Connected Vehicle Pilot

Final System Performance Measurement and Evaluation – WYDOT Connected Vehicle Pilot

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Notice

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16. Abstract

The Wyoming Department of Transportation's (WYDOT) Connected Vehicle (CV) Pilot Deployment Program is intended to develop a suite of applications that utilize vehicle to infrastructure (V2I) and vehicle to vehicle (V2V) communication technology to reduce the impact of adverse weather on truck travel in the I-80 corridor. These applications support a flexible range of services from advisories, roadside alerts, parking notifications and dynamic travel guidance. Information from these applications is made available directly to the equipped fleets or through data connections to fleet management centers (who will then communicate it to their trucks using their own systems). The pilot is conducted in three Phases. Phase 1 includes the planning for the CV pilot including the concept of operations development. Phase 2 is the design, development, and testing phase. Phase 3 includes a real-world demonstration of the applications developed as part of this pilot.

This document describes the performance assessment efforts and summarizes the results from operations during Phase 3

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1 Introduction

1.1 Project Scope

The Wyoming Department of Transportation (WYDOT) Connected Vehicle (CV) Pilot is one of the three efforts to demonstrate the real-world effectiveness of CV Technologies that showcase the use of Dedicated Short Range Communications (DSRC) and other communication methods to improve safety and mobility of travelers. CV technologies enable new applications geared toward enabling collision avoidance, system optimization, and demand management, among other objectives.

As one of the three selected pilots, WYDOT is focusing on improving safety and mobility by creating new ways to communicate road and travel information to commercial truck drivers and fleet managers along the 402 miles of Interstate 80 (I-80 henceforth) in the State. I-80 is a major corridor for east/west freight in the northwest part of the country, supporting the movement of over 32 million tons of freight per year (at 16 tons per truck). Truck volume ranges from 30 to 55% of the total traffic stream on an annual basis, with seasonal rises that can make up as much as 70% of the traffic stream. Furthermore, its elevation is all above 6,000 feet, with the highest point reaching 8,640 feet (2,633 m) above sea level at Sherman Summit.

Systems and applications developed in the pilot enable drivers to have a 360-degree awareness of hazards and situations they cannot even see. Specifically, WYDOT sees this pilot as a key part in their continuous effort to improve operations on the corridor, especially during periods of adverse weather and when work zones are present. Through the outcomes of the pilot, fleet managers are able to make better decisions regarding their freight operations on I-80, truckers are made aware of downstream conditions and provided guidance on parking options as they travel the corridor, and automobile travelers receive improved road condition and incident information through various existing and new information outlets.

WYDOT developed systems that support the use of CV Technology along the 402 miles of Interstate 80 (I-80) in Wyoming. The pilot scope includes the following implementation elements:

- **Deployment of 76 roadside units (RSU)** that can receive and broadcast messages using DSRC along various sections on I-80.

- **Equip around 325 vehicles, a combination of fleet vehicles and commercial trucks, with on-board units (OBU).** Several types of OBU were procured as part of the pilot and differ based on their communication capabilities, ability to integrate with the in-vehicle network, and connectivity to ancillary devices and sensors. All OBUs have the functionality to broadcast Basic Safety Messages (BSM) and include a human-machine interface (HMI) to share alerts and advisories to drivers of these vehicles. A portion of the equipped vehicles have additional capabilities, such as receiving messages from RSUs through DSRC.

- **Develop several vehicle to vehicle (V2V) and vehicle to infrastructure (V2I / I2V) applications** that enable communication with drivers for alerts and advisories regarding various road conditions. These applications include support for in-vehicle dissemination of advisories for collision avoidance, speed management, detours, parking, and presence of work zones, maintenance, and emergency vehicles downstream of their current location.
- **Enable overall improvements in WYDOT's traffic management and traveler information practices** by using data collected from connected vehicles. Targeted improvements include better activation of variable speed limits (VSL) and improved road condition dissemination via 511, Dynamic Message Signs (DMS) and other WYDOT sources.

In addition, the scope includes support for the performance management and evaluation, outreach, training, systems engineering and program management necessary for delivering the CV Pilot (CVP) elements.

The CV Pilot Demonstration Program is being delivered in three phases: Phase 1 – Planning, Phase 2 – System Design and Build, and Phase 3 – Demonstrate.

1.2 Purpose of the Final System Performance Measurement and Evaluation

The purpose of this document, the WYDOT CV Pilot's Final System Performance Measurement and Evaluation, is two-fold:

- **Summarize the performance evaluation approach and results**. The system performance is assessed through 19 measures that capture the impact in road weather condition reporting, CV communication interactions, reach of the information developed and provided through the system, and travel behavior.
- **Highlight additional successes and challenges of the pilot**. The system yielded benefits that surpass the impacts described through the numerical value presented in each measure of performance. This report details the results from efforts in simulation of travel behavior, operational performance and system integration, and achievements beyond the original deployment scope.

1.3 Summary of Pilot's Accomplishments

The WYDOT CV Pilot achieved many accomplishments across the fields of:

1) Integration and Operations
2) Research and Testing
3) Standards and Freight
4) Overarching Outcomes

Table 1 provides a summary of these accomplishments.

Table 1. Summary of Pilot's Accomplishments.

#	Accomplishments	Impact
	Integration and Operations	
1.	The CV pilot is fully integrated into TMC operations (variable speed limit, weather dissemination, road closures, etc.).	Full integration means that there were no CV data silos. This was a key requirement and instrumental in the successful operations of the system from the TMC perspective.
2.	No additional personnel were needed to operate the system and no changes were made to the existing personnel's workload.	Transportation Management Center (TMC) operators have not experienced any increase in their already heavy workload, while still pushing out traveler information messages (TIMs) to the CVs. This is mainly due to this process being completely integrated into their regular process/operations, which helps maintain efficiency, staff morale (through fair workload) and lower operational costs.
3.	WYDOT was able to improve their backoffice processes and monitoring capabilities by integrating new systems and data with legacy ones.	The CVP helped WYDOT identify improvements in WYDOT's processes, from providing better details in their construction reports to developing a new speed data archiving system to be able to simultaneously assess speed and store the data in real time to improved monitoring of field equipment. The new information being generated is also being fed to other dissemination means, such as the Commercial Vehicle Operator Portal (CVOP), therefore improving their impact and performance.
4.	Integration of the Operational Data Environment (ODE) with the V2X Hub.	The ODE, a CV data management tool, would not have happened without this project. The open source V2X Hub managed out of the Saxton Transportation and Operations Laboratory has leveraged the ODE for J2735 logging to assist with managing a corridor of intersections from the cloud. Support has been added for BSM, MAP, and Signal Phase and Timing (SPaT). The V2X Hub also uses the open source ASN.1 encoder/decoder build for the WYDOT CVP.
5.	Integration of the Secure Credential Management System (SCMS) with the TMC, RSUs, and OBUs.	The SCMS provides application certificates that help secure Vehicle-to-Everything (V2X) messages. Integration with the TMC, RSUs, and OBUs means that messages are secured from their origination, improving overall security and integrity of the system.
	Research and Testing	
6.	50+ research documents identifying successes, findings, and gaps in research.	Human factor research that went into the pilot resulted in better understanding of driver behavior. This had a significant impact in the preparation for deployment. The research also identified many areas that need further research to refine the implementation details of such technologies.

#	Accomplishments	Impact
7.	The creation of a testbed for new technologies and software.	Wyoming I-80 can now serve as a testbed, enabling early testing and deployment of systems such as Pikalert. The deployment also yielded robust test plans and templates for sharing test results, usable information for other future implementations.
8.	Help move forward the hardware, firmware, and software.	The pilot tested numerous equipment and systems, as well as directly contributed to the development / improvement of new ones. One key outcome of this is the creation of the open-sourced software that was contributed to the community, namely the TIM generator and ODE. These are now being used by Colorado DOT. The pilot also helped Pikalert identify areas of improvement. One of these was transitioning to the cloud, which allows for more straightforward and consistent deployment on other road segments and/or regions. The pilot also supported the development of a new high wind blow over risk algorithm that adds a new capability to the system that other regions using Pikalert have implemented
Standards and Freight		
9.	Deployment of a CV system that focuses on freight vehicles operating in rural environment, serving as ground proof / empirical data for improving guidelines and standards for these two areas (freight vehicles and rural environments).	The pilot differentiated from others in that it focused on both freight vehicles and rural environment. By focusing on heavy trucks, the pilot was able to yield new insights into the nuances of equipping trucks with CV equipment—particularly the testing and placing of antennas. Furthermore, the pilot was able to significantly contribute to the improvement of standards, such as BSM Part II, Trailers, security related standards, and Provider Service Identifier (PSID) for Distress Notifications (DN).
10.	Successful implementation of Distress Notifications (DN) and Weather Cloud (WC).	The pilot was able to prove the data flow for both DN and WC (a system equipped into vehicles to collect mobile weather data). Furthermore, the pilot helped understand the shortcomings of these technologies/applications and identify areas of improvement—for WC issues were with the hardware, whereas for DN the issue was in exporting it to satellite (Sirius XM).
11.	Engage with security.	Working on the SCMS Manager Working Group for End Entity protection, building guidelines on what all players need to do. This project provides ground truth experience on how to deploy SCMS integrated OBUs and RSUs.
Overarching Outcomes		
12.	Creation of expertise.	The pilot spanned around 7 years and created dozens of highly technical reports. This process yielded significant expertise for WYDOT, USDOT and

#	Accomplishments	Impact
		other participating entities (e.g., subcontractors) in the field of connected vehicles, including planning, designing, testing, deployment, and operations. This expertise can be leveraged on future deployment pilots.
13.	Help identify improvements in how States provide information to drivers (e.g., construction information).	Lessons from the CV Pilot can help other states identify gaps and areas of improvement in their processes. Furthermore, the CV Pilot also serves as a model to improve internal understanding of IPV6. It is important to note that the latter is not a trivial aspect, as it entails dealing with secure and reliable internet connection and firewalls—particularly challenging in remote, rural environments.
14.	Development of a Situation Data Exchange (SDX) and expanding it statewide—in combination to the transition to satellite.	This pilot provides a useful case study on how to use SDX in other states to make CV widely accessible.
15.	Development of an expandable and easy to replicate Alexa skill leveraging CV data.	The pilot developed the Traveler Information Skill, which uses the SDX to identify the conditions along the roadways that drivers are planning to travel. Travelers can then simply request this information through "Alexa"-enabled devices. This skill can be expanded to or replicated in other States.

1.4 Summary of Findings

A baseline report was developed in 2018 as part of Phase 2 of this deployment pilot, the *Connected Vehicle Pilot Deployment Program Phase 2, Final System Performance Report, Baseline Conditions – WYDOT CV Pilot (FHWA-JPO-17-474),* Baseline Report henceforth. This Baseline Report details the pre-deployment data collected and analysis performed to establish a baseline of conditions. Furthermore, this Baseline Report provides insights into the early (i.e., pre-deployment) thinking on the hypotheses made in terms of potential/expected impacts of the pilot and the measures of performance that could be used to assess such impacts—see Appendix I. Overview of Pre-Deployment Measures of Performance for more details.

This final report builds on the initial expectations described in the Baseline Report and highlights them as formal hypothesis for the pilot deployment. Table 2 summarizes these hypotheses, links them to the findings of this project, and details the outcome for each (i.e., Achieved, Partially Achieved, Inconclusive).

Table 2. Summary of key findings.

Hypothesis	Summary of Findings	Outcome	Evidence
Full integration of the CV system, including successful generation, transmission, and	Data describing the dissemination of generated Traveler Information Messages (TIM) indicates an efficient and comprehensive transmission of such messages. Similarly, data on the CV system	Achieved	Sections 4.1.2 and 4.3

Hypothesis	Summary of Findings	Outcome	Evidence
receipt of V2V and V2I messages	operations and logs indicate successful receipt and sharing of information, as well as successful generation of alerts based on V2I and V2V messages.		
Increase the number and coverage of reports, reduce latency of reports	The CVP significantly impacted the generation of reports, increasing its coverage and number and reducing latency. Generation of reports were dependent on weather conditions.	Achieved	Section 4.2
Improvement in speed adherence and variation	Results do not indicate that the CVP had much impact on speed adherence but do indicate improvements in speed variance. Speed adherence and variance seem to be impacted by seasonal and other circumstantial factors. Results also indicate that lack of speed adherence tends to happen when VSL was in use. In addition, the results of the analysis indicated that CVs were more compliant than non-CVs by an average compliance rate of 8.5%. In general, more data and analysis are needed.	Partially Achieved	Section 4.4
Reduce the number of vehicles in a crash	There was a reduction in the total number of vehicles involved in crashes but an increase in the average number of vehicles involved. These results are applicable for incidents with and without secondary crashes. In general, more data and analysis are needed.	Inconclusive	Section 4.5.2
Reduce the number of crashes during all conditions	The crash rate per million vehicle miles traveled decreased for all corridor segments except for one VSL corridor between Laramie and Cheyenne. The corridor experienced an overall crash rate reduction of 18.6%, whereas the truck crash rate was reduced by 9.2%.	Achieved	Section 4.5.4
Reduce critical crashes	The post-deployment and baseline results were similar for both the total and truck crashes with slightly higher critical crash rate percentages during the post-deployment year	Inconclusive	Section 4.5.5

1.5 Document Organization

This report is organized as follows:

- Section 2 provides a high-level overview of the CV System.
- Section 3 explains the performance measurement approach and measures.
- Section 4 details the results of the analysis efforts.
- Section 5 summarizes the efforts from the simulation research on driver behavior.
- Section 6 provides insight into the operational performance analysis of the system.
- Section 7 lists additional achievements beyond the original scope of this project.
- Section 8 summarizes the lessons learned.
- Appendices A-I provide complementing information.

2 System Overview

2.1 System Context

This pilot developed systems that make relevant information directly available to, and shared among, equipped fleets. Information is also shared through linkages with fleet management centers (who can then communicate this information to their trucks using their own communication systems) and other external agencies and partners.

The main objectives of the pilot are as follows:

- Deploy and operate a set of vehicles that are equipped with OBU using DSRC connectivity. These vehicles are a combination of snowplows, fleet vehicles, emergency vehicles and private trucks that broadcast BSM, collect vehicle weather data, and road condition data, and provide it remotely to the WYDOT TMC. These vehicles also receive in-vehicle alerts through the infrastructure and wirelessly from various applications developed as part of the pilot through a human-machine interface (HMI).
- Deploy roadside units (RSUs) with DSRC connectivity that can transmit advisories and alerts to equipped vehicles along I-80.
- Leverage the data provided from the equipped vehicles to develop and demonstrate a suite of V2V and V2I applications. As part of the pilot, several applications were developed to support wide-area travel advisories, variable speed limit postings, forecast road condition information, spot-specific warnings, work zones, distress notifications, and parking notifications.

A high level summary of the Wyoming CV Pilot system and its components is provided in Section 2.2. The reader is referred to *Connected Vehicle Pilot Deployment Program Phase I, Concept of Operations (ConOps) (*Gopalakrishna, et al., 2015) for a detailed explanation of the Wyoming CV Pilot project and overall system.

2.2 System Components

The CV Pilot is considered a System of Systems, with two systems of interest, the *Vehicle System* and the *Wyoming CV System*, and complemented by a suite of external interfaces, as shown in Figure 1. The following sections provide a high-level overview of each subsystems and their component responsible for collecting CV data, generating alerts, support information brokerage, transmitting data, storing data, and manage and maintain the system.
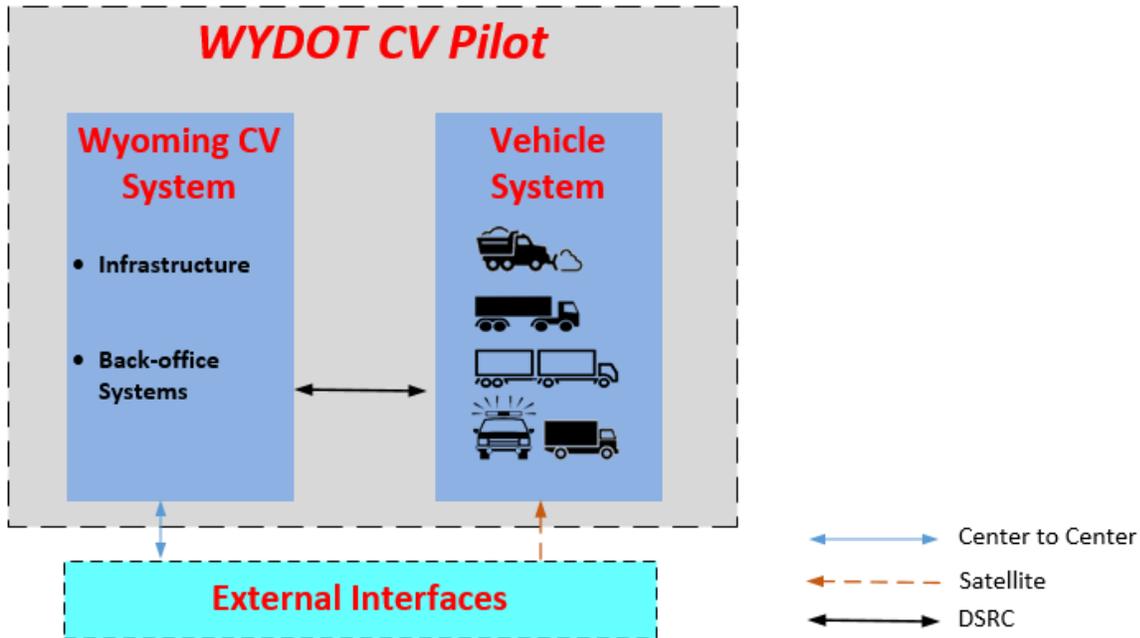
Figure 1. Wyoming CV Pilot System of Systems.
Source: WYDOT

2.2.1 Wyoming System

The *Wyoming CV System* includes the infrastructure used in the pilot and the back-office systems in charge of the various processes that lead to the generation and distribution of advisories and alerts to the CV Pilot vehicles. The *Wyoming CV System* is located at the WYDOT Transportation Management Center (TMC). Additionally, this system provides external interfaces to share the advisories and alerts with the public and commercial vehicle operators.

The *Wyoming CV System* is composed of six Sub-Systems:

- **Roadside Units (RSU)** – These are the physical units for deployment as part of the system along I-80. RSUs include DSRC connectivity, application support, data storage, and other support services to enable CV applications, such as necessary certificates. WYDOT RSUs can be either fixed or portable equipment depending on the use. In general, RSUs serve as a two-way communication portal between connected vehicles that provide information through DSRC and the ODE. A total of 76 RSUs are deployed in the pilot.
- **Operational Data Environment (ODE)** – The ODE receives information collected with connected devices, checks the quality, and then shares this information with other Sub-Systems in charge of analyzing and distributing the information. The ODE is hosted in the WYDOT TMC and uses the same codebase as the USDOT ODE.

- **Hardware Security Module (HSM)** – The Wyoming CV Pilot uses the ISS/GHS[1] rented, TMC Authority as a "black box" HSM in the Cheyenne TMC. The HSM manages the Wyoming CV System's certificates used to sign TIMs being published by the ODE. The HSM also has a link to the ISS/GHS Certificate Management System (CMS) to get updated certificates to sign TIMs.
- **Pikalert System** – The Pikalert System supports the integration and fusion of CV and non-CV weather data to develop alerts and advisories regarding adverse weather conditions along I-80. CV data are received from the ODE, while non-CV data derive from weather sources and the data broker.
- **Data Broker (DB)** – WYDOT DB receives information from the ODE, Pikalert and external systems, analyzes them, and shares them with the corresponding system or service including other sources (e.g., third party).
- **Data Warehouse (DW)** – The WYDOT DW stores various TMC- and CV-related data. The DW includes timestamped and geotagged logs of CV and non-CV data—information collected, generated, and shared within the *Wyoming CV System*—that are used for performance measurement.

2.2.2 Vehicle System

The *Vehicle System* represents the deployment of on-board equipment, sensors, and an HMI that support CV applications. All vehicles that are part of the *Vehicle System* have the following core capabilities:

- Ability to share information via DSRC communication with other connected devices (vehicles and RSUs).
- Ability to broadcast BSM.
- An HMI that allows alerts and advisories to be communicated with the driver.

Additionally, several vehicles that are part of the *Vehicle System* have additional capabilities. The *Vehicle System* is divided into two Sub-Systems, Friendly and Partner CV Fleets. The main differentiator between these subsystems is whether they have static or dynamic identifications (ID). The two main groups of vehicles are described below.

- **Friendly Fleet** is composed by vehicles over which the pilot has more access to and is able to identify in the data, as they have unique IDs. This group includes WYDOT Plows (WY), Trihydro Vehicles (TH), and Highway Patrol Vehicles (HP).

- **Partner CV Fleet** is composed by all other vehicles, namely from partners of the pilot. Note that for security and privacy reasons, these vehicles have dynamic IDs and therefore cannot be tracked and accurately counted.

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[1] ISS/GHS is the company hosting the pilot's certificate management system (i.e., INTEGRITY Software Services/Green Hills Software).

2.2.3 Pilot On-Board Applications

The WYDOT CV Pilot developed five on-board applications that provide key information to the drivers of equipped vehicles. In addition to on-board applications, information generated by the *Wyoming CV System* supports ongoing WYDOT traffic management and traveler information services. WYDOT uses this information from the pilot for:

- Setting and removing VSLs along the I-80 corridor.
- Supporting 511 and other traveler information.
- Supporting road weather advisories and freight-specific travel guidance through WYDOT's CVOP.

The following subsections provide a view of the applications developed the Pilot.

2.2.3.1 Forward Collision Warning

Forward Collision Warning (FCW) is a V2V communication-based safety feature that issues a warning to the driver of the connected host vehicle in case of an impending front-end collision with a connected vehicle ahead in traffic in the same lane and direction of travel on both straight and curved geometry roadways, as shown in Figure 2.
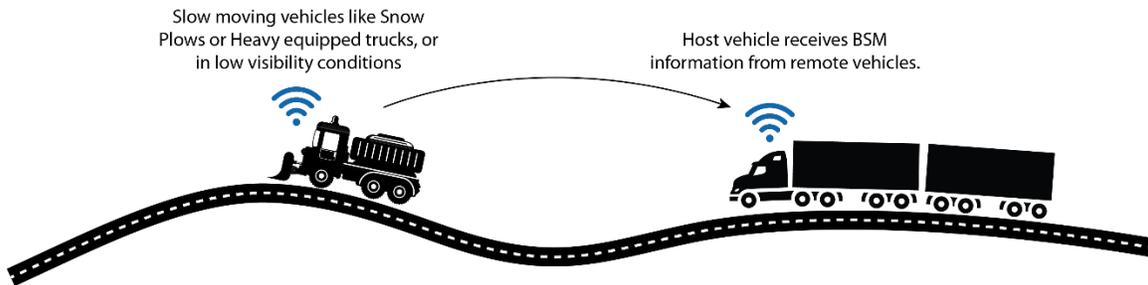
Figure 2. Forward Collision Warning Concept Diagram.
Source: WYDOT

FCW helps drivers avoid or mitigate front-to-rear vehicle collisions in the forward path of travel. This application is critically important for safety along I-80 in conditions when snow plows are moving slower than following traffic and/or when visibility may be limited due to adverse weather. The application does not attempt to control the host vehicle to avoid an impending collision. This application follows the description from standard Society of Automotive Engineers (SAE) J2945/1 March 2016 Section 4.2.4.

2.2.3.1.1 Stationary Vehicle Alert

Stationary Vehicle Alert (SVA) is version of FCW in which the downstream vehicle is parked on the side of the road or an adjacent lane along I-80. SVA notifies the driver of this situation and helps avoid or mitigate a potential collision with this vehicle. Figure 3 illustrates the concept for this application.
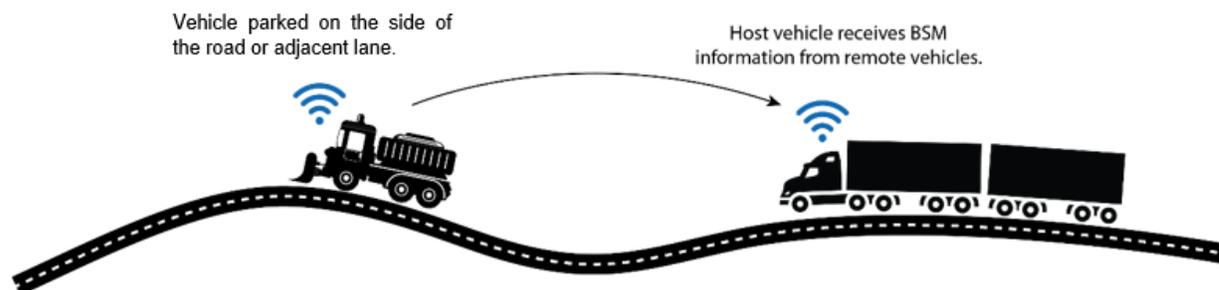
Figure 3. Stationary Vehicle Alert Concept Diagram.
Source: WYDOT

2.2.3.2 Infrastructure-to-Vehicle Situational Awareness

Infrastructure-to-Vehicle (I2V) Situational Awareness assembles important travel information from back-office systems and communications directly to drivers through both DSRC and satellite communications, see Figure 4. This application enables delivery of relevant downstream road condition information to drivers along I-80 in Wyoming, including Weather alerts, Speed restrictions, Vehicle restrictions, Road conditions, Incidents ahead, Truck parking, and Road closures.
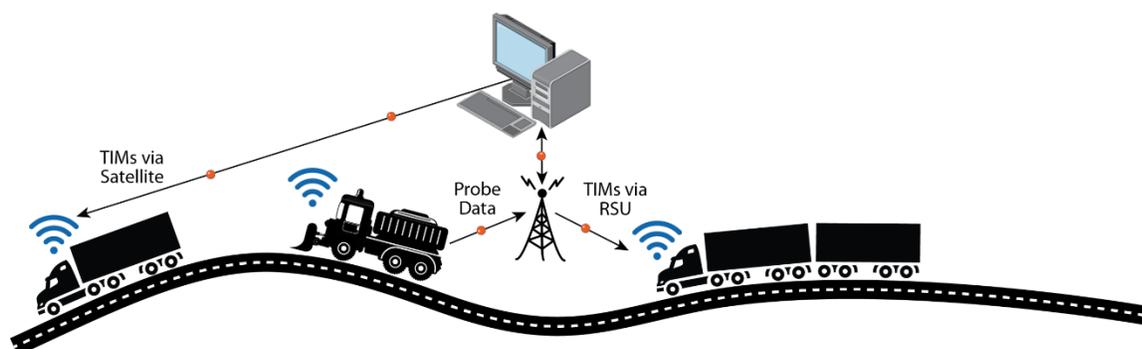
Figure 4. I2V Situational Awareness Concept Diagram.
Source: WYDOT

This information can enhance both safety and traveler mobility along the corridor. This application follows the description from SAE J3067 August 2014 Section 2.9.3.6.

2.2.3.3 Spot Weather Impact Warning

Spot Weather Impact Warning (SWIW) is a special case of I2V Situational Awareness that enables hazardous road condition information due to weather, such as fog or icy roads, to be broadcast from a RSU and received by the connected host vehicles. This application, however, is distinct from other I2V Situational Awareness applications in that it provides more localized information (i.e., at the segment level instead of area wide or region wide), see Figure 5. This application follows the TIM advisory content from part 3 defined in SAE J2735 Section 6.142 for International Traveler Information Systems (ITIS) data elements and in SAE J2540_2 Sections 6.54 for weather conditions and 6.55 for winds.
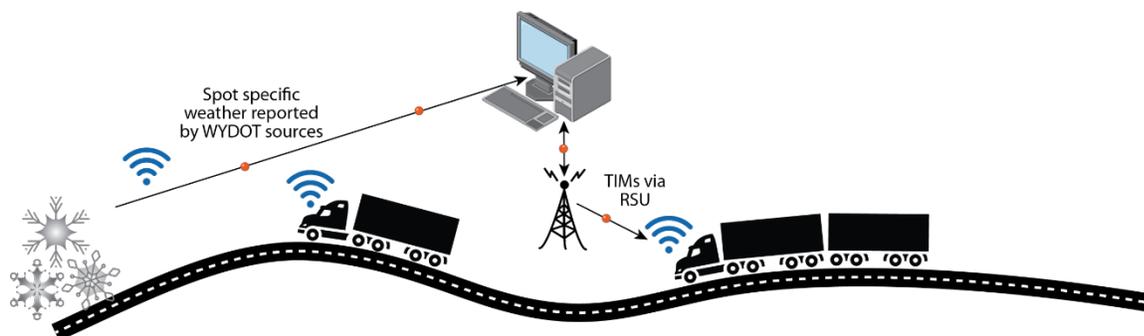
Figure 5. Spot Weather Impact Warning concept diagram.
Source: WYDOT

2.2.3.4 Work Zone Warning

Work Zone Warning (WZW) provides information about the conditions that exist in a work zone which the host vehicle is approaching, see Figure 6. This capability provides approaching vehicles with information about work zone activities that could present unsafe conditions for the workers or the host vehicle, such as obstructions in the vehicle's travel lane, lane closures, lane shifts, speed reductions or vehicles entering/exiting the work zone. This application follows the TIM WZW described in SAE J2735 March 2016 Part 3 in Section 6.142.
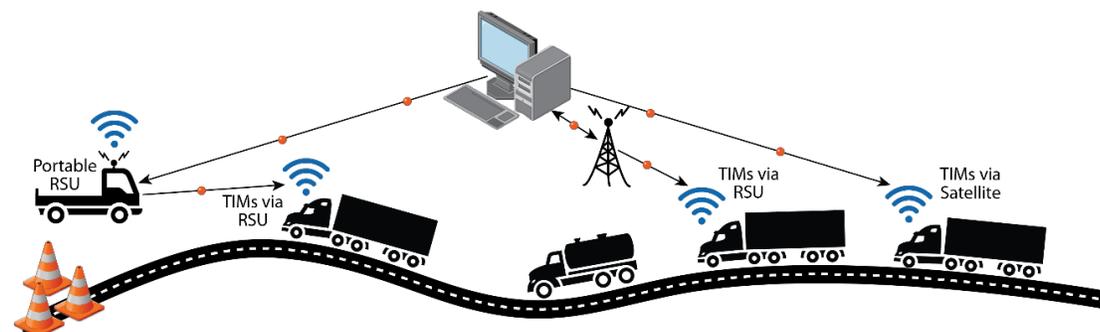
Figure 6. Work Zone Warning Concept Diagram.
Source: WYDOT

2.2.3.5 Distress Notification (DN)

Distress Notification (DN) enables connected vehicles to communicate a distress status back to Wyoming CV System. The CV driver triggers DN and there after the DN is captured by RSU and delivered through system to TMC and displayed to System Operators. In addition, vehicles passing in opposite or same direction to a distressed vehicle captures and relays message to the first RSU out of range of distressed vehicle, whereupon it is delivered through system to TMC and is displayed to system operators. Although this application is loosely based on the Mayday application description from SAE J3067 Section 3.5.9.2.1, it is built on a higher priority TIM communication using SAE J2735 March 2016, Section 5.16, Part 3, Integrated Transport Information System (ITIS) advisory elements.

Figure 7 presents the concept diagram for this application.
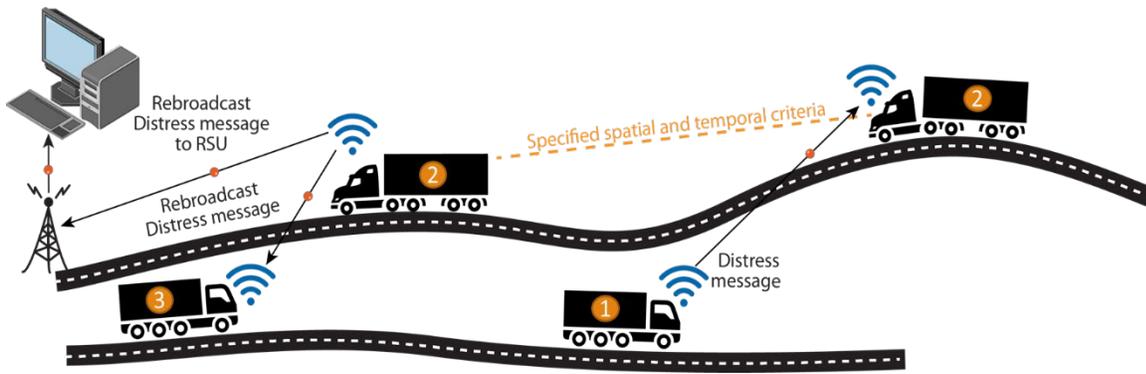
Figure 7. Distress Notification Concept Diagram.
Source: WYDOT

3 System Performance Measurement Approach and Data Collection

3.1 Performance Measurement Evaluation Approach

The overall approach to assess performance of the pilot consist of four key steps, as illustrated in Figure 8. The **first step** is to perform the initial data collection and analysis to assess and understand the current situation within Wyoming roads. The **second step** is to establish the pilot's hypothesis based on the initial data analysis. The **third step** is to define performance measures and metrics, using the initial analysis to establish baselines for comparison. Finally, the **fourth step** is to identify a clear and sound approach to collect and analyze pilot data.

