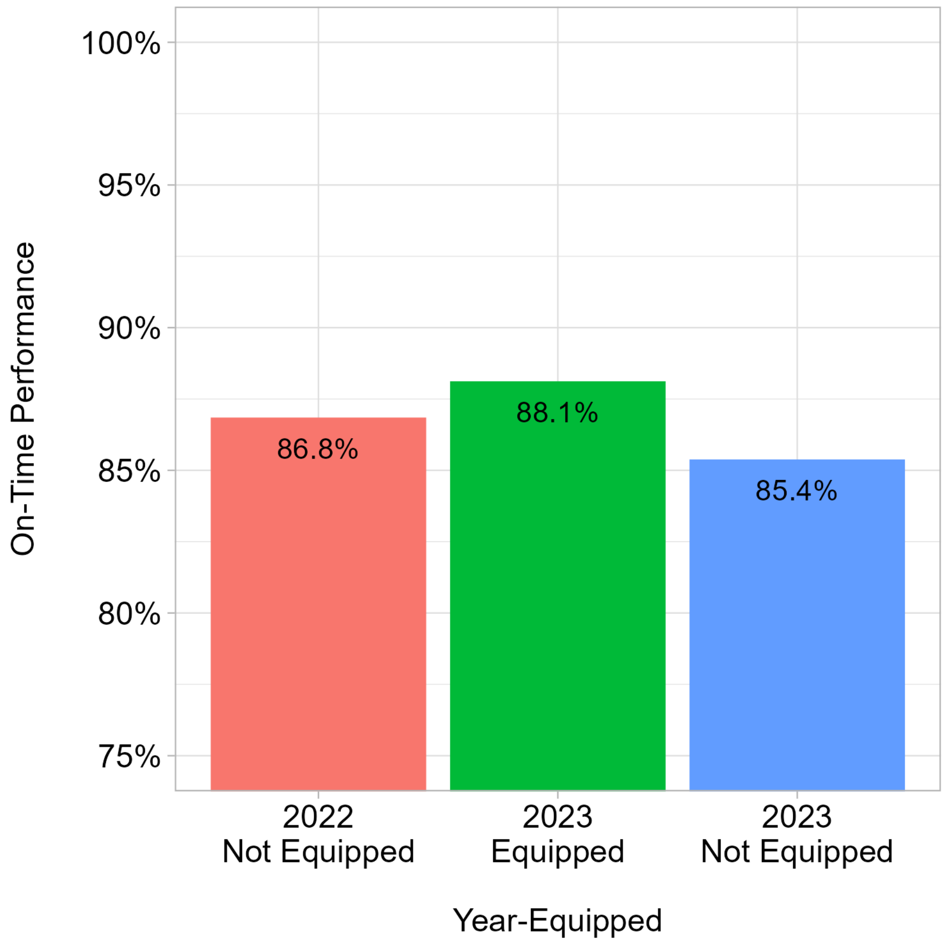

Figure 7 Route 850 corridor-level OTP.

Because the route remained the same throughout the study period, the decrease in OTP from 2022 to 2023 for non-equipped buses suggests that external factors degraded transit operations in 2023; non-equipped bus OTP was expected to be the same in 2022 and 2023 all else equal. Consequently, evaluating equipped and non-equipped buses under the same 2023 operating conditions demonstrates that equipped buses capable of requesting TSP increased OTP by 2.7 percentage points. It was outside the scope of this evaluation to determine the magnitude of bus performance impacts from external factors, but changes in ridership, general traffic conditions, and even bus operator driving behavior can have meaningful impacts on bus performance.

Evaluating OTP at the timepoint level provides additional insight into equipped buses' cumulative improvement to schedule adherence. In both the NB and SB directions, 2022 non-equipped, 2023 non-equipped, and 2023 equipped buses begin the route with approximately the same OTP. By the end of the route, OTP for 2023 non-equipped buses was much lower (see Figure 8).

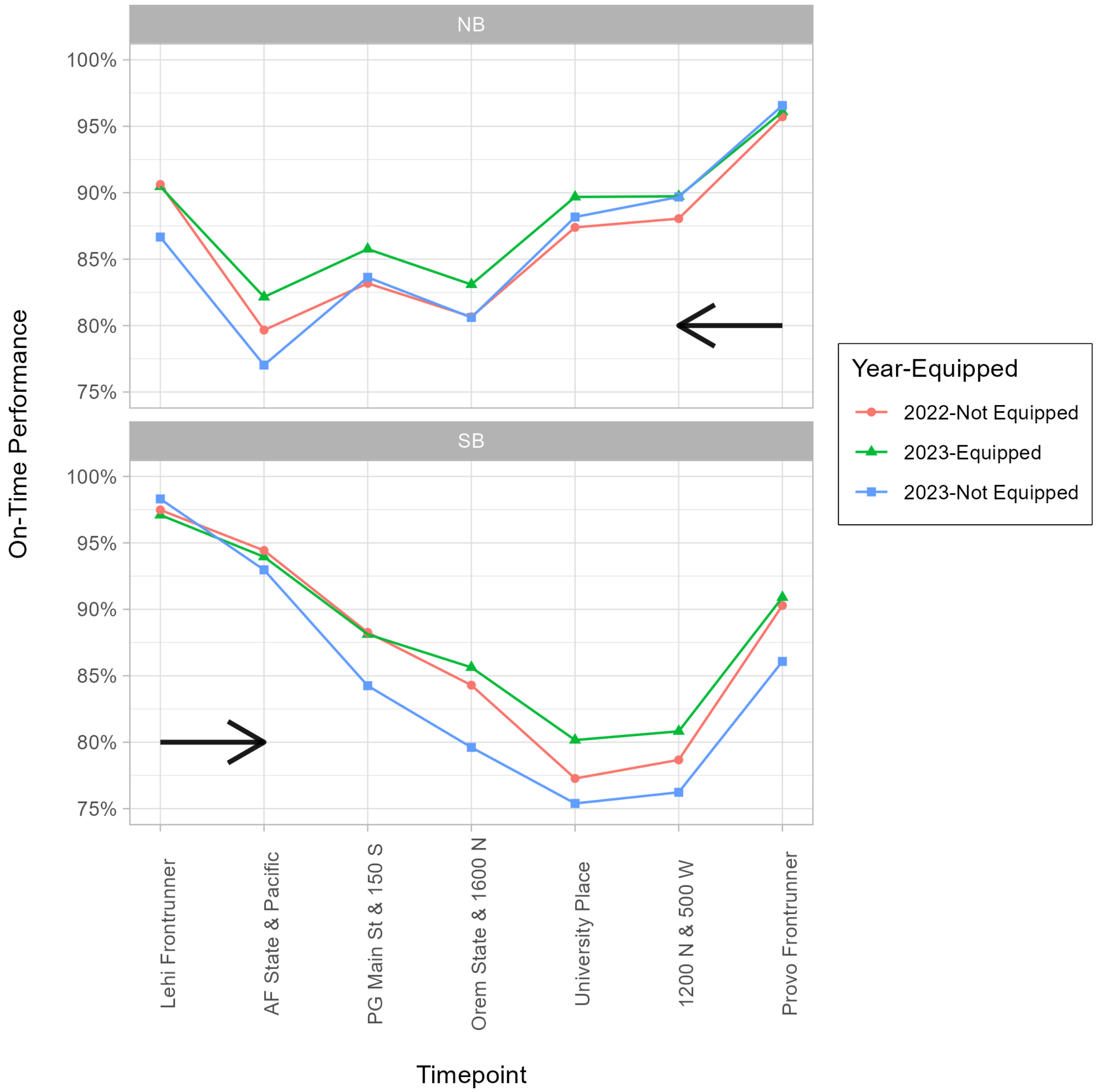

Figure 8 Route 850 timepoint-level OTP.

In 2023, OTP at the beginning of the route for NB equipped buses was 0.5 percentage points lower than non-equipped buses but 3.8 percentage points higher at the end of the route, a net difference of 4.3 percentage points. In the SB direction, OTP at the beginning of the route for equipped buses was 1.2 percentage points lower than non-equipped buses but 4.8 percentage points higher at the end of the route, a net difference of 6.0 percentage points.

Travel Time Results

The evaluation of total route travel time demonstrates a sharp increase in travel time for 2023 non-equipped buses, which took 2.4 minutes longer, on average, to complete their route than their 2022 non-equipped counterparts (see Figure 9). This suggests that the external factors affecting bus performance in 2023 resulted in a 2.4-minute longer travel time. Meanwhile, any TSP benefits provided to equipped buses were not enough to overcome these external factors as 2023 equipped buses completed the route in 69.8 minutes, or 0.1 minutes slower than the 2022 buses pre-deployment. Nevertheless, equipped buses in 2023 completed their route 2.3 minutes faster, on average, than non-equipped buses.

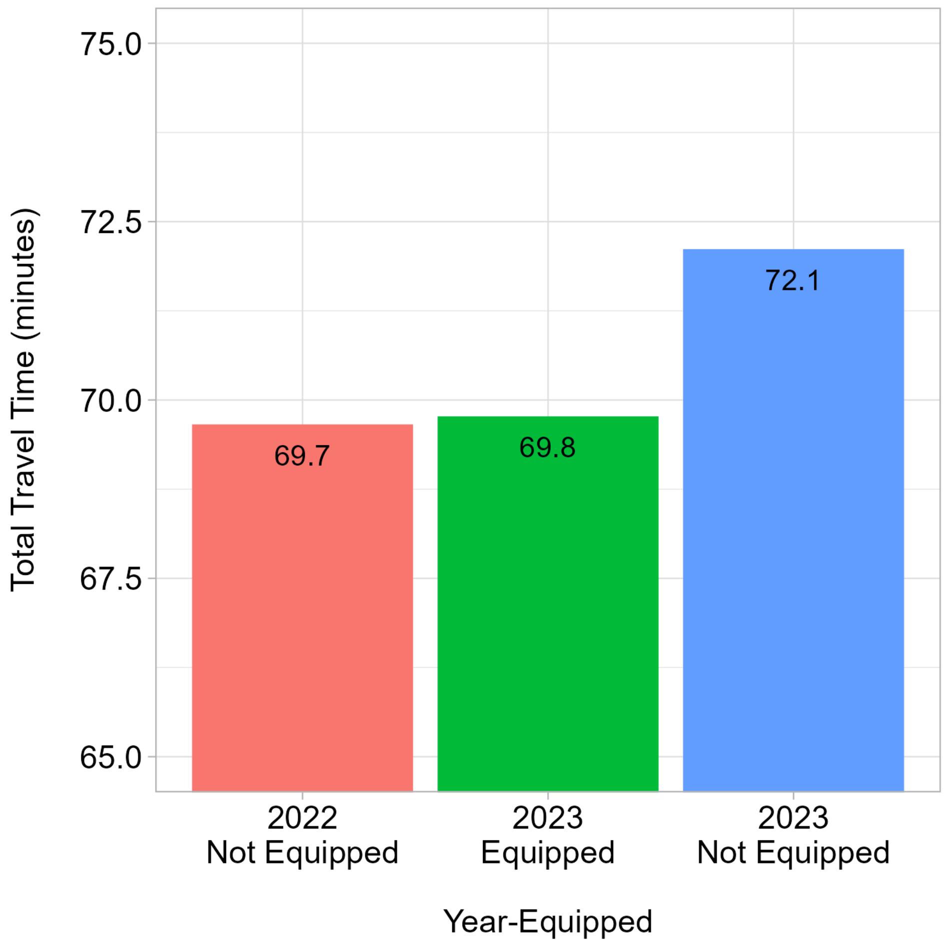

Figure 9 Route 850 total travel time.

4. Lessons Learned, Recommendations, and Conclusions

UDOT's first V2X-based TSP system was deployed in 2017 along Redwood Road in Salt Lake County, on which UTA Route 217 operates. In 2019, V2X TSP was deployed on UVX, a new bus rapid transit route in Utah County that began operation that same year. 73 RSUs and 35 OBUs were deployed for these two routes and several research efforts evaluated the impact of

TSP on bus performance and general traffic. Even with this depth of knowledge and experience deploying V2X TSP, the project team identified several lessons learned, or ways to improve deployment best practices.

First, the expansion of UDOT's TSP deployment footprint, employee turnover, and new deployment contractors increased the number of individuals engaged in this effort. Knowledge obtained from deploying the original TSP corridors did not always get passed along to new participants engaged in *Utah Connected* deployments. Documenting deployment best practices or creating deployment guidebooks would help new participants understand what is required of them, steps to accomplish their work, and common pitfalls.

For example, traffic signal controllers need to be properly configured to allow TSP; a complex workflow that differs among controller manufacturers. UDOT's new signal engineer did not have the same depth of experience as his predecessor and inadvertently overlooked a minute, albeit critical, detail when configuring the Q-Free controllers, which prevented all the Q-Free controllers from acknowledging and granting TSP. This was easily fixed once discovered, but clearly documenting the steps to configure each type of signal controller may have prevented this altogether.

Second, it is essential to confirm functionality of the system and that it is operating as designed. Differences among controller brands, variations in MAP content, and hardware compatibility issues necessitate a variety of troubleshooting steps to identify the cause of common issues. The project team concluded that performing a drive test would be a reasonable action and is recommended to confirm functionality and troubleshoot problems.

A third lesson learned and associated recommendation is to define roles and expectations internally and with project partners. More specific contract language would have resolved ambiguity regarding the work that was needed to be done and by whom; a clear expectation and definition of deliverables would have simplified the final acceptance of completed work; and a mutual understanding of how to assess acceptable device and application performance would have led to the discovery of performance issues much sooner.

Finally, some cursory field evaluation of MAP is needed to validate the published MAP against field conditions, especially before and after construction and lane reconfiguration. Efforts are underway outside of this grant project to identify suitable methods to verify MAP messages.

PROJECT 2.2 SNOWPLOW PREEMPTION

1. Project Summary

Description

Quick and efficient removal of snow from our roadways is a key to safety. A recent study performed by UDOT suggests that up to 89 annual crashes on 5 urban corridors can be addressed by improving the efficiency of snowplow operations. Based on this, UDOT deployed V2X snowplow preemption along four corridors in Salt Lake County in 2019. The snowplow application allows plow trucks to request signal preemption at intersections when the vehicle is actively plowing snow. Early feedback indicates that this system improves plow performance and removes snow and ice faster than without this system. This application was deployed along routes to optimize the use of plows from certain maintenance sheds and was later extended to the UVX corridor in Utah County, leveraging the RSUs already placed on that corridor for TSP.

In this project, preemption capabilities were extended to four additional corridors in Utah County, as shown in Figure 10 and as follows:

- US-89 /State Street from 2100 North to 100 North in Provo
- SR-92 / Timpanogos Highway from I-15 to North Canyon Road
- SR-68 / Redwood Road from the Utah County border to Pony Express Parkway
- SR-194 / 2100 North from Redwood Road to I-15

To accomplish this, 33 RSUs in addition to those from Project 2.1 were deployed along these corridors and 20 UDOT Region 3 snowplows were equipped with OBUs. A tabulated list of each RSU shown in Appendix A: RSU Deployment List.

More information about the deployment and operation of snowplow preemption in this project can be found in Webinars #3 and #4 of the *Utah Connected* Webinar Series, titled *Deploying Connected Vehicle Technology* and *Connected Vehicles Technology for Transit Signal Priority and Preemption*.

Figure 10 Project 2.2 snowplow preemption deployment map.

2. Performance Metrics, Evaluation Methods, and Data Sources

This section describes the project goals that align with Section 6004 of the Fixing America's Surface Transportation (FAST) Act (PL 114-94) and a discussion of the challenges encountered.

Goal: Improved System Performance

An evaluation analyzing the impacts of preemption on snowplow effectiveness in Utah was already underway at the commencement of this grant. It was intended that the results of this evaluation would be applied to the new routes deployed in this project. However, the final experiment design and analysis methodology did not yield conclusive results that could appropriately be applied to this project.

Table 6 Project 2.2 Performance Metrics

Goal Area	Performance Measure	Data Method	Data Source	Data Collection Time Period	Sample Size
Improved System performance (including optimized multimodal system performance)	Plow average speed	Field test (post deployment)	Plow AVL Data	10/19/2019 to 4/16/2020	75,738
Reduced Congestion/Improved mobility (e.g., travel time reliability)	General traffic average speed	Quantitative data comparison	Third party probe data	10/19/2019 to 4/16/2020	262,656
Increase knowledge and understanding of emerging technologies	Duration of preemption call	Field test	ATSPM	10/19/2019 to 4/16/2020	
Increase knowledge and understanding of emerging technologies	Time it takes to return signal to normal, coordinated operation	Field test	ATSPM	10/19/2019 to 4/16/2020	

Project and Data Challenges

At the beginning of this grant's period of performance, a separate UDOT research effort was underway to evaluate the impact of preemption on snowplow operations. The intent was to use the results from that evaluation effort to complete the analysis for Project 2.2. This research compared the performance of five corridors equipped with V2X RSUs and 44 V2X-equipped snowplows with five analogous non-equipped corridors. Several experiment design and data challenges caused inconsistencies in the results when comparing equipped and non-equipped plow performance.

First, every winter storm is different. The snowfall rate, temperature, time of day and day of the week it occurs, storm duration, geographic anomalies of a given storm, how plows are dispatched, and effectiveness of pretreatment each influenced how a given storm affected each corridor.

Second, even though great effort was made to compare an equipped corridor to an analogous non-equipped corridor, they were simply too different to appropriately compare. Differences in travel speeds, speed limit, traffic volume, number of lanes, geometric layout, and signal timing were just some of the confounding factors believed to result in operating conditions that led to inconsistencies in the results.

And third, low sample size likely influenced the inconsistency of the results. Snowplows only operate when there are snow storms, which occurred on 46 different days during the study period. In addition to the low storm sample size, plow AVL data was the only vehicular data available for snowplows on non-equipped routes, which was recorded every 30 seconds. This low granularity prevented an accurate analysis of plow travel time and speed, especially when compared to the equipped snowplows that transmitted BSMs every 0.1 seconds.

For these reasons, an adequate pre-post evaluation was not possible, but the results are still included and discussed in the next section.

3. Evaluation Results

Plow AVL data was used to evaluate the average plow speed, which was 15.5 mph during the study period. By design, snowplow operators are not allowed to travel at a speed greater than 35 mph.

General traffic speed was collected via third party probe data purchased by UDOT. During winter weather events, general traffic average speed was 32.35 mph on equipped corridors that granted snowplow preemption compared to a slightly slower speed of 32.26 mph during normal, non-winter weather conditions.

The average duration of a preemption call lasted 25.7 seconds and ranged from 21.5 seconds to 32.4 seconds.

On average, traffic signals that granted preemption took less than three minutes to return to normal operation. Furthermore, 97 percent of traffic signals were affected for less than five minutes. This was below the maximum acceptable threshold of six minutes identified by UDOT Signal Engineers and led to the general understanding that providing snowplow preemption had minimal impacts on traffic signal performance.

Also, interviews with snowplow shed foremen led to the understanding that the operators noticed that they make fewer stops when plowing corridors capable of granting preemption. This is a significant safety benefit because when snowplows are stopped at a traffic signal, it is common for personal automobiles to pass the snowplow once the light turns green, a dangerous maneuver that has led to many crashes and hinders snow removal operations.

4. Lessons Learned, Recommendations, and Conclusions

Several data challenges prevented the evaluation from taking place as designed. Plow AVL data is only recorded every 30 seconds and the third-party probe data is aggregated in 15-minute bins. Ideally, a pre-post analysis would occur on equipped corridors with preemption turned off and then on while snowplows send BSMs ten times a second. Data at this frequency would be sufficient to evaluate plow speed and travel time with and without preemption. These data limitations are important to understand as subsequent evaluations of snowplow operations are designed and performed.

Despite these challenges, interviews with snowplow shed foremen indicating that they make fewer stops when plowing corridors capable of granting preemption was an important discovery.

PROJECT 2.3 CURVE SPEED WARNING

1. Project Summary

Description

A 2018 UDOT study highlighted and evaluated roadway curves with high numbers of crashes. European studies show that if a driver receives information that they believe is specifically for them, such as an in-vehicle warning, they are more likely to react and utilize the data. Applying that approach to a curve speed warning alert, Project 2.3 developed and deployed a proof-of-concept, connected vehicle, V2I curve speed warning (CSW) system.

Since the highest curve-related crash locations are scattered in various locations in the state, UDOT selected eight high-crash locations within Salt Lake County for initial deployment of this application. Choosing centralized and heavily trafficked locations made the development, testing, and deployment activities of this project more efficient. The CSW curves for deployment are shown in Figure 11 with red markings and include freeway ramps from I-80 Eastbound to I-15 Southbound (two RSUs), I-215 Northbound to SR-201 Westbound (two RSUs), SR-201 Eastbound to I-15 Southbound (two RSUs), and five locations along SR-190 in BCC (eight RSUs). Each of these locations are at curves with high crash frequency and severity. Figure 12 shows a map of the RSUs deployed in this project to directly support the transmission of CSW TIM alerts. A tabulated list of each RSU shown in Appendix A: RSU Deployment List.

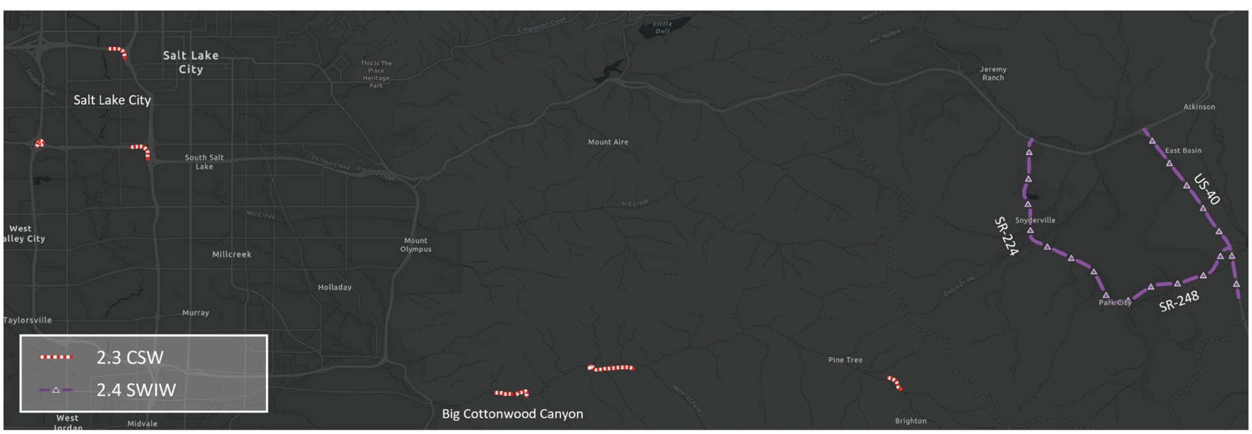

Figure 11 CSW and SWIW highway locations.

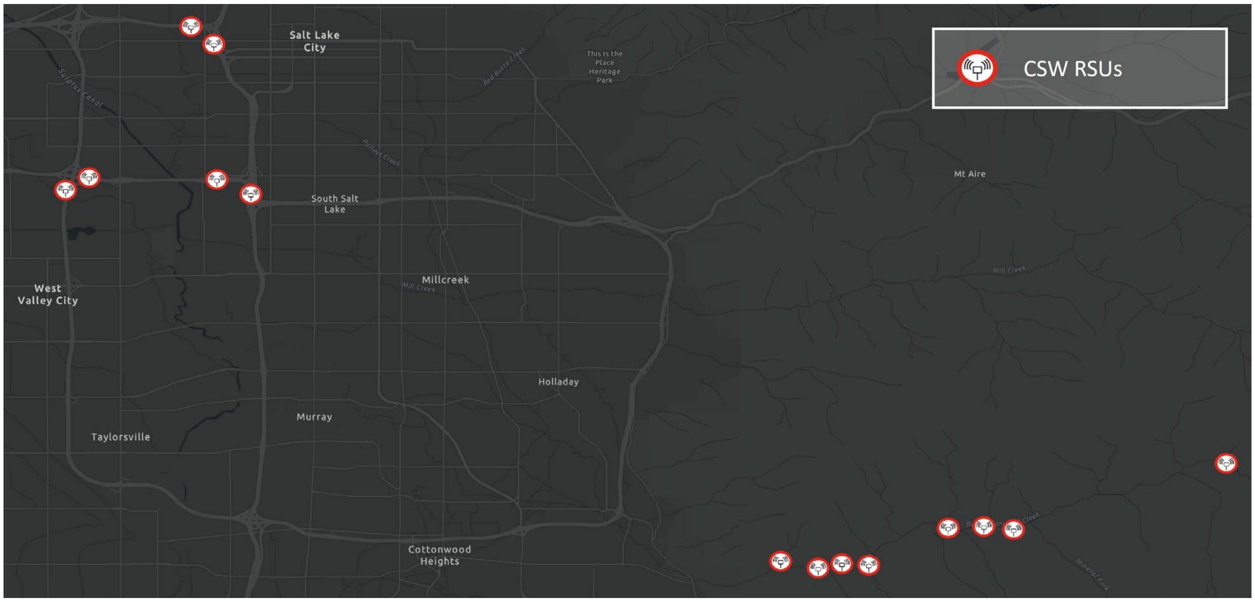

Figure 12 Project 2.3 deployment map.

In total, this project equipped 5 UDOT fleet vehicles with OBUs that frequently travel these areas and 14 RSUs to facilitate the useful dissemination of CSWs. The customized, in-vehicle warning is displayed on a human-machine interface (HMI), which was installed on three UDOT fleet vehicles that were also equipped with OBUs. One of the vehicles with a dash-mounted HMI is shown in Figure 13 with an in-dash HMI shown in Figure 14.

Figure 13 Dash-Mounted HMI.

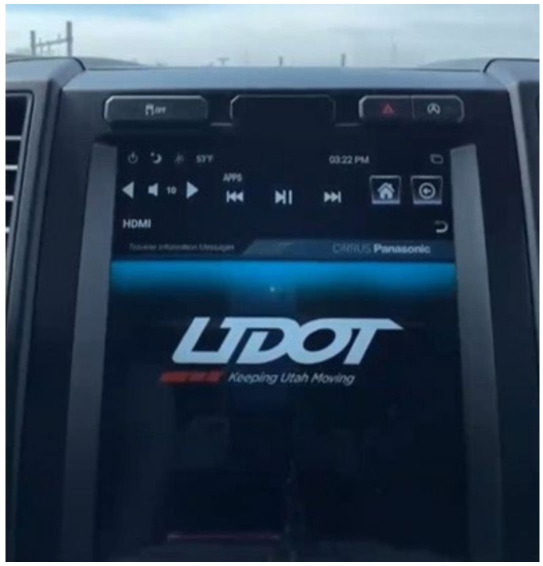

Figure 14 In-Dash HMI.