The following subsections provide more detail on each of these steps.
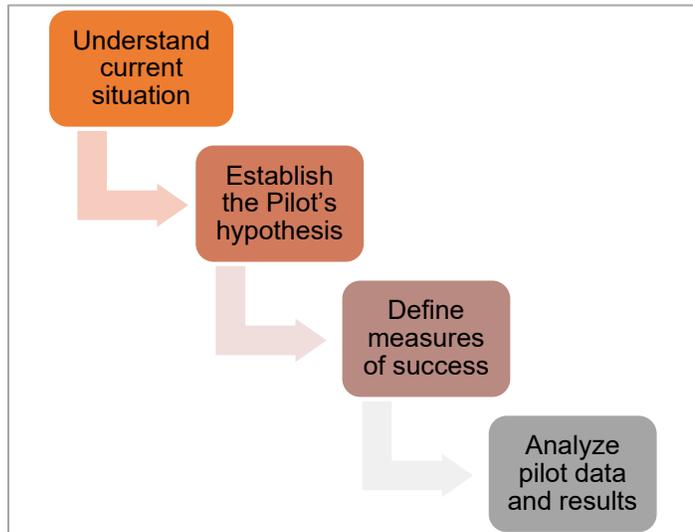
Figure 8. Performance Measurement Evaluation Approach.
Source: WYDOT

3.1.1 Understand Current Situation

The pre-deployment data collection focuses on the period December 2016 through November 2017, including work zone data in the summer of 2017. Crash data before December 2016 is also included in the report given the natural variations inherent in these data.

The 2016-17 winter was one of the most severe on record, especially the number and intensity of strong wind events in the corridor. Forty-one (41) separate significant weather events were documented between December 2016 and May 2017. These weather events resulted in extensive use of variable speed limit systems and dynamic message signs, constant updates of the Wyoming traveler information system and the CVOP, and numerous road closures. Crashes numbered 1,310 in total, of which 225 trucks were blown over due to extreme strong winds. There were 9 fatalities. Indeed, this was a very impactful winter on the traveling public and commercial vehicle operators.

The *Connected Vehicle Pilot Deployment Program Phase 2, Final System Performance Report, Baseline Conditions – WYDOT CV Pilot (FHWA-JPO-17-474)* documents the data collected and analysis performed to assess the current situation at the time and support the establishment of

the pre-deployment (baseline) conditions. The baseline is used as the basis for comparison for many of the performance measures of this pilot, see Section 4 for summary of results.

Simulation – Traffic simulation modeling using VISSIM software was conducted for the analysis of traffic safety performance measures. The use of microscopic traffic simulation modeling allows for the analysis of conflict-event safety surrogates such as time-to-collision, distribution of speeds, speed variation, number of lane changes, etc. It was anticipated that the CV deployment would result in changes to speed selection, lane changing and car following behavior for CV-equipped drivers that can be modeled in a microsimulation environment. Therefore, by using microsimulation, researchers were able to gain insightful understanding of the impacts of the safety effectiveness of CV technology. Results from this approach are detailed in Section 5.

3.1.2 Establish Pilot Hypothesis

The primary focus of the Wyoming CV Pilot is to improve safety in the I-80 corridor. The analysis of historical speed adherence and crash data presented in the report on Baseline Conditions (FHWA-JPO-17-474) provided insight into how CV technology could help achieve the goal of improved safety. Based on this initial research effort, the research team drafted the following hypothesis:

- The WYDOT TMC has stablished systems that, while being state of practice and even advance in many ways, are still limited by the legacy backoffice processes for data collection, management, and analysis structure.
    - o **Hypothesis 1:** WYDOT expects that the successful integration of the CV System and data (including the generation, transmission, and receipt of V2V and V2I messages) will improve backoffice processes [TMC, construction, GIS/ITS, winter maintenance, freeway management, etc.], helping identify areas of improvements.
- The WYDOT TMC collects and stores all field maintenance reported road conditions by day/time and location. The road condition reporting measures focus on the quantity of reports (number of road condition reports), the coverage of the reports (number of road sections with at least one report), and the latency of the reports (average refresh rate of reports).
    - o **Hypothesis 2:** WYDOT expects that the quantity of road reports and the coverage will increase during the CV Pilot deployment. Conversely, WYDOT expects the latency of reports will decrease.
- During the 2016-17 winter, about 40% of vehicles are currently traveling 5 mph above the post speed (speed adherence is low) and a little over half of the vehicles are traveling outside a +/- 10 mph buffer (speed variation is high). These conditions can translate or contribute to the number of crashes and crash severity.
    - o **Hypothesis 3**: WYDOT anticipates an improvement in these values through CV-technologies to improve Situational Awareness (TIM messages) regarding posted speeds, especially in VSL areas. Additionally, the VSL systems and DMS will have more accurate and timely information based on improved and expanded data collection.
- Historically, about 25% of crashes on I-80 are multi-vehicle crashes, which include some events with tens of vehicles involved. Our goal is to reduce the number of secondary

crashes by using CV technologies to alert drivers of a crash ahead so they can stop earlier or otherwise avoid becoming a crash victim. Further, these crashes can be the reason a section of I-80 need to be closed. During the October 2016 to May 2017 timeframe, a cumulative total of 515 hours of closure on 52 road closure segments were issued.

- o **Hypothesis 4:** WYDOT anticipates that implementation of CV applications such as FCW, WZW, and in-vehicle TIM messages have the potential to reduce the number of vehicles in a crash by warning the driver of a crash just ahead.
- In terms of crashes, the 2016-17 winter recorded 1,310 crashes. Weather conditions existing during the crashes included clear (48%) and snowing (21%). Road conditions existing during the crashes included ice/frost (39%), dry (36%) and snow (15%).
  - o **Hypothesis 5**: WYDOT believes CV-enabled technologies can help to reduce the number of crashes during all conditions. FCW can help avoid a crash in any condition. SWIW can alert a driver to poor weather or road conditions resulting in an avoided crash. Improved driver Situational Awareness can also result in an avoided crash, especially during inclement weather and hazardous road conditions.
- From 2010 through 2017, 4.4% of the 12,641 crashes during that period were reported as critical crashes on I-80.
  - o **Hypothesis 6**: Through implementation of CV technologies mentioned above, WYDOT believes it has the potential to significantly reduce these numbers either by drivers avoiding a crash all together or speeds being reduced during a crash.

3.1.3 Measures of Success and Performance Metrics

The project team identified high level measures of success to guide the development of performance measurements and the overall assessment of the system's performance—see Figure 9. These measures of successes focus on the system's impact on accurate and timely reports on road weather condition, information dissemination, and safety.

Road Weather Condition Reporting	**Information Dissemination**	**Safety Outcomes**
• Improve road weather condition reports received into the TMC • Improve ability of TMC to generate alerts and advisories	• Effectively transmit and receive V2I/V2V messages	• Improve speed adherence and reduce speed variation • Reduce vehicle crashes • Improve drive behavior compliance

Figure 9. WYDOT CV Pilot Measures of Success.
Source: WYDOT

Following these high level measures of success, the project team identified 17 performance measures (PM), listed below. The PMs focus on improvements to efficiency, safety, and mobility and represent the primary activities and outcomes of the Wyoming CV Pilot system, including data collection, information dissemination, alerts, and advisories shared between vehicles and

roadside, improved speed adherence and reduced crash rates. The PMs are described in more detail in Section 4.

- **Road Weather Condition Reporting**
    1. Number of Road Condition Reports
    2. Number of Road Sections With At Least One Report
    3. Average Refresh Time of Road Reports
- **Information Dissemination**
    4. Percentage of TIMs received by at least one RSU
    5. Percentage of TIMs received by at least one OBU on I-80 through satellite
    6. Percentage of TIMs received by at least one Friendly vehicle from RSUs
    7. Percentage of TIMs received by at least one OBU, through either satellite or RSU
- **Safety Outcomes**
    8. Total vehicles traveling at no more than 5 mph over the posted speed
    9. Total vehicles traveling within +/- 10 mph over the posted speed
    10. CVs Speed compliance compared to non-CVs
    11. Connected Vehicles Involved in Initial or Secondary Crash
    12. Reduction of the number of vehicles involved in a crash
    13. Reduction of total and truck crash rates within a work zone area
    14. Reduction of total and rates of truck crash along the corridor
    15. Reduction of critical total and truck crash rates in the corridor
    16. CVs that likely took action following receipt of an alert
    17. CVs that likely took action following receipt of a V2V alert

The measure presented here follow as close as possible the original set of measures identified during the baselining effort. However, after a better understanding of the available data, what is feasible from an analysis perspective, and changes in system capabilities, the research team modified the list to better account and describe the performance of the system. A detailed description of the transition from the old set of metrics to the new one is provided in Appendix I. Overview of Pre-Deployment Measures of Performance.

3.1.4 Collect and Analyze Pilot Data

The key approach for CV performance evaluation is "Before-After" study with statistical tests. This approach quantitatively compares data under baseline conditions (before deployment) with data during the Wyoming CV Pilot demonstration (during/after deployment). Results from this approach are detailed in Section 4.

Data Collection

The data collected for the analysis is listed and described in Section 3.2. The complete dataset consists of data collected and/or produced by WYDOT (e.g., road reports, crash, and weather) and CV system generated data (e.g., data produced by OBUs, RSUs and backoffice systems). While the first data type is accessible through WYDOT's database and public records available

upon request through inter-agency agreements, CV system data is stored and managed through the Secure Data Commons (SDC).[2]

Data Analysis

WYDOT accesses the CV Pilot data (historic and near real time) stored at the SDC. The SDC enables the use of tools and functionalities to perform data queries, preprocessing, analytics and to collaborate and share code across the other CVP team members.

The project team uses of SDC to perform the following type of data analysis:

1. Develop, and host a custom tool (using Python), called "Data Tool", to enable analysts to (1) query BSM, driver alert, and speed data, (2) perform geospatial based conversions, (3) convert unprocessed speed data, generate speed reports from processed speed data, and (4) export data out of the SDC.
2. Use R to develop ad hoc data analysis to estimate performance metrics and performance measures based of BSMs, TIM, and driver alert data.
3. Use SQL Workbench and LibreOffice to perform additional data queries and analysis based on the BSM, TIM, and driver alert data.

Figure 10 provides an example of a query used to extract speed data from CVs using the SDC functionalities. The tables produced through this query can then be used to performed more in-depth analysis of speed data.

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[2] The SDC is a USDOT-sponsored cloud-based analytical platform designed to create wider access to sensitive transportation data sets, with the goal of advancing the state of the art of transportation research and state/local traffic management. The SDC stores sensitive transportation data made available by participating data providers, and grants access to approved researchers to these datasets.
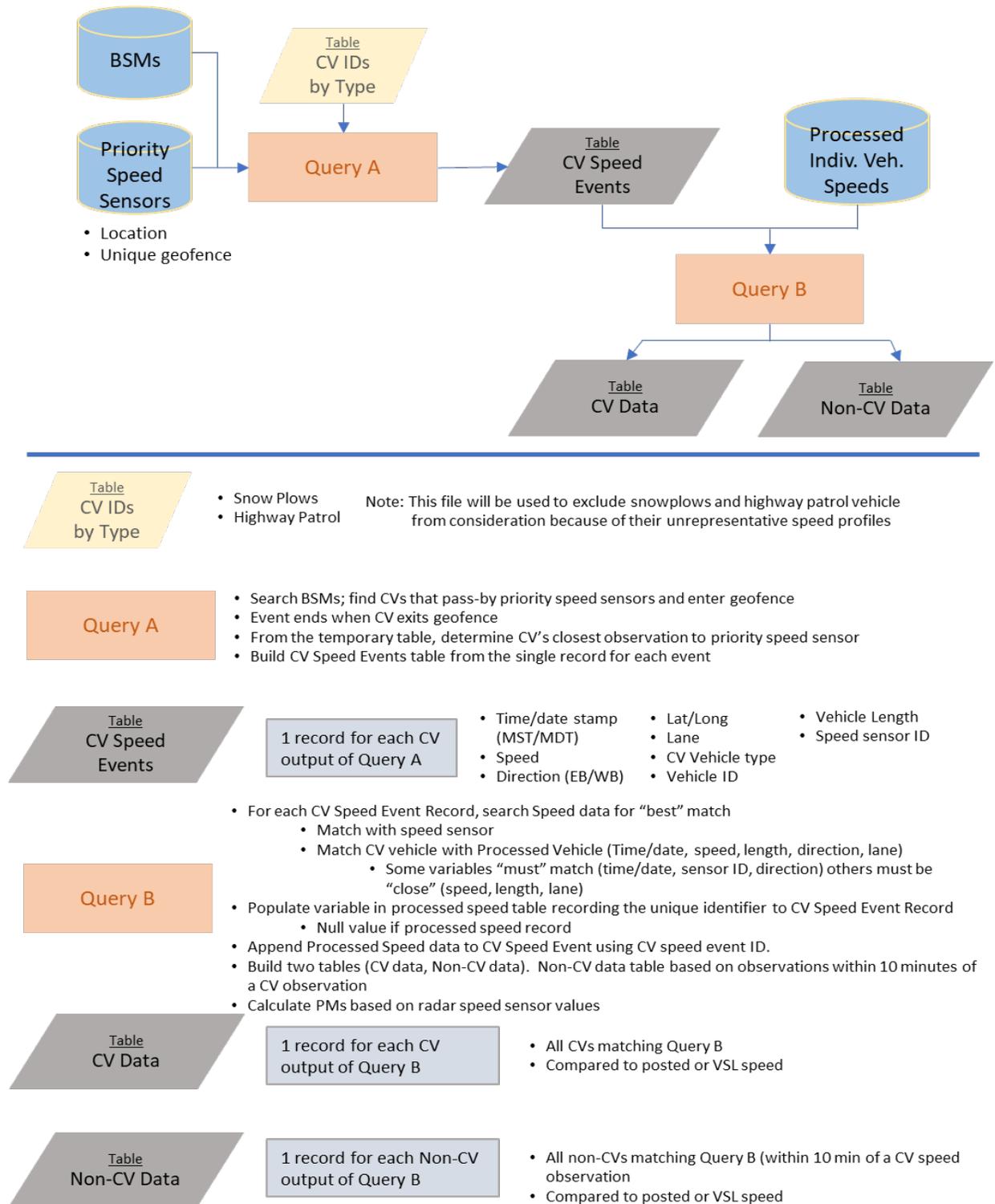
Figure 10. Example Query for Extracting and Analyzing CV Speed Data.
Source: WYDOT

3.2 Data Collection

This section provides an overview of the data sets used as part of the CV pilot performance measurement. The data is grouped into two types: Non-CV System data and CV System data.

3.2.1 Non Connected Vehicle System Data

The following are the primary non-CV system data sets used in the performance measurement analyses.

- **Crash –** Crash records for the state of Wyoming are maintained by the Wyoming Department of Transportation's Highway Safety Program. All reported crashes in the state, regardless of roadway jurisdiction, are contained in this crash database. WYDOT adopted a Model Minimum Uniform Crash Criteria compliant electronic crash form on January 1, 2008. The Highway Safety Program runs periodic (quarterly) queries and provides the updated crash data to the CV Pilot project. This report includes data until the quarter ending on Feb 2022.
- **Road Weather Information Stations (RWIS) Sensor Data –** RWIS sensor data is collected from ten priority stations of the 50 total stations installed along I-80. RWIS data are currently used to account for weather in the speed-related performance measures.
- **Variable Speed Limit Data –** Posted data comes from 66 VSL signs located along the I-80 corridor. These devices are integrated into four separate sections along I-80. The four VSL corridors are located between Evanston and Three Sisters, Rock Springs and Green River, along Elk Mountain, and from Cheyenne to Laramie. Latitude and longitude as well as mileposts are used to describe the approximate location of each VSL sign.
- **Road Closure Data –** A road closure database is maintained by the WYDOT TMC. In severe or potentially harmful weather conditions along the I-80 corridor, there are road closure gates put in place as a safety measure for drivers. Roadway closures along the project corridor are relatively common occurrences due to weather and crash events. Closures are controlled by road closure gates at the edges of urban areas, so a closure affects a range of mileposts for a given direction of travel. The Wyoming TMC is able to monitor the weather conditions and remotely close the gates as needed.
- **Work Zone Data –** WYDOT maintains active construction project information in a database called the Construction Console. This database has information on active and historical work zones, including the project number, location, and start and end dates.
- **Traffic Volume Data –** Information on traffic volumes on WYDOT facilities can be obtained from the WYDOT Traffic Data website and the annual WYDOT Vehicle Miles Book. This traffic data comes from inductive loops along the corridor and WYDOT splits the corridor into 98 sections based on the location of these loops.
- **Dynamic Message Sign Data –** This data comes from 40 DMS located along the corridor. DMS on the corridor are either overhead or roadside mounted signs. For this project, the DMS data are only used to verify conditions on the roadway and are not formally part of any performance measure analyses.
- **Road Condition Reports –** The WYDOT TMC collects and stores all field maintenance reported road conditions by day/time and location. WYDOT rates the overall impact to the traveler (low, moderate, high) by various road conditions, weather conditions, advisories, and restrictions. The CV Pilot defines a "weather event" as anything other than a low

rating. The WYDOT TMC provided analysis data only for weather events with the designated non-low impact rating (i.e., moderate and high impact).

- **Individual Speed –** Individual speed data comes from 74 of the 88 Wavetronix speed radar devices listed in the WYDOT device inventory installed along I-80 prior to the CV Pilot project. The density of sensors is greatest in the four VSL corridors with a lesser amount installed in the non-VSL areas. This report includes data until Feb 2022.

3.2.2 Connected Vehicle System Generated Data

3.2.2.1 Basic Safety Message

Connected V2V safety applications are built around the capability to transmit BSM, following the SAE J2735 standard. The BSM is transmitted over DSRC over a range of approximately 300 meters.

In general, BSMs are broadcasted frequently to provide CVs with data content necessary for the different safety-oriented applications. The BSM is divided into two parts, described below.

- Part I, transmitted approximately 10 times per second, contains the core data elements: Message Count, Temporary ID, Time (through a Second Mark), Latitude, Longitude, Elevation, Positional Accuracy, Transmission State, Speed, Heading, Steering Wheel Angle, Acceleration, Brake System Status, and Vehicle Size.
- Part II, transmitted less frequently, is added to Part I depending on events (e.g., antilock braking system activated) and contains a variable set of data elements drawn from many optional data elements (availability by vehicle model varies).

For this pilot, only Part I is used. BSMs are sent at a 10 Hz frequency before and after an "interaction" for the first minute, then drop to 1Hz; and, a snapshot every 30 seconds at all times. These BSMs are always received by another vehicle when CVs are within range.

3.2.2.2 Alerts

Driver alerts are generated and logged following events that prompt reactions from OBUs. Examples of these events are receiving BSMs from nearby stationary vehicles or messages from the WYDOT TMC indicating change in road or traffic conditions downstream. These alerts are based on the on-board applications described in Section 2.2.3.

3.2.2.3 Traveler Information Messages

The TIMs are used by the WYDOT TMC to send various types of information (advisory and road sign types) to equipped devices. TIMs are defined in the SAE J2735 specification. It makes heavy use of the ITIS encoding system to send well known phrases but allows limited text for local place names. The supported message types specify several sub-dialects of ITIS phrase patterns to further reduce the number of octets to be sent. The expressed messages are active at a precise start and duration period, which can be specified to a resolution of a minute. The affected local area can be expressed using either a radius system or one of the systems of short defined regions.

The primary sub-sections of J2735 which define TIMs are:

- Section 5.16   Message: MSG_TravelerInformation Message (TIM)
- Section 6.142 Data Frame: DF_TravelerDataFrame

4 Results of System Performance Measurement

This section describes all the performance measures that were assessed as part of Phase 3 of the deployment pilot. Each subsection holds information related to PM's estimation methodology and results. In addition, the section provides high level statistics information regarding the I-80 road conditions and CVP operations bound to I-80 and during the period of analysis.

4.1 Summary of the Road Condition and CV Operations

This section provides an overview of the road conditions and system operations for the period of Jan' 2021 – Apr' 2022. This summary of conditions sets the tone for the results of the performance metrics detailed in the following sections. At a high level, this subsection provides summary statistics for:

1. **Road Condition and Events**
   Provides information regarding (1) weather events spotlights, number of weather events, and hours of storm; (2) I-80 incidents highlights; and (3) I-80 work zone related events.

2. **CV System Operations**
   Provides high level information regarding the overall CVP operations, include (1) CV count summary, (2) statistics of the BSM data, (3) statistics of the driver alerts, and (4) CV hours of operation.

4.1.1 Road Condition and Events Statistics

4.1.1.1 Weather Events

A total of 499 severe weather events lasting 5,807 hours were recorded around I-80 between January 2021 and April 2022. Table 3 provides insight into the most severe weather events within this period. These were selected based on three factors:

(1) Hours of storm,
(2) Number of road sections affected by the event, and
(3) Percentage of reports with medium and high severity conditions.

Table 3. Weather Event Spotlight from Jan 2021 to Apr 2022.

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

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

Number of unique reporting sections indicates the CV pilot coverage of the I-80 corridor.

The majority of these events impacted at least half of the I-80 corridor. As expected, severity, complexity and coverage of the storms was higher during winter, with a mixture of conditions, and lower during the summer, with the most severe events impacting I-80 through strong winds instead of multiple conditions.

Figure 11 presents the number of the events between January 2021 and April 2022; whereas Figure 12 presents the event-hour distributions per month. Comparing these two figures indicates that, while the number of events during winter could be lower, the events may continue for a significantly longer period. For example, for February 2021 and January 2022 we observed 5 weather events that each lasted (in average) about 100 hours. In contrast, during summer, while the number of events increased significantly (between 45 and 80 events), the average hours of storm per event, dropped to the range of 2.5 hours and 5 hours.
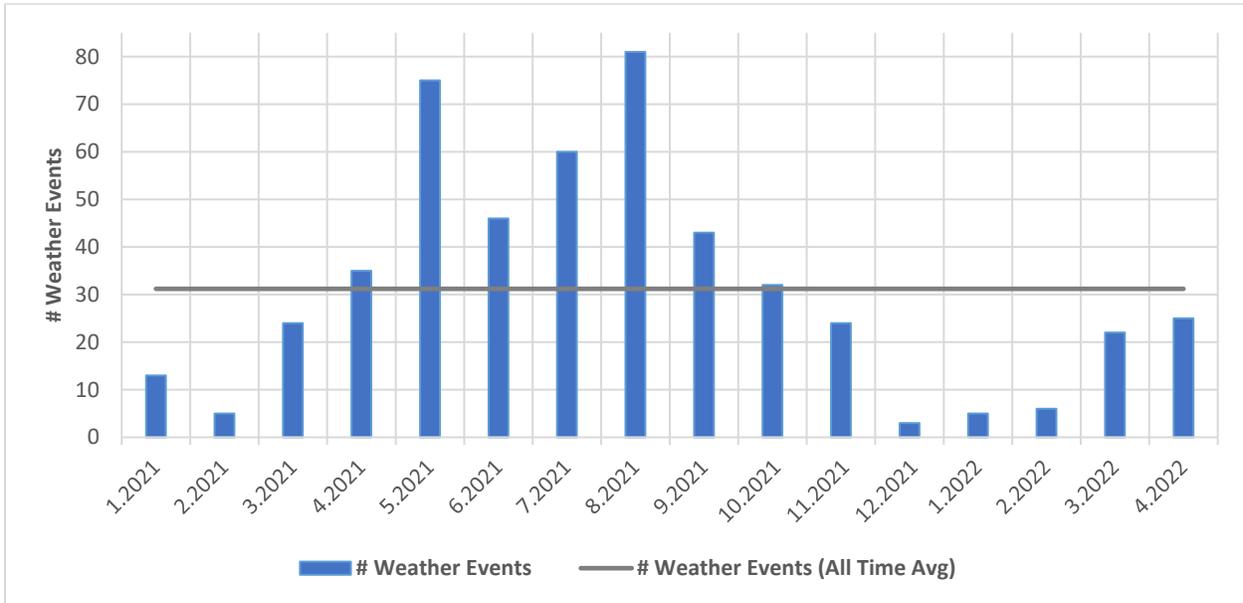
Figure 11. Number of weather events between Jan 2021 and April 2022.
Source: WYDOT
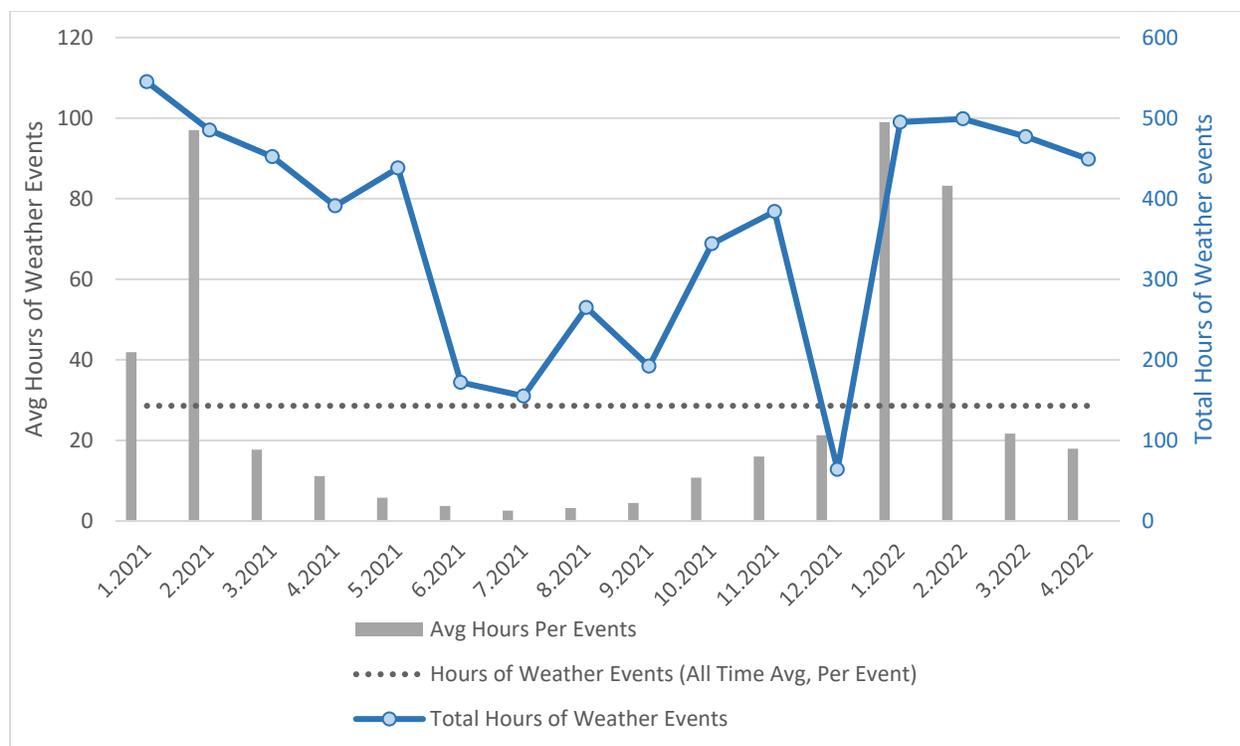
Figure 12. Statistics on hours of weather events from Jan 2021 to April 2022.
Source: WYDOT

4.1.1.2 Crashes

Between December 2020 and February 2022, 1,964 crashes occurred within the I-80 corridor. Most of these crashes (56%) involved a truck vehicle—see Figure 13. The average number of crashes per month is 131 and 73 for total crashes and crashes involved a truck, respectively.

More vehicle crashes were experienced in Wyoming during the winter months (both total and truck involved crashes), typically due to increased instances of extreme weather. Fewer crashes are experienced in the summer months, with an especially low number of crashes seen among truck drivers. High level crash related statistics are provided below and displayed in Figure 14 and Figure 15.
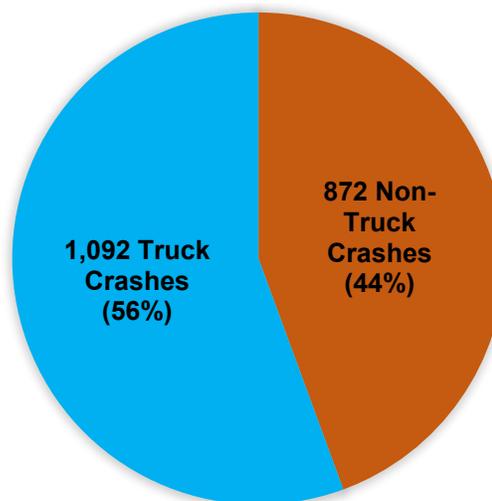
Figure 13. Crash distribution from Dec' 20 to Feb' 22.
Source: WYDOT

- The highest number of crashes occurred in December 2021 with 228 total crashes and 153 truck related crashes.
- The lowest number of total crashes occurred in September 2021 with 72 crashes.
- June 2021 was the safest month for truck vehicles with only one truck related crash.

- The overwhelming majority of the crashes were non-critical.
- Majority of the crashes occurred during daytime hours, particularly during the morning (7-10am) and afternoon (3-5am) peak hours.
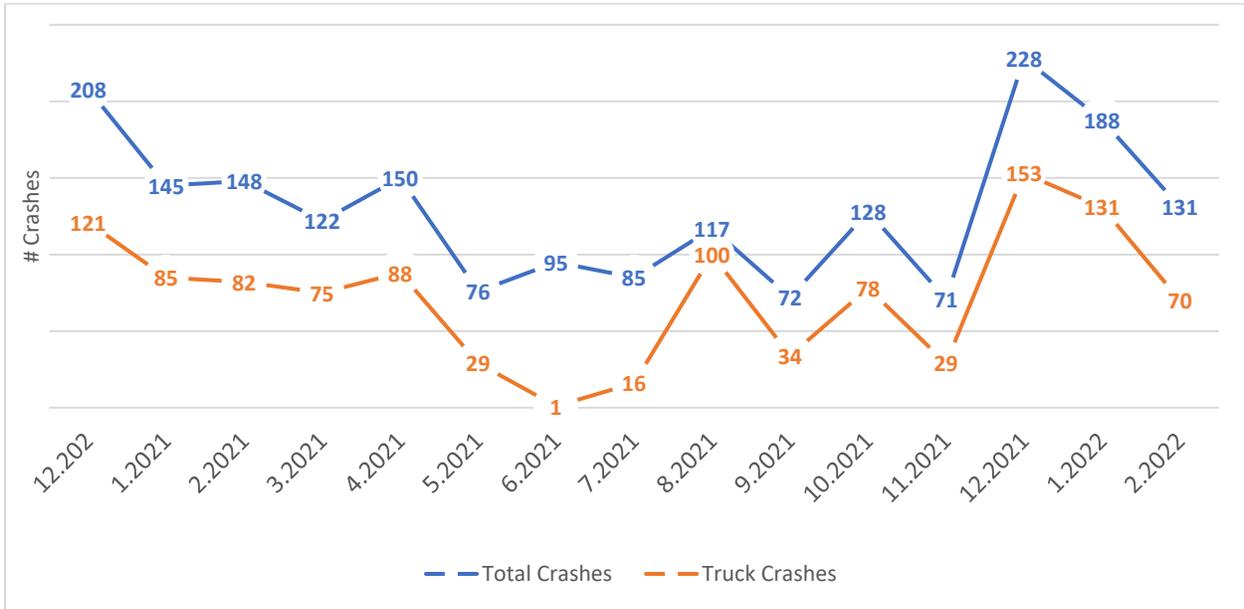
Figure 14 Monthly crash numbers from Dec 2020 to Feb 2022.
Source: WYDOT
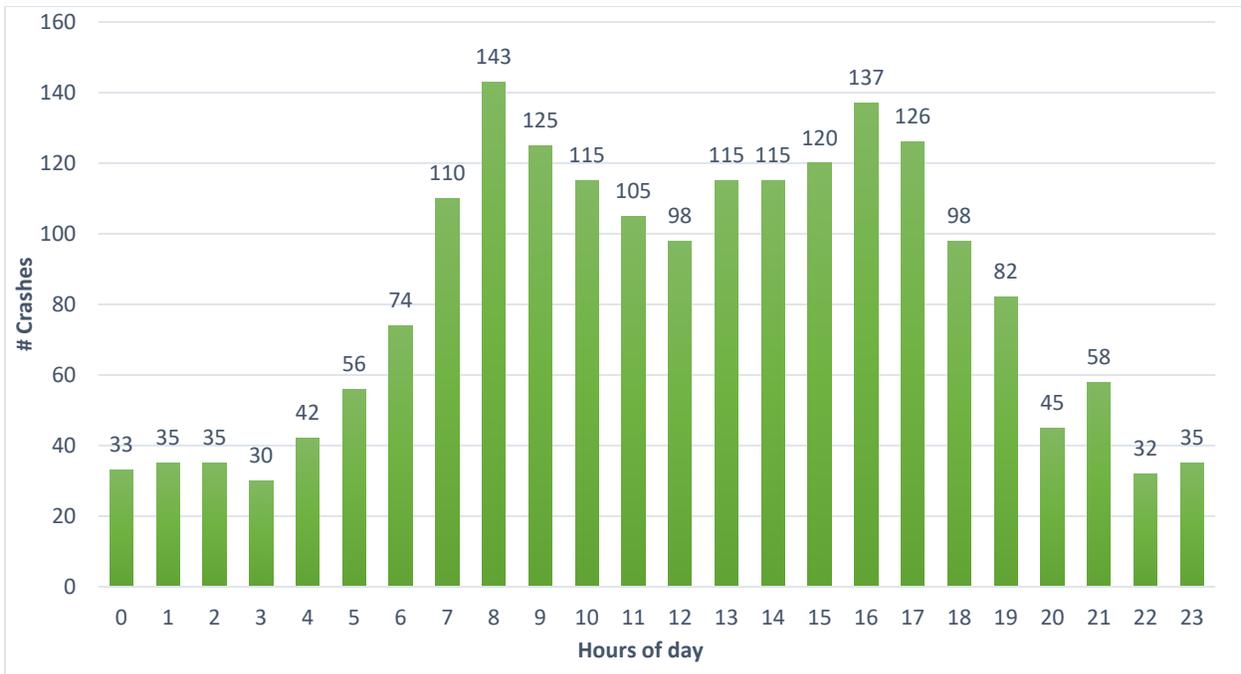
Figure 15 Crashes per hours of day from Dec 2020 to Feb 2022.
Source: WYDOT

4.1.1.3 Work Zones

Between January 2021 and April 2022, 17 work zones impacted traffic within the I-80 corridor. These construction projects impacted about 123 miles out of 402 miles of the I-80 corridor at various time intervals. The list of all work zone projects is provided in Table 4.