2. Performance Metrics, Evaluation Methods, and Data Sources

This section describes the project goals that align with Section 6004 of the Fixing America's Surface Transportation (FAST) Act (PL 114-94) and a discussion of the challenges encountered.

Goal: Improved Safety

The primary goal of the CSW application is to improve safety at dangerous curves. The proposed evaluation for this project sought to evaluate changes in driver behavior when the CSW alert was displayed in the vehicle and survey participants regarding their perception of the usefulness of the alert. Several issues were discovered that affected the performance of this application, some of which were not resolved until the final weeks of the period of performance. Accordingly, the complexity and duration of these issues prevented this evaluation from taking place as designed.

Notwithstanding, we are confident that the CSW application can improve safety. Several drive tests were performed to confirm CSW functionality and Figure 15 shows a CSW alert displayed on the HMI during one of them as the vehicle is approaching one of the CSW curves. This application and the associated infrastructure elements of the system are functional and ready for OEM adoption.

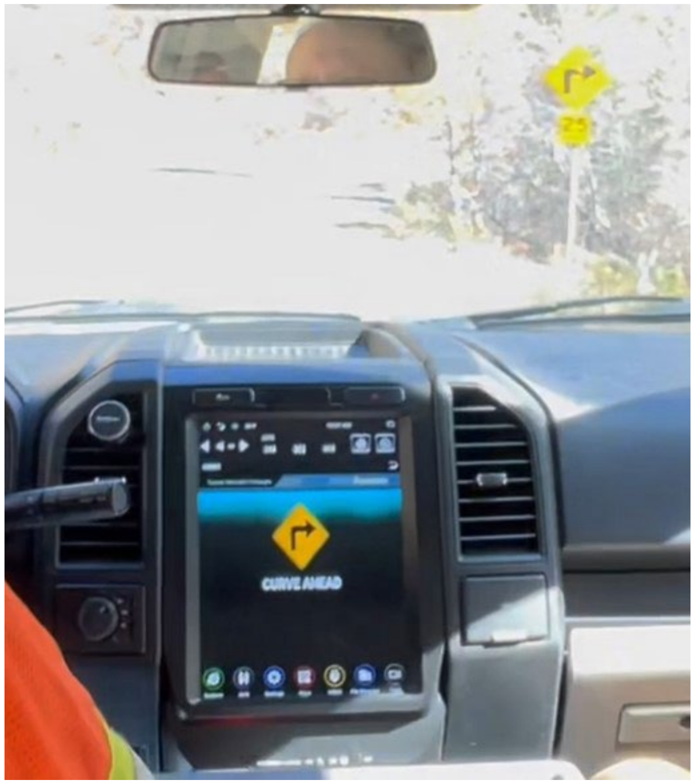

Figure 15 CSW alert during a drive test in BCC.

Goal: Improved Technology Performance

One of the primary issues affecting this project was inaccurate GPS locations being reported in the BSM. These GPS issues and the implemented solution led to the unexpected identification of improved system performance as a new project goal that could be measured in our post-deployment evaluation. Meeting this goal is evaluated through the analysis of GPS accuracy before and after the identified solution was implemented. Table 7 lists the performance measure of distance from reported GPS location to nearest highway centerline, along with its associated goal areas, data methods, data sources, data collection time periods, and sample size.

Table 7 Project 2.3 Performance Metrics

Goal Area	Performance Measure	Data Method	Data Source	Data Collection Time Period	Sample Size
Improved Technology Performance	Distance from GPS location to nearest highway centerline	Field test, Quantitative data comparison	BSM Data	6/2/2020 – 12/24/2023	5,760,300

Project and Data Challenges

Several BSM integrity issues were discovered during the preliminary CSW evaluation, including GPS errors, incorrect values for vehicle speed, and difficulties decoding the controller area network (CAN) data for equipped vehicles. Also, errors in the application itself prevented the CSW alerts from properly displaying on the HMI. Each of these challenges are discussed in further detail below.

GPS Errors

The GPS errors observed include severe GPS drift, GPS "jumping", and GPS coordinates showing (0, 0). While these errors were observed throughout the deployment footprint, they were more prevalent in BCC.

A variety of solutions were investigated, and these GPS errors surprisingly took over three years to resolve. The investigation discovered that the dead reckoning algorithm was not working properly on the OBU. The identified solution was to disable the algorithm, which was successfully completed for all OBUs in July of 2023. Once disabled, GPS accuracy improved immensely and not a single BSM has since contained the coordinates of (0, 0). Figure 16 shows, along with the embedded map displaying the BSMs at or near (0, 0), the reported location of every BSM received by RSUs in BCC. This illustrates the severity and prevalence of GPS drift within the canyon. Figure 17, on the other hand, shows the reported location of BSMs after the dead reckoning algorithm was disabled and demonstrates the remarkable improvement that was observed.

Figure 16 Reported BSM location in BCC.

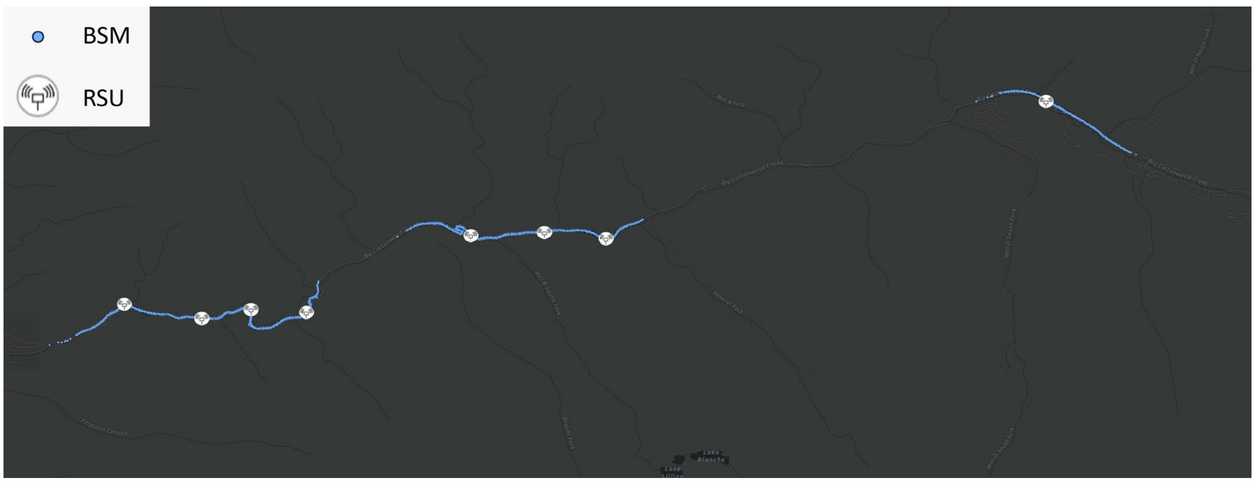

Figure 17 Reported BSM location in BCC after the dead reckoning algorithm was disabled.

Figure 18 shows an example of the GPS jumping and drifting issues. In this example, subsequent BSMs “jumped” 75 meters and 32 meters, and they drifted up to 354 meters from the roadway. Figure 19 illustrates that the BSMs with severe GPS drift often still match the roadway geometry and curvature but are offset by a certain distance. GPS errors associated with jumping and drifting report GPS coordinates with various proximity to the actual location of the vehicle, but 6.8 percent of BSMs reported GPS coordinates of or near (0, 0) when the dead reckoning algorithm was still enabled.

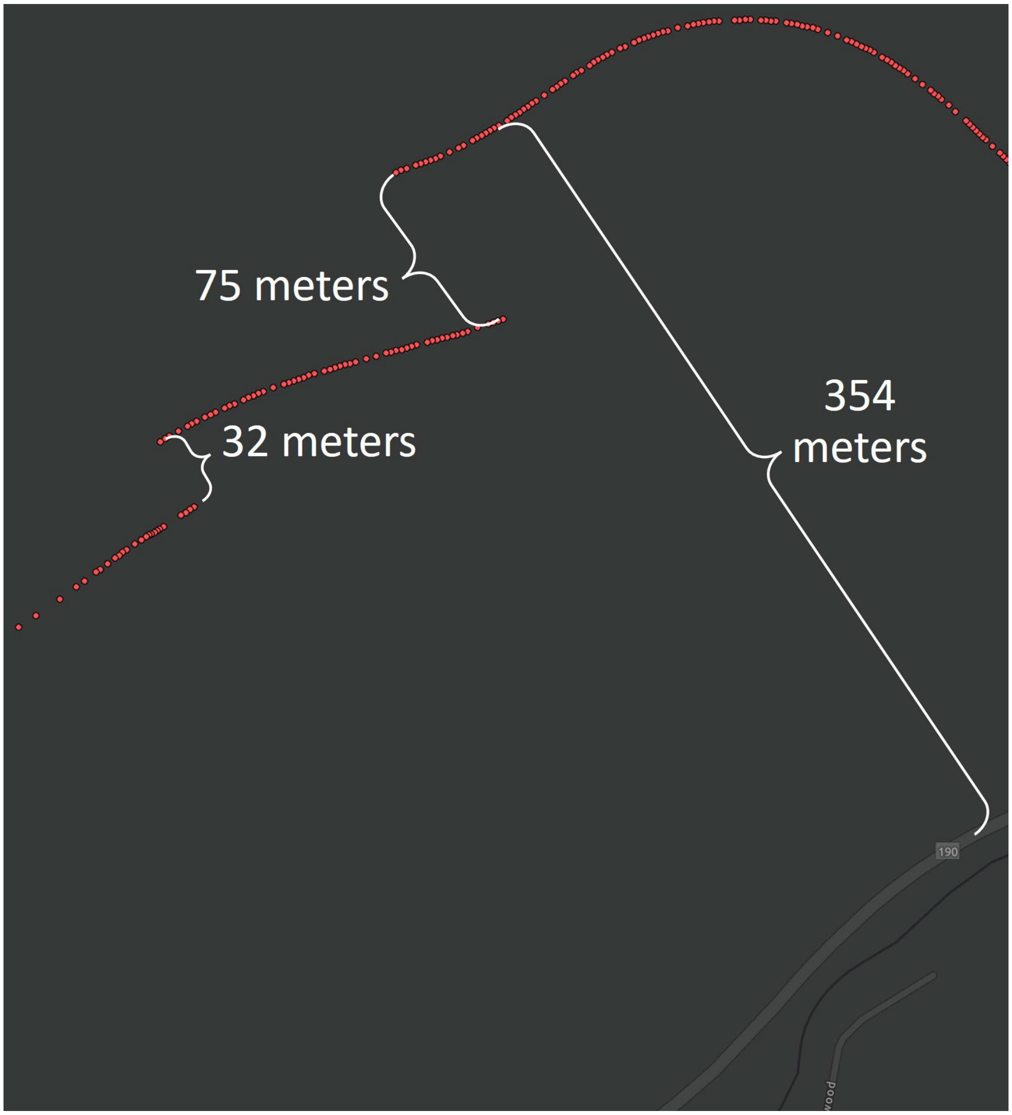

Figure 18 GPS jumping and drifting in Big Cottonwood Canyon.

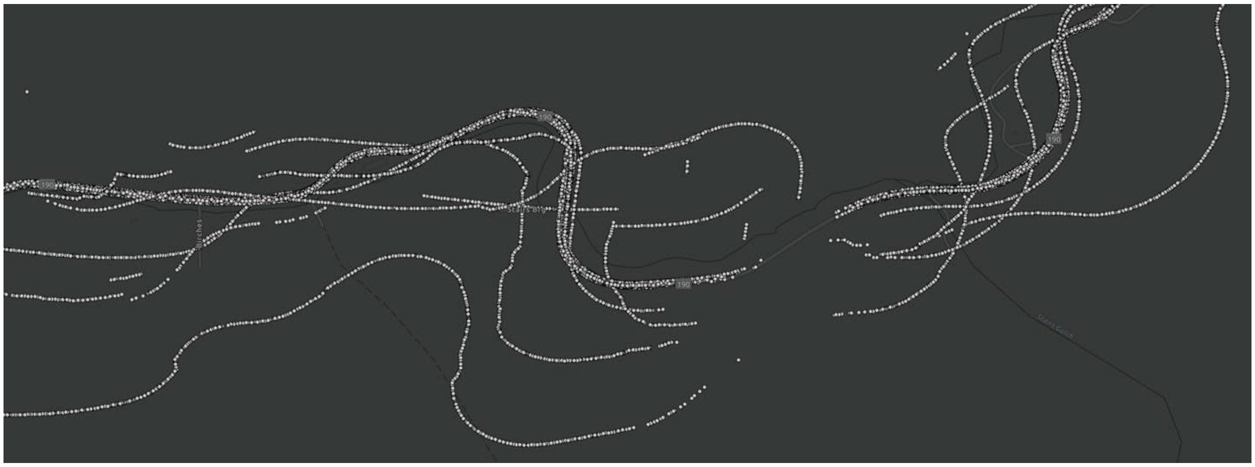

Figure 19 GPS drifting in Big Cottonwood Canyon.

Incorrect Vehicle Speed
Incorrect values for vehicle speed were frequently observed throughout the canyon. The highest posted speed limit in BCC is 45 mph yet approximately 3 percent of BSMs in the canyon have values for speed greater than 70 mph and values as high as 350 mph. The frequency of these high speed values was approximately the same after the dead reckoning algorithm was disabled. Therefore, the cause of these high speed values is unknown and this issue remains unresolved. Our investigations point to issues with the CAN data, but a solution for this issue is out of our control. To overcome this issue, we exclude everything greater than 30 mph over the posted speed limit. Nevertheless, we remain unsure of the accuracy of these speeds, and other speeds, too, that appear to be within an acceptable range.

CAN Decoding Difficulties
The CSW evaluation sought to evaluate driver behavior—brake status, speed, acceleration, etc.—as the vehicle approached and traversed the curve. The hypothesis is that drivers who receive the CSW alert will brake sooner as they approach the curve, will be traveling at lower and safer speeds as they traverse the curve, and will not decelerate as hard when compared to drivers who do not receive the alert. Thus, confidence in the precise location of the vehicle when the brakes are applied, or when speeds drop below a certain threshold, is critical to performing the evaluation. Furthermore, the HMI-equipped vehicles must be within a specified geofence (i.e., approaching the curve) for the alert to even display in the vehicle. With the presence and prevalence of the severe GPS drift that was demonstrated in Figure 16, the evaluation was postponed until the GPS issues were resolved. Postponing the evaluation led to the delayed realization of additional problems that critically impacted our ability to perform the evaluation as anticipated.

First, two of the three HMI-equipped vehicles continuously reported a speed of 0 mph despite having GPS coordinates that seemingly matched the vehicle's location as it traveled along the road. Although standards exist for vehicle CAN data such as SAE J1979 and SAE J1939, vehicle manufacturers are not required to implement all data elements outlined in these standards and can include propriety data that are not listed. Consequently, each unique combination of vehicle make, model, and year (MMY) may have its own CAN decoding "map" that is utilized to obtain the vehicle data used to populate the data elements in the BSM. The wrong "map" was used for these two HMI-equipped vehicles and was fixed by using the appropriate CAN decoder map for these MMYs. The process of discovering and implementing the correct CAN decoding map to fix the speed issue for these HMI-equipped vehicles has led to additional insights that enhances the CAN data obtained for other vehicles equipped in other *Utah Connected* projects, such as snowplows, transit buses, and other fleet vehicles.

Second, inadequate CAN decoding also resulted in an alarmingly high number of equipped vehicles without an HMI that did not have brake data in their BSMs. Many other expected BSM data elements were also unavailable, such as antilock brake status, traction control status, acceleration, and transmission state. This hindered our ability to establish a baseline driver behavior profile for vehicles that are unable to display the CSW alert. Furthermore, inadequate CAN decoding also represents a significant opportunity loss as many of the envisioned benefits of connected vehicles require this data.

Application Design
During the first drive test, it was discovered that the CSW alert did not properly display on the HMI at most CSW locations. This prompted an immediate and thorough investigation that revealed issues with the CSW application itself. This problem has been fully resolved and CSW alerts are properly displayed at each of the eight CSW locations. This experience provided the noteworthy insight that contractual language with the V2X deployment and installation contractor needs to address device, application, and system performance expectations in sufficient detail. Unwritten assumptions did not always align between the project team and deployment contractor, which strengthened the need for clarifying details in deployment contracts.

3. Evaluation Results

A pre-post evaluation was performed for this project that analyzed the distance from the reported GPS location to the nearest highway centerline before and after the dead reckoning algorithm was disabled. Cumulative distribution function curves show the probability (y-axis) of the observed values being less than or equal to the corresponding x-axis value and were generated for this evaluation. Figure 20 uses a logarithmic scale for the measured distance from highway centerline, which is the x-axis of the chart, and shows a stark contrast between the data collected when dead reckoning was enabled (blue curve, n = 4,978,717) and disabled (red curve, n = 781,583).

When dead reckoning was enabled, GPS coordinates at or near (0, 0) were often reported. This is apparent in the blue cumulative distribution curve that has a vertical jump at an x-axis value of approximately 10,000,000. Interpreting the chart at this location provides the understanding that when dead reckoning was enabled approximately 6.8 percent of all records reported GPS coordinates that were more than 10,000,000 meters from the nearest centerline of SR-190 in BCC.

In contrast, the red curve represents data obtained after dead reckoning was disabled. Once disabled, the maximum distance reported in the BSM from the highway centerline was 26.3 meters. Furthermore, the dead reckoning disabled line plateaus at 1, or 100%, at a distance from highway of about 18 meters while the enabled line plateaus at 0.94, or 94%, at a distance from highway of about 700 meters.

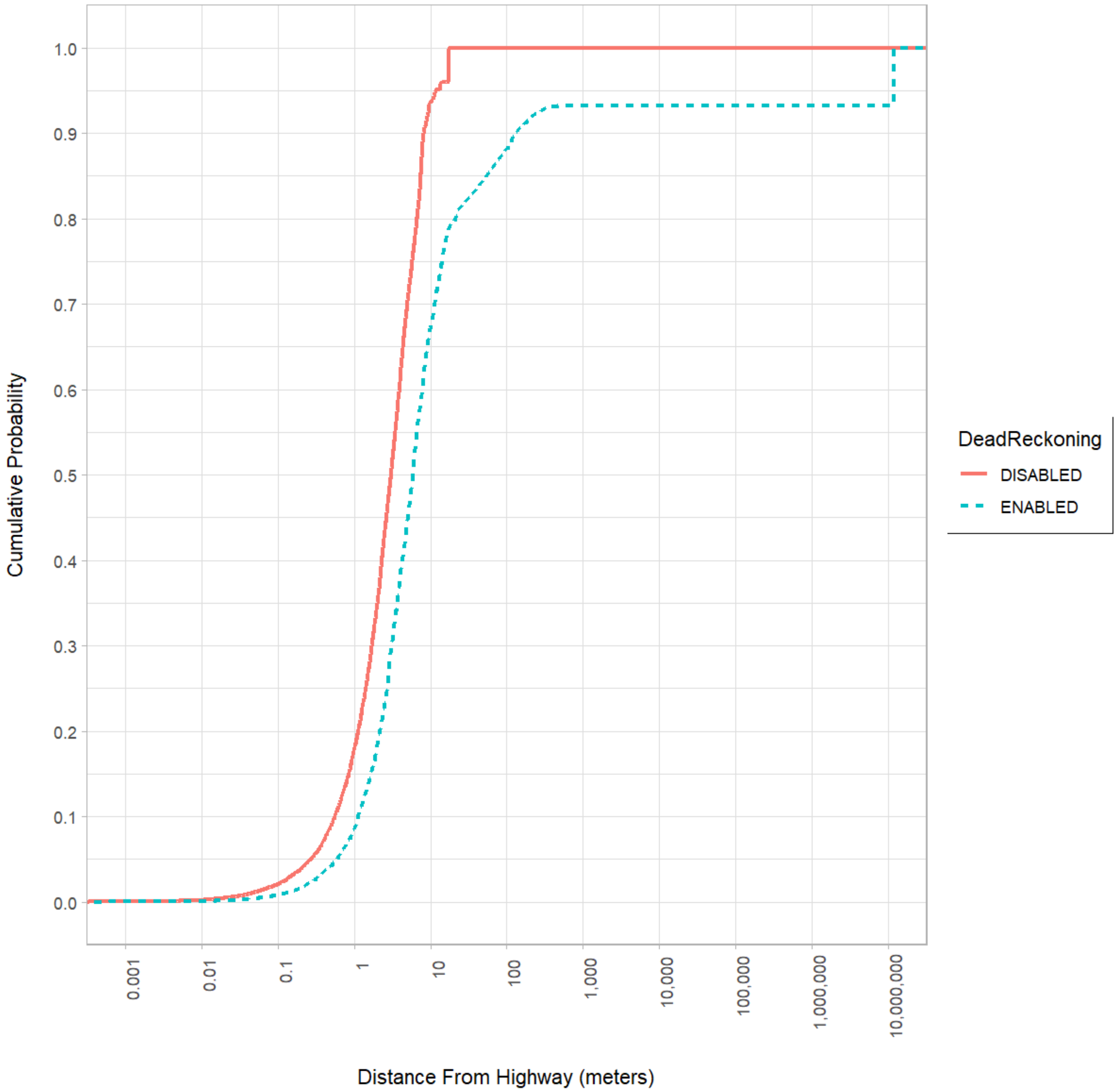

Figure 20 Distance from highway centerline cumulative distribution curve.

The logarithmic transformation makes it challenging to interpret smaller x-axis values; therefore, Figure 21 displays the same cumulative distribution curves when the x-axis is not transformed. It shows that 99.9 percent of reported GPS coordinates are within 17.5 meters of the highway centerline.

Further interpretation shows that the probability of the reported GPS coordinates being within the highway edge lines (less than or equal to 4 meters from the centerline) is 37.4 percent with dead reckoning enabled and 60.6 percent with it disabled.

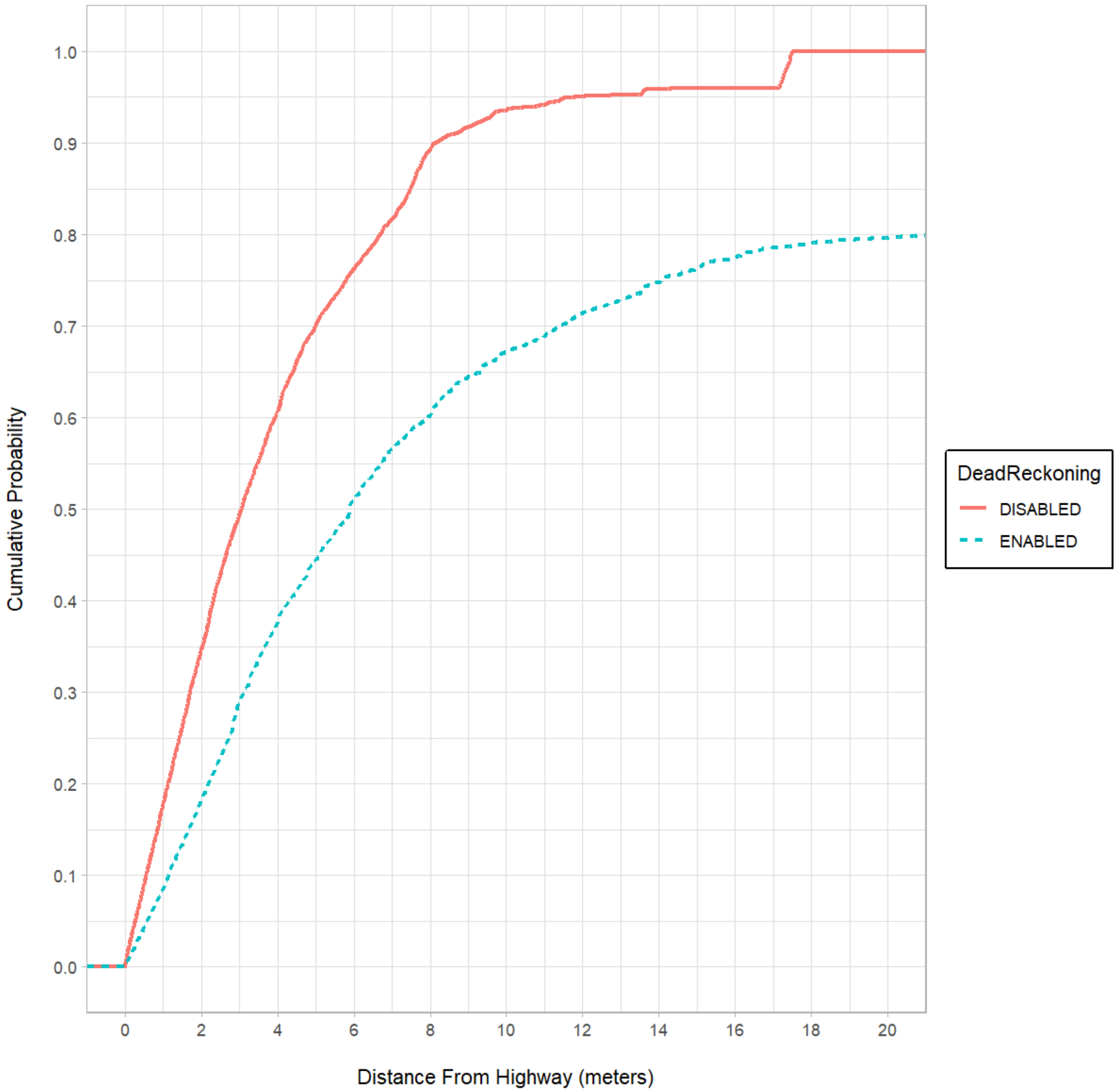

Figure 21 Distance from highway centerline cumulative distribution curve (cropped).

Thus, it is clear that disabling the dead reckoning algorithm on the OBU drastically improves GPS accuracy and completely overcomes the problem of coordinates at or near (0, 0) being reported in the BSM. Anecdotal evidence also suggests that the GPS drift and jumping issues are also greatly minimized; the maximum observed distance from centerline was 26.3 meters and the most severe jumping is shown in Figure 22 and amounts to about half a lane width, or 2 meters. This is within generally accepted tolerances for uncorrected GPS measurements in vehicle-based

GPS systems. It is worth noting that RTCM corrections were not applied during the evaluation. Upcoming work performed outside of this grant will soon evaluate the impact of RTCM on GPS accuracy, especially within this canyon where GPS accuracy is a known issue.