Table 4. Work Zone projects impacted I-80 traffic between Jan 2021 and April 2022.

ID	Title	Start Date	Completion Date	Affected Corridor Length (mile)
1	District 3 Bridge Rehab	4/14/2020	7/31/2021	21.0
2	Snake River South	4/1/2020	7/31/2022	0.1
3	I-80 Hillsdale Bridge Replacement	4/27/2020	11/30/2021	13.0
4	Rock Springs - Rawlins (Rock Springs East	3/8/2021	11/30/2021	15.0
5	I-80 Fort Steele to Laramie	10/20/2020	10/30/2022	7.1
6	Thayne - Alpine Junction (Etna North US89)	10/22/2020	6/30/2022	2.0
7	I-80 in Laramie	4/5/2021	10/31/2021	5.9
8	District 5 Bridge Rehab US 14 A	4/12/2021	1/30/2022	8.81
9	Rock Springs Streets (I-80 Interchange)	3/8/2021	6/30/2023	6.9
10	Tensleep East	4/26/2021	6/30/2022	10.0
11	I-80 Sinclair to Walcott	3/4/2021	10/31/2021	7.0
12	D3 Bridge Rehabilitation Project I-80 mile post 97	4/14/2021	7/31/2022	0.6
13	I-80 MP 310-313 Bridge Rehabilitation	3/29/2021	10/31/2021	3.0
14	I-80 Quealy Dome West Laramie	10/20/2020	10/30/2022	10
15	I-80 Paving Elk Mountain	5/24/2021	10/31/2021	6.0
16	I-80 WB mile post 6 to 5 road work in driving lane	7/6/2021	10/31/2021	1.0
17	Rock Springs-Rawlins (Bitter Creek Section) Sweetwater County	6/26/2021	8/31/2022	5.0

4.1.2 CV System Operations Statistics

Towards the end of April 2022, the WYDOT CV Pilot had deployed over 320 OBUs to be equipped in Friendly and Partner fleets (described in Section 2.2.2). These fleets frequently operate statewide and along Wyoming's 402 miles of the I-80 corridor. However, it is important to note that WYDOT only had control over its own fleet of vehicles. As such, Partners Fleets were responsible for installing and maintaining their equipment—with support from WYDOT when requested.

Figure 16 presents some highlights of the vehicles' operations between January 1, 2021, and April 30, 2022, within the I-80 corridor. Throughout this period, the CV Pilot registered over 412 million BSMs and 635 thousand driver alerts. The following subsections provide more details into these numbers and high level statistics regarding CV operations.

412 Million BSMs	635k Driver Alerts

4.5 Million BSMs/wk (by Friendly Fleet)	1.5 Million BSMs/wk (by Partner Fleet)	100 /wk FCWs	55 /wk SVAs	9k/wk TIMs

Vehs/wk: 8 WY, 9 TH, and 32 HP	BSMs/Vehs*wk: 22k WY, 29k TH, and 122k HP
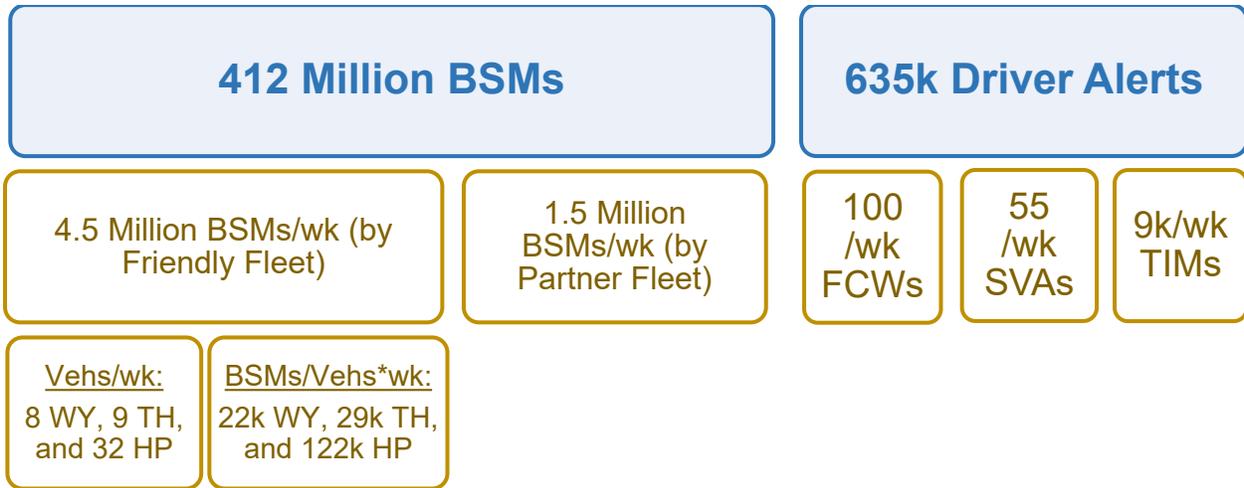
Figure 16. Summary of CV Operations from Jan 2021 to Apr 2022.
Source: WYDOT

4.1.2.1 Vehicle Count

CVs create unique logs when traversing through I-80, which can be analyzed to determine the number of CVs that traveled through the corridor at any given months. However, as previously explained, only Friendly Fleet CVs have unique IDs and therefore are the only one we can discretely count. Figure 17 provides a comparison of the number of unique Friendly Fleet CVs that operated within I-80 between January 2021 and April 2022. Note that these are number of unique vehicles, not the number of instances each Friendly Fleet CV was present in I-80 (i.e., vehicles are not counted more than once). On average, there were 50 unique Friendly Fleet traveling on I-80 throughout our period of analysis. The monthly breakdown shows that most of the Friendly CVs were highway patrol vehicles with the minimum of 17 vehicles (in March and April 2022) and maximum of 48 vehicles in April 2021. The number of WYDOT plows and Trihydro vehicles were significantly lower compared to HPs and fluctuated between 2 to 20 vehicles per month.
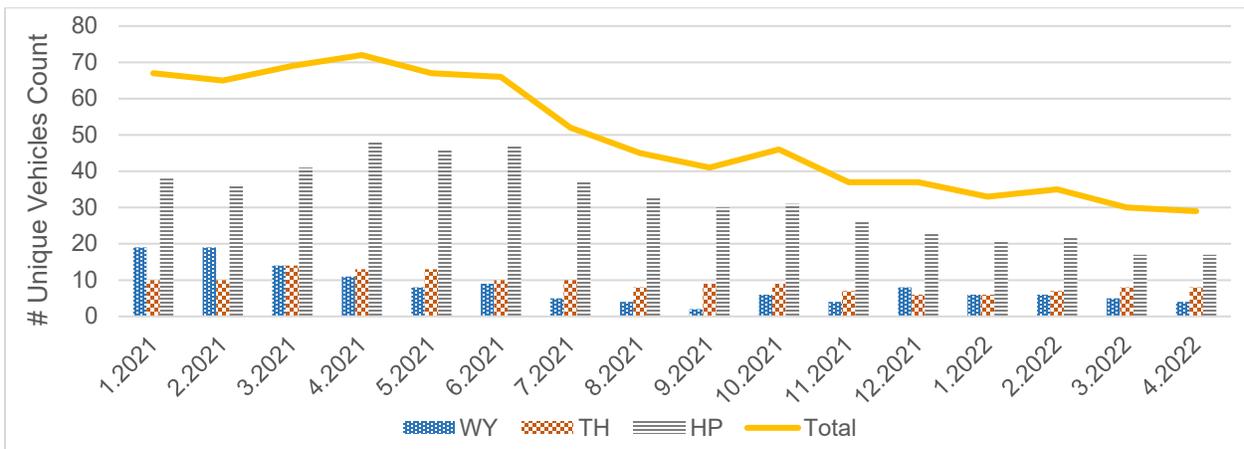
Figure 17. Count of Friendly Vehicle's: Jan 2021 – Apr 2022.
Source: WYDOT

A similar assessment was performed to estimate the number of Partner Fleet CVs present in I-80 every month, with the caveat that it is not possible to determine the number of unique Partner CVs in operation, but instead we estimate the number of dynamic IDs. Figure 18 represents the number of dynamic IDs between January 2021 and April 2022. This figure shows an increasing trend, where more partner vehicles were operating (within I-80 corridor) during the second half of the time interval. This trend was at its highest in April 2022, which is expected as more partner vehicles are joining the CVP fleet.
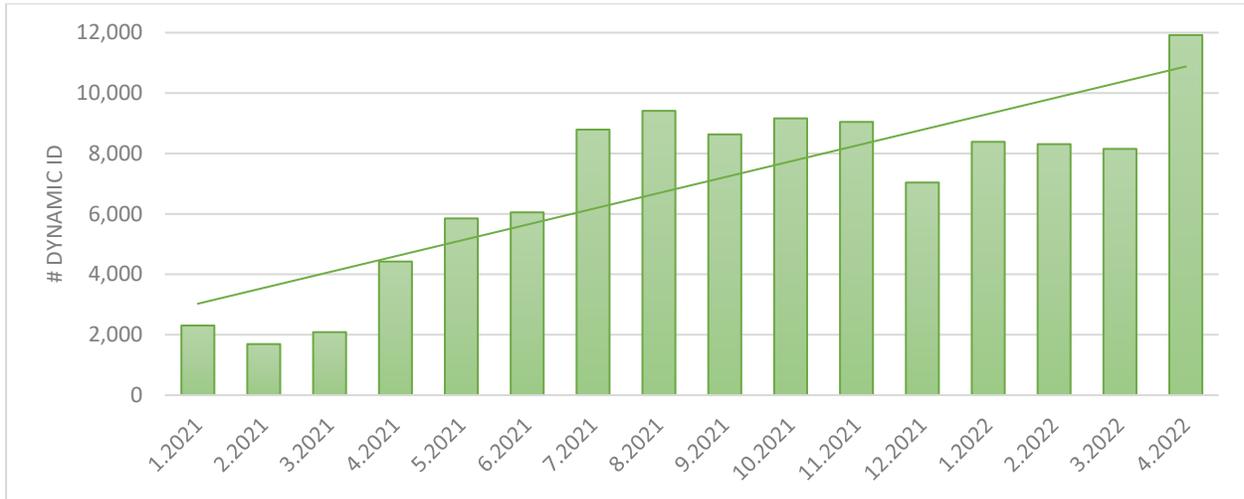
Figure 18. Friendly Partner Dynamic IDs between Jan 2021 – Apr 2022.
Source: WYDOT

4.1.2.2 Basic Safety Message Statistics

Estimating the number of BSMs generated within the I-80 is another metric that shows the extent of the CV Pilot operation. Figure 19 provides a comparison between the BSMs that were generated by the Friendly vehicles and Partners vehicles. On average, between January 2021 and April 2022, the CV Pilot (including all vehicle fleets) generated around 25.8 million BSMs per month, with a minimum and maximum count of 16.4 (Mar' 2022) and 37.2 (Aug' 2021) million BSMs per month, respectively. The figure shows an increasing trend with respect to the Partner vehicles BSMs. However, this trend has more fluctuations regarding the BSM counts for the Friendly vehicles. Furthermore, in average, Friendly vehicles generated 12.5 million more BSMs every month than Partner vehicles. The highest difference occurred during March 2021 where Friendly CVs generated 25.6 million more BSMs.
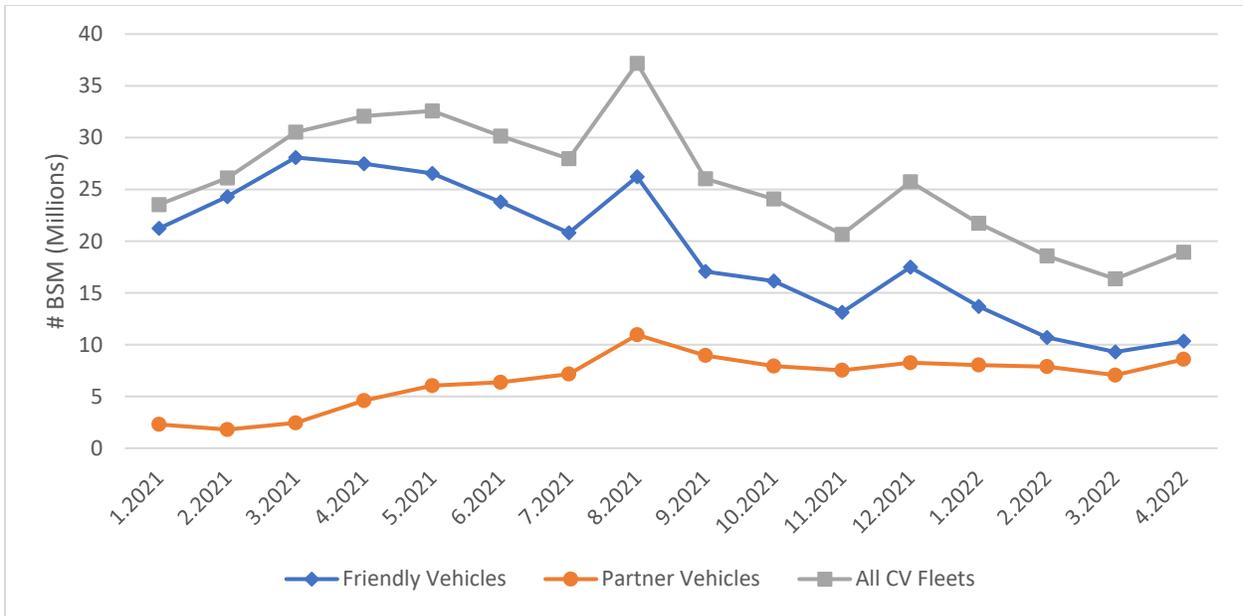
Figure 19. Overall BSM Count Comparison between Jan 2021 – Apr 2022
Source: WYDOT

Figure 20 shows the monthly breakdown of the number of BSMs generated by Friendly Fleet vehicles during the period of analysis. Since the operation of the Friendly CVs (WY, TH, and HP vehicles) are dependent on the number of road events, the BSM data is expected to fluctuate at certain times. For example, during 2021 first quarter, the WYDOT snow plows generated more than 7.5 million BSMs as I-80 was undergoing 42 severe weather events and 1,500 hours of weather events (many of which being severe storm related). However, between Sept' and Nov' 2021, the operation of the WYDOT plows was limited. During this timeframe, traffic in I-80 corridor endured 900 hours less of weather events.

Figure 20 also shows consistent behavior with the Friendly Fleet's count trend, with the majority of the BSMs were generated by the HPs. The HPs generated the highest number of BSMs during March 2021 with about 25 million BSMs. The BSM count for WY and TH vehicles are significantly lower. The WY vehicles generated in average around 1 million BSMs per month with its highest of 3.2 million in January 2021. The TH vehicles generated in average about 1.1 million BSMs with its highest of nearly 1.8 million in August 2021.
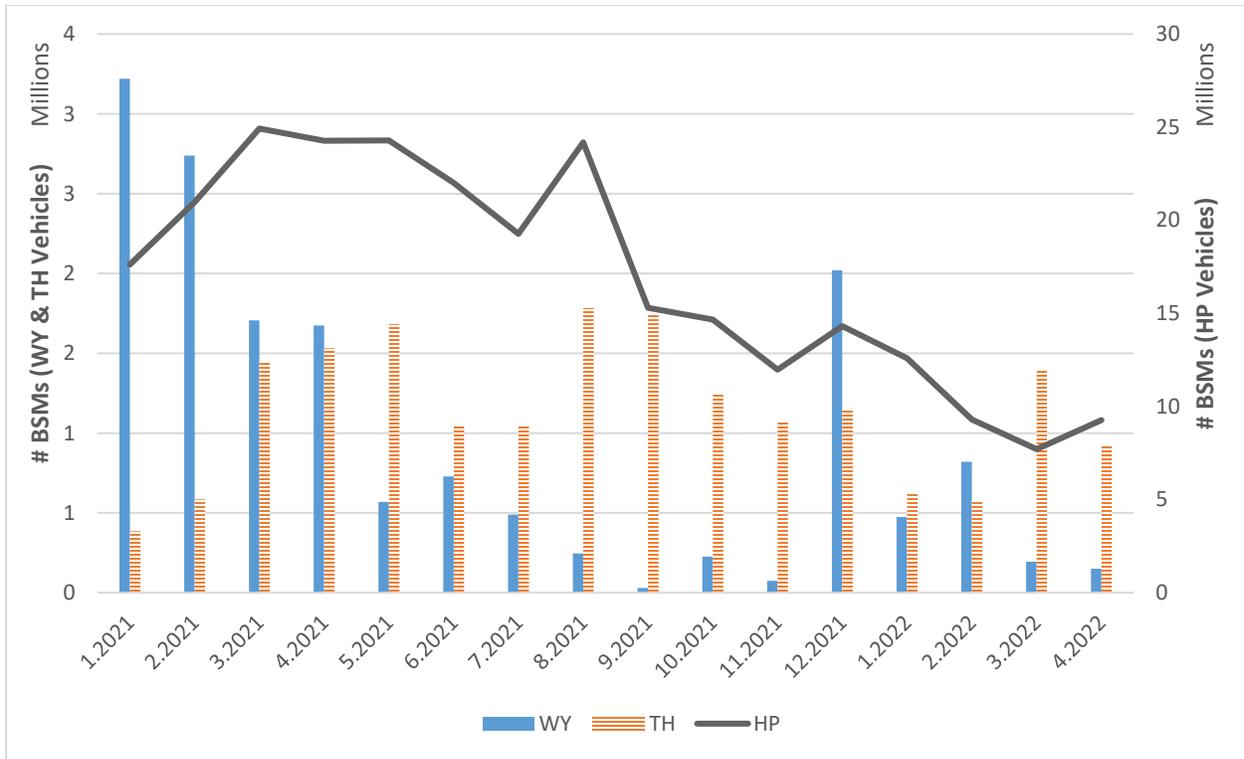
Figure 20. Friendly Fleet BSMs Count between Jan 2021 – Apr 2022.
Source: WYDOT

Figure 21 illustrates the monthly BSM counts statistics for Partner Fleet vehicles. The BSM data for partner vehicles for the past 16 month, indicates a linear increasing trend. The lowest count was 1.8 million for Feb' 2021, and the highest count was 11 million for Aug' 2021. Overall, Partner Fleet generated more than 106 million BSMs during the period of analysis. The project team expects growing number of BSMs as 100 more OBUs were shared with a new Partner Fleet between January and February 2022.
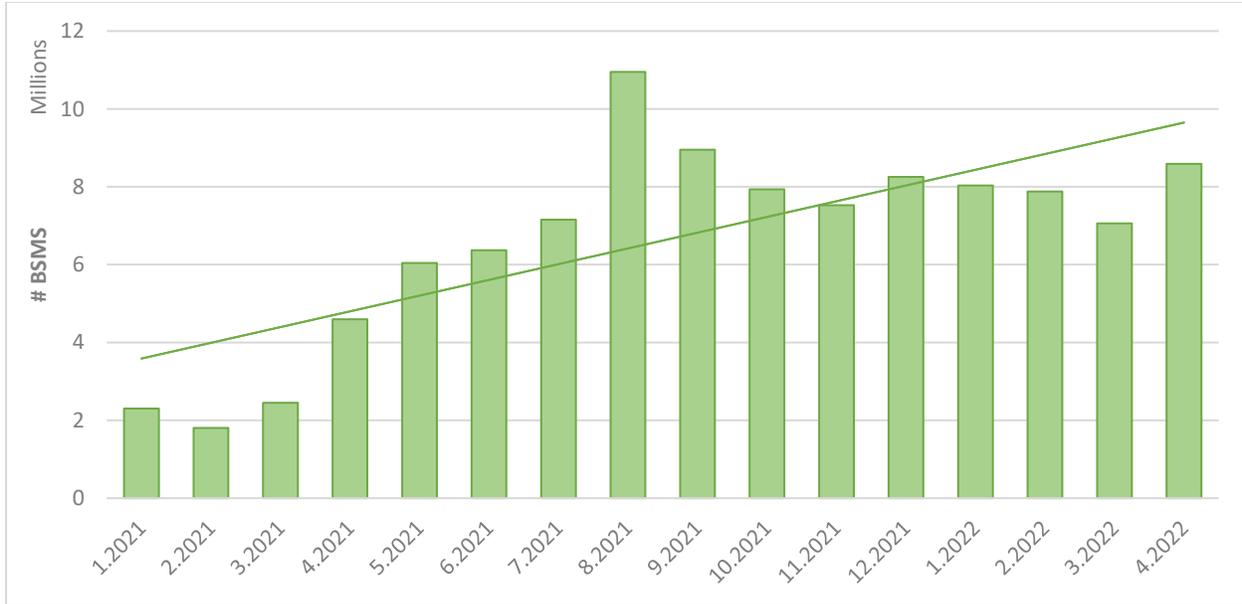
Figure 21. Partner Fleet BSMs count between Jan 2021 - Apr' 22
Source: WYDOT

4.1.2.3 Driver Alerts Statistics

The overwhelming majority of the driver alerts consists of TIMs, which provide information on weather, road, and work zone conditions, including the ones sent from the TMC to the RSUs and from the TMC directly to vehicles through satellite—all alerts generated by information provided through TMC communication routes make up what this report refers to as *V2I alerts*. TIM distribution is not bound to a particular trend but is dependent of road conditions and events that are occurring within I-80. The same statement applies to the FCWs and SVAs, which combined make up what this report refers to as *V2V alerts*.

Figure 22 provides a comparison between different types of driver alerts between January 2021 and April 2022. Summary statistics for each are provided below:

- Total TIMs monthly count ranged between 16.9k (Mar' 2022) and 68.5k (Mar' 2021). In average, 40k TIMs were generated every month.
- Total FCWs monthly count ranged between 45 (Feb' 2022) and 750 (Jan' 2021). In average, 422 FCWs were generated every month.
- Total SVAs monthly count ranged between 50 (Nov' 2021) and 964 (Dec' 2021). In average, 250 SVAs were generated every month.
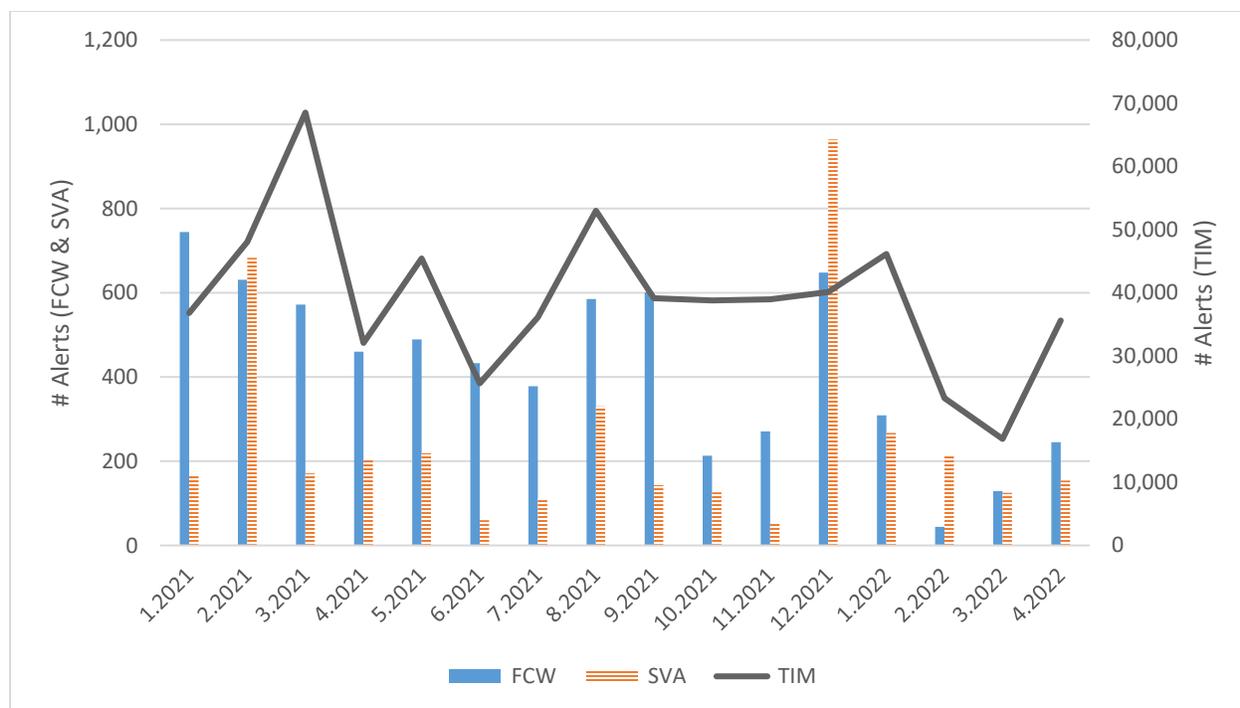
Figure 22. Driver Alert Stat: Jan' 21 - Apr' 22
Source: WYDOT

4.1.2.3.1   V2V Messages Outliers

Between January 2021 and April 2022, the project team detected a few days where SVA and FCW alerts were significantly higher than the monthly average numbers. During the first three months of 2021, the number of V2V interactions were skewed by circumstances that appear to place several CVs in nearby locations for an extended period while keeping "communication" open. This situation forced the system to generate thousands of additional SVAs and FCWs in a matter of days—see Table 5 for details on the dates. For instance, the data indicates that on January 7, 2021, two HPs parked near each other, producing the vast majority of the alerts generated in January (roughly 90k SVAs).

Similar data anomalies occurred in 31 days (out of the near 484 days) of operation analyzed. While these occurrences only account for roughly 6.4% of the total days of CVP operation, they amount to 600k redundant alerts. As such, it was pivotal for the project team to detect these outliers and remove them from the performance measurement analysis.

Table 5. V2V Messages Outliers

Month	FCW Outliers	SVA Outliers
Year 2021		
January	Jan' 23-24: 3,084	Jan' 6-7: 113,983 Jan' 23-24: 6,159 Jan' 30: 579
February	Feb' 11: 955	Feb' 5: 511
March	*No outliers detected.*	Mar' 16: 11,158

Month	FCW Outliers	SVA Outliers
August	Aug' 10: 3,604	*No outliers detected.*
November	Nov' 20: 3,344	Nov' 20: 1,430
December	Dec' 9: 793 Dec' 13-14: 3,941 Dec' 27: 4,557 Dec' 30-31: 6,549	Dec' 10-11: 4,889 Dec' 27: 1,328
Year 2022		
January	Jan' 11: 13,075	*No outliers detected.*
February	Feb' 16: 8,367	Feb' 16: 896
March	Mar' 7: 9,940 Mar' 15: 18,444	Mar' 10: 10,655 Mar' 15: 48,592
April	Apr' 1: 13,815 Apr' 6-7: 65,566 Apr' 11: 1,463 Apr' 20: 449	Apr' 1: 501 Apr' 4; 30,611 Apr' 7-8: 152,324 Apr' 18; 476 Apr' 20: 64,990

4.1.2.4 Hours of Operation

To obtain total hours of operation (per vehicle) on I-80 corridor, the total time of each trip was first determined by subtracting the start time from the end time. Then, all trip times were totaled for each vehicle ID to obtain the total hours of operation per month, per vehicle.

This analysis is only bound to trips completed within I-80 corridors. Thus, this analysis does not account for journeys that left the I-80 corridor boundaries for certain amount of time, referred to as ping delay, and exclude those from the analysis. The "maximum ping delay" is specified by the user upon running the script. The maximum ping delay is used to determine the pings that mark the end of one [vehicle ID] travel trip and the start of a new travel trip.

For example, if the maximum ping delay is 30 seconds, pings that are spaced less than or equal to 30 seconds apart are assumed to belong to the same trip. Pings that are spaced greater than 30 seconds apart are assumed to belong to different trips. Thus, when pings are spaced apart greater than the maximum ping delay, the first ping in sequence is assumed to be the end of the previous trip, and the second ping is assumed to be the start of the next trip. For this analysis, the maximum ping delay of 30 seconds was selected after observing that most pings were spaced apart by 30 seconds or less.

Generally, this metric is a valuable add on to the CVP operation where CVs travel time at specific locations and certain timeframe could be determined. Figure 23 represents the comparison for hours of operation between friendly and partner fleets. As expected, hours of operations are higher during the months of summer.

Figure 24 exhibits the distribution in which friendly and partner vehicles are operating within the I-80 corridor against the CV total fleet hours of operations. The figure shows that overwhelming majority of the CV's hours of operation is linked to friendly fleet (WY, TH, HP vehicles), with an average of 80%. The figure also shows a constant increase in hours of operations by Partner

CVs, which is in line with the steady increase in of Partner's BSM generation (see Figure 19) and in the overall number of Partner fleets, especially towards the end of 2021 and beginning of 2022.
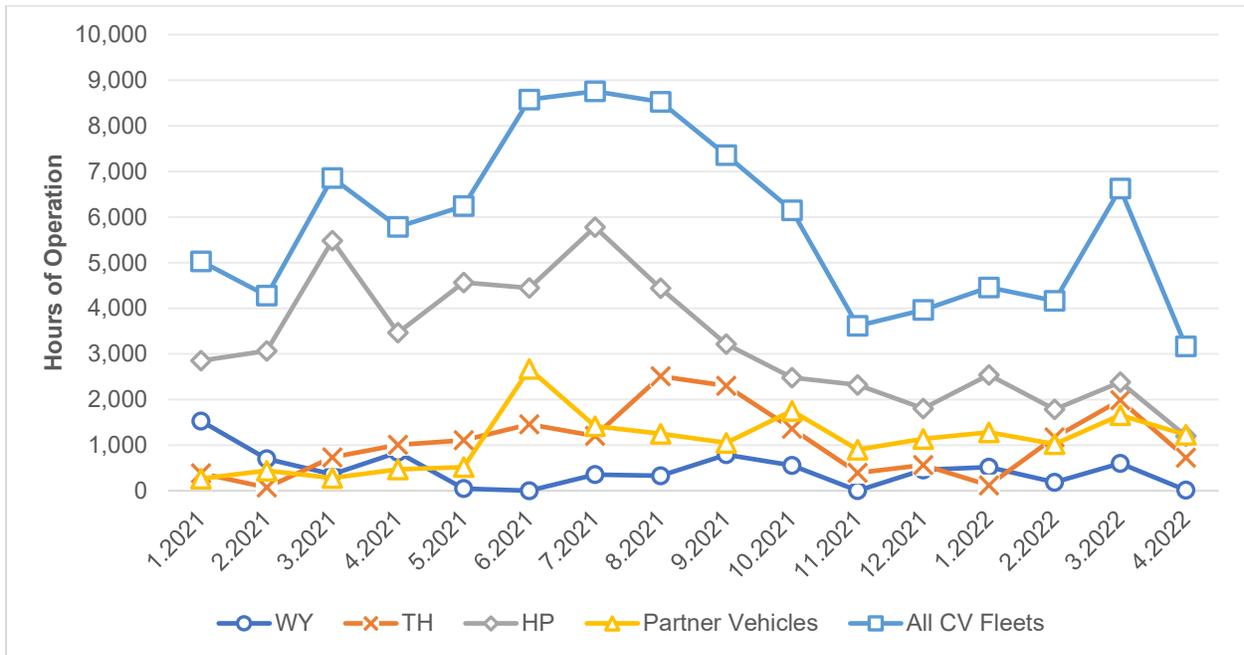
Figure 23. CVP Fleets' Hours of Operation from Jan' 21 to Apr' 22.
Source: WYDOT
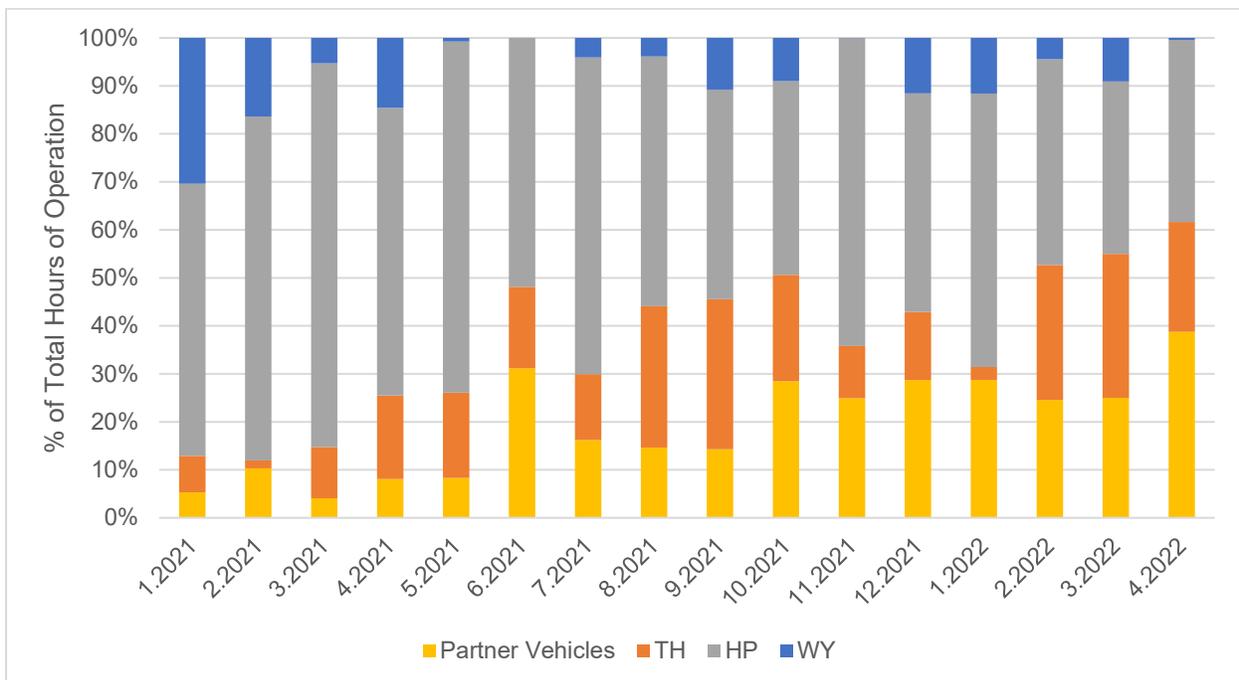
Figure 24. CV Fleets Share of Total Hours of Operation from Jan' 21 to Apr' 22.
Source: WYDOT

The quantification of hours of operations enables the assessment of two interesting perspective of the CV System: generations of BSMs and TIMs communication by Hours of Operations. The following subsections provide details on each.