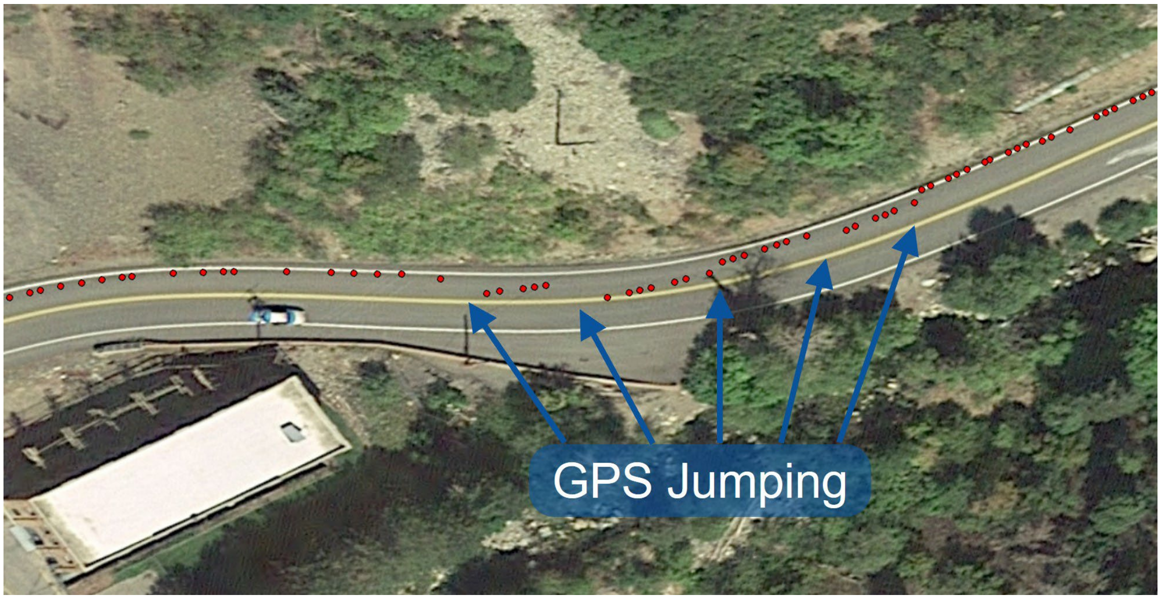

Figure 22 Minimal GPS jumping with the dead reckoning algorithm disabled.

4. Lessons Learned, Recommendations, and Conclusions

Although the impact on safety could not be evaluated during the period of performance, we are confident that the CSW application can improve safety and we plan to deploy this feature at more locations in the future. Most of the issues we encountered were associated with vehicles (e.g., GPS and CAN decoding), and are associated with the necessary after-market installation of OBUs. We are hopeful that as OBUs are integrated more fully into the vehicle by the OEMs that these issues will be resolved. A pressing need to enhance the quality of V2X deployments is greater transparency with vehicle CAN decoding so that the entire BSM can be populated with real and accurate data generated by the vehicle itself.

On the infrastructure side of the application, we successfully deployed a functional CSW application that is ready for OEM use and adoption.

Additionally, part of this deployment challenge was the lack of maturity regarding V2X device and the application itself; we were unaware that certain performance issues would be observed. In future deployment contracts, clarifying language will be added and a phased approach considered to better define expected performance, require demonstration of that performance, and phase the full deployment in accordance with performance milestones.

PROJECT 2.4 SPOT WEATHER IMPACT WARNING

1. Project Summary

Description

The 2018 UDOT study referenced in the Project 2.3 description also highlighted rural roadway segments with high rates of weather-related crashes. Similarly considering that the provision of location-specific warnings directly to drivers through V2I systems can reduce these crash rates, Project 2.4 developed a proof-of-concept, connected vehicle, V2I system to report hazardous roadway conditions directly to individual drivers.

The highest weather-related crash locations are scattered in various locations in the state. To make the development, testing, and deployment activities of this project more efficient, UDOT selected a series of corridors that are near Salt Lake City and prone to frequent winter weather events for initial deployment of this application. As shown in Figure 23, the locations for the SWIW deployment application are along US-40, SR 224 and SR-248 near the Park City area (purple marking) where 15 RSUs were installed. The location of each deployed RSU in this project that supports the transmission of icy road TIM alerts is shown in Figure 24. A tabulated list of each RSU shown in Appendix A: RSU Deployment List.

However, this application was intentionally built for ease in scalability, so any RSU integrated into the Data Ecosystem is capable of transmitting TIMs if properly configured. Thus, the coverage area of this application was expanded by leveraging the RSUs deployed in Projects 2.1, 2.2, and 2.3, as well as the 35 RSUs deployed by another project along I-80 east of Salt Lake City (blue marking).

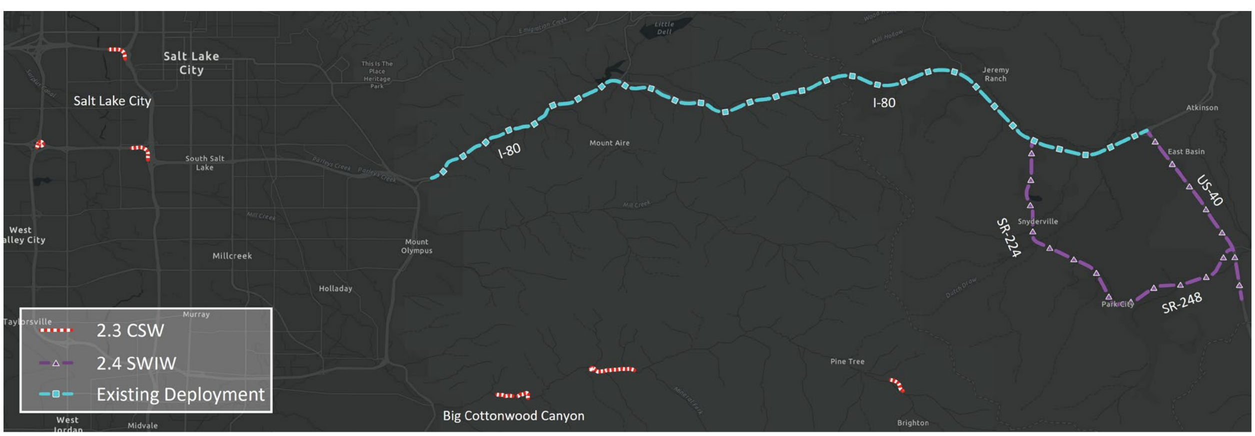

Figure 23 CSW, SWIW, and existing I-80 deployment locations.

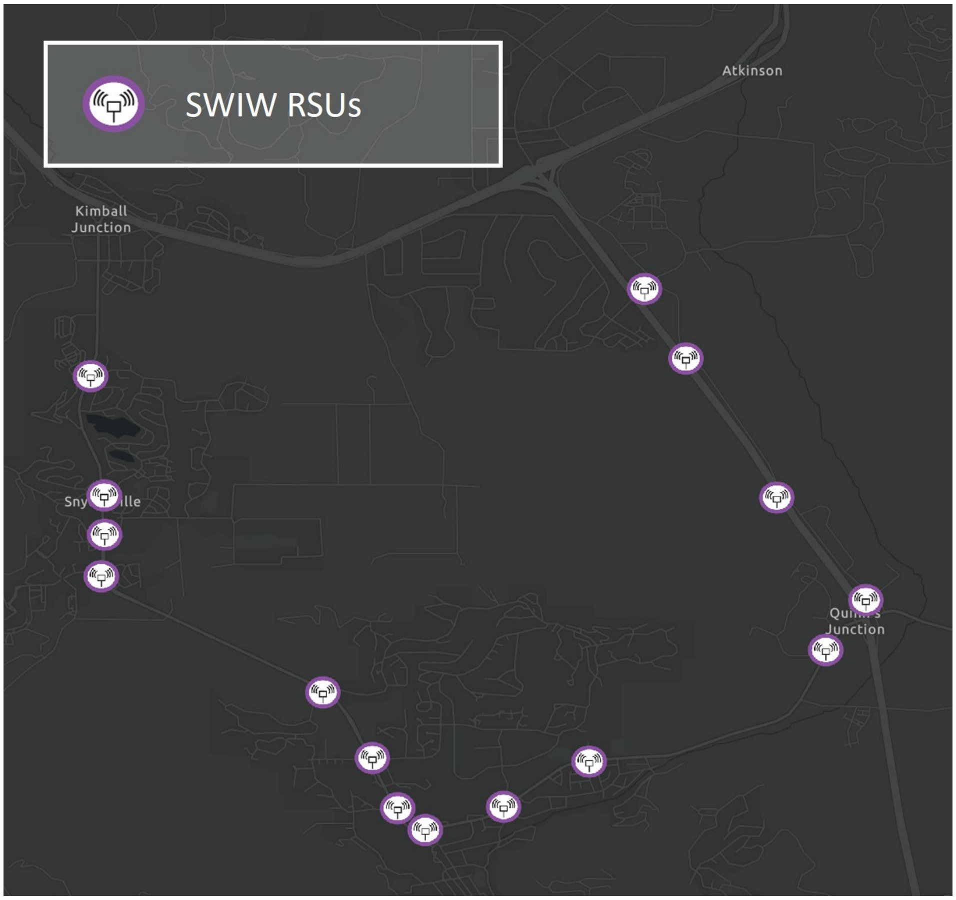

Figure 24 Project 2.4 deployment map.

2. Performance Metrics, Evaluation Methods, and Data Sources

This section describes the project goals that align with Section 6004 of the Fixing America's Surface Transportation (FAST) Act (PL 114-94) and a discussion of the challenges encountered.

Goal: Improved Safety

The original evaluation plan for this project focused on evaluating the effectiveness of this application through a survey of drivers that received SWIWs to assess the perceived helpfulness of the alert, a quantitative analysis assessing changes in vehicle behavior when the alert was received, and a quantitative analysis identifying how often the alerts should have been sent but weren't. Rather than intentionally asking participants to drive in inclement weather and dangerous conditions, the evaluation shifted to measure improved safety through the number of unique SWIWs generated from 1) RWIS Data, 2) CV Data, and 3) a combination of RWIS and CV data. Table 8 lists each of these performance measures along with its associated goal areas, data methods, data sources, data collection time periods, and sample size.

Other factors that influenced this shift in the evaluation were that only three vehicles had an HMI and sample size would be limited, the HMI experienced periodic display issues, which were ultimately resolved, and existence of BSM data accuracy issues.

Table 8 Project 2.4 Performance Metrics

Goal Area	Performance Measure	Data Method	Data Source	Data Collection Time Period	Sample Size
Improved Safety (e.g., reduced crashes)	Number of unique Icy Road events generated from RWIS data alone	Field test	RWIS data, Cirrus logs	1/1/2023 to 12/31/2023	528,367
Improved Safety (e.g., reduced crashes)	Number of unique Icy Road TIMs generated from RWIS data alone	Field test	TIM data, Cirrus logs	1/1/2023 to 12/31/2023	2,356
Improved Safety (e.g., reduced crashes)	Number of unique Icy Road events generated from a combination of RWIS and CV data	Field test	RWIS data, BSM data, Cirrus logs	1/1/2023 to 12/31/2023	528,367
Improved Safety (e.g., reduced crashes)	Number of unique Icy Road TIMs generated from a combination of RWIS and CV data	Field test	TIM data, Cirrus logs	1/1/2023 to 12/31/2023	2,356
Improved Safety (e.g., reduced crashes)	Number of unique Icy Road events generated from CV data alone	Field test	BSM data, Cirrus logs	1/1/2023 to 12/31/2023	528,367
Improved Safety (e.g., reduced crashes)	Number of unique Icy Road TIMs generated from CV data alone	Field test	TIM data, Cirrus logs	1/1/2023 to 12/31/2023	2,356

Project and Data Challenges

A critical deployment challenge was a low penetration rate of equipped vehicles with adequate CAN decoding capabilities to support the SWIW application. In order for the Data Ecosystem to generate an icy road TIM based on vehicle data, equipped vehicles must transmit BSMs with actual vehicle data to populate the ambient air temperature, traction control status, ABS status, and stability control status data elements. Without this information, the Data Ecosystem cannot generate an alert sourced from BSM data. As time went on, the OBU installation team was able provide enhanced CAN decoding capabilities for many equipped vehicles, but successful efforts were limited to select MMYs.

3. Evaluation Results

The Data Ecosystem supports the dissemination of recorded data and we are working on improvements to improve data sharing capabilities and accessible message types. A data challenge experienced was that the underlying data to support this evaluation was not readily available in the data sharing platform. Other data types have been processed and formatted for easy access and readability by members of our Data Access Community, but this dataset was not. The Data Ecosystem development team was ultimately able to provide the data in a usable way, and this need helped act as a catalyst for additional discussions on data sharing practices and expectations as additional deployments outside of this grant occur.

An Icy Road Event is created in the Data Ecosystem whenever:

- An RWIS station reports a surface status of "ice" and a surface temperature between 26- and 32-degrees Fahrenheit; or
- An RSU receives a BSM indicating that the ambient air temperature is less than 35.6 degrees Fahrenheit and at least one of the following data elements is set to TRUE: traction control status, ABS status, or stability control status.

An Icy Road TIM is only created if the Icy Road Event occurs within one kilometer of an RSU. The evaluation results below compares the number of Icy Road Events and TIMs generated by the project based on RWIS data alone, connected vehicle (CV) data alone, and a combination of the two.

RWIS-Generated Events and TIMs

Out of the 528,367 RWIS records ingested, the Data Ecosystem (i.e., Cirrus) logs identified 1,233 Icy Road Events of various durations during 2023, from which 214 unique Icy Road TIMs were produced by the system and transmitted by nearby RSUs.

CV Data-Generated Events and TIMs

Out of the 2,356 weather events generated by equipped vehicles during 2023, the Data Ecosystem (i.e., Cirrus) logs identified 6 Icy Road Events of various durations, from which 3 unique Icy Road TIMs were produced by the system and transmitted by nearby RSUs.

RWIS- and CV Data-Generated Events and TIMs

Out of the 528,367 RWIS records and 2,356 weather events generated by equipped vehicles during 2023, the Data Ecosystem (i.e., Cirrus) logs did not identify any instances where RWIS and vehicle data simultaneously reported icy roadway conditions within the same region. This strengthens the value of CV data-generated TIMs since the vehicle was slipping on the road without nearby RWIS stations reported icy road conditions.

4. Lessons Learned, Recommendations, and Conclusions

Although the impact on safety could not be evaluated during the period of performance, we are confident that the SWIW application can improve safety and we plan to deploy this feature at more locations in the future. Most of the issues we encountered were associated with vehicles (e.g., GPS and CAN decoding), and are associated with the necessary after-market installation of OBUs. We are hopeful that as OBUs are integrated more fully into the vehicle by the OEMs themselves that these issues will be resolved. A pressing need to enhance the quality of V2X deployments is greater transparency with vehicle CAN decoding so that the entire BSM can be populated with real and accurate data generated by the vehicle itself.

As more vehicles transmit BSMs containing the required data elements to generate Icy Road TIMs, the effectiveness of this application will be greatly enhanced.

On the infrastructure side of the application, we successfully deployed a functional SWIW application that is ready for OEM use and adoption.

PROJECT 3.1 LESSONS LEARNED FROM AN AUTONOMOUS SHUTTLE PILOT DEPLOYMENT

1. Project Summary

Description

Project 3.1 focused on the lessons learned from the deployment of a 12-passenger, low-speed, electric shuttle with Level 4 automation that occurred concurrently with this grant period of performance. UDOT and UTA partnered together for this pilot deployment, which began in April 2019 and took place at eight distinct locations throughout Utah. A picture of the EasyMile shuttle operating at one of these sites, Park City Mountain Resort (known as The Canyons Resort at the time of this photo), is shown in Figure 25.

Figure 25 Autonomous Shuttle at Park City Mountain Resort - Canyons Village.

The deployment was focused on three goals: 1) understand the operational characteristics and constraints surrounding the shuttle, to inform potential permanent operations in a transit network; 2) assess the viability of the shuttle as a solution to the first-mile-last-mile problem, specifically by gathering information from the public about whether the presence of a shuttle would influence their decisions to use transit; and 3) interact with the public to assess their opinions, attitudes, and trust of automated operation, or automated vehicles (AVs).

Project 3.1 leveraged this on-going project by expanding data gathering efforts, performing more detailed public trust studies, and capturing lessons learned in a project report so these can be shared more broadly. Cognitive psychology researchers at the University of Utah have developed expertise in automated systems and vehicle distraction. They previously performed a public trust study at one shuttle pilot site to provide insight into public attitudes. Project 3.1 included a more detailed study to provide greater insights into these issues by evaluating participants under one of two distinct scenarios: the shuttle host (on-board operator) was either visibly the shuttle host or disguised as a fellow passenger.

This information was broadly shared within the industry at conferences, workshops, and in publications. Throughout the project, UDOT and UTA gathered a broad variety of information and insight about the operation of a low-speed shuttle system. Project 3.1 supported the compilation of that information into the "Utah Autonomous Shuttle Pilot Final Report", which has been shared with the USDOT as an Intermediate Working Paper (referenced as the Lessons Learned document), and supported outreach efforts to interact with the public and share that data through various webinars and conference presentations.

2. Performance Metrics, Evaluation Methods, and Data Sources

This section describes the project goals that align with Section 6004 of the Fixing America's Surface Transportation (FAST) Act (PL 114-94) and a discussion of the challenges encountered.

Goal: Increase Knowledge and Understanding of Emerging Technologies

One of the primary goals of this project was to increase knowledge and understanding of emerging technologies, specifically surrounding automated vehicle operation. Meeting this goal was evaluated through the administration and analysis of surveys as the shuttle toured the state. Highly specialized cognitive psychology researchers at the University of Utah administered surveys and observed passenger behavior to assess attitudes towards and interactions with the AV shuttle.

Goal: Lessons Learned

Compiling lessons learned from a multi-year AV shuttle deployment was the other primary goal of this project. Throughout the shuttle's deployment, which occurred concurrently with this grant's period of performance, data were collected, surveys were administered, and deployment expectations were adjusted. Meeting this goal was accomplished through the comprehensive compilation and publication of a Final Report, which was provided as an Intermediate Working Paper and can be obtained by visiting UDOT's Transportation Technology website[3].

[3] https://transportationtechnology.utah.gov/what-were-learning/

Table 9 lists this project's performance measures aimed at assessing public trust of AVs and lessons learned from the deployment, along with their associated goal areas, data methods, data sources, data collection time periods, and sample size.

Table 9 Project 3.1 Performance Metrics

Goal Area	Performance Measure	Data Method	Data Source	Data Collection Time Period	Sample Size
Increase knowledge and understanding of emerging technologies	How safely do passengers feel the shuttle was operated	Survey	Survey response in post-survey	5/20/2019 – 8/7/2020	822 survey responses
Increase knowledge and understanding of emerging technologies	How well do passengers feel the shuttle is being monitored	Survey	Survey response in post-survey	5/20/2019 – 8/7/2020	822 survey responses
Increase knowledge and understanding of emerging technologies	How well do passengers feel the shuttle can communicate information and intent?	Survey	Survey response in post-survey	5/20/2019 – 8/7/2020	822 survey responses
Increase knowledge and understanding of emerging technologies	Lessons Learned	Project documentation, survey, interview	Survey response in post-survey, interviews	4/11/2019 – 9/4/2020	822 survey responses, 30 stakeholder interviews

Project and Data Challenges

While several issues caused project delays and increased costs, it was the COVID-19 pandemic and resulting restrictions that impacted this project's evaluation. The University of Utah's research occurred during some of the most restrictive times of the pandemic, so few people were on campus, there was almost no traffic on the road, and the number of passengers at a given time was limited. The researchers stated, "this highly constrained environment provided few opportunities for our participants to witness the shuttle interact with other vehicles and pedestrians." This means that participants likely experienced shuttle operations in the most favorable conditions, which could explain the overwhelmingly positive attitudes towards the shuttle.

3. Evaluation Results

Passenger perception regarding the safe operation of the AV shuttle was very positive with 98 percent of surveyed participants indicating that they felt safe on board. Additionally, on a scale of 1-10 where 1 is extremely poor and 10 is extremely well, the average response to the question "How successful was the shuttle in making you feel safe and comfortable?" was 9.65 when the shuttle host was visible and 9.52 when the host was disguised as a fellow passenger. Further research provided the insight that experiencing the AV technology firsthand increases passenger understanding and trust of AVs.

Similarly, passenger perception of how well they felt the shuttle is being monitored improved slightly during the host visible scenario. On a scale of 1-10 where 1 is extremely poor and 10 is extremely well, the average response to the question "How well did you feel the environment was being safely monitored?" was 9.69 when the shuttle host was visible and 9.48 when the host was disguised as a fellow passenger.

Two survey questions addressed passenger perception of the shuttle's ability to communicate information and intent. On a scale of 1-10 where 1 is extremely poor and 10 is extremely well, the average response to the question "How well was crucial information (stop location and times, safety instructions, etc.) communicated to you?" was 9.10 when the shuttle host was visible and 8.35 when the host was disguised as a fellow passenger. On the same scale, the average response to the question "How well did the shuttle communicate its intentions to other road users (pedestrians, bikes, cars, etc.)?" was 8.42 when the shuttle host was visible and 8.19 when the host was disguised as a fellow passenger.

Finally, a considerable amount of detail is available in the published Final Report. This wealth of knowledge was compiled using project documentation, survey results, and stakeholder interviews. A brief summary is provided in the following section.

4. Lessons Learned, Recommendations, and Conclusions

The Utah Autonomous Shuttle Pilot ran from April 11, 2019, to September 4, 2020. It successfully served eight locations across eleven deployments during this time. Nearly 7,000 people rode the shuttle and experienced this technology first-hand. Through the set-up, deployment, and analysis of these demonstrations, the project team addressed the following six core goals:

- Expose the public to CAV technology and provide an educational rider experience for policy influencers, transit customers, and residents who are interested in the technology.
- Assess the viability of the shuttle as a potential solution to creating first/last mile connections.
- Understand the operational characteristics and constraints of the shuttle to help inform potential permanent operations in a transit network.
- Interact with the public to assess opinions and attitudes about vehicle automation and the desirability of automated shuttles in the transport network.

- Test the capability and readiness of the automated shuttle to communicate with traffic signal infrastructure using Vehicle to Infrastructure (V2I) communication.
- Research and understand the factors that influence passenger and pedestrian trust in automated vehicles.

By conducting this pilot project, the project team and both agencies were able to meet these goals, forming a better understanding of CAV technology and starting to educate the public on the path forward. This pilot has already jump-started the conversation locally, with many site partners and members of the public now discussing the opportunities technologies like this can enable and the options it will provide in the future.

Having the automated shuttle deployed at multiple locations for short periods of time was good for exposure and for enabling comparisons between different environments. By doing the pilot project this way, there is now a level of experience locally to reference when talking about automated shuttles, rather than just speculation. However, the regulatory burden associated with multiple, short deployments was significant, resulting in some delays and downtime between deployments. Looking forward, another rotational deployment like this one would not be recommended in Utah. Instead, further learnings would be best facilitated by operating an automated shuttle on a single, more permanent route for a longer period of time. This would allow passenger experiences and use cases to coalesce into more of a steady state and enable learnings on other potential challenges, like what happens when demand exceeds capacity or when year-round operations need to remain consistently available. Eventually, a dynamic route may be interesting to explore, but a fixed route would be more feasible in the short- to medium-term as a next step.

This pilot deployment provided operational insight into the limitation of this shuttle to move around obstacles, the frequency of disengagements caused by seemingly minor events, sensitivity to surrounding conditions (such as long grass, tall vegetation near the road, heavy rain, and strong wind), the need for signs to be placed to support vehicle localization through open areas such as parking lots, limitations of the LiDAR sensors as the vehicle encounters rapidly changing road slope, the value of accessibility features, such as a wheelchair ramp, and the limitations of those features, limitations on battery life in hot and cold environments, challenges with maintenance of a vehicle that doesn't return to a central garage at the end of the day, issues with battery charging, and cost of operations. Detailed discussions on these issues are found in the Utah Autonomous Shuttle Pilot Final Report.

For any other jurisdictions considering pursuing an automated shuttle pilot project, whether at one or many locations, this experience has shown that there is definitely value in learning by doing. The many challenges and permits and people to engage along the way led to an experience that helped both UDOT and UTA understand at the most basic level what it would take to get this type of service on the street, serving residents and visitors, and keeping the State of Utah actively engaged in shaping the future of transportation.

UTAH CONNECTED CONCLUDING REMARKS

The seven projects undertaken during the Utah Connected initiative proved incredibly valuable to UDOT and our partners. Expansion of the TSP system increased the performance of UTA's transit system. Expansion of the snowplow preemption system has decreased the time it takes to plow a corridor, as reported by various drivers, and removes snow and ice from the roads sooner. The Curve Speed Warning and Spot Weather Impact Warning applications, while only proof-of-concept applications, provided insight into the value of these warnings and shed light on how they can be more effectively deployed in the future. The unanticipated benefit of these two projects is that they revealed serious hardware and firmware issues that might not have been recognized otherwise, resulting in improvements to this hardware. The data ecosystem that was developed in conjunction with these projects forms a central component of our larger V2X system and will be invaluable as we continue to expand our system. We will continue to improve this ecosystem. The fiber sensing project demonstrated the feasibility of a new approach to situational awareness monitoring. The system required more fine-tuning than expected but shows real promise as a transportation tool. Finally, the evaluation of our automated shuttle deployment shed light on the benefits and challenges of automated technology and demonstrated that humans, while initially skeptical of these systems, can improve their opinions by experiencing the technology, particularly when the experiences are positive. Not only were the lessons learned on these projects valuable to UDOT, UTA and our partners, agencies and organizations around the country have benefited from these insights through our numerous conference presentations and our Utah Connected Webinar Series.

UDOT is grateful for the support, funding, and patience from the FHWA for these Utah Connected projects. The learning experience and insights gained have been valuable and could not have been gained without these projects. UDOT intends to leverage this experience as we continue to expand V2X and other beneficial technologies through subsequent ATCMTD and ATTAIN grants and expansions funded from state sources.

APPENDIX

The Appendices provide details about the Utah Connected deployments, including a comprehensive list of RSU locations deployed.

Appendix A: RSU Deployment List

The following table identifies each deployed RSU by its intersection ID or highway mile marker, location (latitude and longitude), and the applications deployed.