4.1.2.4.1 Generation of BSMs by Hours of Operations

Figure 25 offers a linear comparison between total BSMs generated and the CVs total hours of operation between January 2021 and April 2022. While data pattern fluctuations are expected due to the CV Pilots' complex system and environmental conditions, the result is consistent with the main expectation that higher hours of operation lead to higher number of BSMs. This finding is important as it infers that these BSMs are generated inherently and are not redundant or as a result of system malfunctions.
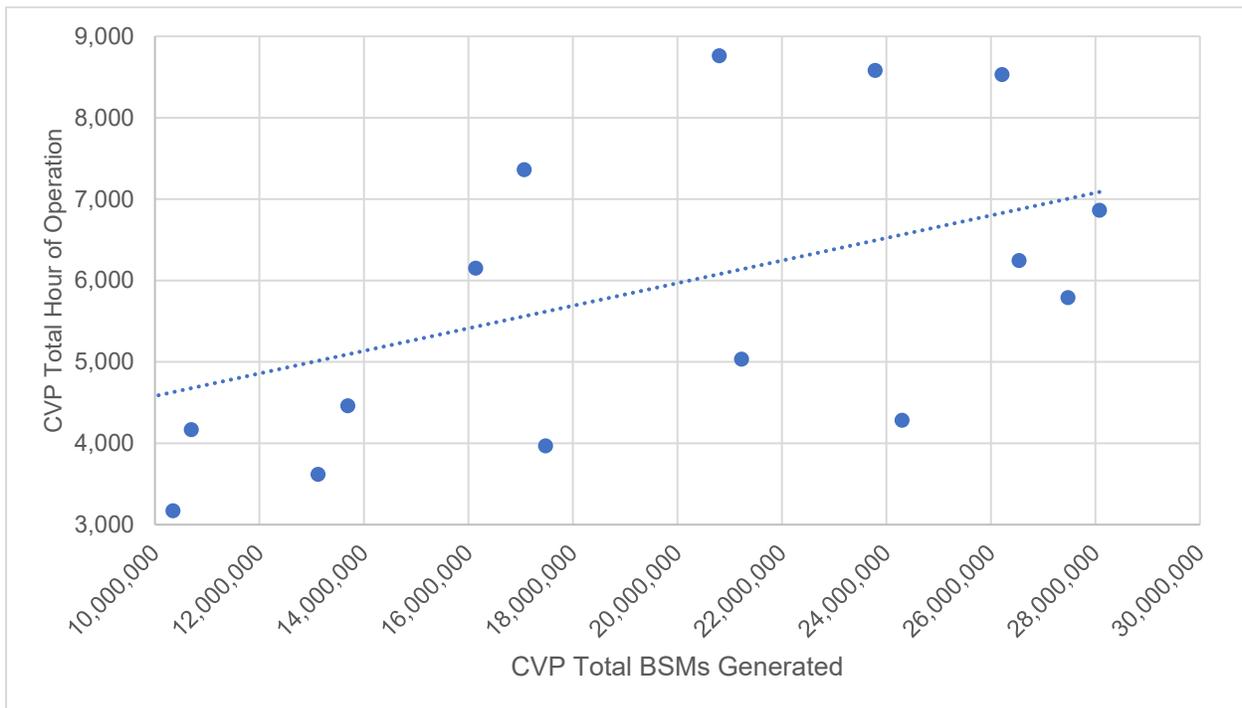
Figure 25. Hours of operation Vs. total BSMs
Source: WYDOT

4.1.2.4.2 TIMs Communication by Hours of Operation

The number of TIMs per hour of CVs operation measures the extent in which TMC communicates with the CV fleet. This analysis compares the total number of TIMs transmitted by CV fleet hours of operation for each month between January 2021 and April 2022—see Figure 26. The result shows that in average 7.3 TIMs were transmitted for every hour of CV operation. The fluctuations are in line with the seasonal impacts as road and weather condition changes. The higher values are associated with months with long hours of storm (e.g., Feb' 2021 with 11.2 TIMs per hour of operation) and lower values are associated with months with short-duration storms (e.g., June 2021 with 3 TIMs per hour of operation).
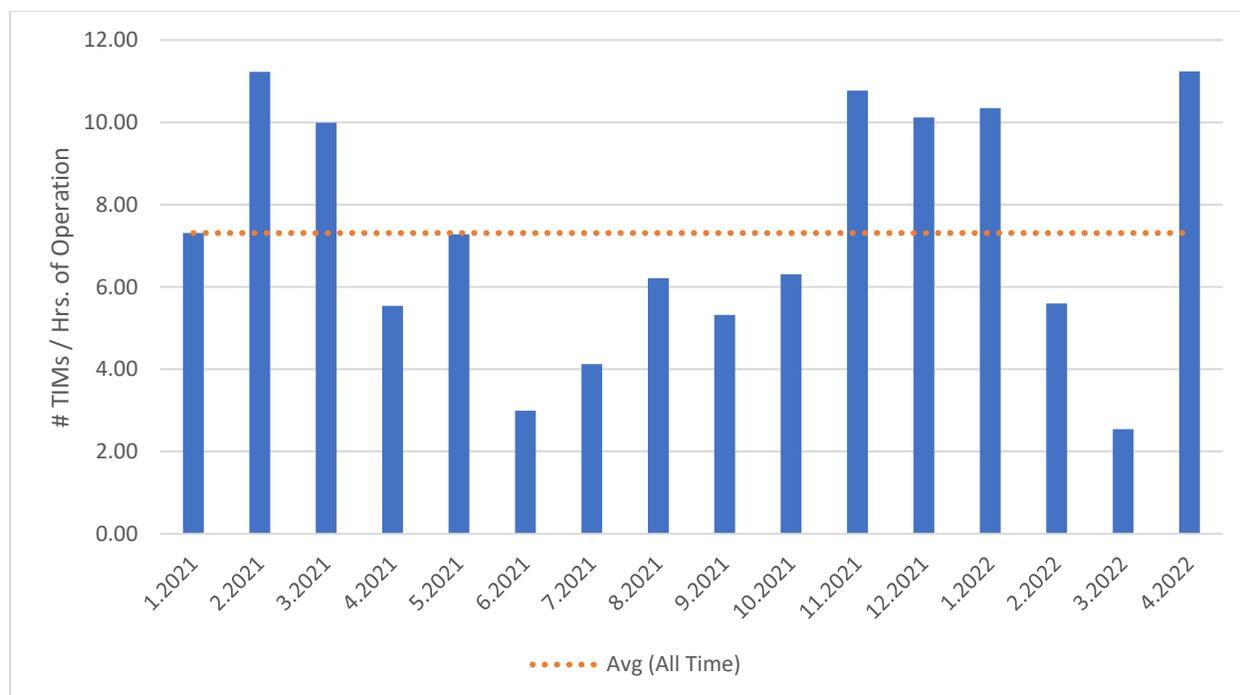
Figure 26. TIMs Per Hour of CVP Operation: Jan' 2021 - Apr' 2022
Source: WYDOT

4.2 Road Weather Condition Reporting

The road condition reporting measures focus on the quantity, coverage, and latency of reports received by the TMC. These three qualities are captured in the following performance measures:

- Quantity (PM 1 - Number of Road Condition Reports)
- Coverage (PM 2 - Number of Road Sections With At Least One Report)
- Latency (PM 3 - Average Refresh Time of Road Reports)

The assessment of these measures is limited to when weather events with conditions deemed as moderate or high severity. To make these calculations from the data collected (see Section 3.2), two important values were needed for each of the identified 499 weather events (from Jan' 2021 to Apr' 2022):

- Number of unique reporting sections – There are a total of 64 reporting sections along the 402 mile I-80 corridor (32 reporting sections in each direction of travel). The number of reporting sections for each weather event were extracted from the raw data. The values ranged from a low of 2 sections for a strong wind event to a high of all 64 sections for several corridor-wide events.
- Hours of each weather event – The raw data contains the total number of hours for which at least one report was made for each weather event. These values were logged for each event and used in the PM calculations below. It is important to note that the hours per weather event logged are when a report was made, not the total number of hours the event took place (start and end dates/times) – these were not always the same. The values

ranged from 1 hour for a strong wind event to 293 hours for a major winter storm in February 2021.

The WYDOT TMC collects and stores all field maintenance reported road conditions by day/time and location. Special software was written to extract the data required during weather events. WYDOT rates the overall impact (low, moderate, high) to the traveler by various road conditions, weather conditions, advisories, and restrictions. A table of these ratings is provided in Appendix C. Road Condition Ratings.

As previously stated, this research defines a "weather event" as anything other than a low rating. Therefore, the data provided by the WYDOT TMC for analysis was only during weather events as defined in this way. The "Non-low number of road conditions" is the number of road reports that have a rating of anything other than "low." Table 6 represents the road condition reports data that was used to estimate the PM 1-3.

Table 6. Road Condition Reports Data Collected

Data Element	Data Description
Road Condition Reports Per Road Section Per Day	
Event start	Date and time (when rating moved from L to M or H)
Event end	Date and time (when rating moved from M or H to L)
Road section code	Maintenance road section abbreviation
Total number of condition reports	Number of reports by road section
Non-low number of condition reports	Number of reports by road section
Condition reported	Condition by road section
Road Sections Reported Per Hour	
Event start	Date and time same as above
Event end	Date and time same as above
Report hour	Hour value, within event start/end
Total number of condition reports	Number of reports within each hour
Non-low number of condition reports	Number of reports within each hour
Average Refresh Time Per Section	
Event start	Date and time same as above
Event end	Date and time same as above
Road section code	Maintenance road section abbreviation
Total average refresh time	Minutes, time between reports by section
Road open average refresh time	Minutes, time between reports by section
Other Supportive Data	
Road closed time	Day/time, by event and road section code
Road open time	Day/time, by event and road section code
Road section code beginning point	Mile post and landmark
Road section code end point	Mile post and landmark

It is important to note that, based on the approach shown in Figure 27, PMs 1-3 are standardized by hours of mid- and high-level storms and by roadway segments. This helps mitigate potential differences between winter seasons and other factors.
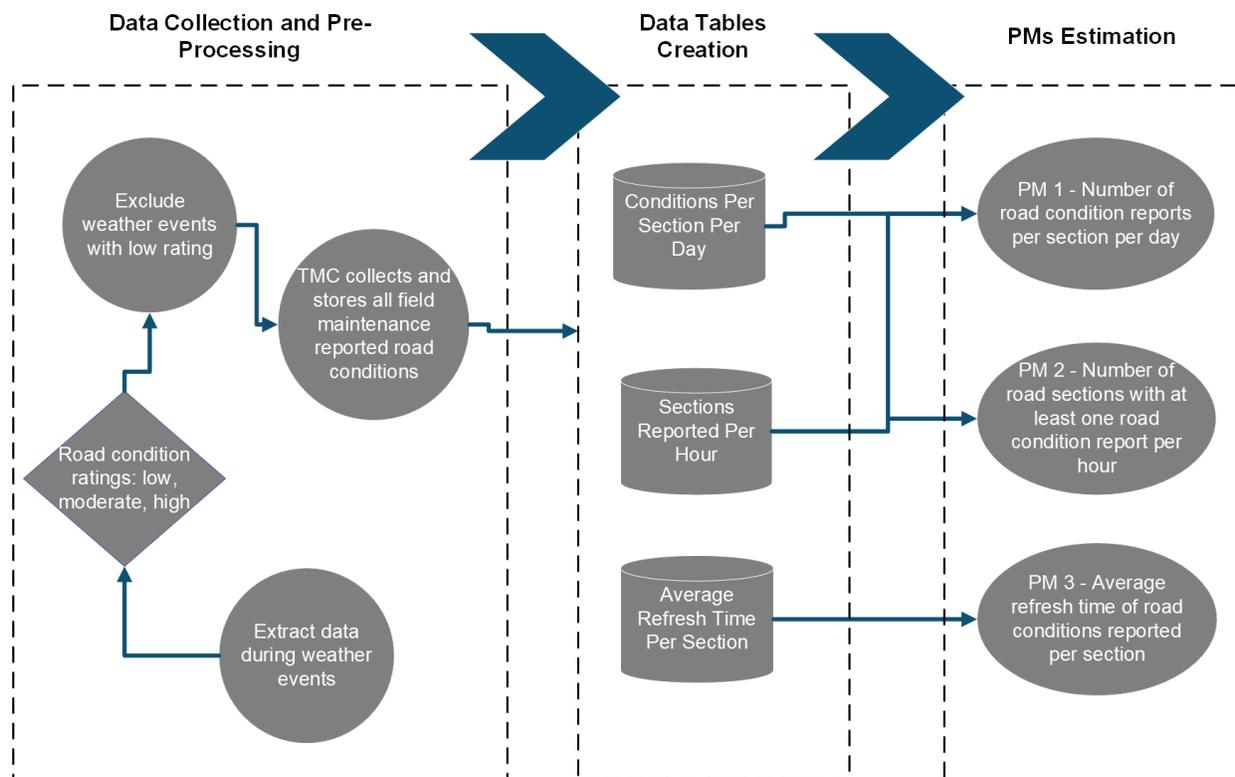
Figure 27. Overall methodology to estimate PMs 1-3
Source: WYDOT

Confirming the pilot's hypothesis 2 (Section 3.1.2), the result shows significant improvements (compared to the baseline) with respect to the three performance measures. This indicates that WYDOT was able to maintain a high degree of situational awareness using their road condition reporting systems between January 2021 and April 2022.

4.2.1 PM 1 - Number of Road Condition Reports

The baseline condition estimate for the average number of road condition reports per section per day during weather events was 4.3 reports. The baseline value ranged from 1.4 to 12 reports per section per day, with a median of 3.6. The target for this measure is to increase the performance by 30% compared to the baseline estimate.

Figure 28 shows a breakdown of the PM1 estimates for every month between January 2021 and April 2022. As can be seen, the number of reports per section per day of event significantly increased throughout the entirety of the pilot—values above the dash orange line indicate months when the system outperformed the target. The post-deployment average number of reports was 16.88 (293% increase), with the numbers ranging from 7.24 (53% increase) to 27.92 (423% increase) and a median of 14.47 (236% increase). During the period of the pilot, there were no

major improvements to WYDOT's system besides the pilot itself. As such, the pilot could be identified as a determining factor (if not the only one) acting to improve the numbers

Figure 28 also highlights the impact of seasons on the number of reports. During summer months, with less road closures, the system can provide almost double the number of reports than during winter months. Severe and extended weather events are common in Wyoming. An example of this is the single weather event that started on December 6, 2021, and ended on January 18, 2022. This event had a significant impact on the roads and their availability. While the number of reports during the month of January 2022 was drastically lower than previous months, the system still generated enough reports (7.5) to surpass the target.
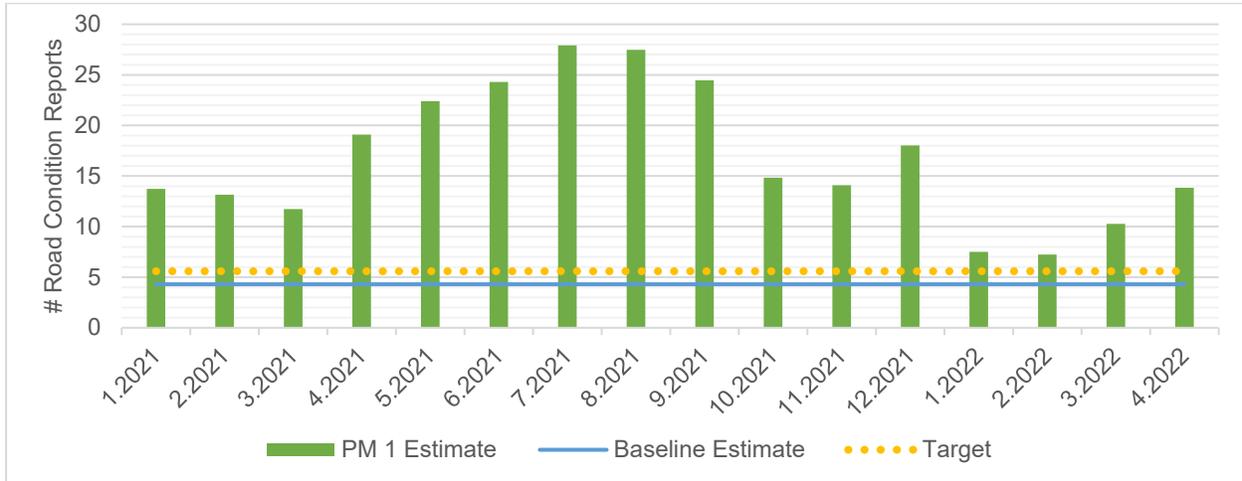
Figure 28. Results of PM 1 – Number of Road Condition Reports.
Source: WYDOT

4.2.2 PM 2 - Number of Road Sections With At Least One Report

The baseline condition estimate for the average number of road sections with at least one road condition report per hour during weather events was 5 sections. The baseline value ranged from 1.4 to 10.5 sections and a median of 4.5 sections. The target for this measure is to increase the performance by 25% compared to the baseline estimate.

Post-deployment, the number of reports per section per day between January 2021 and April 2022 increased to an average of 6.4 (29% increase). The post-deployment numbers ranged from 3.54 (29% decrease) to 7.88 (57.6% increase), with median of 6.62 (32.4% increase).

Figure 29 shows a breakdown of the PM 2 estimates for every month of the analysis period— values above the dash orange line indicate months when the system outperformed the target. The data shows that at certain months the PM 2 did not meet the target. For instance, in July (a summer month), the I-80 corridor encountered less severe weather conditions that last shorter period of time (see Figure 12) and that do not impact as many of the road sections. This would eliminate the need for maintenance vehicles to generate a road condition report. Causing the PM 2 estimates to fall below the projected target value. The same occurs during severe winter events that partially or completely close the I-80 corridor, which limits the number of vehicles on the road and, therefore, the number of reports being generated.
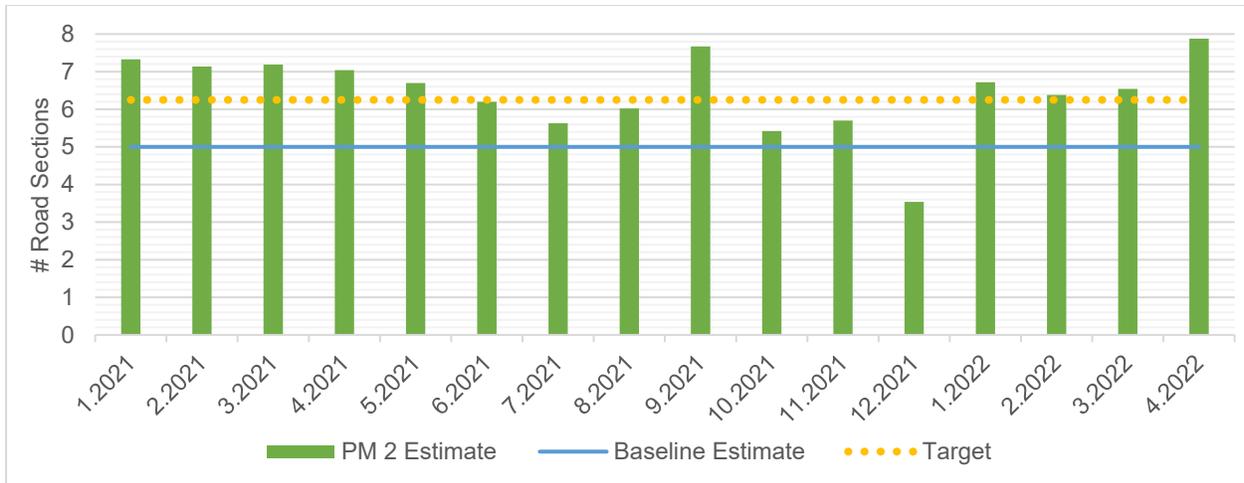
Figure 29. Results of PM 2 – Number of Road Sections With At Least One Report.
Source: WYDOT

4.2.3 PM 3 - Average Refresh Time of Road Reports

The baseline condition estimate for the average refresh time (in hours) of road conditions reported per section during weather events was 3.9 hours. The baseline value ranged from 0.7 to 7.8 hours with a median of 3.7 hours. The target is to decrease the average refresh time by 30% compared to the baseline estimate.

In general, for the post-deployment the average refresh time per section improved to an average of 3.2 (13.5% decrease). The post-deployment numbers ranged from 0.66 (83.10% decrease) to 6.7 (71.5% increase), with median of 3.15 (20% decrease). Figure 30 shows a breakdown of the PM 3 estimates for every month between January 2021 and April 2022—values below the dash orange line indicate months when the system outperformed the target.

While not meeting the target, the result was expected since Wyoming experienced record-breaking storms and winter seasons during our period of analysis. During the both winter seasons, the I-80 corridor experienced severe weather storms which lasted for couple days. Similar to PM 2, these storms caused road closures that impacted the number of CVs that operated within the corridor and, therefore, increasing the average refresh time of road reports.
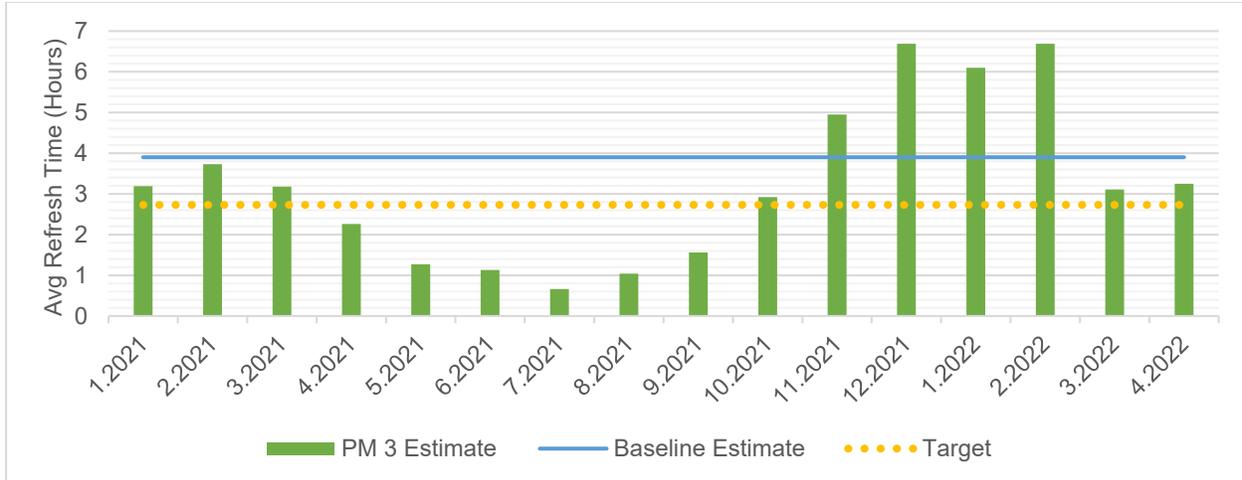
Figure 30. Results for PM 3- Average Refresh Time of Road Reports.
Source: WYDOT

4.3 Information Dissemination - V2V and V2I Interactions

To assess the effective dissemination of information through TIMs, the "TIM package" produced by the system must be analyzed. A TIM package consists of several TIM records that are destined to different locations/infrastructures, with different ITIS Codes. That is, one TIM package logs the transmission of a single TIM as it is disseminated across different RUSs and/or OBUs. Table 7 lists the number of TIM packages (and TIM records within each package) analyzed between January 2021 and April 2022. March 2022 had a significant lower number of TIM records. The drop in TIMs received in vehicle was confirmed to be caused by invalid signatures on the TIMs— see Lesson Learned #70 in Section 8 for more details.

Table 7. Number of TIM Packages and TIM Records between January 2021 and April 2022.

Timeframe	No. TIM Packages	No. TIM Records
01.2021	1,860	36,784
02.2021	9,956	48,053
03.2021	6,236	68,520
04.2021	4,835	32,064
05.2021	3,524	45,436
06.2021	1,443	25,656
07.2021	1,405	36,111
08.2021	2,173	52,981
09.2021	936	39,135

Timeframe	No. TIM Packages	No. TIM Records
10.2021	5,152	38,777
11.2021	2,995	38,957
12.2021	13,239	40,117
01.2022	10,989	46,134
02.2022	9,121	23,312
03.2022	6,754	16,861
04.2022	5,791	35,602

All CVs are equipped with satellite communication and can receive the TIMs directly from the TMC. Similarly, all CVs can share their logs with the TMC through the RSUs. However, several CVs within the Friendly fleet are equipped with DSRC that enables communication from the RSUs to the CVs. When such Friendly CVs pass by the vicinity of an RSU, it could pick up a TIM that is active in the RSU. Figure 31 provides a schematic view of the TIMs flow within the CVP network, accounting for the two ways an OBU can receive a TIM, depending on its communication capabilities.
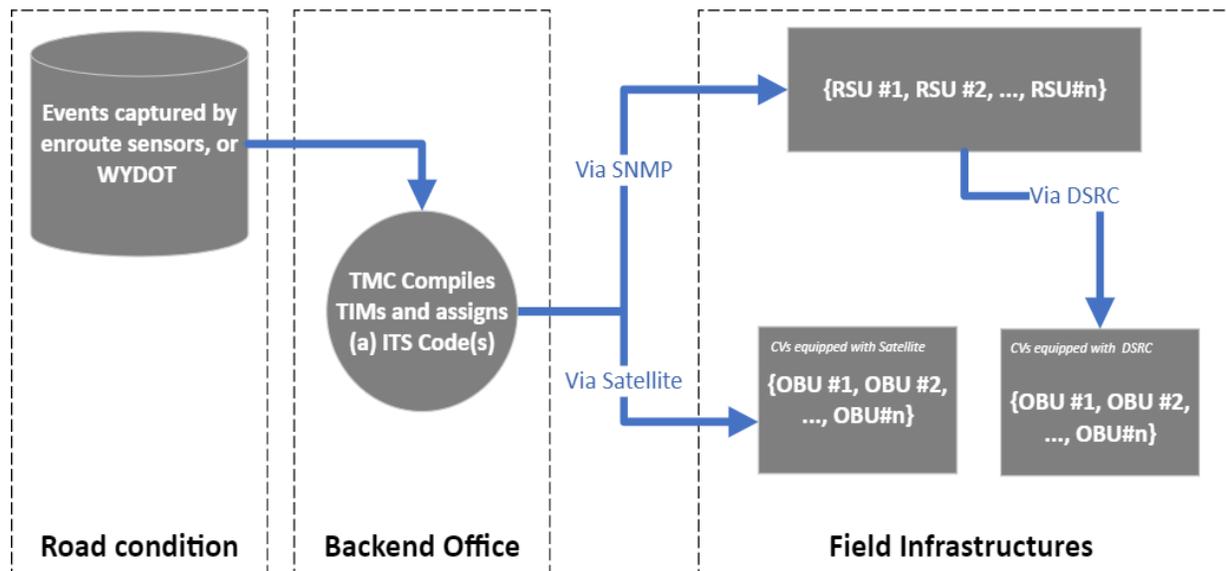
Figure 31. TIMs Generation and Flow.
Source: WYDOT

Understanding the number of TIMs generated, distributed, and received enables the estimation of metrics that provide insight into the percentages of TIMs being received by specific devices from the total number of TIMs generated. The overall approach to estimate these metrics and their results are provided in the following subsections.

4.3.1 PM 4 - Percentage of TIMs Received by at Least One RSU

To estimate PM 4, first the TIM data table needs to be queried and categorized into TIM packages. The data indicates whether a TIM package contained a TIM record that was transmitted from TMC to a RSU.

Based on this piece of information, every TIM package could be labeled as a TIM where at least one RSU received it or not. Dividing the total count of these packages by the total number of TIM packages would lead to the estimation of the PM 4. Figure 32 represent the estimation flow regarding PM 4.

The result of this analysis is summarized in Figure 33. The result indicates an upward trend during January 2021 and April 2022 indicating a significant coverage of the CVP over the I-80 corridor. The least coverage is associated with January 2021 and the highest coverage measured for October 2021. Overall, during the analysis timeframe, an average of 92.1% of the TIM packages were received by at least one RSU within the CVP network.
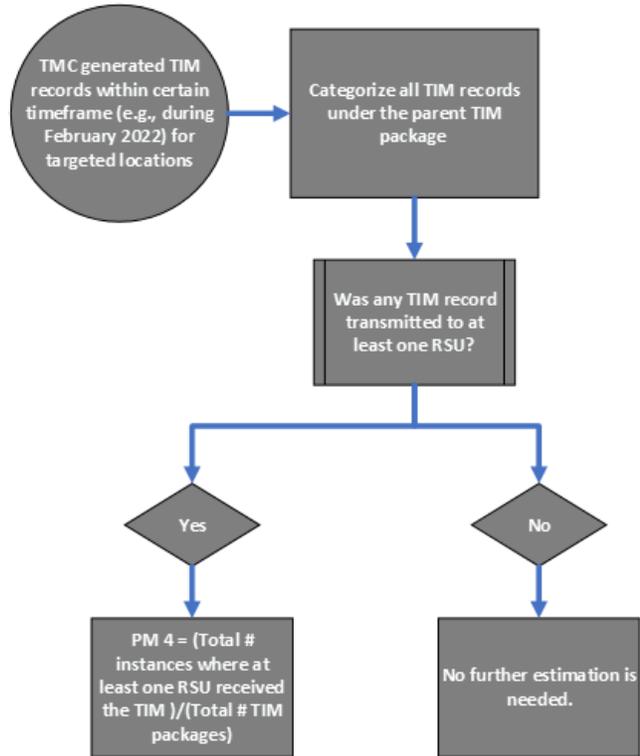
Figure 32. PM 4 Estimation Logic.
Source: WYDOT

	1.2021	2.2021	3.2021	4.2021	5.2021	6.2021	7.2021	8.2021	9.2021	10.2021	11.2021	12.2021	1.2022	2.2022	3.2022	4.2022
Estimate	71.1%	86.4%	94.5%	91.7%	92.2%	85.8%	93.5%	96.0%	91.0%	96.6%	94.0%	95.7%	95.2%	96.0%	97.0%	97.0%
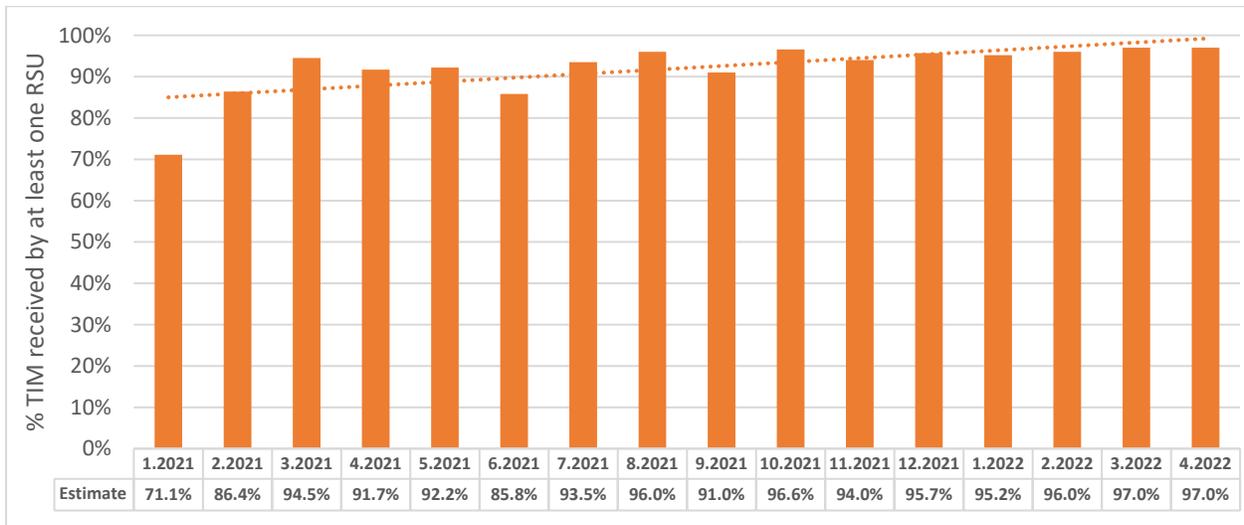
Figure 33. PM 4 Results from January 2021 to April 2022.
Source: WYDOT

4.3.2 PM 5 - Percentage of TIMs Received by at Least One OBU on I-80 Through Satellite

Figure 34 represents the PM 5 estimation logic. Similar to PM 4, the TIM data first needs to be categorized under the parent TIM package. However, this time the data flagged is the one that contains a TIM record that was transmitted from TMC to an OBU (via satellite). Dividing the total count of this record type by the total number of TIM packages would lead to the estimation of the PM 5.

Figure 35 provides a summary of the results during January 2021 and April 2022. The results show a lower percentage during the summer. This is explained by the dependency of PM 5 on the road condition and vehicle presence at the time—note from Table 7 that June through September 2021 had the lowest number of TIM packages within our period of analysis. Despite the results from the summer 2021, the overall trend is on the rise. This is indicative of a seamless and reliable TMC to CVs interaction for the past 16 month, which had an average of around 90% of TIM packages being received by at least one OBU through satellite.
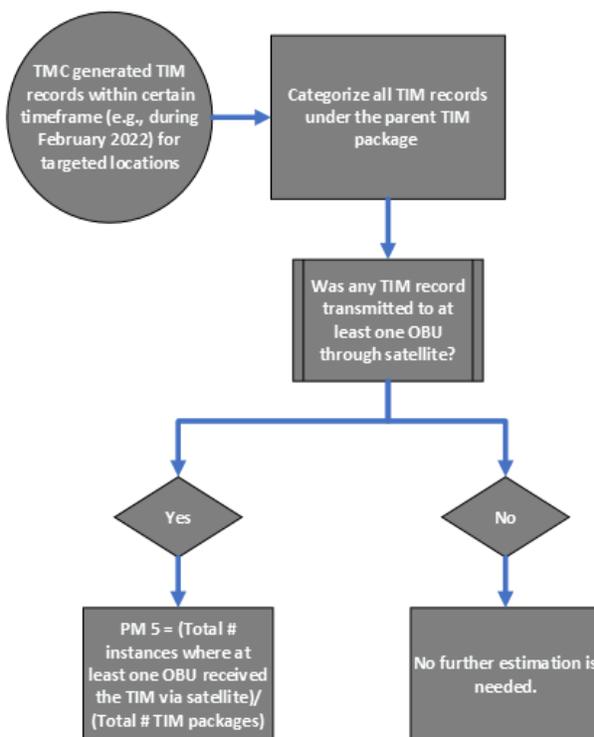
Figure 34. PM 5 Estimation Logic.
Source: WYDOT

	1.2021	2.2021	3.2021	4.2021	5.2021	6.2021	7.2021	8.2021	9.2021	10.2021	11.2021	12.2021	1.2022	2.2022	3.2022	4.2022
Actual value	91.8%	92.8%	89.2%	90.6%	86.0%	87.6%	81.5%	85.7%	81.4%	92.0%	94.4%	91.3%	93.1%	93.7%	82.3%	91.0%
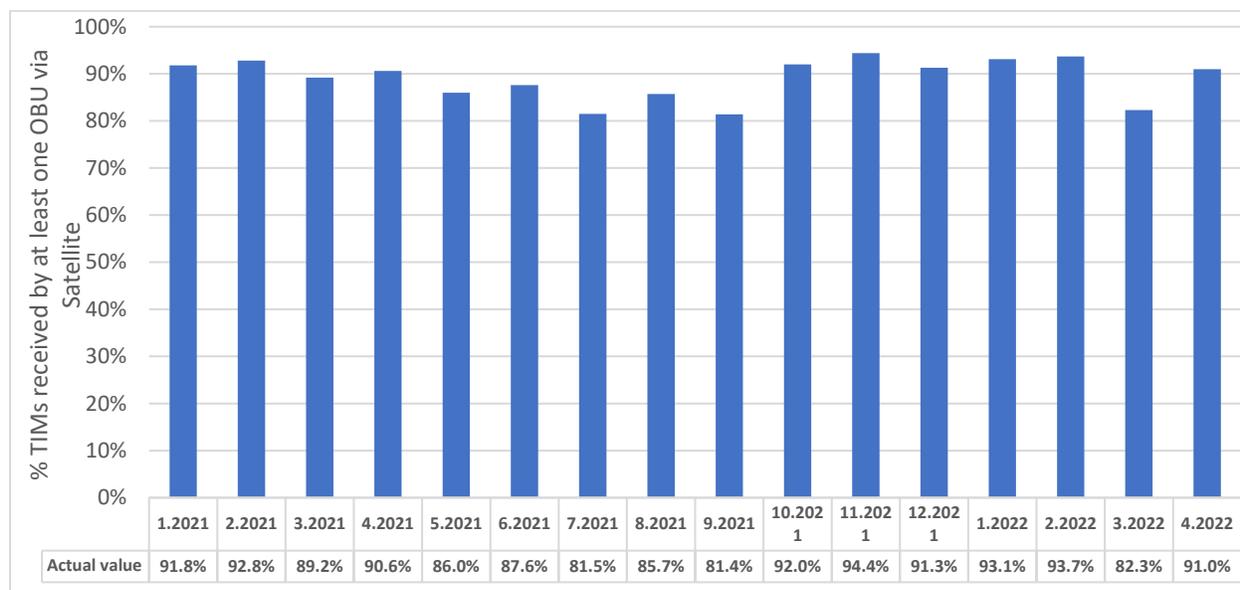
Figure 35. PM 5 Results from January 2021 to April 2022
Source: WYDOT

4.3.3 PM 6 - Percentage of TIMs Received by at Least one Friendly Vehicle from RSUs

Quantifying the interactions between CVs and RSUs involves more computational steps when compared to PMs 4 and 5—as evidenced in Figure 36. The main objective of this PM is to track the percentage of TIMs that were received by at least one Friendly CV fleet from RSUs. This interaction is dependent on the passage of a Friendly CV through the vicinity (1.5 miles radius) of an RSU with an active TIM (i.e., the TIM that was transmitted from TMC to that RSU).

Note that only a subset of Friendly CVs (WYDOT Vehicles) is equipped with the DSRC communication that enables them to receive TIMs directly from RSUs. As such, PM 6 does not apply to the rest of CVs.
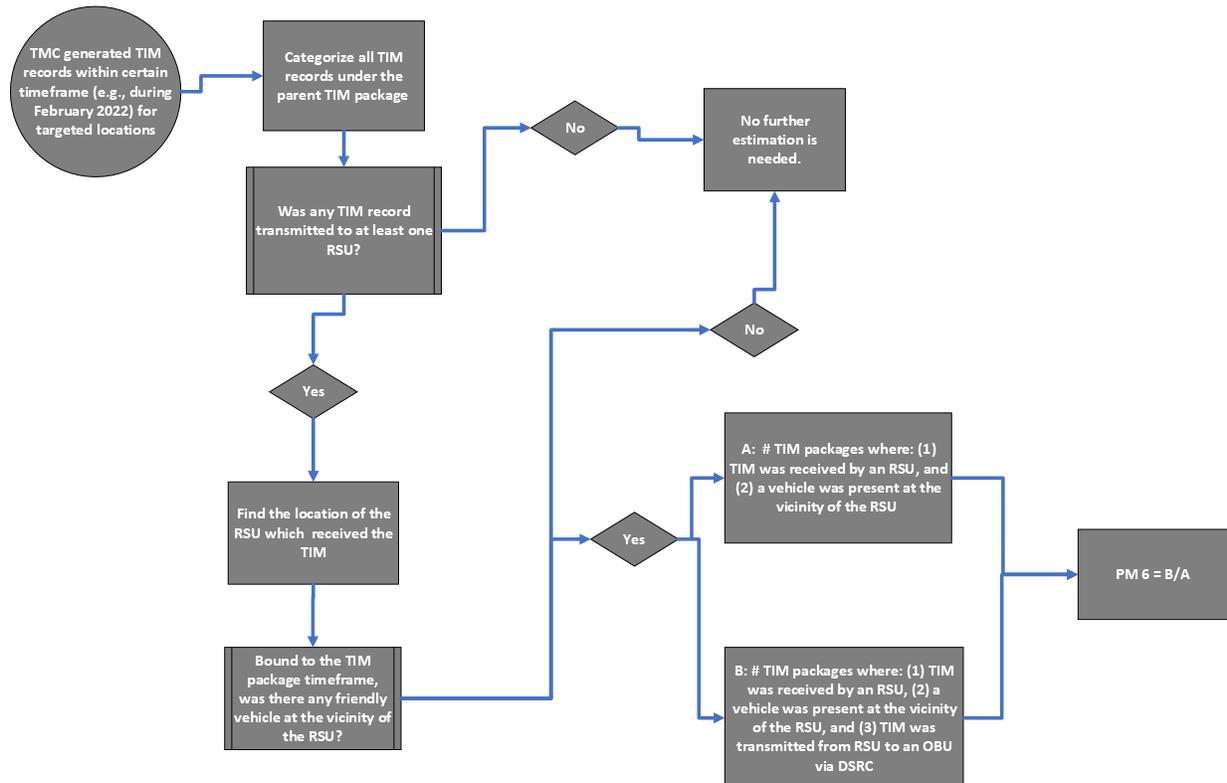
Figure 36. PM 6 Estimation Logic.
Source: WYDOT

The result of PM 6 presents fluctuations during the summer and early Fall period of 2021—see Figure 37. This is consistent with the results from PM 5 where TIM transmission to the CVs through satellite decreased. In addition to a lower number of TIMs being transmitted, during the summer and early fall the operation of WYDOT vehicles is limited, thus the number of equipped vehicles operating within I-80 would be lower compared to the other timeframes. In addition, at certain months such as March and April 2022, I-80 was impacted by severe storm led to lower number of vehicles travelling within the corridor.

The estimates show an overall upward trend, led by more Friendly CVs operating during winter 2022—which is consistent with a growing number of road condition events. In average, 66.2% of the TIM packages were received by at least one friendly CV (from a RSU) between January 2021 and April 2022 within the I-80 corridor. The lowest rate is associated with March 2022 (32%) and the highest rate was estimated for February 2022 (89%). The lowest rate in March 2022 could be due to the combination of severe weather events and a system issue with generation of valid TIM signatures.

	1.2021	2.2021	3.2021	4.2021	5.2021	6.2021	7.2021	8.2021	9.2021	10.2021	11.2021	12.2021	1.2022	2.2022	3.2022	4.2022
■ Actual value	78.4%	81.0%	60.3%	77.9%	75.8%	45.7%	37.5%	68.6%	44.4%	80.0%	84.8%	79.3%	86.8%	88.4%	32.0%	38.5%
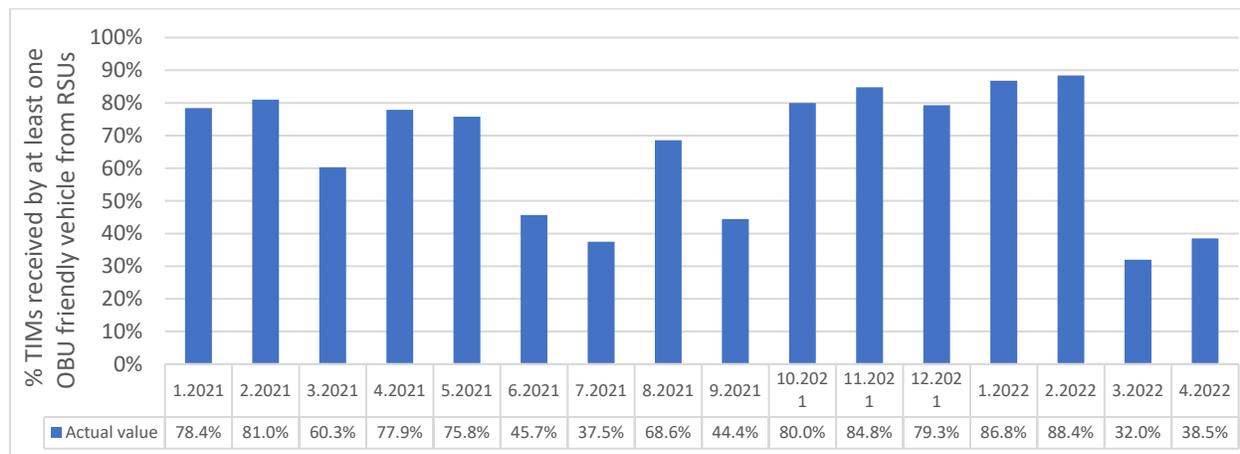
Figure 37. PM 6 Results from January 2021 to April 2022.
Source: WYDOT

4.3.4 PM 7 - Percentage of TIMs Received by at Least One OBU on I-80, Through Satellite or RSU

This performance measure aims to provide a more holistic view regarding the TMCs ability to convey information to all CVs. To achieve this, we developed an aggregated (mutually exclusive) PM based of PM 5 and 6. This PM provides statistics of what percentage of the TIMs packages were received by at least one CV either through satellite or RSU (excluding non-WYDOT CVs for the latter). This estimation counts as 1 record each instance where TIM packages received by an OBU, regardless of the mean.

The results show a similar pattern consistent with PM 5—see Table 8. This is indicative of that overwhelming majority of CVs received TIMs from the TMC through satellite, which is expected since the minority of vehicles have the equipment to receive TIMs from RSU. This result also infers that adding RSU-to-CV communication capability provides marginal improvement in TIMs dissemination.

Table 8. PM 7 Results from January 2021 to April 2022.

Timeframe	No. TIM Packages	% TIMs received by at least one OBU via Satellite	% TIMs received by at least one OBU via Satellite _or_ RSU
01.2021	1,860	91.8%	92.0%
02.2021	9,956	92.8%	93.0%
03.2021	6,236	89.2%	89.3%
04.2021	4,835	90.6%	91.0%

Timeframe	No. TIM Packages	% TIMs received by at least one OBU via Satellite	% TIMs received by at least one OBU via Satellite or RSU
05.2021	3,524	86.0%	86.2%
06.2021	1,443	87.6%	87.7%
07.2021	1,405	81.5%	81.5%
08.2021	2,173	85.7%	85.7%
09.2021	936	81.4%	81.5%
10.2021	5,152	92.0%	92.0%
11.2021	2,995	94.4%	94.4%
12.2021	13,239	91.3%	91.5%
01.2022	10,989	93.1%	93.3%
02.2022	9,121	93.7%	94.1%
03.2022	6,754	82.3%	82.43%
04.2022	5,791	91.0%	91.0%

4.4 Improved Speed Adherence and Reduced Speed Variation

The following subsections discuss the methodology and analysis results for the three speed related performance measures (see Table 9). More details on the methodology and the selection of these performance measures can be found in the document *Connected Vehicle Pilot Deployment Program Phase 2, Final System Performance Report, Baseline Conditions – WYDOT CV Pilot (FHWA-JPO-17-474).*[3]

Table 9. Speed Related Performance Measures and Target.

No.	Performance Measure	Target
8	Total vehicles traveling at no more than 5 mph over the posted speed (compare before and after CV Pilot)	20% improvement over baseline of total vehicles traveling no more than 5 mph over posted speed during CV Pilot. Baseline determined what percentage is traveling no more than 5 mph over posted speed prior to CV Pilot.
9	Total vehicles traveling within +/- 10 mph of the posted speed (compare before and after CV Pilot)	20% improvement over baseline of total vehicles traveling within +/- 10 mph of the posted speed during CV Pilot. Baseline determined what percent is traveling within +/- 10 mph of the posted speed prior to CV Pilot.
10	Speed of applicable connected vehicles are closer to posted speed when compared to non-connected vehicles	Connected vehicles are 20% closer to posted speed.

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[3] As previously mentioned in this report, the numbering of performance measures changed between Phase 2 and Phase 3 of the project, so each of the following sub-section lists the former PM number to use when referring to the earlier report—see Appendix I. Overview of Pre-Deployment Measures of Performance.

It should be noted that part of Phase 2 involved developing automated data collection and analysis methodologies which required substantial changes WYDOT's data archiving system. Prior to the CV Pilot project, speed data was used in real-time by TMC operators but not archived. During the baseline period, speed data collection was limited because it required the speed sensors to be taken offline from the TMC operations and moved to a data logging mode. As such, a balance had to be found between baseline data collection and ensuring there were no loss of safely operating the system until new programming could be developed and installed that allowed for both real-time operations and data archiving. Because of this, there were considerably smaller speed data sets to analyze in pre-deployment versus post-deployment periods.

The resulting speed data archive system was important because it alleviated the need for the manual downloading of data from each individual speed sensors. This improvement also provides a useful data archive for WYDOT to explore trends of speed behavior on the system beyond just the CV Pilot project.

4.4.1 PM 8 - Total Vehicles Traveling at No More than 5 mph Over the Posted Speed

PM 8 focuses on speed compliance as defined by the number of vehicles traveling no more than 5 mph over the posted speed. Analysis of this performance measure requires use of the processed speed data where individual vehicle speeds observed by roadside speed radar units are compared to the posted speed. Depending on the location of the radar unit, the posted speed is either a static or variable speed limit. Another key piece involved in this analysis is the consideration of weather conditions at the time of speed observation. Eleven storm categories were developed to account for speed behavior differences in different weather conditions—see Table 10. Storm categories are based on the relative humidity, wind speed, road surface temperature, road surface condition, and visibility condition as recorded at the closest RWIS to each speed sensor, which are each converted to two to four categories using threshold values based on speed behavior analyses, which resulted in 216 unique storm variable combinations. More details about the selection of these weather variables, the threshold values used in each of these variables, and the analyses that determined the final 11 storm categories can be found in the Baseline Report.

Table 10. Storm Categories.

Storm Category	Description
0	No category assigned
1	Ideal Conditions
2	Wind Event
3	Snow or Ice Surface Condition
4	Low Visibility
5	Wet pavement, moderate wind
6	Ice, high wind
7	Ice, low visibility or moderate wind
8	High wind, high RH, wet roads
9	Mixed Conditions 1
10	Wind Events with Cold Surface Temps
11	Mixed Conditions 2

It is important to note that two of the storm categories are labeled as "Mixed Conditions". These storms categories contain a variety of different storm events that were found to have similar speed distributions. However, storm category 9 is comprised of 19 unique storm variable combinations, whereas storm category 11 is comprised of 31 unique storm variable combinations. Because of this, there is no succinct weather description that can be assigned to these storm types.

A daily query is run in the SDC to combine the speed observations with variable speed limits and RWIS data to provide a database of what is referred to as "processed speed data." A separate query is also run daily on the processed speed data to compile the speed compliance data into a single storm category report. The analysis of PM 8 compiles these daily reports into a monthly summary to determine the percent compliant for the month for each storm category and for all speed observations combined. Table 11 shows an example of these results for December 2021, demonstrating that 11.5 million vehicles out of the 15.0 million vehicles (76.7%) that were observed at the speed sensors were within ±5 mph of the posted speed limit. For that month, weather conditions were mostly ideal with over 84% of the observations found in Storm Category 1. The other 16% of the observations were in storm categories 2 (wind event), 4 (low visibility), and 9 (mixed weather conditions).

Table 11. Example of the Monthly PM 8 Results for December 2021

Storm Category	Storm Description	# Vehicles	# Speed Compliant Vehicles	% Compliant (PM 8)
1	Ideal Conditions	12,681,144	9,625,950	75.91%
2	Wind Event	2,260,383	1,820,324	80.53%
3	Snow or Ice Surface Condition			
4	Low visibility	74,981	58,463	77.97%
5	Wet pavement, moderate wind			
6	Ice, high wind			
7	Ice, low visibility, or moderate wind			
8	High wind, high RH, wet roads			
9	Mixed conditions 1	2,398	1,541	64.26%
10	Wind Events with Cold surface temps			
11	Mixed conditions 2	68,857	65,658	95.35%
Total		**15,087,763**	**11,571,936**	**76.7%**

To establish the baseline for PM 8 in Phase 2 of the CV Pilot, 48.4 million speed observations from January to November 2017 were analyzed to determine the distribution of speed observations by storm category and to see the existing level of speed compliance. Table 12 shows the results of the PM 8 Baseline analysis. As may be observed, speed compliance was found to be fairly high, with multiple storm categories boasting compliance rates in excess of 85%. It can also be observed that some storm categories had very few observations, such as low visibility events, which had only 147 observations. As discussed at the start of Section 4.4, the baseline speed data set contained smaller sample sizes than the post-deployment data set, which may explain some of the differences between the speed compliance rates observed in the post-deployment data.

Table 12. Baseline Results for Speed Compliance by Storm Category (PM 8) from January to November 2017.

Storm Category	Storm Description	Baseline Number	% Compliant (PM 8)
0	Undefined	2,235	88.8%
1	Ideal Conditions	40,524,982	86.3%
2	Wind Event	3,430,866	87.4%
3	Snow or Ice Surface Condition	1,951,772	80.7%
4	Low visibility	147	64.2%
5	Wet pavement, moderate wind	164	53.4%
6	Ice, high wind	268	61.5%
7	Ice, low visibility or moderate wind	31,088	86.2%
8	High wind, high RH, wet roads	2,610	81.7%
9	Mixed conditions 1	197,985	79.1%
10	Wind Events with Cold surface temps	13,211	74.7%
11	Mixed conditions 2	2,241,121	80.1%
Total		**48,396,449**	**77%**

It was believed that CVs would exhibit better speed selection behavior when compared to non-CVs due to in-vehicle devices alerting the drivers of connected vehicles to the current speed limits. Therefore, during Phase 2 of the project, a target value of 20% improvement in the percentage of vehicles traveling no more than 5 mph above the posted speed as compared to the baseline percentage was established. It was also believed that the improvement of the backoffice TMC operations would improve the timeliness and accuracy of the entire traveler information system, leading to better speed compliance among the non-CVs as well. It should be noted that the target value was established prior to the baseline analysis, which resulted in baseline compliance rates that would make achievement of the target value mathematically impossible to achieve in some cases.

The analysis of PM 8 compares the monthly and overall compliance results against the pre-deployment baseline. Table 13 shows these results for the monthly PM 8 analyses including the total number of vehicles observed in each storm category, the compliance rate (percent of vehicles found at or below the posted speed plus 5 mph), and the percent difference between the monthly compliance rates and the baseline results. Speed observations were not found for all storm categories in the post-deployment data. Most of the missing storm categories were ones with few observations in the baseline except for Storm Category 3, which is where the surface conditions were snow or ice but all other weather variables considered favorable. The baseline data had over 1.9 million speed observations for this storm category while the post-deployment data had none.

Table 13 also shows that the number of speed observations by month changes more than what would be expected from seasonal traffic variations with February 2021 having 4.5 million observations and June 2021 having almost 76 million observations. In addition to seasonal variation, some fluctuations in the number of observations are to be expected as sensors

periodically go offline and require maintenance or firmware updates. There does not appear to be a trend between months with higher or lower number of observations and speed compliance results that are unusually high or low.

Table 13 shows values for the percent speed compliance ranging from 26.7% for March 2021 for low visibility conditions (Storm Category 4) to 97.9% for January 2021 for mixed conditions (Storm Category 9). The largest differences between post deployment and baseline conditions were found in the spring with the largest negative difference of -37.5% occurring in March 2021 for Storm Category 4 conditions, indicating the baseline had larger percentage of speed compliance during these conditions than the post deployment observations for that month. The largest positive difference of 25.8% occurred in April 2021 and was also found in Storm Category 4 observations. Note that the baseline compliance values are averaged over the entire baseline period while the values in Table 13 are for a single month only and are likely to see higher levels of variation.

Table 13. PM 8 Results by Month and Storm Category: Dec 2020 – Feb 2022.

| Date * | Value Type | Storm Category | | | | | Total |
| | | 1 | 2 | 4 | 9 | 11 | |
		Ideal Conditions	Wind Event	Low visibility	Mixed Conditions 1	Mixed Conditions 2	
Dec. 2020	# Vehicles	9,693,924	1,010,281	40,997	1,115	200,522	10,946,839
	% Compliant	70.7%	78.6%	78.2%	94.8%	90.8%	71.8%
	% Difference	-15.6%	-8.8%	14.0%	15.7%	10.7%	-5.2%
Jan. 2021	# Vehicles	6,909,087	1,237,162	76,217	1,563	130,003	8,354,032
	% Compliant	61.0%	74.9%	75.7%	97.9%	78.6%	63.4%
	% Difference	-25.3%	-12.3%	11.5%	18.8%	-1.5%	-13.6%
Feb. 2021	# Vehicles	3,812,825	644,323	22,619	1,108	57,430	4,538,305
	% Compliant	68.4%	55.7%	84.2%	78.8%	94.9%	67.0%
	% Difference	-17.9%	-31.7%	20.0%	-0.3%	14.8%	-10.0%
Mar.2021	# Vehicles	11,797,310	378,187	67,868		237,419	12,480,784
	% Compliant	53.8%	72.9%	26.7%		93.7%	55.0%
	% Difference	-32.5%	-14.5%	-37.5%		13.6%	-22.0%
Apr. 2021	# Vehicles	7,296,686	131,432	60,902		297,315	7,786,335
	% Compliant	78.9%	82.1%	90.0%		74.6%	78.8%
	% Difference	-7.4%	-5.3%	25.8%		-5.5%	1.8%
May 2021	# Vehicles	59,356,461	490,556	1,306,939		2,490,325	63,644,281
	% Compliant	58.9%	61.6%	54.1%		82.7%	59.7%
	% Difference	-27.4%	-25.8%	-10.1%		2.6%	-17.3%
June 2021	# Vehicles	72,602,341	369,565	2,941,572		55,443	75,968,921
	% Compliant	51.5%	51.8%	44.5%		59.6%	51.3%
	% Difference	-34.8%	-30.2%	-14.3%		-16.4%	-24.3%
July 2021	# Vehicles	30,254,840	71,056	1,021,605		52,679	31,400,180
	% Compliant	52.7%	57.2%	49.9%		63.7%	52.7%
	% Difference	-33.6%	-34.6%	-22.2%		-20.5%	-31.6%
Aug.2021	# Vehicles	19,137,350	104,610	604,131		15,574	19,861,815

Date *	Value Type	Storm Category					Total
		1	2	4	9	11	
		Ideal Conditions	Wind Event	Low visibility	Mixed Conditions 1	Mixed Conditions 2	
	% Compliant	79.9%	83.9%	80.4%		93.3%	79.9%
	% Difference	-6.4%	-3.5%	16.2%		13.1%	2.9%
Sept. 2021	# Vehicles	49,485,426	208,954	112,710		107,885	49,914,975
	% Compliant	82.6%	83.5%	83.5%		89.2%	82.6%
	% Difference	-3.7%	-3.9%	19.3%		9.1%	5.6%
Oct.2021	#Vehicles	24,992,641	664,068	230,970	12	310,949	26,198,640
	% Compliant	82.0%	76.7%	85.9%	75.0%	96.2%	82.1%
	% Difference	-4.3%	-10.7%	21.7%	-4.1%	16.1%	5.1%
Nov. 2021	#Vehicles	23,286,791	2,760,629	20,778		306,429	26,534,627
	% Compliant	82.0%	82.8%	75.8%		95.0%	82.1%
	% Difference	-4.3%	-4.6%	11.6%		14.9%	5.1%
Dec. 2021	#Vehicles	13,346,806	2,386,591	75,364	2,398	68,857	15,880,016
	% Compliant	76.4%	80.8%	78.0%	64.3%	95.4%	77.1%
	% Difference	-9.9%	-6.6%	13.8%	-14.8%	15.3%	0.1%
Jan. 2022	#Vehicles	15,151,682	1,568,229	78,695	752	192,226	16,991,584
	% Compliant	51.49%	61.46%	62.71%	97.21%	84.6%	52.84%
	% Difference	-34.8%	-25.9%	-1.5%	18.1%	4.5%	-24.2%
Feb. 2022	#Vehicles	9,663,004	1,300,434	64,706	15	71,335	11,099,494
	% Compliant	58.20%	63.39%	72.67%	86.67%	95.48%	59.13%
	% Difference	-28.1%	-24.0%	8.5%	7.6%	15.4%	-17.9%

Table 14 summarizes the monthly results and shows the difference in speed compliance rates between the baseline and post-deployment periods by storm category. Generally, the results of the system post-deployment showed lower speed compliance post-deployment than the baseline results except for the case of mixed condition storms (storm categories 9 and 11) which showed a 3.5% and a 4.9% improvement in speed compliance, respectively. Overall speed compliance was shown to decrease from 77.1% to 65.8%, a reduction of 11.3% across all weather conditions. The results are showing an improving trend over the post-deployment period. Some of the reduction of speed compliance in the system performance can be explained by national trends of increased speeding during the COVID-19 pandemic[4] but this is unlikely to fully explain the differences. It is also clear that the winter weather conditions experienced in the evaluation period were different than the baseline given that many of the storm categories were not experienced during the evaluation period. It can also be seen that the higher percentage of the observations

[4] COVID-19 Impacts on Speed and Safety for Minnesota Roads and Work Zones (2021), Minnesota DOT Report MN 2021-21 and A Descriptive Analysis of the Effect of the COVID-19 Pandemic on Driving Bahavior and Road Safety (2020), Transportation Research Interdisciplinary Perspectives, Vol. 7.

during the evaluation period were during ideal conditions (93.5%) as compared to 83.7% of the observations during the baseline were in ideal conditions.

Table 14. Comparison of Baseline and PM 8 Results by Storm Category.

Storm Cat.	Baseline Jan. – Nov. 2017		Post-Deployment * Dec. 2020 – Dec. 2021		Comparison to Baseline
	Baseline #	% Compliant	# Vehicles	% Compliant	% Difference
0	2,235	88.8%			
1 (ideal)	40,524,982	86.3%	356,787,174	65.4%	-20.9%
2 (wind)	3,430,866	87.4%	13,286,077	73.3%	-14.1%
3 (Snow/Ice)	1,951,772	80.7%			
4 (Low Vis)	147	64.2%	6,926,073	55.0%	-9.2%
5 (Wet pvmt, wind)	164	53.4%			
6 (Ice, high wind)	268	61.5%			
7 (Ice, low vis. or mod. wind)	31,088	86.2%			
8 (High wind, wet roads)	2,610	81.7%			
9 (Mixed 1)	197,985	79.1%	6,963	82.6%	3.5%
10 (Wind, cold pvmt.)	13,211	74.7%			
11 (Mixed 2)	2,241,121	80.1%	4,594,541	85.0%	4.9%
Total	48,396,449	77.1%	381,600,828	65.8%	-11.3%

4.4.2 PM 9 - Total Vehicles Traveling within +/- 10 mph of Posted Speed

PM 9 is a measure of speed variation by determining the number of vehicles that are within 10 mph above and below the posted speed. This performance measure captures speed behavior where drivers are selecting speeds more than 10 mph below the posted speed in addition to those traveling 10 mph above, giving an indication of variance in speed behaviors. Using the same processed speed data as PM 8, the speed variation measure compares the difference between the posted and observed speed. If the absolute value of this difference is less than or equal to 10 then the observation is considered within the speed buffer.

Similar to PM 8, the results for PM 9 are aggregated by storm category in order to view driver behavior differences by different weather types. This PM also uses the same storm category daily report from the SDC.

To establish the baseline for PM 9 in Phase 2 of the project, 39.7 million speed observations from January to November 2017 were analyzed to determine the percent of vehicles in the speed buffer (posted speed ± 10 mph), shown in Table 15. As can be seen, speed compliance varied considerably from a high of 71.6% of the vehicles in the buffer during ideal conditions to a low of 45.0% during conditions where the road surface was wet and moderate winds (between 30-45 mph) in Storm Category 5—it should be noted that limited observation points were available for that storm category (N=138). All storm conditions led to reductions in the buffer percentage, which was expected given the likelihood of some drivers being cautious in their speed selection. It is also notable that the percentages for PM 9 were considerably lower than the percentages for PM 8 for speed compliance (Table 12), This likely indicates that many vehicles are selecting speeds more than 10 mph lower than the posted speeds, although it also captures vehicles traveling between 5 and 10 mph over the speed limit, given how the two performance measures are defined.

As discussed at the start of Section 4.4, the baseline speed data set contained smaller sample sizes than the post-deployment data set, which may explain some of the differences between the speed buffer rates observed in the post-deployment data.

Table 15. Pre-Deployment Baseline Results (January - November 2017) for PM 9.

Storm Cat.	Storm Description	Baseline Number	% Buffer (PM 9)
0	Undefined	1,720	68.3%
1	Ideal Conditions	33,619,787	71.6%
2	Wind Event	2,618,285	66.7%
3	Snow or Ice Surface Condition	1,595,658	66.0%
4	Low visibility	134	58.5%
5	Wet pavement, moderate wind	138	45.0%
6	Ice, high wind	268	61.5%
7	Ice, low visibility or moderate wind	17,382	48.2%
8	High wind, high RH, wet roads	1,689	52.9%
9	Mixed conditions	137,739	55.1%
10	Wind Events with Cold surface temps	9,222	52.2%
11	Mixed conditions	1,694,709	60.6%
Total		**39,696,731**	**58.9%**

During Phase 2 of the project, a target value of 20% improvement in the percentage of vehicle traveling within 10 mph of the posted speed was established with the belief that CVs would exhibit improved speed selection behavior given the in-vehicle devices alerting them of current speed limits. It was also believed that the improvement of the backoffice TMC operations would improve the timeliness and accuracy of all the entire traveler information systems, leading to reduction in speed variation. It should be noted that the target value was established prior to the baseline analysis, which resulted in baseline compliance rates that would make it hard to achieve the target value.

The analysis of PM 9 compares the monthly and overall speed buffer percentages against the pre-deployment baseline. Table 16 shows these results for the monthly PM 9 analyses including

the total number of vehicles observed in each storm category, the buffer rate (percent of vehicles found within 10 mph of the posted speed), and the percent difference between the monthly buffer rates and the overall baseline percentage by storm category. Speed observations were not found for all storm categories in the post-deployment data. Most of the missing storm categories were ones with few observations in the baseline except for Storm Category 3, which is where the surface conditions were snow or ice, but all other weather variables considered favorable.

Similar to the speed compliance performance measure, Table 16 shows that the number of speed observations by month changes more than what would be expected from seasonal traffic variations with February 2021 having 4.5 million observations and June 2021 having almost 76 million observations. In addition to seasonal variation, some fluctuations in the number of observations are to be expected as sensors periodically go offline and require maintenance or firmware updates. There does not appear to be a trend between months with higher number of observations and speed buffer results that are unusually high or low.