Table A 1 Deployed RSUs

Signal ID or Mile Marker	Latitude	Longitude	Application
6017	40.40615	-111.860	TSP & Preemption
6061	40.40362	-111.857	TSP & Preemption
6065	40.40169	-111.854	TSP & Preemption
6067	40.39710	-111.848	TSP & Preemption
6066	40.39280	-111.837	TSP & Preemption
6020	40.38884	-111.827	TSP & Preemption
6021	40.38689	-111.822	TSP & Preemption
6022	40.38299	-111.815	TSP & Preemption
6023	40.37680	-111.812	TSP & Preemption
6074	40.37684	-111.806	TSP & Preemption
6024	40.37678	-111.799	TSP & Preemption
6025	40.37683	-111.796	TSP & Preemption
6016	40.37513	-111.791	TSP & Preemption
6026	40.37392	-111.785	TSP & Preemption
6027	40.37281	-111.781	TSP & Preemption
6028	40.37019	-111.769	TSP & Preemption
6134	40.36808	-111.760	TSP & Preemption
6132	40.36569	-111.751	TSP & Preemption
6192	40.36105	-111.747	Preemption
6131	40.35910	-111.741	Preemption
6142	40.35795	-111.739	TSP & Preemption
6139	40.35556	-111.736	TSP & Preemption
6133	40.35190	-111.732	TSP & Preemption
6141	40.34954	-111.729	TSP & Preemption
6137	40.34469	-111.723	TSP & Preemption
6147	40.33792	-111.717	TSP & Preemption
6389	40.33364	-111.713	TSP & Preemption
6393	40.32649	-111.708	TSP & Preemption
6394	40.31928	-111.705	TSP & Preemption
6303	40.31185	-111.701	TSP & Preemption

Signal ID or Mile Marker	Latitude	Longitude	Application
6308	40.30453	-111.698	TSP & Preemption
6311	40.29716	-111.695	TSP & Preemption
6313	40.28974	-111.692	TSP & Preemption
6314	40.28231	-111.688	TSP & Preemption
6525	40.28239	-111.686	TSP & Preemption
6526	40.28233	-111.679	TSP & Preemption
6527	40.28234	-111.676	TSP & Preemption
6528	40.27869	-111.676	TSP & Preemption
6530	40.27505	-111.676	TSP & Preemption
6324	40.27342	-111.685	TSP & Preemption
6323	40.27515	-111.685	Preemption
6326	40.26788	-111.682	TSP & Preemption
6327	40.26487	-111.680	TSP & Preemption
6449	40.25907	-111.675	TSP & Preemption
6448	40.25654	-111.673	TSP & Preemption
6447	40.25350	-111.670	TSP & Preemption
6446	40.25060	-111.667	TSP & Preemption
6445	40.24648	-111.667	TSP & Preemption
6444	40.24435	-111.667	TSP & Preemption
6443	40.24042	-111.667	TSP & Preemption
6442	40.23514	-111.667	TSP & Preemption
6011	40.43132	-111.891	Preemption
6012	40.43160	-111.887	Preemption
6090	40.43177	-111.881	Preemption
6091	40.43270	-111.869	Preemption
6092	40.43283	-111.850	Preemption
6093	40.43213	-111.831	Preemption
6094	40.43167	-111.822	Preemption
6095	40.43191	-111.802	Preemption
6096	40.43182	-111.812	Preemption
6097	40.43192	-111.785	Preemption
6098	40.43205	-111.773	Preemption
6086	40.41296	-111.923	Preemption
6082	40.39939	-111.919	Preemption
6081	40.39052	-111.917	Preemption
6080	40.38749	-111.916	Preemption
6198	40.38282	-111.916	Preemption
6202	40.37924	-111.916	Preemption
6039	40.37283	-111.916	Preemption
6087	40.36941	-111.916	Preemption
6078	40.36199	-111.916	Preemption
6014	40.34423	-111.916	Preemption

Signal ID or Mile Marker	Latitude	Longitude	Application
6099	40.33709	-111.916	Preemption
6079	40.32606	-111.906	Preemption
6200	40.32018	-111.901	Preemption
6201	40.31570	-111.895	Preemption
6206	40.37276	-111.911	Preemption
6038	40.37621	-111.887	Preemption
6037	40.37606	-111.877	Preemption
6032	40.37521	-111.867	Preemption
6036	40.37380	-111.857	Preemption
6018	40.37347	-111.849	Preemption
6035	40.37741	-111.832	Preemption
SR-190 @ MM10.75	40.65034	-111.650	CSW
SR-190 @ MM 3.20	40.62478	-111.767	CSW
SR-190 @ MM 3.75	40.62299	-111.757	CSW
SR-190 @ MM 4.10	40.62412	-111.751	CSW
SR-190 @ MM 4.65	40.62374	-111.744	CSW
SR-190 @ MM 6.40	40.63344	-111.723	CSW
SR-190 @ MM 6.90	40.63383	-111.713	CSW
SR-190 @ MM 7.30	40.63304	-111.706	CSW
I-15 @ MM 304.90	40.72062	-111.905	CSW
SR-201 @ MM16.55	40.72442	-111.914	CSW
I-215 @ MM19.30	40.72168	-111.953	CSW
SR-201 @ MM14.85	40.72494	-111.947	CSW
I-80 @ MM118.70	40.76437	-111.921	CSW
I-15 @ MM 307.75	40.75977	-111.915	CSW
SR-248 @ MM0.48	40.66301	-111.501	SWIW
SR-248 @ MM1.10	40.66787	-111.492	SWIW
SR-248 @ MM 2.80	40.67987	-111.466	SWIW
SR-248 @ MM10.30	40.70932	-111.546	SWIW
SR-248 @ MM 6.05	40.66051	-111.510	SWIW
SR-248 @ MM 6.30	40.66285	-111.513	SWIW
SR-248 @ MM 6.50	40.66825	-111.515	SWIW
SR-248 @ MM 7.25	40.67531	-111.521	SWIW
SR-248 @ MM 8.78	40.68780	-111.544	SWIW
SR-248 @ MM 9.10	40.69227	-111.544	SWIW
SR-248 @ MM 9.40	40.69648	-111.544	SWIW
US-40 @ MM1.30	40.71868	-111.486	SWIW
US-40 @ MM1.85	40.71120	-111.482	SWIW
US-40 @ MM 3.00	40.69625	-111.472	SWIW
US-40 @ MM 3.90	40.68523	-111.462	SWIW

Appendix B: Project-Specific Scope, Budget, and Timeline

Utah Connected projects experienced various challenges throughout the deployment planning, procurement, installation, and evaluation stages. Some of these obstacles required a schedule extension to address while others demanded a schedule and budget modification. In total, five schedule and budget amendments were made, which extended the period of performance originally ending on September 16, 2021, to October 30, 2023, and increased the overall project budget from $6,000,000 to $6,387,001 through the addition of state funds. Additional details can be found in the Quarterly Reports. A summary of project scope, budget and schedule is included below by project.

Project 1.1

Scope

The tasks and deliverables for this project are listed below, followed by a description of scope changes from the original award.

Tasks:

- Task 1.1.1 Planning and Development
- Task 1.1.2 Concept of Operations
- Task 1.1.3 External Weather Data Integration
- Task 1.1.4 Security Credential Management System (SCMS)
- Task 1.1.5 Training and Support
- Task 1.1.6 Outreach
- Task 1.1.7 Project Final Report

Deliverables:

- Project Management Reports
- Product Roadmap
- Concept of Operations
- Data Integration for External Weather Data
- Project Final Report

Project Scope Changes

The scope of the original award only included the integration of the Data Ecosystem and SCMS with Projects 2.3 and 2.4. Following a series of FCC decisions affecting the 5.9 GHz spectrum, it was decided to also integrate Projects 2.1 and 2.2.

Budget

Table B 1 contains the budgeted cost for this project and the cost sharing breakdown between the UDOT match and the federal share for the project.

Table B 1 Project 1.1 Budget and Cost Sharing

Project 1.1 Data Ecosystem	Budgeted Cost	UDOT Match	Federal Share
Planning, Development, and Management	$ 180,000	$ 90,000	$ 90,000
Concept of Operations	$ 70,000	$ 35,000	$ 35,000
External Weather Data Integration	$ 900,000	$ 450,000	$ 450,000
Security Credential Management System (SCMS)	$ 50,000	$ 25,000	$ 25,000
Training, Support & Maintenance	$ 220,000	$ 122,500	$ 97,500
Outreach	$ 80,000	$ 55,000	$ 25,000
Final Report	$ 30,000	$ 15,000	$ 15,000
SUBTOTAL:	**$ 1,530,000**	**$ 792,500**	**$ 737,500**

Timeline

Figure B 1 contains a Gantt chart that illustrates the schedule for each project task.

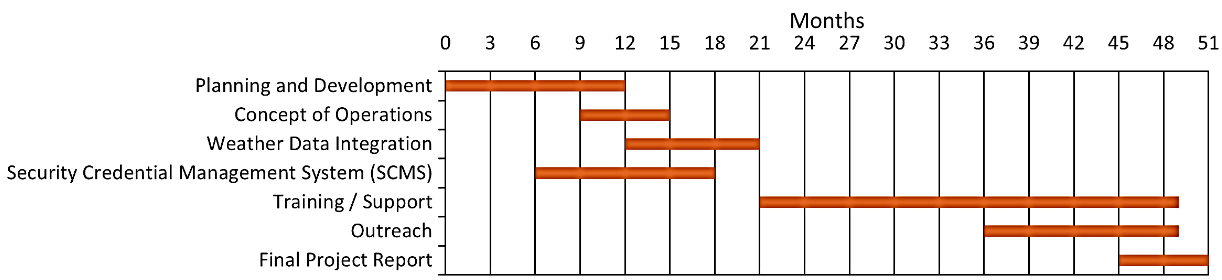

Figure B 1 Project 1.1 schedule.

Project 1.2

Scope

The tasks and deliverables for this project are listed below, followed by a description of scope changes from the original award.

Tasks:

- Task 1.2.1 Planning and Development
- Task 1.2.2 System Design
- Task 1.2.3 System Procurement
- Task 1.2.4 Installation and Integration
- Task 1.2.5 Data Management and Interpretation
- Task 1.2.6 Final Project Report
- Task 1.2.7 Outreach to Report Project Results and Lessons

Deliverables:

- Project Management Reports
- System Design Document
- Procurement Specifications and Procurement Documents
- Installation and Integration of Hardware
- Data Analytics Dashboard
- Project Final Report
- Outreach Materials with Lessons Learned

Project Scope Changes

The scope of the original award only included deployment in LCC, but Budget and Schedule Revision #2 expanded the scope of this project to also deploy in BCC. As the DAS RFP was being prepared, it became apparent that the hardware needed to monitor LCC would also support monitoring BCC from the same fiber hub location. It was decided to include both canyons in the RFP description and the resulting bid, including both canyons, was within the overall budget.

DAS data collected from BCC and LCC revealed poor detection capabilities due to installation techniques despite having ideal fiber placement along the roadway. Budget and Schedule Revision #3 described that either remedial action would be taken on the fiber sections with poor detection capabilities or arrange for a temporary deployment under ideal fiber location and installation conditions. The latter was selected as more data were collected and an assessment of potential temporary locations was performed.

Finally, Budget and Schedule Revision #5 added work for the Utah Connected Webinar Series to produce a 2-hour webinar dedicated to this project titled *Webinar #5: Using Fiber for Situational Awareness Along Roadways*.

Budget

Table B 2 contains the budgeted cost for this project and the cost sharing breakdown between the UDOT match and the federal share for the project.

Table B 2 Project 1.2 Budget and Cost Sharing

Project 1.2 Fiber Sensing	Budgeted Cost	UDOT Match	Federal Share
Planning, Development and System Design	$ 20,000	$ 10,000	$ 10,000
Procurement & Installation	$ 475,000	$ 237,500	$ 237,500
Data management and interpretation	$ 155,000	$ 90,000	$ 65,000
Final Project Report	$ 20,000	$ 10,000	$ 10,000
Outreach and training	$ 20,000	$ 16,000	$ 4,000
SUBTOTAL:	**$ 690,000**	**$ 363,500**	**$ 326,500**

Timeline

Figure B 2 contains a Gantt chart that illustrates the schedule for each project task.

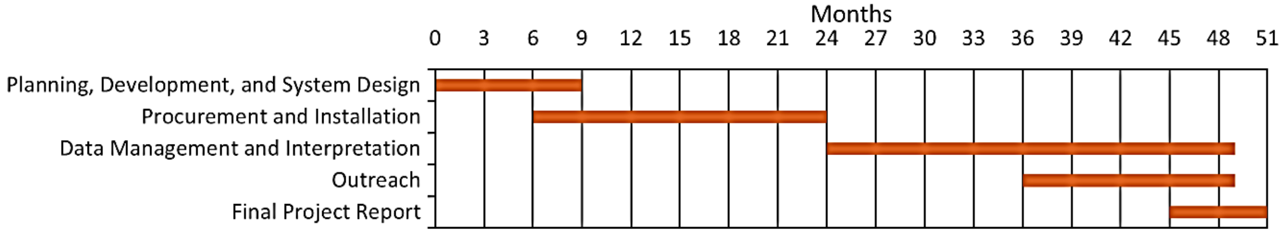

Figure B 2 Project 1.2 schedule.

Project 2.1

Scope

The tasks and deliverables for this project are listed below, followed by a description of scope changes from the original award.

Tasks:

- Task 2.1.1 Planning and Development
- Task 2.1.2 Infrastructure Hardware Installation and Integration
- Task 2.1.3 Vehicle Hardware Installation and Integration
- Task 2.1.4 System Testing
- Task 2.1.5 Final Project Report

Deliverables:

- Design Document
- Installed V2X and Related Hardware (Infrastructure and Buses)
- System Testing Report
- Project Final Report

Project Scope Changes

The scope of the original award included deployment of 98 DSRC RSUs along three additional transit routes and 60 DSRC OBUs on transit buses, none of which were to be integrated into the Data Ecosystem developed in Project 1.1. A series of FCC decisions affecting the 5.9 GHz spectrum caused a shift in the hardware platform from DSRC to C-V2X and encouraged the integration of these devices with the Data Ecosystem. This integration was expected to occur outside this grant and at a future date but was accelerated by the shift to C-V2X. Both the shift to C-V2X and integration with the Data Ecosystem had scope, schedule, and budget ramifications such that 49 C-V2X RSUs along one additional transit route and 30 C-V2X OBUs were ultimately deployed.