Table 16 shows values for the percent speed compliance ranging from a low of 13.5% for December 2021 for mixed conditions (Storm Category 11) to a high of 79.3% for August 2021 for low visibility conditions (Storm Category 4). The results show an improving trend over the post-deployment period.

Table 16. PM 9 Results by Month and Storm Category from Dec 2020 to Feb 2022.

| Date * | Value Type | Storm Category | | | | | Total |
| | | 1 | 2 | 4 | 9 | 11 | |
		Ideal Conditions	Wind Event	Low Visibility	Mixed Conditions 1	Mixed Conditions 2	
Dec. 2020	# Vehicles	9,693,924	1,010,281	40,997	1,115	200,522	10,946,839
	% Buffer	65.6%	59.3%	46.3%	23.9%	41.0%	64.5%
	% Difference	-6.0%	-7.4%	-12.2%	-31.2%	-19.6%	5.6%
Jan. 2021	# Vehicles	6,909,087	1,237,162	76,217	1,563	130,003	8,354,032
	% Buffer	55.7%	56.6%	47.7%	23.7%	36.4%	55.5%
	% Difference	-15.9%	-10.1%	-10.8%	-31.4%	-24.2%	-3.4%
Feb. 2021	# Vehicles	3,812,825	644,323	22,619	1,108	57,430	4,538,305
	% Buffer	61.1%	45.9%	39.5%	58.5%	25.6%	58.4%
	% Difference	-10.5%	-20.8%	-19.0%	3.4%	-35.0%	-0.5%
Mar.2021	# Vehicles	11,797,310	378,187	67,868		237,419	12,480,784
	% Buffer	52.3%	62.1%	29.3%		36.6%	52.1%
	% Difference	-19.3%	-4.6%	-29.2%		-24.0%	-6.8%
Apr. 2021	# Vehicles	7,296,686	131,432	60,902		297,315	7,786,335
	% Buffer	74.0%	74.4%	50.7%		41.0%	72.6%
	% Difference	2.4%	7.7%	-7.8%		-19.6%	19.6%
May 2021	# Vehicles	59,356,461	490,556	1,306,939		2,490,325	63,644,281
	% Buffer	65.5%	64.5%	62.9%		58.6%	65.1%
	% Difference	-6.1%	-2.2%	4.4%		-2.0%	6.3%
June 2021	# Vehicles	72,602,341	369,565	2,941,572		55,443	75,968,921
	% Buffer	62.0%	59.9%	58.6%		57.5%	61.9%

Date *	Value Type	Storm Category					Total
		1 Ideal Conditions	**2** Wind Event	**4** Low Visibility	**9** Mixed Conditions 1	**11** Mixed Conditions 2	
	% Difference	-9.6%	-6.9%	0.1%		-3.1%	3.0%
July 2021	# Vehicles	30,254,840	71,056	1,021,605		52,679	31,400,180
	% Buffer	61.4%	58.1%	52.3%		63.7%	61.1%
	% Difference	-10.2%	-8.6%	-6.2%		3.1%	2.2%
Aug.2021	# Vehicles	19,137,350	104,610	604,131		15,724	19,861,815
	% Buffer	71.3%	65.6%	79.3%		56.7%	71.5%
	% Difference	-0.3%	-1.1%	20.8%		-3.9%	12.7%
Sept. 2021	# Vehicles	49,485,426	208,954	112,710		107,885	49,914,975
	% Buffer	76.2%	72.6%	74.3%		70.7%	76.1%
	% Difference	4.6%	5.9%	15.8%		10.1%	17.3%
Oct.2021	#Vehicles	24,992,641	664,068	230,970	12	310,949	26,198,640
	% Buffer	75.1%	65.9%	66.1%	33.3%	36.3%	74.3%
	% Difference	3.5%	-0.8%	7.6%	-21.8%	-24.3%	15.4%
Nov. 2021	#Vehicles	23,286,791	2,720,629	220,778		306,429	26,534,627
	% Buffer	76.3%	69.1%	67.8%		43.7%	75.2%
	% Difference	4.7%	2.4%	9.3%		-16.9%	7.5%
Dec. 2021	#Vehicles	13,346,806	2,386,591	75,364	2,398	68,857	15,880,016
	% Buffer	67.5%	62.7%	43.1%	46.8%	13.5%	66.4%
	% Difference	-4.1%	-4.0%	-15.4%	-8.3%	-47.1%	12.8%
Jan. 2022	#Vehicles	15,151,682	1,568,229	78,695	752	192,226	16,991,584
	% Buffer	60.5%	60.9%	57.8%	25.0%	62.8%	60.5%
	% Difference	-11.1%	-5.8%	-1.2%	-30.1%	2.2%	1.6%
Feb. 2022	#Vehicles	9,663,004	1,300,434	64,706	15	71,335	11,099,494
	% Buffer	61.2%	62.0%	43.1%	60.0%	39.5%	60.1%
	% Difference	-10.4%	-4.7%	-15.4%	4.9%	-21.1%	2.1%

Table 17 summarizes the monthly results and shows the difference in the percentage of vehicle in the speed buffer (posted speed ± 10 mph) between the baseline and post-deployment periods by storm category. Generally, the results of the system post-deployment showed lower speed buffer post-deployment than the baseline results except for the case of low visibility storms which shows a 1.7% improvement in speed compliance. Overall speed compliance was shown to increase from 58.9% to 66.4%, a 7.5% improvement across all weather conditions. It should be noted that this improvement is primarily coming from the absence of storm conditions that resulted in particularly low speed buffer results in the baseline period. If storm categories that were not observed during the post-deployment period (0, 3, 5-8, and 10) were removed, then the overall baseline performance goes from 58.9% to 64.7%, reducing the overall performance improvement from 7.5% to 1.7%.

Table 17. Comparison of Baseline and PM 9 Results by Storm Category.

Storm Cat.	Baseline Jan. – Nov. 2017		Post-Deployment Dec. 2020 – Feb. 2022		Comparison to Baseline
	Baseline	% Buffer	# Vehicles	% Buffer	% Difference
0	1,720	68.3%			
1	33,619,787	71.6%	356,787,174	66.9%	-4.7%
2	2,618,285	66.7%	13,286,077	62.5%	-4.2%
3	1,595,658	66.0%			
4	134	58.5%	6,926,073	60.2%	1.7%
5	138	45.0%			
6	268	61.5%			
7	17,382	48.2%			
8	1,689	52.9%			
9	137,739	55.1%	6,963	37.5%	-17.6%
10	9,222	52.2%			
11	1,694,709	60.6%	4,564,541	51.6%	-9.0%
Total	**39,696,731**	**58.9%**	**381,600,828**	**66.4%**	**7.5%**

4.4.3 PM 10 - CVs Speed Compliance Compared to Non-CVs

PM 10 compares the speed compliance of CV and non-CV as defined by the number and percentage of vehicles traveling no more than 5 mph over the posted speed. Analysis of this performance measures requires comparing speeds of connected vehicles as reported in the BSM data as they traveled in front of a corridor speed sensor to the speeds of non-connected vehicle as reported by the roadside radar speed sensor. To ensure that the CV and non-CVs had similar road and weather conditions, only non-CV speed observations around the CV observations were used in the analysis. A window of 2 minutes and 30 seconds before and after the CV observation was selected as a reasonable timeframe to ensure similar conditions. Given the relatively low number of CV vehicles in the traffic stream, it was expected that the sample size of CVs would be much lower than the number of non-CVs.

Each month, the analysis of PM 10 begins by running a spatial query around 11 radar speed sensor along I-80. These sensors were selected in Phase 2 to represent specific areas of the corridor and were located in areas where vertical and horizontal roadway alignments were not expected to significantly impact the speed selection behavior of the drivers—more details of this selection process is available in the Baseline Report. Table 18 lists information for each speed sensor used in the PM 10 analysis including the sensor ID number, site name, milepost along I-80, and whether that sensor is located in a variable speed limit corridor or not.

Table 18. Speed Sensors on I-80 Used in PM 10.

Sensor ID	Site Name	Milepost	VSL?
2359	Painter	11.86	Yes
2395	US 189 Interchange	17.66	Yes
2607	Leroy	24.56	Yes

Sensor ID	Site Name	Milepost	VSL?
3296	East Green River	91.99	Yes
2032	Dewar Drive	101.71	Yes
2070	Elk Street	104.55	Yes
2578	Baxter Rd	110.36	No
3901	MP 246.7	246.65	Yes
1219	Elk Mountain	256.17	Yes
2178	Vedauwoo	329.88	Yes
2246	Remount	339.86	Yes

For each speed sensor location, a geofence was created in Google Earth to use in spatial queries of the BSM data. It was initially believed that the sensor geofences had to be long enough to capture a record of the vehicle in a 30 second window since the system was designed to allow the OBU to drop BSM records if no driver alert or other significant event occurred in the window. This was done to allow the OBU to prioritize storage and data transmission to 30 second "bread crumb" observations as opposed to the high-resolution data the system generates at a tenth of a second. At the beginning of the data analysis period, it was found that the system was in fact keeping the high-resolution data and the longer geofences were resulting in large data sets with duplicate CV event records. The geofences were then modified to include only a small area in front of each sensor, limiting the number of duplicate records.

Highway patrol and snow plow vehicles are then identified in the CV speed event data through their static ID and are excluded as these vehicles do not exhibit typical speed selection behavior. The remaining data are assigned CV event ID numbers for that month and a query start and end time is determined by centering the non-CV five-minute event window around the time of the CV event.

A query is then run on the processed speed data that was described in the previous speed performance measures sections. The resulting query compiles all speed sensor events within a 5-minute time window and assigns the non-CV event records with its corresponding CV event number. In addition to the speeds from the radar sensor, the non-CV events also contain information about the current posted speed (static or variable) and weather conditions from the nearest RWIS.

The next step of the analysis is to review the non-CV speed events and perform data quality checks. For example, sometimes the speed sensor treats trailers of freight trucks as separate vehicles with zero time headway between vehicles. It was also found that for unknown reasons the sensors occasionally pick up on non-vehicle events and will record hundreds or thousands of vehicle speed events in the 5-minute window. These events typically show very low recorded speeds. To remove these data anomalies, all non-CV speed events with greater than 120 observations per event number were removed. The 120-vehicle threshold corresponds to the upper limit of what would be expected on the corridor given the peak hour and daily volumes.

To avoid double counting of vehicles, the CV event is removed from the non-CV event by matching the closest time and speed from the CV event record to the corresponding non-CV event. Given that the two speeds records utilize different technology for determining vehicle

speeds and recording time, the two events will be unlikely to exactly match but the closest match is determined manually and removed from the non-CV event dataset. The posted speed and storm category data from the non-CV data records is added back to the CV records since the BSM data does not contain this information. Table 19 shows the number of CV and non-CV speed observations by analysis months. As expected, the total number of connected vehicle events (2,778) were far outnumbered by the number of non-connected vehicle events (120,782). The last column shows the percentage of connected vehicles by month and can be viewed as an approximation of the penetration rate of connected vehicles in the corridor. This column shows wide fluctuation in the percentages from as low as 0.8% to as high as 19.6%. The overall percentage for the analysis period was 2.3% or approximately 1 connected vehicle per 43 non-connected vehicle.

Table 19. Number of CV and Non-CV Speed Events by Month for PM 10.

Analysis Month	# CV Events	# Non-CV Events	% CV in Traffic Stream
Dec. 2020	0	627	1.8%
Jan. 2021	49	3,171	1.5%
Feb. 2021	82	2,625	3.1%
Mar. 2021	244	12,960	1.9%
Apr. 2021	158	7,886	2.0%
May 2021	157	2,031	7.7%
Jun. 2021	314	39,399	0.8%
Jul. 2021	216	8,235	2.6%
Aug. 2021	209	1,065	19.6%
Sep. 2021	205	3,171	6.5%
Oct. 2021	109	899	12.1%
Nov. 2021	239	13,729	1.7%
Dec. 2021	369	14,493	2.5%
Jan. 2022	241	2,265	10.6%
Feb. 2022	175	8,223	2.1
Total	**2,778**	**120,782**	**2.3%**

The last step is to compile the number of events for both the CV and non-CV vehicles and to assign the compliance variable to all records if the observed speed was found to be no more than 5 mph above the posted speed. The percentage of compliant vehicles is then calculated for both datasets.

Since this is a comparison (with and without) of the performance measure during post-deployment period there, is no Phase 2 baseline to report. The target for PM 10 was set at a 20% improvement in compliance of CVs when compared to non-CVs. It was hypothesized that CVs would be more compliant than non-CVs given the increased accessibility to posted speed and road and weather condition information.

Table 20 shows the results of PM 10 by month and for the total analysis period. The righthand column is the percent difference between the compliance rates of CVs and non-CVs. The percent compliance rates of CVs compared to non-CVs has generally been improving over time and the

overall results shows a 5.7% increase (or an 8.5% difference) in the speed compliance of CVs over non-CVs. The last five months of the performance evaluation period all showed CVs have a higher compliance rate than non-CVs.

Table 20. PM 10 Results by Month.

Month	Percent CV Compliant	Percent Non-CV Compliant	Compliance Difference (CV – Non-CV)	% Compliance Difference
Dec. 2020	72.7%	83.6%	-10.8%	-14.9%
Jan. 2021	69.4%	77.2%	-7.8%	-11.2%
Feb. 2021	81.7%	77.0%	4.7%	5.7%
Mar. 2021	39.1%	55.5%	-16.4%	-42.1%
Apr. 2021	72.2%	76.0%	-3.8%	-5.3%
May 2021	52.2%	61.7%	-9.4%	-18.0%
Jun. 2021	45.4%	45.6%	-0.2%	-0.4%
Jul. 2021	32.9%	37.0%	-4.1%	-12.6%
Aug. 2021	87.6%	72.5%	15.1%	17.2%
Sep. 2021	78.5%	82.7%	-4.2%	-5.4%
Oct. 2021	80.7%	80.6%	0.1%	0.1%
Nov. 2021	93.3%	86.3%	7.0%	7.5%
Dec. 2021	86.2%	78.0%	8.2%	9.5%
Jan. 2022	61.4%	51.6%	9.8%	16.0%
Feb. 2022	61.1%	53.2%	8.0%	13.0%
Total*	**66.3%**	**60.6%**	**5.7%**	**8.5%**

*Percentages in the bottom row are weighted averages based on total number of observations during the post-deployment period.

The PM 10 results above include speed compliance results during ideal (storm category 1) and non-ideal conditions (storm category 2 -11) and at locations in variables speed limit corridors where the posted speed may have been lowered. In order to analyze the results in greater depth, histograms were created that compared the speed distributions for both CVs and non-CVs, separating observations based on posted speed and roadway conditions.

Figure 38 graphs the difference between observed and posted speeds for CV and non-CVs for the 15-month post-deployment period, which included 103,950 observations of non-CVs and 2,599 CVs. Results are shown as percentages to normalize the disparate size of the two datasets. For both vehicle types, the mode occurs for the interval from the posted speed to 5 mph above the posted speed (0,5) with 18% of CV observations and 20% of non-CVs. Both speed distributions are generally normal shaped but it is noted that the CV distribution slightly favors speed below the posted speed with 44% of the observations occurring in bins below the posted speed while 38% of the Non-CVs were found to be traveling below the posted speed.
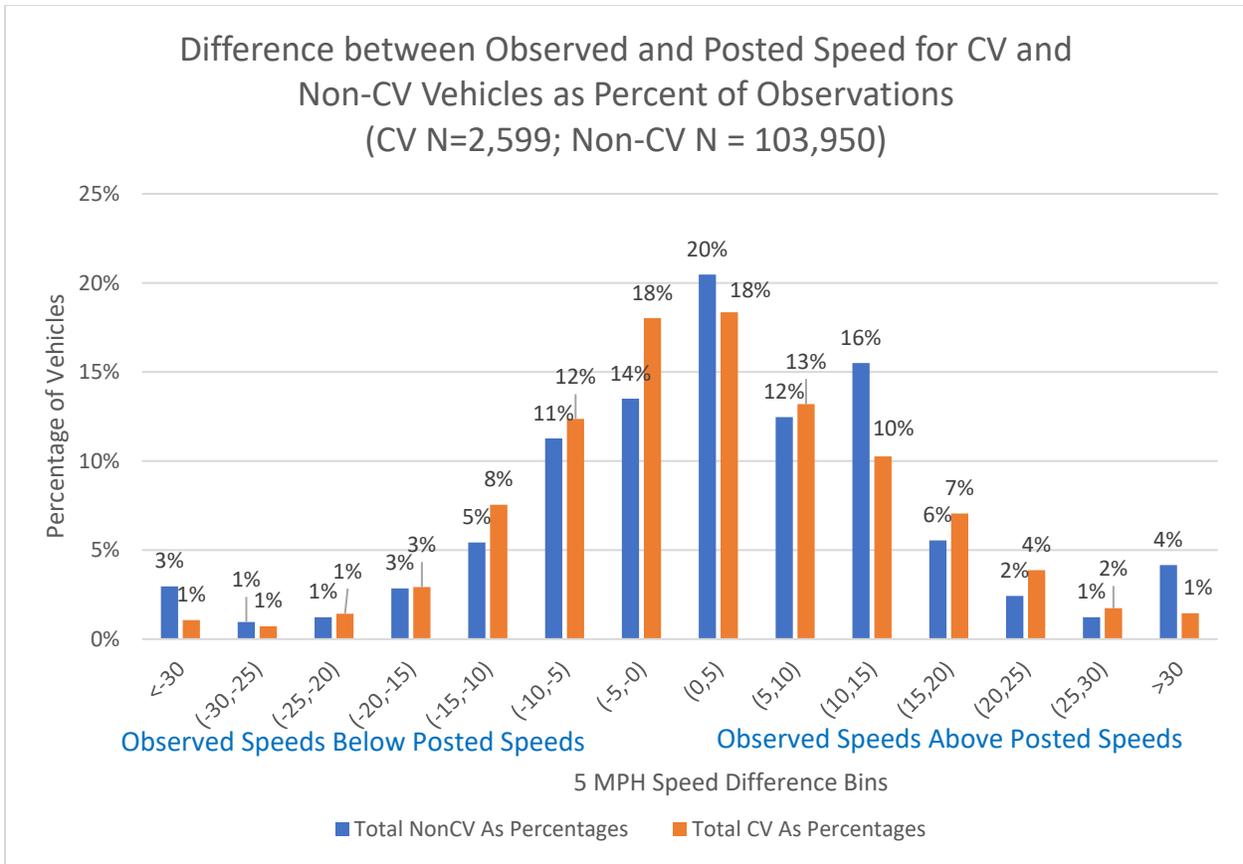
Figure 38. Comparison of CV and Non-CV Speed Distributions
Source: WYDOT

The datasets for PM 10 were separated between observations during ideal conditions (storm category 1) and non-ideal conditions (storm categories 2-11) to determine if there were noticeable differences between the speed distributions of CVs and Non-CVs. Most of the observations were found to be during ideal conditions with only 84 observations (5%) of CVs and 4638 observations (4%) for non-CVs occurring during no-ideal conditions. The histograms representing these two road condition cases are shown in Figure 39 (Ideal conditions) and Figure 42 (Non-Ideal conditions). As expected, the percentage of vehicles observed to traveling below the posted speed increases as the road conditions deteriorate. During ideal conditions (see Figure 39) the cumulative percentage of CVs below the speed limit is 53% while the non-CVs percentage is 43%. During non-ideal conditions (see Figure 42), the cumulative percentage of CV below the speed limit is 55% while the non-CV percentage is 62%.
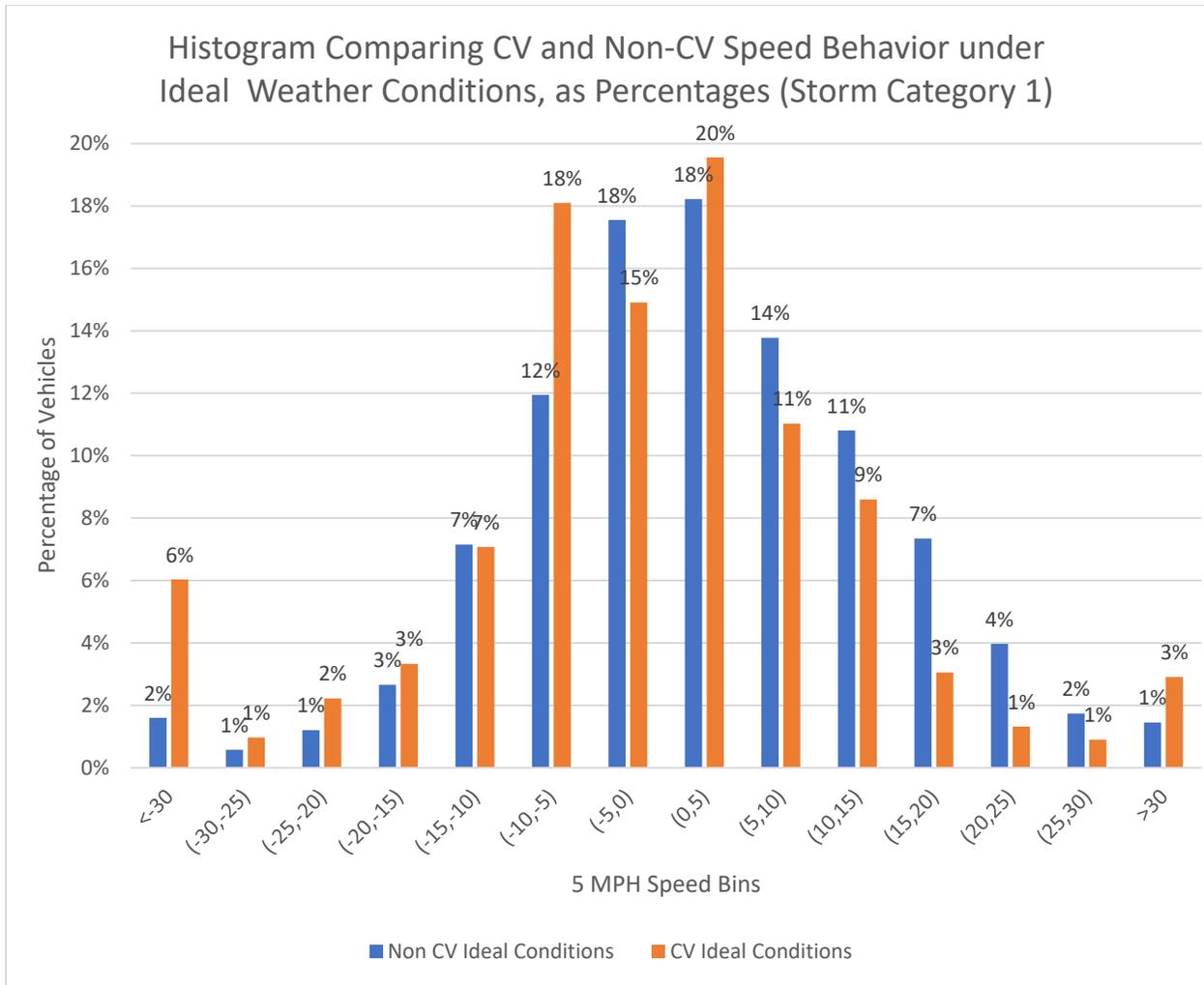
Figure 39. Comparison of CV and Non-CV Speed Distributions during Ideal Weather Conditions
Source: WYDOT

The datasets for PM 10 were also separated between observations based on the posted speed at the time of the observation to determine if there were noticeable differences between the speed distributions of CVs and Non-CVs. Posted speeds of 45, 55, 65, and 75 mph were considered since there were too few observations at 35 mph. Figure 41 shows the results for the 2,599 CVs and Figure 40 shows the results for the 103,950 non-CVs. Both figures show similar results in that you see the curves shift to the right for each higher posted speed limit, which indicates the difference between the observed speed and the posted speed increases as the posted speed increases. Another way of viewing this is that the impact of the posted speed reductions for the most part is to increase the amount over the speed that the vehicles are observed to be traveling and that this behavior is seen in both the connected and non-connected vehicles.
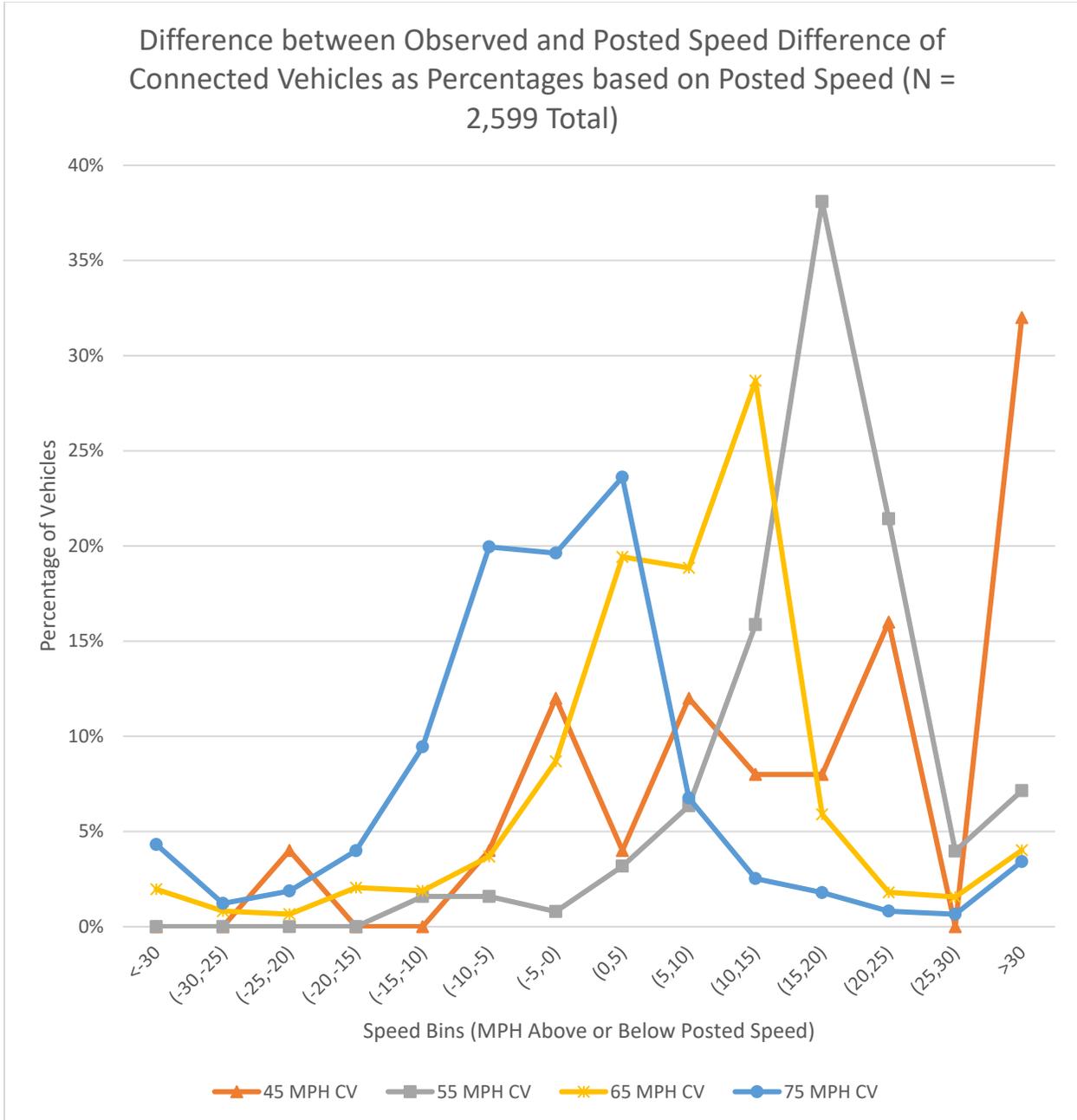
Figure 40. Comparison of CV Speed Differences Based on Posted Speeds.
Source: WYDOT
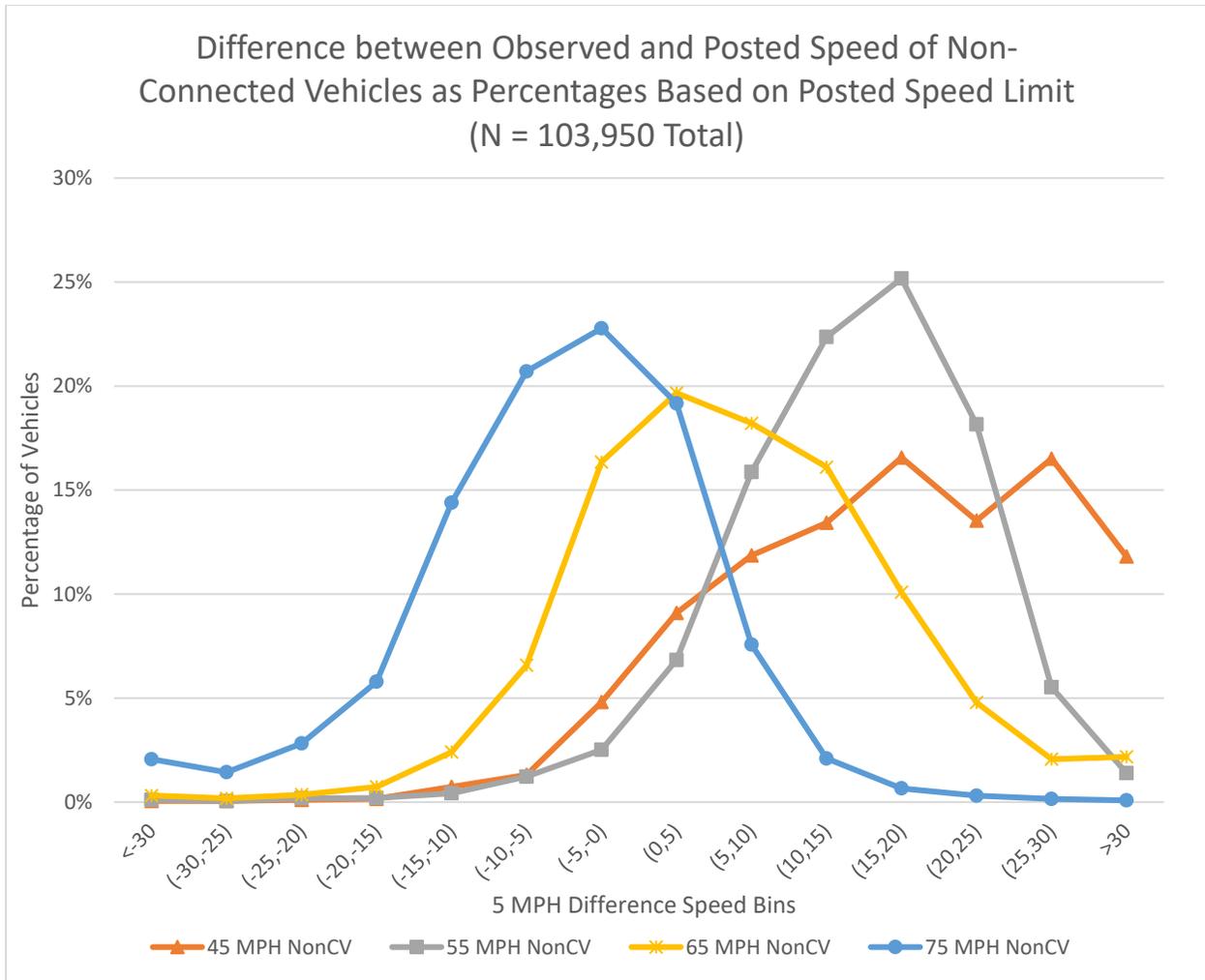
Figure 41. Comparison of Non-CV Speed Differences Based on Posted Speeds
Source: WYDOT
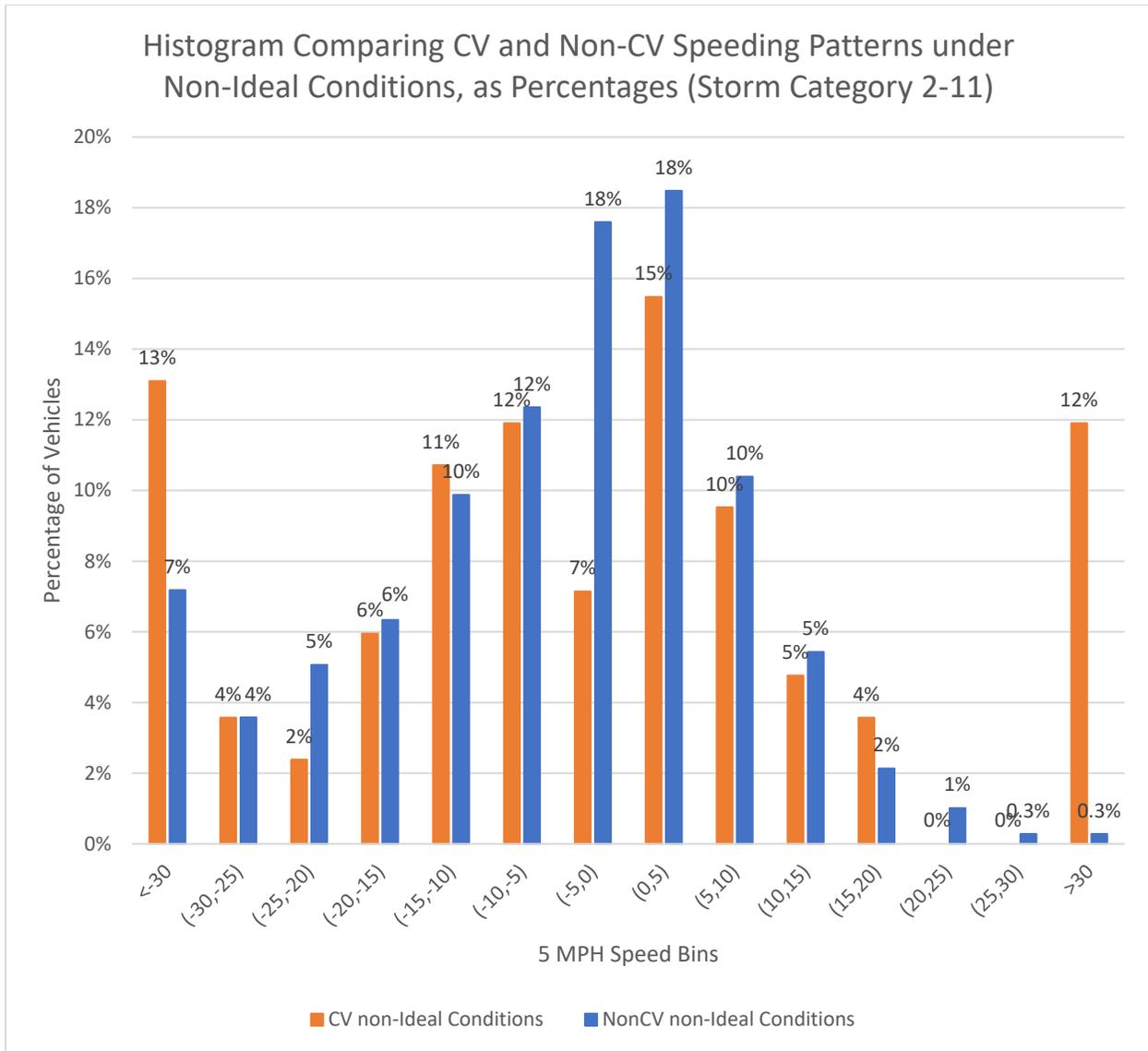
Figure 42. Comparison of CV and Non-CV Speed Distributions during Non-Ideal Weather Conditions.
Source: WYDOT

4.5 Safety Improvements

The following subsections describe the methodology and analysis results for the five crash-related performance measures—see Table 21. Four of the five PMs had baseline analyses performed during Phase 2 of the project and target values established. More details on the methodology and the selection of these performance measures can be found in the Baseline Report (FHWA-JPO-17-474). The numbering of performance measures changed between Phase 2 and Phase 3 of the project so each of the following sub-section lists the former PM number to use when referring to the earlier report.

Table 21. Safety Performance Measures (PM 11-15).

No.	Performance Measure	Target
11	Number of connected vehicles involved in a crash • Initial crashes • Secondary crashes (total and specifically rear-end crashes	N/A
12	Reduction of the number of vehicles involved in a crash (compare a 5-year average before Pilot to CV Pilot data)	25% reduction in the number of vehicles involved in a crash
13	Reduction of total and truck crash rates within a work zone area (compare a 5-year average before Pilot to CV Pilot data)	10% reduction in total and truck crash rate within work zones
14	Reduction of total and rates of truck crash along the corridor (compare a 5-year average before Pilot to CV Pilot data)	10% reduction in total and truck crash rates
15	Reduction of critical (fatal or incapacitating) total and truck crash rates in the corridor (compare a 5-year average before Pilot to CV Pilot data)	10% reduction in total and truck critical crash rates

It should be noted that regression to the mean bias is inherent in crash data, making it impossible to form conclusions from a simple comparison of a single year of post deployment data to the baseline data. This is particularly true in corridors subject to wide variations in seasonal weather where one winter season may be considerably different than another. Therefore, the results in this section are provided as a starting point for discussing the long-term safety impacts of the CV Pilot system.

Crash data for post-deployment was analyzed from December 2020 through February 2022 and combined into five, three-month quarters (Q1 – Q5). When yearly results are reported it is for data for the final four quarters from March 2021 through February 2022 Q2 – Q5). Crash reports were requested on the 15th of month following the end of each quarter to allow for the lag in reporting that is common in crash data. Below are the date ranges for the five analysis periods used in the safety performance measures:

- Q1: December 2020 – February 2021

- Q2: March 2021 – May 2021

- Q3: June 2021 – August 2021

- Q4: September 2021 – November 2021

- Q5: December 2021 – February 2022

- Post Deployment Year (Q2 – Q5): March 2021 – February 2022

- Cumulative (Q1 – Q5): December 2020 – February 2022

4.5.1 PM 11 - CVs Involved in Initial or Secondary Crashes

This performance measures tracks the number of initial and secondary crashes that connected vehicles were involved in during the post deployment stage. This PM requires self notification by the CV fleets managers (Friendly and Partner). During the period from December 2020 through February 2022 no crashes involving a connected vehicle were reported to WYDOT.

4.5.2 PM 12 - Reduction of the number of vehicles involved in a crash

PM 12 considers the number of vehicles (trucks and non-trucks) involved in each crash, which is reported by the responding officer at the scene of the crash. Each crash report includes data on the number of vehicles involved—a car that hits an animal would be a single vehicle collision, while a rear-end collision would have at least two vehicles involved in the crash.

This PM is used to determine how effective the CV technology is in reducing the number of vehicles involved in crash events. Vehicles equipped with CV technology alert drivers of hazardous road conditions or crashes ahead and a primary goal of the Wyoming CV Pilot was to reduce secondary crashes and crashes involving a large number of vehicles.

The baseline analysis for PM 12 used crash data from 2013 through 2017 and computed a yearly average. Initial analysis of the baseline considered only the number of vehicles as reported in the crash records. The baseline analysis found that this method did not consider secondary crashes and missed the magnitude of vehicles involved in the very large pileup crashes where there would have been multiple officers reporting to the crash scene. During Phase 2, various traditional definitions of secondary crashes were reviewed and it was determined that a modified version that considered any crash occurring withing 1 mile in either direction and within 75 minutes of the initial crash be defined as a secondary crash related to the first would capture the intent of the CV Pilot. For this report both the initial and expanded definition of number of vehicles involved in a crash are reported.

The PM 12 results are reported for all crashes and for truck crashes only—see Table 22. A truck crash is defined as a crash involving at least one vehicle that is reported as being a bus; motor home; light, medium or heavy truck; farm equipment, or construction vehicle in the crash database.

Table 22. Baseline Results for Number of Vehicles in a Crash from 2013-2017 (PM 12)

Number of Vehicles in Crash	All Crashes		Truck Crashes Only	
	Secondary Crashes not Considered	Secondary Crashes Considered	Secondary Crashes not Considered	Secondary Crashes Considered
1	9,377	8,102	3,072	2,499
2	2,985	2,802	2,288	2,008
3	205	300	180	154
4	39	129	35	90
5	11	55	11	39
6	5	34	5	26
7	7	16	7	13

Number of Vehicles in Crash	All Crashes		Truck Crashes Only	
	Secondary Crashes not Considered	Secondary Crashes Considered	Secondary Crashes not Considered	Secondary Crashes Considered
8	2	13	2	9
9	3	4	3	3
10+	7	30	7	28
Avg # of Vehs	1.29	1.41	1.53	1.68

During Phase 2 of the project, a target value of 25% improvement in the number of vehicles involved in a crash was established with the belief that CVs would have greater chances at both initial and secondary crash avoidance due to improvement in the quality and timeliness of information on upcoming crash hazards. It was also hypothesized that the improvement of the backoffice TMC operations would improve the timeliness and accuracy of the entire traveler information system, leading to improved safety.

Table 23 shows the quarterly results by the number of vehicles involved in the crash from the crash data without considering secondary crashes and when secondary crashes are considered. The average number of vehicles involved in a crash is shown in the far right column. The bottom of the table summarizes these results for all five quarters (Q1-Q5) and for the year going from March 1, 2021 – February 28, 2022 (Q2-A5). The highest number of crashes were reported in winter (Q1 and Q5) and spring (Q2). Winter crashes (Q1 and Q5) showed a higher percentage of single vehicle crashes than other quarters. Crashes involving more than two vehicles remained rare in all quarters. It should be noted that the annual number of crashes was much lower during the post deployment evaluation period (1,463 crashes) than the annual average over the baseline period (2,528), which is a reduction of 42.1%.

Table 23. Quarterly Results for Crashes by Number of Vehicles and Average Number of Vehicles (PM 12).

All Crashes	Number of Vehicles in Crash										Total	Avg # of Vehs
	1	2	3	4	5	6	7	8	9	10+		
Q1: 12/20-2/21												
w/o Secondary Crashes	381	110	8	1	1	0	0	0	0	0	501	1.27
w/ Secondary Crashes	324	107	11	5	4	0	2	0	1	0	454	1.40
Q2: 3/21-5/21												
w/o Secondary Crashes	218	114	14	0	1	0	1	0	0	0	348	1.44
w/ Secondary Crashes	186	111	15	3	5	0	0	0	0	1	321	1.56
Q3: 6/21-8/21												
w/o Secondary Crashes	172	110	13	2	0	0	0	0	0	0	297	1.48
w/ Secondary Crashes	171	107	14	3	0	0	0	0	0	0	295	1.49
Q4: 9/21-11/21												
w/o Secondary Crashes	149	107	11	1	2	0	0	0	0	1	271	1.55
w/ Secondary Crashes	136	99	1	3	2	2	1	0	0	1	255	1.64

All Crashes	Number of Vehicles in Crash										Total	Avg # of Vehs
	1	2	3	4	5	6	7	8	9	10+		
Q5: 12/21-2/22												
w/o Secondary Crashes	388	145	10	2	1	0	0	0	0	1	547	1.34
w/ Secondary Crashes	323	140	1	8	4	2	3	0	0	1	492	1.49
Cumulative Q1-Q5												
w/o Secondary Crashes	1,308	586	56	6	5	0	1	0	0	2	1,964	1.39
w/ Secondary Crashes	1140	564	62	22	15	4	6	0	1	3	1,817	1.50
Annual Q2-Q5: 3/21-2/22												
w/o Secondary Crashes	927	476	48	5	4	0	1	0	0	2	1,463	1.43
w/ Secondary Crashes	816	457	51	17	11	4	4	0	0	3	1,1363	1.53

Table 24 contains the same information as Table 23 but includes data from truck crashes only. Generally, the average number of vehicles involved in a crash is higher for truck crashes than all crashes as trucks are involved in a lower percentage of single vehicle crashes. The truck crash trends in Table 24 were similar to those in Table 23 in that winter (Q1 and Q5) had the highest number of crashes and higher percentage of single vehicle crashes. Similar to the previous table, the annual number of truck crashes in the post-deployment evaluation period (807 crashes) was much lower (28% reduction) than the average number of annual truck crashes in the baseline (1,122).

Table 24. Quarterly Results for Truck Crashes by Number of Vehicles and Average Number of Vehicles (PM 12)

All Crashes	Number of Vehicles in Crash										Total	Avg # of Vehs
	1	2	3	4	5	6	7	8	9	10+		
Q1: 12/20-2/21												
w/o Secondary Crashes	192	86	8	1	1	0	0	0	0	0	288	1.38
w/ Secondary Crashes	166	76	9	6	1	0	2	0	1	0	261	1.52
Q2: 3/21-5/21												
w/o Secondary Crashes	90	90	13	0	1	0	1	0	0	0	195	1.65
w/ Secondary Crashes	69	83	13	3	5	0	0	0	0	1	174	1.84
Q3: 6/21-8/21												
w/o Secondary Crashes	64	46	6	1	0	0	0	0	0	0	117	1.52
w/ Secondary Crashes	64	46	6	1	0	0	0	0	0	0	117	1.52
Q4: 9/21-11/21												
w/o Secondary Crashes	62	67	8	1	2	0	0	0	0	1	141	1.73
w/ Secondary Crashes	54	59	8	2	2	2	1	0	0	1	129	1.88
Q5: 12/21-2/22												
w/o Secondary Crashes	218	123	10	1	1	0	0	0	0	1	354	1.45
w/ Secondary Crashes	118	114	7	6	6	2	1	0	0	1	318	1.61

All Crashes	Number of Vehicles in Crash										Total	Avg # of Vehs
	1	2	3	4	5	6	7	8	9	10+		
Cumulative Q1 - Q5												
w/o Secondary Crashes	626	412	45	4	5	0	1	0	0	2	1,095	1.51
w/ Secondary Crashes	534	378	43	18	14	4	4	0	1	3	9999	1.65
Annual Q2-Q5: 3/21-2/22												
w/o Secondary Crashes	434	326	37	3	4	0	1	0	0	2	807	1.56
w/ Secondary Crashes	368	302	34	12	13	4	2	0	0	3	738	1.70

Table 25 and Table 26 show the post deployment results compared to the baseline for all crashes and truck only crashes, respectively. Table 25 indicates a reduction in the total number of vehicles involved in the crashes but an increase in the average number of vehicles involved in all crashes Similar results apply when analyzing crashes that involved trucks, see Table 26. The hypothesis that the CV Pilot would reduce the average number vehicles involved in crashes was not realized in the post-deployment evaluation period. The average number of vehicles increased from 1.29 to 1.43 (10.3%) when secondary crashes were not considered and increased from 1.41 to 1.53 (8.9%) when secondary crashes were considered – see Table 25. For the truck crash data, the hypothesis that the average number of trucks involved in a crash would be lower was also not realized. However, the percent increase was much smaller than seen in the data for all crash types, with the average number of vehicles increasing from 1.53 to 1.56 (1.8%) when secondary crashes were not considered and increased from 1.68 to 1.70 (1.5%) when secondary crashes were considered – see Table 26. It is important to note that these results are based on a single year of post deployment crash data and care must be taken in interpreting the meaning of after a single year of crash history.

Table 25. Comparison of Baseline and Post Deployment Results for Number of Vehicles in All Crashes (PM 12).

# Vehicles in Crash	Post Deployment (Q2- Q5: 3/21-2/22)		Baseline (Annual Avg. 2013-2017)	
	w/o Secondary Crashes	w/ Secondary Crashes	w/o Secondary Crashes	w/ Secondary Crashes
1	927	816	1,875	1,620
2	476	457	597	560
3	48	51	41	60
4	5	17	8	26
5	4	11	2	11
6	0	4	1	7
7	1	4	1	3
8	0	0	0	3
9	0	0	1	1
10+	2	3	1	6
Sum	1,463	1,363	2,528	2,297
Avg # of Vehs.	**1.43**	**1.53**	**1.29**	**1.41**

Table 26. Comparison of Baseline and Post Deployment Results for Number of Vehicles in Truck Crashes Only (PM 12).

# Vehicles in Crash	Post Deployment (Q2- Q5: 3/21-2/22)		Baseline (Annual Avg. 2013-2017)	
	w/o Secondary Crashes	w/ Secondary Crashes	w/o Secondary Crashes	w/ Secondary Crashes
1	434	368	614	500
2	326	302	458	402
3	37	34	36	31
4	3	12	7	18
5	4	13	2	8
6	0	4	1	5
7	1	2	1	3
8	0	0	0	2
9	0	0	1	1
10+	2	3	1	6
Sum	807	738	1,122	974
Avg # of Vehs.	**1.56**	**1.70**	**1.53**	**1.68**

4.5.3 PM 13 - Reduction of Total and Truck Crash Rates within a Work Zone Area

PM 13 focuses on the number of vehicles (trucks and non-trucks) involved in a work zone related crash. Given elevation and terrain of the I-80 corridor, the construction season is short and intense. Vehicles equipped with CV technology alert drivers of upcoming work zones and one of the Wyoming CV Pilot's use cases was to improve safety in these zones. In addition to in-vehicle alerts for CVs, there was also work done to improve the quality and timeliness of work zone traveler information for all users of the corridor.

The baseline analysis for PM 13 used crash data from 2013 through 2017 and computed a yearly average. Initial analysis of the baseline considered only crashes that were identified in the crash records as being work zone related as reported in the crash records such as hitting construction equipment or temporary traffic control devices. During these efforts, it became clear that adoption of a broader definition of work zone crashes was necessary.

The Construction Console is a database maintained by the Construction Office of WYDOT to track current construction and maintenance projects. This database became the foundation for creating work zone TIMs for the CV Pilot. The Construction Console database provides the start and end dates and the start and end mileposts for the projects along I-80 with a description of the work that's to be done. Some projects in the Construction Console are minor in nature and/or extensive in their scope and are excluded both from TIM generation and from the work zone crash analysis. An example would be a contract to handle roadside mowing operations which may last the entire summer and extend over the entire corridor.

Each quarter, crashes associated with an active work zone from the Construction Console are tagged as work zone crashes using the reported date and milepost of the crash. The PM 13

results are reported for all crashes and for truck crashes only. A truck crash is defined as a crash involving at least one vehicle that is reported as being a bus; motor home; light, medium or heavy truck; farm equipment, or construction vehicle in the crash database. To account for the varying lengths of the work zones and the difference in construction from season to season, a crash rate in crashes per million vehicle miles traveled (RMVMT) in a work zone or per million vehicle miles traveled by trucks (RMVMTT) in a work zone are also calculated for this PM. The VMT and VMTT use monthly traffic volume reports from the WYDOT Traffic Office where the entire corridor is divided into nine sub-segments that are associated with a permanent traffic data collection site. Monthly average daily traffic values and truck percentages are then converted to weighted averages for the quarter. Monthly truck percentages averaged close to 50% ranging from 37% to almost 64%.

The baseline results for PM 13 are shown in Table 27. Crash frequencies are yearly averages over the five-year baseline period and show that work zone crashes averaged 187 crashes per year and represented just under 12% of the crashes along the corridor. Work zone truck crashes made up a similar percentage of the truck crashes and averaged 86 per year. Crash rates for all crashes were about 0.88 crashes per million vehicle miles traveled and had a similar rate of 0.86 per million vehicles miles traveled for trucks.

Table 27. Baseline (2013-2017) Results for Work Zone Crashes (PM 13).

Crash Type	Yearly Average	% Crashes
Work Zone Crashes	187	11.80%
Non-Work Zone Crashes	1,393	88.20%
Work Zone Truck Crashes	86	11.90%
Non-Work Zone Truck Crashes	633	88.10%
Work Zone Crash Rate (RMVMT)	**0.88**	---
Truck Work Zone Crash Rate (RMVMTT)	**0.86**	---

During Phase 2 of the project, a target value of 10% reduction in work zone crashes was established with the belief that connected vehicles would have improved safety due to improvement in the quality and timeliness of information on upcoming work zones. It was also believed that the improvement of the back office TMC operations would improve the timeliness and accuracy of all the entire traveler information system on work zones.

Table 28 shows the quarterly results of the work zone crash frequencies compared to non-work zone crashes and the overall crash rates for all work zone crashes and truck-related work zone crashes. To help interpret the crash rate numbers, the estimated work zone vehicle miles traveled in million vehicle miles traveled (MVMT) and million truck vehicle miles traveled (MVMTT) are included in the table. The MVMT and MVMTT illustrate one of the primary challenges with defining work zones for the CV Pilot in that the construction console database reports work zones as when the contract becomes active as opposed to when the work zone itself may become active. This can be seen in the high number of work zone vehicle miles traveled during quarters when it is unlikely that contractors would be actively working given the frequency and severity of winter weather events in the corridor, such as in Q1, Q2, and Q5.

Table 28. Quarterly Results of Work Zone Crash Frequencies and Rates (PM 13).

Crash Type	Q1: Dec.2020 - Feb.2021		Q2: Mar.2021 - May.2021		Q3: Jun. 2021 - Aug. 2021		Q4: Sep. 2021 - Nov. 2021		Q5: Dec. 2021 - Feb. 2022	
	Count	%	Count	%	Count	%	Count	%	Count	%
Work Zone Crashes	56	11.2%	54	15.5%	55	18.5%	53	19.6%	51	9.3%
Non-Work Zone Crashes	445	88.8%	294	84.5%	242	81.5%	218	80.4%	496	90.7%
Work Zone Truck Crashes	34	11.8%	33	17.2%	22	18.8%	33	23.4%	39	11.0%
Non-Work Zone Truck Crashes	254	88.2%	159	82.8%	95	81.2%	108	76.6%	315	89.0%
Work Zone MVMT	40.2	---	82.1	---	95.7	---	40.0	---	15.8	---
Work Zone MVMTT	22.5	---	40.4	---	39.8	---	18.9	---	8.9	---
Work Zone Crash Rate (RMVMT)	0.139	---	0.66	---	0.57	---	1.32	---	3.21	---
Truck Work Zone Crash Rate (RMVMTT)	0.151	---	0.82	---	0.55	---	1.75	---	4.37	---

Table 29 shows the post deployment results compared to the baseline results indicating increases in the percentages of work zone related crashes, from 11.8% of total crashes to 14.6%, along with an increase in crash rates, from 0.88 RMVMT to 0.91. Truck work zone crashes also increased as a percentage (12.0% to 14.7%) along with a larger increase in crash rates (0.86 RMVMTT to 1.18).

The Construction Console used in this performance measure to identify work zones is also the database used to generate work zone traveler alerts. Throughout the CV Pilot it became clear that significant improvements to the database were necessary to generate reliable and timely work zone TIMs. Therefore, the results from this performance measure must be interpreted carefully as the underlying construction database has not remained the same between the baseline to the post-deployment periods.

Table 29. Comparison of Baseline and Post Deployment Results for Work Zone Crashes (PM 13)

Crash Type	Post Deployment Results (Q2 – Q5: 3/ 2021 – 2/2022)		Baseline (2013-2017)	
	Count	%	Yearly Average	%
Work Zone Crashes	213	14.6%	187	11.8%
Non-Work Zone Crashes	1,250	85.4%	1,393	88.2%
Work Zone Truck Crashes	127	15.8%	86	12.0%
Non-Work Zone Truck Crashes	677	84.2%	633	88.0%
Work Zone Crash Rate (RMVMT)	0.91	---	0.88	---
Truck Work Zone Crash Rate (RMVMTT)	1.18	---	0.86	---

4.5.4 PM 14 - Reduction of Total and Rates of Truck Crash Along the Corridor

PM 14 focuses on the rate of all crashes (RMVMT) and truck crashes (RMVMTT) along the corridor. For this performance measure, the corridor was divided into nine analysis sections based on whether the corridor was under static speed limits (N1-N5) or variable speed limit control (V1-V4). Currently 124 miles (~30%) of the corridor are operated with variable speed limits (VSL) where the regulatory speed limit is set by the central TMC in Cheyenne based on current weather and crash conditions.

The baseline analysis for PM 14 used crash data from 2010 through 2016 and computed an average crash rate for each of the nine analysis segments and for the corridor overall. VSL corridors are used by WYDOT as a mitigation measure in high crash corridors with challenging weather and terrain, which is why these segments are seen to have higher crash rates even with the VSL implementation—see Table 30. In all segments, the truck crash rate was found to be lower than the overall crash rates during the baseline period. The overall crash rate is a length-based average of the nine segment rates.

Similar to PM 13, the VMT and VMTT use monthly traffic volume reports from the WYDOT Traffic Office and the same approach was used to estimate weighted averages for each quarter.

Table 30. Baseline Crash Rates (2010-2016) for All Crashes and Truck Crashes by Corridor Segment (PM 14).

Corridor Segment *	Length (Miles)	Crash Rate (RMVMT)	Truck Crash Rate (RMVMTT)
N1 (MP 0-8.5)	8.5	1.000	0.820
V1 (MP 8.5-27.6)	19.1	1.110	1.030
N2 (MP 27.6-88.9)	61.3	0.610	0.560
V2 (MP 88.9-107.9)	19	1.140	0.830
N3 (MP 107.9-238.8)	130.9	0.720	0.710
V3 (MP 238.8-289.5)	50.7	1.240	1.420
N4 (MP 289.5-317.7)	28.2	0.920	0.910
V4 (MP 317.7 - 353.0)	35.3	1.070	1.260
N5 (MP 353.0-402.8)	49.8	0.720	0.570
Total	**402**	**0.860**	**0.840**

N for Static Speed Limit Segments, V for Variable Speed Limit Segments.

During Phase 2 of the project, a target value of 10% reduction in crash rates was established with the hypothesis that CVs would have improved safety due to the in-vehicle alerts about upcoming conditions. It was also believed that the improvement of the back office TMC operations would improve the timeliness and accuracy of all the entire traveler information system on work zones.

Table 31 shows the quarterly results of crash rates and truck crash rates by the nine analysis segments. Similar to the baseline period, the variable speed limit corridors (V1 – V4) experienced higher crashes and crash rates, which is expected as these are the corridors that experience the

most challenging weather and road conditions. Winter quarters (Q1 and Q5) had the highest crash rates.

Table 31. Quarterly Results of Crash Rates and Truck Crash Rates by Corridor Segment (PM 14)

	N1	V1	N2	V2	N3	V3	N4	V4	N5	Total
Q1: Dec. 2020- Feb. 2021										
Total Crashes	3	26	45	51	105	122	22	83	44	501
Truck Crashes	3	10	21	31	54	80	13	52	24	288
Quarterly ADT	13,028	11,321	11,039	17,321	9,800	9,040	9,473	9,905	9,014	10,270
Crash Rate (RMVMT)	0.301	1.336	0.739	1.722	0.909	2.958	0.915	2.637	1.089	1.345
Truck Crash Rate (RMVMTT)	0.622	0.967	0.592	2.788	0.740	3.056	0.915	3.023	1.006	1.312
Q2: Mar. 2021- May. 2021										
Total Crashes	10	15	19	44	106	40	33	38	43	348
Truck Crashes	5	10	10	20	62	29	17	26	13	192
Quarterly ADT	16,649	14,974	14,554	21,351	12,973	12,362	12,586	12,810	11,657	13,490
Crash Rate (RMVMT)	0.768	0.570	0.231	1.179	0.678	0.694	1.011	0.913	0.805	0.696
Truck Crash Rate (RMVMTT)	0.836	0.757	0.219	1.430	0.689	0.841	0.913	1.153	0.427	0.690
Q3: Jun. 2021 - Aug. 2021										
Total Crashes	7	16	27	34	82	41	33	21	36	297
Truck Crashes	2	7	4	17	39	14	14	7	13	117
Quarterly ADT	21,474	19,190	18,024	24,438	17,389	16,356	16,618	16,881	15,123	17,468
Crash Rate (RMVMT)	0.417	0.474	0.266	0.796	0.392	0.537	0.765	0.383	0.520	0.459
Truck Crash Rate (RMVMTT)	0.310	0.486	0.081	1.076	0.421	0.367	0.679	0.280	3.92	3.92
Q4: Sep. 2021 - Nov. 2021										
Total Crashes	7	13	16	42	71	33	25	38	26	271
Truck Crashes	2	7	5	18	42	17	13	27	10	141
Quarterly ADT	18,647	16,500	15,604	22,335	15,119	13,972	14,608	15,243	13,293	15,267
Crash Rate (RMVMT)	0.485	0.453	0.184	1.088	0.394	0.512	0.667	0.776	0.432	0.484
Truck Crash Rate (RMVMTT)	0.361	0.572	0.119	1.260	0.527	0.527	0.725	1.208	0.347	0.546
Q5: Dec. 2021- Feb. 2022										
Total Crashes	17	33	64	28	144	100	20	101	40	547

	N1	V1	N2	V2	N3	V3	N4	V4	N5	Total
Truck Crashes	9	15	45	10	95	82	12	65	21	354
Quarterly ADT (veh/day)	12,486	11,377	11,182	17,528	9,901	9,9009	9,596	10,184	8,733	10,318
Crash Rate (RMVMT)	1.780	1.687	1.037	0.934	1.235	2.433	0.821	3.122	1.022	1.462
Truck Crash Rate (RMVMTT)	1.332	1.006	1.068	0.705	0.930	1.999	0.511	2.152	0.556	1.112
Cumulative (Q1 – Q5)										
Total Crashes	44	103	171	199	508	336	133	281	186	1,964
Truck Crashes	21	49	85	96	292	222	69	177	81	1,092
Crash Rate (RMVMT)	0.690	0.806	0.435	1.116	0.653	1.197	0.823	1.343	0.700	0.798
Truck Crash Rate (RMVMTT)	0.769	0.810	0.419	1.447	0.726	1.409	0.795	1.650	0.559	0.857
Annual (Q2 - Q5)										
Total Crashes	41	77	126	148	403	214	111	198	145	1,463
Truck Crashes	18	39	64	65	238	142	56	125	57	804
Crash Rate (RMVMT)	0.762	0.711	0.379	0.996	0.608	0.893	0.807	1.114	0.632	0.700
Truck Crash Rate (RMVMTT)	0.800	0.778	0.383	1.177	0.723	1.081	0.771	1.384	0.471	0.762

Table 32 shows the post deployment results compared to the baseline results for overall crash rates and truck crash rates by analysis segment and for the total corridor. The crash rate per million vehicle miles traveled decreased for all corridor segments except for V4, which is the variable speed limit corridor between Laramie and Cheyenne. The overall crash rate for the corridor decreased from 0.860 to 0.700, which is an 18.6% reduction that exceeds the target of 10%. The truck crash rate reduced from 0.840 to 0.762, which is a 9.2% reduction which is slightly below the target of 10%.

Table 32. Comparison of Baseline and Post Deployment Results for Crash Rates and Truck Crash Rates (PM14)

Road Section	Post Deployment (Q2 - Q5): Mar. 2021 - Feb. 2022		2010-2016 Baseline	
	Crash Rate (RMVMT)	Truck Crash Rate (RMVMTT)	Crash Rate (RMVMT)	Truck Crash Rate (RMVMTT)
N1 (MP 0-8.5)	0.762	0.800	1.000	0.820
V1 (MP 8.5-27.6)	0.711	0.778	1.110	1.030
N2 (MP 27.6-88.9)	0.379	0.383	0.610	0.560
V2 (MP 88.9-107.9)	0.996	1.177	1.140	0.830
N3 (MP 107.9-238.8)	0.608	0.723	0.720	0.710

Road Section	Post Deployment (Q2 - Q5): Mar. 2021 - Feb. 2022		2010-2016 Baseline	
	Crash Rate (RMVMT)	Truck Crash Rate (RMVMTT)	Crash Rate (RMVMT)	Truck Crash Rate (RMVMTT)
V3 (MP 238.8-289.5)	0.893	1.081	1.240	1.420
N4 (MP 289.5-317.7)	0.807	0.771	0.920	0.910
V4 (MP 317.7 - 353.0)	1.114	1.387	1.070	1.260
N5 (MP 353.0-402.0)	0.632	0.471	0.720	0.570
Total	**0.700**	**0.762**	**0.860**	**0.840**

4.5.5 PM 15 - Reduction of Critical Total and Truck Crash Rates in the Corridor

PM 15 focuses on critical crashes in the corridor by considering the number and percentage of fatal and incapacitating injury crashes (K and A crashes on the KABCO scale[5]). PM 15 results are reported for all crashes and truck crashes. The baseline analysis for PM 15 used crash data from 2010 through 2017 and found that 4.4% of the 12,641 total crashes during that period were reported as critical crashes – see Table 33. Considering only truck crashes, the percentage of critical crashes were a similar 4.5% of all truck crashes for the baseline period.

Table 33. Baseline (2013-2017) Results for Critical Crashes (PM 15).

Crash Type	Yearly Average	% Crashes
Non-Critical Crashes	1,511	95.6%
Critical Crashes	69	4.4%
Total	1,580	
Truck Non-Critical Crashes	670	95.5%
Truck Critical Crashes	31	4.5%
Total Truck Crashes	701	

During the post deployment period the frequency and percentage of critical crashes were compiled with critical crash percentages ranging from 2.8% to 7.4 % for each quarter—see Table 34. The higher percentage of critical crashes occurred during the summer and fall quarters (Q3 and Q4). The percent of critical truck crashes had similar results with the highest percentages during Q3 and Q4.

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[5] KABCO Scale established by the FHWA to evaluate the severity of auto collision injuries and expresses how they impact crash costs. More info here: https://safety.fhwa.dot.gov/hsip/spm/conversion_tbl/pdfs/kabco_ctable_by_state.pdf

Table 34. Quarterly Results of Critical Crashes (PM 15).

Period	All Crashes			Truck Crashes		
	Non-critical	Critical	Total	Non-critical	Critical	Total
Q1: Dec. 20 - Feb. 21	487	14	501	280	8	288
Percentage	97.2%	2.8%		97.2%	2.8%	
Q2: Mar. 21 - May 21	334	14	348	187	5	192
Percentage	96.0%	4.0%		97.4%	2.6%	
Q3: Jun. 21 - Aug. 21	275	22	297	105	12	117
Percentage	92.6%	7.4%		89.7%	10.3%	
Q4: Sep. 21 - Nov. 21	252	19	271	131	10	141
Percentage	93.0%	7.0%		91.9%	7.1%	
Q5: Dec. 21 - Feb. 22	526	21	547	341	13	354
Percentage	96.2%	3.8%		96.3%	3.7%	
Cumulative Q1-Q5	1,874	90	1,964	1,044	48	1,092
Percentage	95.4%	4.6%		95.4%	4.6%	
Annual Q2-Q5	1,387	76	1,463	764	40	804
	94.8%	5.2%		95.0%	5.0%	

During Phase 2 of the project, a target value of 10% reduction in critical crashes was established with the hypothesis that connected vehicles would have improved safety due to the in-vehicle alerts about upcoming conditions. It was also believed that the improvement of the back office TMC operations would improve the timeliness and accuracy of all the entire traveler information system.

Table 35 shows the post deployment results compared to the baseline results for critical crashes. From this table, the post-deployment and baseline results were similar for both the total and truck crashes with slightly higher critical crash rate percentages during the post-deployment year.

Table 35. Comparison of Baseline and Post Deployment Results for Critical Crashes (PM 15).