Budget

Table B 3 contains the budgeted cost for this project and the cost sharing breakdown between the UDOT match and the federal share for the project.

Table B 3 Project 2.1 Budget and Cost Sharing

Project 2.1 Transit Signal Priority	Budgeted Cost	UDOT Match	Federal Share
Planning and Development	$ 42,000	$ 21,000	$ 21,000
Infrastructure Hardware	$ 745,847	$ 384,424	$ 361,423
Vehicle Hardware	$ 91,253	$ 45,627	$ 45,627
System testing	$ 138,000	$ 80,500	$ 57,500
Final Project Report	$ 30,000	$ 15,000	$ 15,000
SUBTOTAL:	**$ 1,047,100**	**$ 546,551**	**$ 500,550**

Timeline

Figure B 3 contains a Gantt chart that illustrates the schedule for each project task.

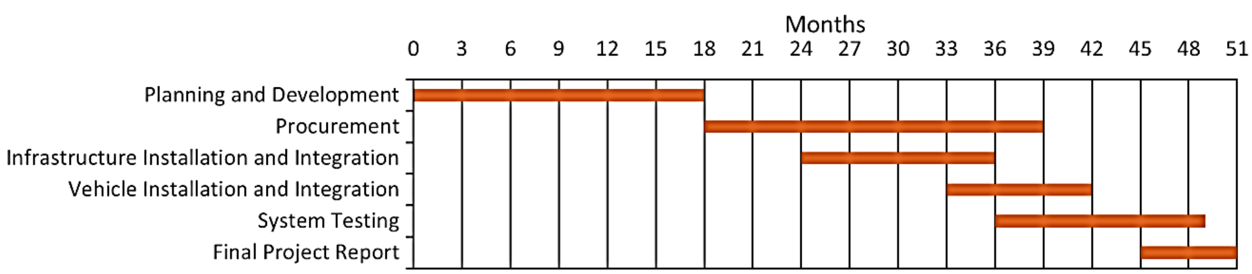

Figure B 3 Project 2.1 schedule.

Project 2.2

Scope

The tasks and deliverables for this project are listed below, followed by a description of scope changes from the original award.

Tasks:

- Task 2.2.1 Planning and Development
- Task 2.2.2 Infrastructure Hardware Installation and Integration
- Task 2.2.3 Vehicle Hardware Installation and Integration
- Task 2.2.4 System Testing
- Task 2.2.5 Final Project Report

Deliverables:

- Design Document
- Installed V2X and Related Hardware (Infrastructure and Plows)
- System Testing Report
- Project Final Report

Project Scope Changes

The scope of the original award included deployment of 67 DSRC RSUs along seven additional plow routes and 30 DSRC OBUs on snowplows, none of which were to be integrated into the Data Ecosystem developed in Project 1.1. A series of FCC decisions affecting the 5.9 GHz spectrum caused a shift in the hardware platform from DSRC to C-V2X and encouraged the integration of these devices with the Data Ecosystem. This integration was expected to occur outside this grant and at a future date but was accelerated by the shift to C-V2X. Both the shift to C-V2X and integration with the Data Ecosystem had scope, schedule, and budget ramifications such that 35 C-V2X RSUs along four additional plow routes and 20 C-V2X OBUs were ultimately deployed.

Budget

Table B 4 contains the budgeted cost for this project and the cost sharing breakdown between the UDOT match and the federal share for the project.

Table B 4 Project 2.2 Budget and Cost Sharing

Project 2.2 Snowplow Preemption	Budgeted Cost	UDOT Match	Federal Share
Planning and Development	$ 39,000	$ 19,500	$ 19,500
Infrastructure Hardware	$ 492,622	$ 318,711	$ 173,911
Vehicle Hardware	$ 55,579	$ 27,790	$ 27,790
System Testing	$ 105,800	$ 62,550	$ 43,250
Final Project Report	$ 10,000	$ 5,000	$ 5,000
SUBTOTAL:	**$ 703,001**	**$ 433,551**	**$ 269,451**

Timeline

Figure B 4 contains a Gantt chart that illustrates the schedule for each project task.

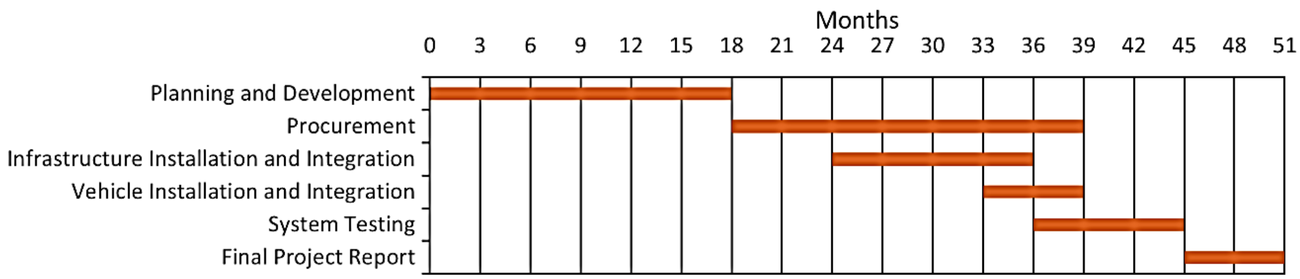

Figure B 4 Project 2.2 schedule.

Project 2.3

Scope

The tasks and deliverables for this project are listed below, followed by a description of scope changes from the original award.

Tasks:

- Task 2.3.1 Planning and Development
- Task 2.3.2 Concept of Operations
- Task 2.3.3 Software Development
- Task 2.3.4 Hardware Deployment and Integration
- Task 2.3.5 System Testing and Verification
- Task 2.3.6 Training and Support
- Task 2.3.7 Final Project Report

Deliverables:

- Product Roadmap

- Concept of Operations
- Proof-of-Concept Software System
- Hardware Installation and Integration
- Project Final Report

Project Scope Changes

There was not a change in scope from the original award for this project.

Budget

Table B 5 contains the budgeted cost for this project and the cost sharing breakdown between the UDOT match and the federal share for the project.

Table B 5 Project 2.3 Budget and Cost Sharing

Project 2.3 Curve Speed Warning	Budgeted Cost	UDOT Match	Federal Share
Planning & Development	$ 30,000	$ 15,000	$ 15,000
Concept of Operations	$ 56,000	$ 28,000	$ 28,000
Software development	$ 500,000	$ 250,000	$ 250,000
Hardware Deployment and Integration	$ 200,000	$ 110,000	$ 90,000
System testing and integration	$ 95,000	$ 47,500	$ 47,500
Training and Support	$ 25,000	$ 12,500	$ 12,500
Final Project Report	$ 45,000	$ 22,500	$ 22,500
Outreach	$ 20,000	$ 15,000	$ 5,000
SUBTOTAL:	**$ 971,000**	**$ 500,500**	**$ 470,500**

Timeline

Figure B 5 contains a Gantt chart that illustrates the schedule for each project task.

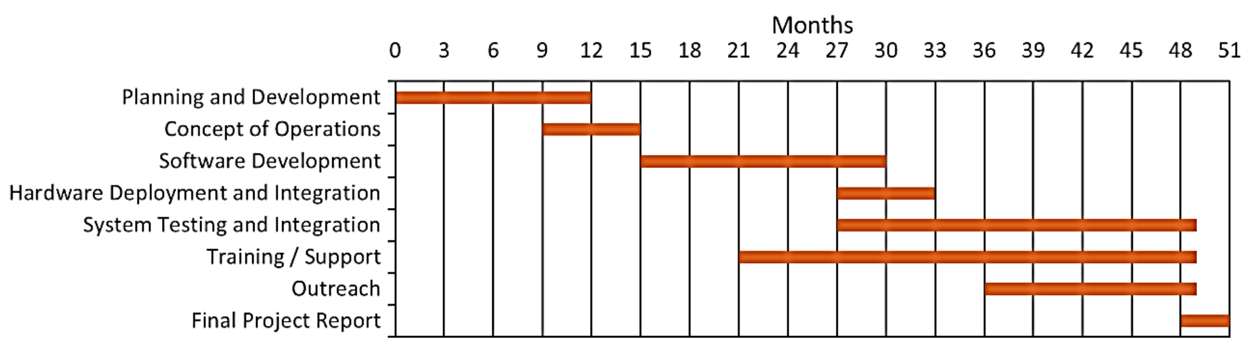

Figure B 5 Project 2.3 schedule.

Project 2.4

Scope
The tasks and deliverables for this project are listed below, followed by a description of scope changes from the original award.

Tasks:
- Task 2.4.1 Planning and Development
- Task 2.4.2 Concept of Operations
- Task 2.4.3 Software Development
- Task 2.4.4 Hardware Deployment and Integration
- Task 2.4.5 System Testing and Verification
- Task 2.4.6 Training and Support
- Task 2.4.7 Final Project Report

Deliverables:
- Product Roadmap
- Concept of Operations
- Proof-of-Concept Software System
- Hardware Installation and Integration
- Project Final Report

Project Scope Changes
There was not a change in scope from the original award for this project.

Budget
Table B 6 contains the budgeted cost for this project and the cost sharing breakdown between the UDOT match and the federal share for the project.

Table B 6 Project 2.4 Budget and Cost Sharing

Project 2.4 Spot Weather Impact Warning	Budgeted Cost	UDOT Match	Federal Share
Planning & Development	$ 30,000	$ 15,000	$ 15,000
Concept of Operations	$ 68,000	$ 34,000	$ 34,000
Software development	$ 500,000	$ 250,000	$ 250,000
Hardware Deployment and Integration	$ 235,000	$ 127,500	$ 107,500
System testing and integration	$ 110,000	$ 55,000	$ 55,000
Training and Support	$ 25,000	$ 12,500	$ 12,500
Final Project Report	$ 45,000	$ 22,500	$ 22,500
Outreach	$ 20,000	$ 15,000	$ 5,000
SUBTOTAL:	**$ 1,033,000**	**$ 531,500**	**$ 501,500**

Timeline

Figure B 6 contains a Gantt chart that illustrates the schedule for each project task.

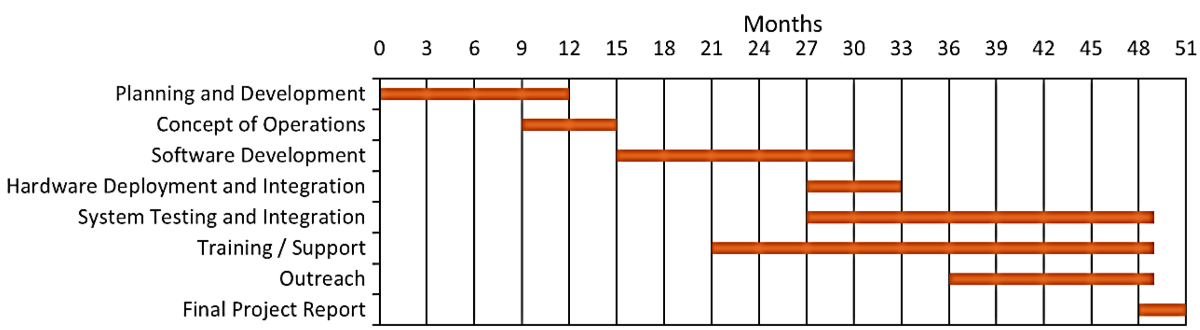

Figure B 6 Project 2.4 schedule.

Project 3.1

Scope

The tasks and deliverables for this project are listed below, followed by a description of scope changes from the original award.

Tasks:

- Task 3.1.1 Public Trust Surveys and Evaluations
- Task 3.1.2 Compilation of Lessons Learned and Operational Insights
- Task 3.1.3 Outreach to Share Results and Insights

Deliverables:

- Report on Public Trust Issues

- Project Final Report

Project Scope Changes

This project experienced two changes in scope from the original award, which were effected through Budget and Schedule Revisions #1 and #2.

One change in scope was the need for a schedule extension and increased operating budget due to NHTSA's nationwide suspension of EasyMile operations following an injured passenger incident in Ohio and shutdowns associated with the COVID-19 pandemic.

The second change in scope was the removal of outreach efforts since we performed over a dozen independent outreach efforts or presentations outside this grant with in-house labor.

Budget

Table B 7 contains the budgeted cost for this project and the cost sharing breakdown between the UDOT match and the federal share for the project.

Table B 7 Project 3.1 Budget and Cost Sharing

Project 3.1 Autonomous Shuttle Deployment	Budgeted Cost	UDOT Match	Federal Share	Actual Cost
Field testing and evaluation	$ 198,000	$ 99,000	$ 99,000	
Final Project Report	$ 25,000	$ 12,500	$ 12,500	
SUBTOTAL:	**$ 223,000**	**$ 111,500**	**$ 111,500**	

Timeline

Figure B 7 contains a Gantt chart that illustrates the schedule for each project task.

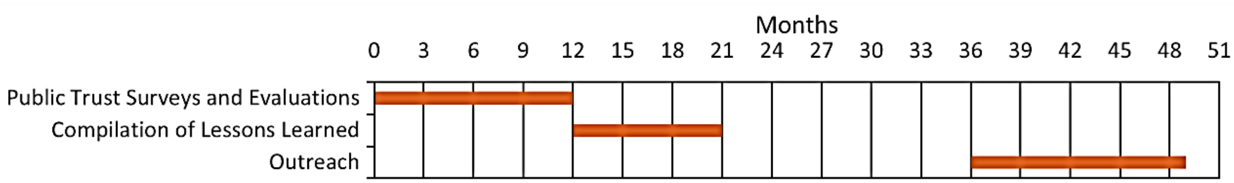

Figure B 7 Project 3.1 schedule.