Post Deployment	All Crashes			Truck Crashes		
	Non-critical	Critical	Total	Non-critical	Critical	Total
Annual Q2 - Q5	1,387	76	1,463	764	40	804
Percentage	94.8%	5.2%		95%	5%	
Annual Average Baseline (2010-2017)	1,511	69	1,580	670	31	701
Percentage	95.6%	4.4%		95.5%	4.5%	

4.6 CV Driver Behavior Compliance

The last two performance measures look at the action taken by drivers after receipt of an alert. During the development of the performance measures in Phase 2 it was determined that driver action be classified as one of the following:

- **Vehicle Reduced Speed** was assigned to events where a notable speed reduction was witnessed after the driver alert was given.
- **Vehicle Stopped** was assigned for events where the analyst found the vehicle speed came to zero after the driver alert was given but the driver remained on the roadway, either in the lane or shoulder areas.
- **Vehicle Exited** was assigned for events where the analyst found the vehicle exited after the driver alert was given.
- **No Action** taken was assigned for events where the analyst found no evidence of deceleration, stopping, or exiting.

No specific thresholds for defining these actions were set during performance measure development. As expected during the development of the Performance Measures for this project, these analyses were time consuming due to the volume of data generated by the CV Pilot and the privacy-by-design nature of the data, which ensures participant's privacy. Because the driver alert data does not contain vehicle identification information, it is a time-consuming process to link alert data with vehicle BSM data to determine the likely action taken by the driver after receiving the alert.

Other complicating factors are the uncertainty in whether the driver saw the alert and whether the alert matched with real-time road conditions. Privacy of the system was the overriding concern and so vehicles were not instrumented with in-vehicle or external cameras. For analysis of the PM, additional data from nearby weather sensors and notes from construction personnel had to be tracked down to provide insight into what the driver might have been experiencing at the time of the alert. System data was not available to confirm if the driver had the HMI turned on at the time of the alert, so driver actions at the time of the alert can only be hypothesized.

The following sections provide an overview of case study analyses that were performed. More details on the individual events in the case studies can be found in Appendices D-G.

4.6.1 PM 16 – CVs that Likely Took Action Following Receipt of an Alert

Three snapshot analyses were done to evaluate the driver reactions after receiving an alert:

- High wind alerts for a wind event on June 22, 2021
- Work zone alerts for a construction zone during the month of June 2021
- Winter storm event on February 2, 2022

4.6.1.1 High Wind Alert Analysis

This driver reaction analysis was done on a significant high wind event on June 22, 2021 that impacted the corridor, particularly in the southeastern part of the state. The high wind driver alerts for that day were compiled and 18 events were found to have occurred within the boundaries of the I-80 corridor. When BSM data for the vehicles were queries, only data from 10 events were found. This was most likely due to the query excluding WYDOT maintenance and highway patrol vehicles.

Each of the events were mapped to determine the vehicle path. Speed and acceleration data from the BSM files were graphed against time. Wind speed, wind gust speed, and wind direction data

from the closest RWIS were also graphed to provide information on wind conditions at the time of the alert. From these graphs and vehicle paths, a driver reaction was assigned to each event, as shown in Table 36.

From the 10 events that were analyzed, four vehicles (40%) took no action, four (40%) reduced speed, and two (20%) stopped. The BSM acceleration graphs, particularly for yaw acceleration, showed the vehicles were being impacted by the wind in many of these events. The vehicles experiencing these effects were generally associated with the events where the driver took action.

Table 36. Summary of Driver Actions for High Wind Alerts (PM 16)

Latitude	Longitude	Speed (MPH)	Record Generated At	Analysis
41.12546	-105.313	21.74	6/22/2021 22:40	Vehicle Stopped
41.74118	-106.831	77.40	6/22/2021 23:23	No Action
41.67464	-107.981	69.88	6/22/2021 21:40	No Action
41.12569	-105.313	13.96	6/22/2021 22:41	Vehicle Stopped
41.12541	-105.307	54.27	6/22/2021 22:21	Vehicle Reduced Speed
41.23018	-105.438	77.31	6/22/2021 23:49	Vehicle Reduced Speed
41.23011	-105.438	77.67	6/22/2021 22:52	No Action
41.12484	-105.305	75.70	6/22/2021 23:58	No Action
41.71611	-107.785	33.33	6/22/2021 21:30	Vehicle Reduced Speed
41.24081	-105.438	78.69	6/22/2021 22:52	Vehicle Reduced Speed

More information on the analysis and results can be found in Appendix D. Drivers Behavior Under High Wind Alert.

4.6.1.2 Work Zone Analysis

This driver reaction analysis was done on work zone driver alert data for events on the I-80 corridor compiled for the month of June 2021. From the comprehensive driver alert dataset, a list of 6,994 CV alerts with an It is code of 1025 for construction zone alerts were found. The location of all the alerts were mapped and four locations stood out as regions of major activity; these sites were identified for potential further analysis. After communicating with the WYDOT construction office and the Resident Engineers associated with the project, it was determined that the Hillsdale Bridge Replacement project east of Cheyenne (MP 372-382) was an acceptable project for the analysis. This particular project was an active work zone during the entire month and involved substantial construction traffic control as it directed all traffic to the eastbound lanes utilizing median crossovers so that the resulting traffic was one lane in each direction.

The BSM data was queried and data for highway patrol and WYDOT maintenance vehicles were removed, resulting in 16 events where at least one work zone alert was broadcast to a vehicle approaching or within the work zone—see Table 37. From the 16 events that were analyzed, seven vehicles (44%) took no action; eight (50%) reduced speed; and one (6%) vehicle exited following the construction alert.

Table 37. Summary of Driver Actions for Construction Alert Events (PM 16).

Event	Number of Alerts	Time of First Alert	Time of Last Alert	Driver Action
1	8	6/17/2021 21:38:24	6/17/2021 21:50:43	Vehicle Exited
2	6	6/17/2021 22:30:29	6/17/2021 22:58:26	No Action
3	2	6/23/2021 14:12:03	6/23/2021 14:21:38	No Action
4	6	6/24/2021 14:02:31	6/24/2021 14:54:38	Reduced Speed
5	1	6/24/2021 22:44:57		Reduced Speed
6	6	6/24/2021 23:31:36	6/24/2021 23:36:06	Reduced Speed
7	1	6/26/2021 18:24:46		Reduced Speed
8	2	6/26/2021 20:09:41	6/26/2021 20:10:02	Reduced Speed
9	2	6/28/2021 10:54:30	6/28/2021 10:57:55	Reduced Speed
10	1	6/28/2021 11:07:14		No Action
11	6	6/28/2021 13:59:00	6/28/2021 14:11:29	Reduced Speed
12	1	6/28/2021 16:36:55		Reduced Speed
13	3	6/28/2021 16:42:38	6/28/2021 16:47:18	No Action
14	3	6/28/2021 18:03:23	6/28/2021 18:03:31	No Action
15	1	6/28/2021 18:13:12		No Action
16	4	6/28/2021 22:43:18	6/28/2021 22:49:39	No Action

More information on the analysis and results can be found in Appendix E. Drivers Behavior Under Work Zone Alert.

4.6.1.3 Winter Storm Event Analysis

A low-pressure storm event occurred in Wyoming from Tuesday, February 1st through Thursday, February 3rd, 2022. Periods of moderate snow led to slick and snow packed roads with portions of black ice. The temperatures dropped near the end of the storm. Southeastern Wyoming was not hit the hardest by the storm but all areas of I-80 were impacted. Figure 43 shows the forecasted impacts of the storm in a YouTube video prepared by WYDOT to inform travelers of the upcoming storm. Note that CV pilot data is stored in UTC time and the times in the impact video are in local time, which is Mountain Standard Time or six hours behind UTC.
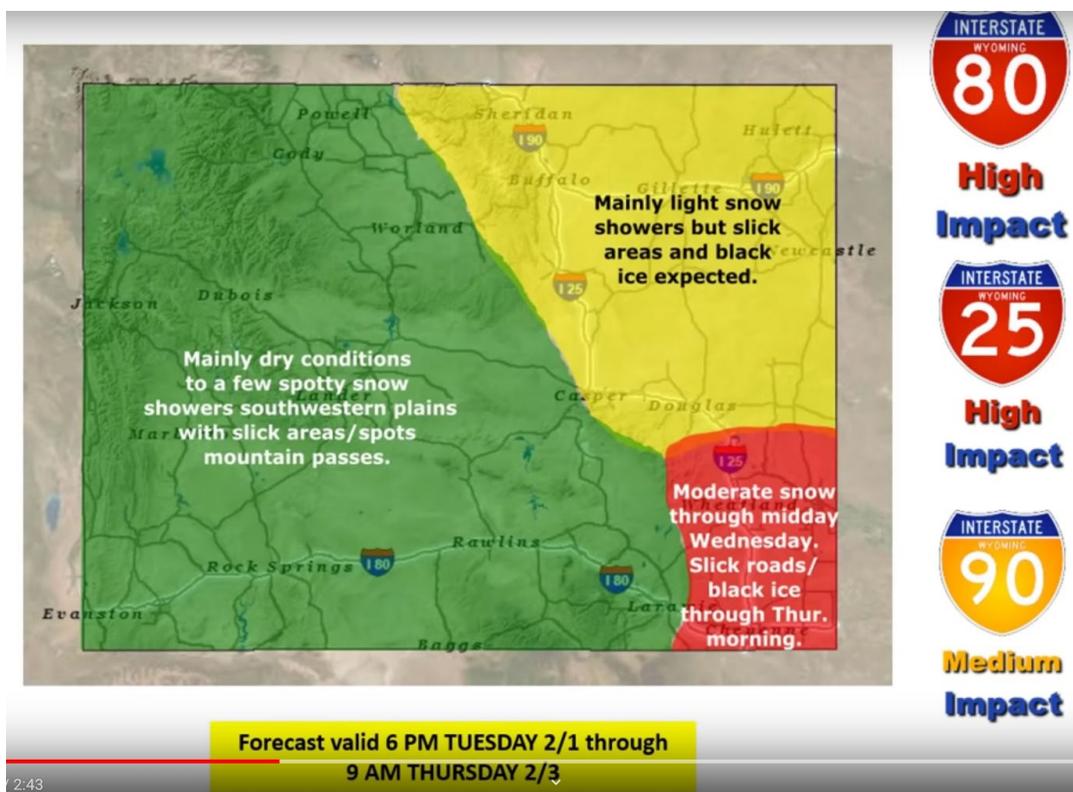
Figure 43. Forecasted Impacts for February Winter Storm Event.
Source: WYDOT YouTube Channel https://youtu.be/D4WlfctRNfA

Driver alerts for February 2nd were compiled and 1,930 driver alerts were found once speed limit violation alerts (SLVA) and forward collision warning (FCW) were removed. Table 38 summarizes these alerts by It is code. Seven of it isITIS codes (highlighted in Table 38) were identified as being most relevant to the winter storm event. There were 1,047 of these alerts, which were then mapped in Google Earth (Figure 44). Three clusters of alerts located outside of the urban areas were selected for analysis, shown in red in Figure 44 and listed in Table 39. These corridors were labeled A, B, and C from west to east.

Table 38. Summary of Driver Alerts for February 2, 2022

ITIS Code	Count	Code Description
2	7	Accidents / Incidents
268	665	Speed limit
1025	74	Construction
4868	**518**	**Snow**
5127	9	Strong Winds
5383	**40**	**Visibility Reduced**

ITIS Code	Count	Code Description
5385	**119**	**Blowing Snow**
5895	92	Wet Pavement
5906	**186**	**Ice**
5907	**116**	**Icy Patches**
5908	**60**	**Black Ice**
5927	**8**	**Snow drifts**
6011	13	Dry Pavement
6156	7	Snow Tires or Chains Required
7443	16	Reduce Your Speed
1,930		Sum of all alerts
1,047		**Sum of Key Winter Storm Related Alerts** *(highlighted rows)*

Figure 44. Mapping of February 2nd Winter Strom Driver Alerts.
Source: WYDOT & Google Earth.

The BSM data for each of these corridors were queries for February 2nd. The BSM data for all static ID associated with snowplows and highway patrol vehicles were removed from the dataset since these vehicles are excluded from the driver action analyses given their unique driver behaviors. Since the alert data does not contain vehicle IDs as part of the system design to protect privacy, the alert and BSM data has to be matched based on time and spatial data.

For Corridor A, there were 16,810 BSM records after the snowplow and highway patrol records were removed. From the alert data, it was found that the winter storm associated alerts in the corridor began around 16:33 UTC time and the last alert for the day was at 22:09 UTC time. Almost half of the BSM records (8,565) occurred before the first winter storm alert, indicating they were associated with an alert-type that was not part of this analysis. Note that these 8,565 BSM

records were associated with two unique vehicle events. An event with 3,841 BSM records matched alerts records for the time period between 20:01 and 20:19 UTC time but when viewed spatially the alerts were found to be in the westbound lane, while the BSM records were in the eastbound lane. There were also a few minutes time lag between the two data types indicating that a westbound vehicle (likely a snow plow or highway patrol) was receiving alerts, while the eastbound vehicle was not. This could be because the eastbound vehicle received the alerts outside of the geofence that the BSM data was queried from or that the conditions in the two directions of the interstate warranted different weather TIMs. The remaining BSM observations weren't found to match with the alert data resulting in no candidate events from this corridor.

For Corridor B, there were 6,371 BSM records after snowplow and highway patrol vehicles were removed. The BSM records were found to contain three unique vehicle events that corresponded to 9 of the corridor B winter storm alerts. Event B1 had 1,666 BSM records associated with five alerts. Two of these alerts were "Icy Patches" and the remaining alerts were for "Snow", "Blowing Snow" and "Ice". Event B2 had 1,717 BSM records associate with two "Snow" alerts. Event B3 had 2,988 BSM records associated with a "Snow" and an "Icy Patches" alert.

For Corridor C, there were 3,107 BSM records after snowplow and highway patrol vehicles. All of these records occurred after the last winter storm alert at 21:29:02 indicating that the winter storm alerts were likely given to snowplow and highway patrol vehicles. Therefore, no qualifying events were found in this corridor.

From the four events that were analyzed, 2 (50%) vehicles reduced speed; and 2 (50%) vehicles took no action directly responding to the alert. No vehicles exited the highway or stopped as a response to the alert, though in one case the vehicle had previously been stopped just prior to the alert. Therefore, it was determined that 50% of vehicles took some action.

Table 39. Summary of Driver Actions for Winter Storm Alert Events

Event	Number of Alerts	Time of First Alert	Time of Last Alert	Alert Types	Driver Action after Alert
B1	5	2/2/2022 14:35:23	2/2/2022 14:36:03	Icy Patches (2), Snow, Blowing Snow, Ice	Vehicle Reduced Speed
B2	2	2/2/2022 21:33:51	2/2/2022 21:34:40	Snow (2)	Vehicle Reduced Speed
B3	1	2/2/2022 22:37:30	N/A	Snow	No Action
B4	1	2/2/2022 22:42:52	N/A	Icy Patches	No Action

More information on the analysis and results can be found in Appendix F. Drivers Behavior Under Winter Storm Alert.

4.6.2 PM 17 - CVs that Likely Acted Following Receipt of a V2V Alert

FCW and SVA are the two primary V2V applications in the CV Pilot. These applications rely on V2V communications through the system's DSRC capabilities. Due to changes in the communication spectrum allocation, these applications will not be operational once DSRC is disabled in the Summer of 2022, unless modifications to the system are made. Another challenge with these applications is that they rely on two CVs to be within close range of each other. Given the overall low number of instrumented vehicles with DSRC communication capability and the large geographic extent of the project corridor, the probability of an interaction warranting an actionable FCW alert is low. Because of these factors, the analysis of this PM is limited to a small number of events when compared to other PMs.

A sample of FCW alerts was collected for the first 15 days in February of 2022, which returned 89 alerts. Five of these days (1st, 2nd, 4th, 5th, and 12th) had no FCW alerts while February 3rd had 39 alerts. All 89 alerts were mapped in Google Earth and 36 (40%) were found not to have occurred off the I-80 mainline. The dates and time stamps of the remaining 53 alerts were reviewed and many of the alerts were found to be clustered spatially and temporally, indicating they were related events where multiple alerts were given. These were combined into 10 unique events for further analysis and geofences were constructed around them in order to spatially query the BSM data.

The BSM data files were then reviewed to determine the number of vehicles involved in each event and whether these vehicles had static or dynamic vehicle IDs. Statics IDs can be used to determine if the vehicle was a highway patrol or snow plow as these vehicles are generally excluded from the driver reaction analysis. Even if the driver reaction cannot be analyzed, events involving highway patrol and snow plow vehicles still provide insight into how the system was working. For the 10 events, all but one event was found to involve highway patrol vehicles. The results for the events are summarized in Table 40 and fall into three outcomes:

- 5 events involved two highway patrol vehicles and FCWs were issues when the following vehicle approached a stopped patrol car or when it was closely following another patrol car.
- 4 events involved a single highway patrol vehicle and BSM data did not show another connected vehicle nearby. Further investigation is needed to determine what took place here— however, this would take additional time to wait until all vehicles upload their logs, which happens at different rate as it is dependent on vehicles passing by RSUs. At the time of this report, data was still missing from the SDC.
- 1 event involved two Partner fleet vehicles (dynamic IDs) with a faster moving vehicle approaching a slower moving one and then passing this vehicle. This analysis indicated that the driver reduced speed at the time of the FCW alert.

Table 40. Forward Collision Warning Events for Analysis.

Event	Record Generated	MP Location	# of Alerts	Description	Driver Action
A	2022-02-03 14:04:22	67	39	Two vehicles with non-statics IDs traveling WB. Second vehicle approached then passed the slower moving lead vehicle.	**Driver reduced speed**
B	2022-02-08 17:17:25	209	3	Two highway patrol vehicles, 1 stopped on shoulder and the second approaching to park alongside	Driver reaction not analyzed.
C	2022-02-06 20:27:02	211	1	Single highway patrol vehicle, no other connected vehicles nearby	Driver reaction not analyzed.
D	2022-02-06 20:53:30	214	1	Two highway patrol vehicles following closely	Driver reaction not analyzed.
E	2022-02-07 19:40:17	215	1	Single highway patrol vehicle, no other connected vehicles nearby	Driver reaction not analyzed.
F	2022-02-07 21:26:30	292	2	Single highway patrol vehicle, no other connected vehicles nearby	Driver reaction not analyzed.
G	2022-02-07 21:43:33	296	1	Two highway patrol vehicles, 1 stopped on shoulder and the second approaching to park alongside	Driver reaction not analyzed.
H	2022-02-11 00:51:40	297	2	Two highway patrol vehicles following each other, then stopping on the shoulder	Driver reaction not analyzed.
I	2022-02-10 05:57:53	310	1	Two highway patrol vehicles, 1 stopped on shoulder and the second approaching to park alongside	Driver reaction not analyzed.
J	2022-02-10 03:58:07	314	2	Single highway patrol vehicle, no other connected vehicles nearby	Driver reaction not analyzed.

More information on the analysis and results can be found in Appendix G. Analysis of Forward Collision Warning Alerts.

5 Results for Simulation Analysis of Driver Behavior to CV Applications

This section summarizes the University of Wyoming's effort to provide a new traffic safety perspective for the safety performance evaluation of the WYDOT CV Pilot; the full report can be found in Appendix H. Simulation Analysis of Driver Behavior. To this aim, the procedure and the analytical inference for developing a pre-deployment baseline, and Analysis, Modeling, and Simulation (AMS) framework to assess the safety efficacy of the pilot are presented in several peer-reviewed journal publications using two distinct but complementary approaches; 1) conducting a before/after analysis to explore contributing factors to crashes and their severity during CV pre-deployment as a baseline, and 2) the AMS framework in with/without analyses to quantify drivers' behavioral alteration under the effect of various WYDOT CV applications.

Results from the first approach identified statistically significant real-time traffic and environmental factors contributing to crashes and critical crashes during CV pre-deployment. In the with/without analysis and based on the calibrated and validated AMS framework, the results affirmed promising safety benefits of the WYDOT CV applications. The quantified impact of several CV applications including Spot Weather Impact Warning (SWIW), Distress Notification (DN, not implemented in the pilot), Situational Awareness (SA), Work Zone Warning (WZW), Forward Collision Warning (FCW), and rerouting applications showed a positive alteration of drivers' behavior at a trajectory-level. Moreover, the Surrogate Measures of Safety (SMoS) analysis utilizing microscopic simulation indicated an enhanced traffic safety performance under varying CV Market Penetration Rates (MPRs).

5.1 Pre-deployment Baseline Safety Assessment

The baseline safety assessment was conducted in two levels of analyses; 1) Aggregate level analysis, in which Safety Performance Functions (SPFs) were developed for the CV pilot deployment corridor, as well as assessment of the efficacy of existing safety countermeasures, and 2) Disaggregate level analysis, in which real-time safety assessments were conducted to identify traffic-related contributing factors to crashes.

5.1.1 Aggregate Level Analyses

Aggregate crash analyses are required to unveil the statistical linkage between the crash probabilities and the environmental factors, roadway geometry, and crash characteristics. As a result of such analysis, crash prediction models, known as SPFs are developed. SPFs are statistical models predicting the likelihood of crashes on a certain roadway facility. In addition, they investigate the effect of various variables on crash occurrence. Using the developed SPFs, crash modification factors (CMF) could be calculated for the countermeasures and roadway treatments implemented on the investigated roadway facility. To this aim, parametric, non-parametric, and spatial statistical modeling techniques were utilized to develop pre-deployment

baselines for I-80. Additionally, CMFs for the WYDOT weather-based VSL corridors were estimated.

5.1.2 Disaggregate Level Analysis

Real-time Crash Prediction Models (CPMs) are required to unveil the statistical linkage between traffic flow characteristics and the probability of crashes. In the Real-Time Risk Assessment (RTRA) arena, it is known that traffic crashes can be predicted by investigating crash precursors during a period preceding crash occurrence. Under RTRA, most previous analyses investigated RTRA in a particular section of a corridor or limited length of a segment. However, the safety performance assessment of disruptive technology such as CVs on I-80 in Wyoming required looking into a long corridor. Accordingly, this analysis dealt with two main problems in developing a unique CPM for the applicable 402-mile of I-80. First, it was essential to deal with nonlinear predictors due to a remarkable variation in traffic patterns throughout the 402-miles I-80 corridor. Secondly, the study addressed the small number of real-time traffic observations within a predefined time window, selected based on crash precursors, on I-80 with comparatively low traffic volume.

5.2 Analysis, Modeling, and Simulation

A two-prong approach was used to evaluate the effectiveness of the CV pilot utilizing several Performance Measures (PM). The first approach was utilizing the University of Wyoming (UW) driving simulator lab, WyoSafeSim, while the second approach was incorporating the changes in driving behaviors observed during the driving simulator experiment within the microsimulation model using VISSIM microsimulation models. The FHWA Surrogate Safety Assessment Model (SSAM) was used to examine the microsimulation outputs and to quantify the gained safety benefits of the WYDOT CV Pilot. (*6*, *7*).

5.2.1 Evaluation Using the UW Driving Simulator

The WyoSafeSim provided a controlled environment, in which critical events that mimic real life conditions were simulated in multiple CV and non-CV scenarios. An extensive training program preceded an evaluation module utilizing using a high-fidelity truck driving simulator, and a passenger vehicle driving simulator located at the University of Wyoming. The two simulators have open architecture software with a complete source code of the simulation creator tools. The open architecture offers a flexible tool that allows development of driving scenarios and building of roadways that replicate actual environments. The training program contained an E-training module and a hands-on driving simulator training module. The E-training explained the concept of various CV warnings and notifications, including FCW, SWIW, WZW, among other applications, utilizing an online Learning Management System (LMS) developed and hosted by the UW.

Participants had to pass the E-training with a minimum of 85% score to start the hands-on simulator training and evaluation. Simulators baseline scenarios were developed to compare the changes in driving behavior with and without the CV applications using the driving simulator vehicle kinematics and eye-tracking data. Afterwards, the experiment tests the effect of introducing the CV technology to observe the change/enhancement in the investigate PMs. Two subject groups participated in the driving simulator training and evaluation: 1) Commercial truck

drivers, and 2) the Wyoming highway patrol. Distinct scenarios were developed for each subject group to account for the variation in driving performance and regular tasks conducted performed on daily basis. Pre- and post-training survey questionnaires were administered to collect participants' feedback on the effectiveness of the training program. Figures Figure 45Figure 46 illustrate the driving simulator training and evaluation for each subject group.
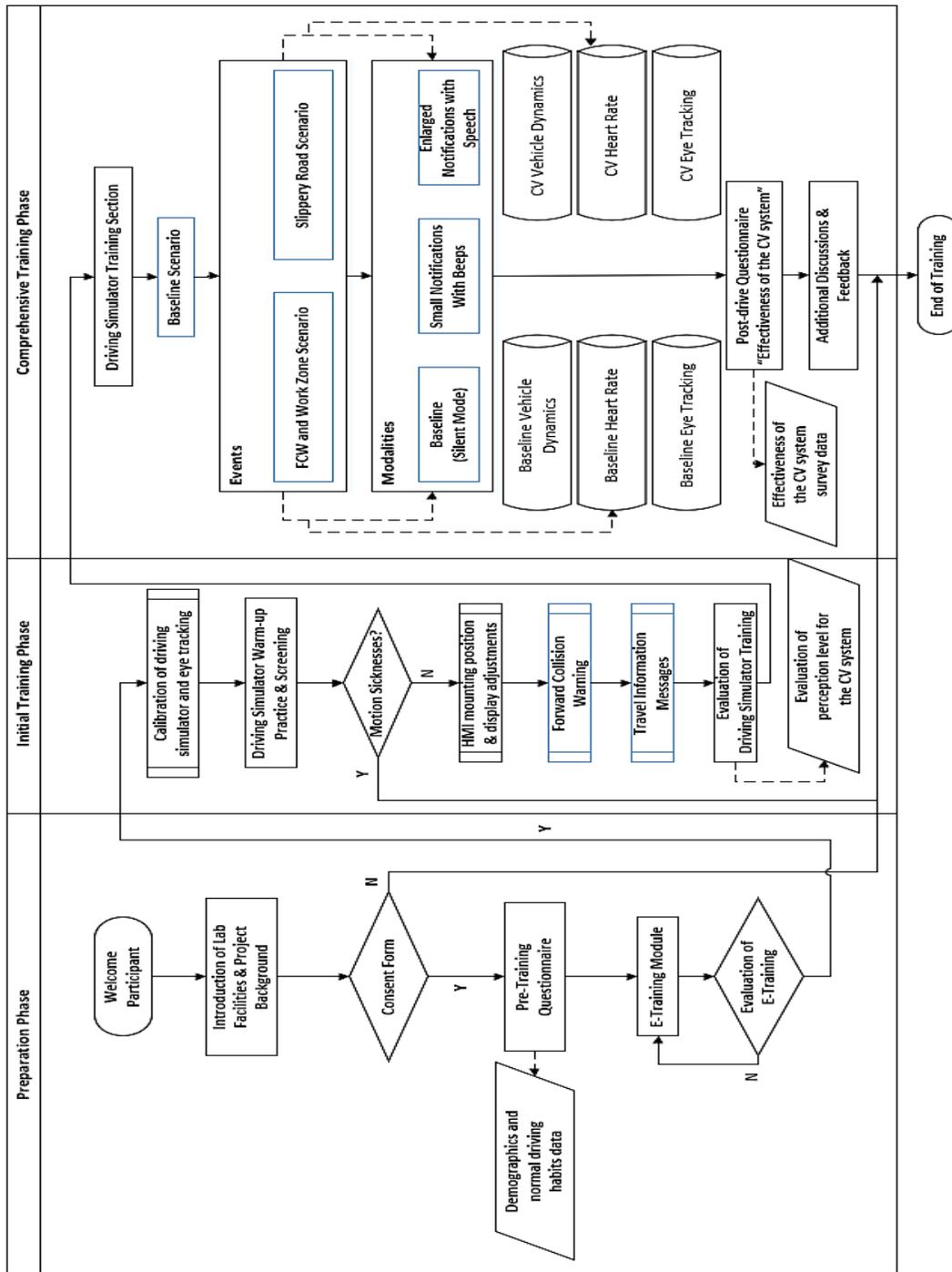
Figure 45 Training Framework for Wyoming Highway Patrol Troopers
Source: WYDOT
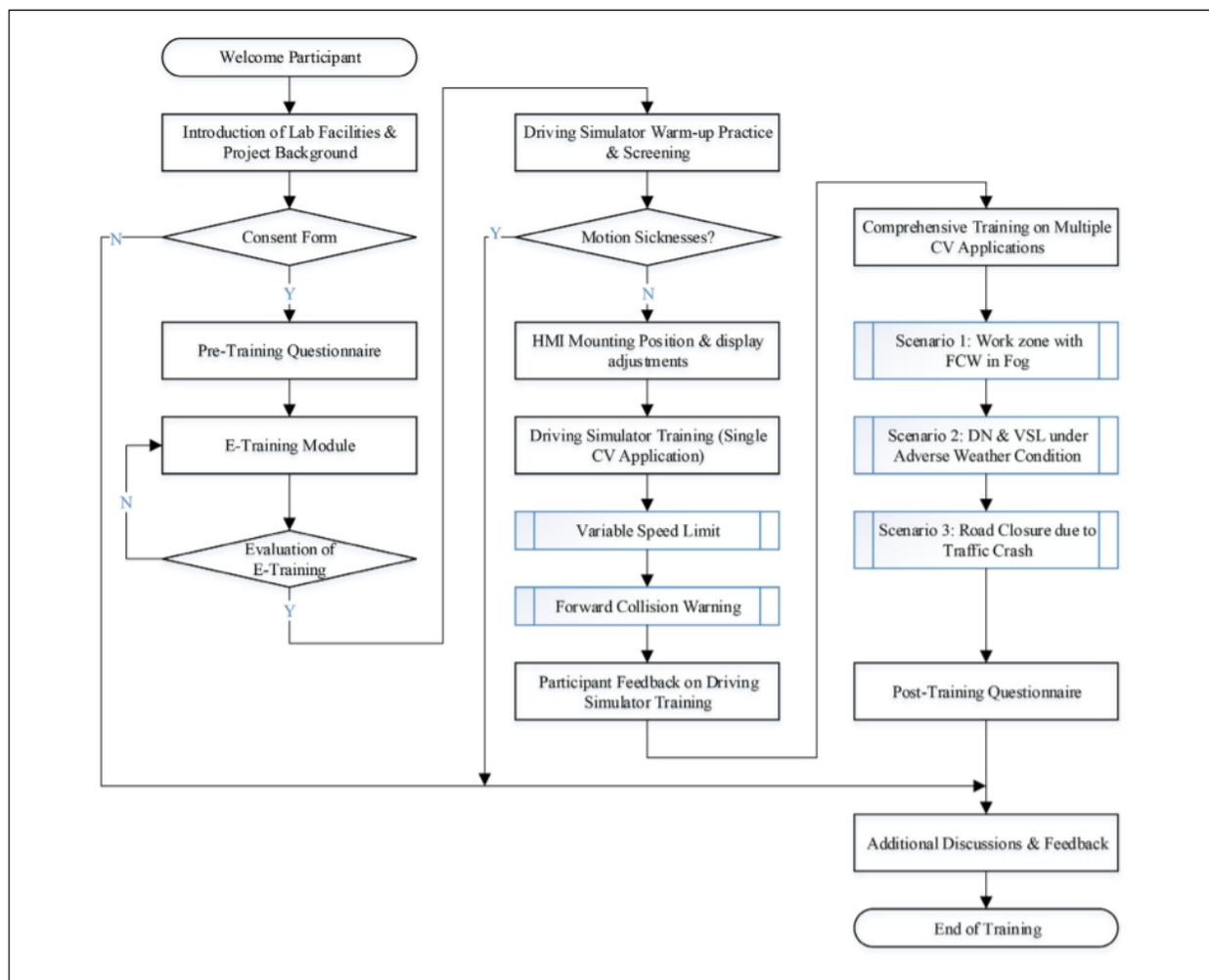
Figure 46 Training Framework for Commercial Truck Drivers
Source: WYDOT

5.2.1.1 Results of the Driving Simulator Vehicle Kinematics for Truck Drivers

Driving simulator vehicle trajectories were collected and speed analyses for CV and baseline scenarios were conducted to compare the participants' performance with and without the CV technology. The data analysis was developed to serve two main objectives: 1) assess the successive impact of exposure to the notifications within the CV scenario, and 2) compare the driver behavior and performance change between the CV scenario and the baseline scenario where the CV notifications are muted. To assess the behavioral effects of the CV warnings on longitudinal control of the vehicle, several behavioral measures were used for both CV and non-CV scenarios comprised of mean speeds, speed standard deviations, mean accelerations, maximum decelerations, and percent of participants activating brakes.

Table 41 provides summary statistics of the CV weather notifications on longitudinal control within the WZW scenario for truck drivers. This table is based on reference (*22*). The results depicted that receiving CV warnings generally improved safety indicated by relatively lower average

maximum deceleration rates and activation of brakes compared to baseline counterpart scenarios. More details about the scenarios are provided in reference (*22*).

Table 41. Summary statistics of the longitudinal control analysis (WZW).

Space-Time interval	Prior to fog warning		After fog warning		After 55 advisory speed notification		When encountered with fog	
Scenario	**CV**	**Baseline**	**CV**	**Baseline**	**CV**	**Baseline**	**CV**	**Baseline**
Mean velocity (m/s) / (mph)	30.61 / 68.46	30.55 / 68.33	30.34 / 67.87	30.79 / 68.88	27.81 / 62.10	30.82 / 68.94	24.58 / 54.98	26.37 / 58.99
Mean acceleration (m/s^2)	-	-	-0.10	-0.02	-0.50	-0.04	-0.29	-0.69
Average maximum deceleration (m/s^2)	-	-	-0.23	-0.11	-1.18	-0.16	-0.54	-1.81
Percent participants activating brakes	-	-	5%	0%	50%	0%	15%	65%

A lane exceedance occurs when one of the vehicle's tires departs the outer edge of the 4-in. standard width lane marker. The exposure to the CV advance warning area notifications was found to slightly increase the number of lane exceedances experienced in the WZ advance warning area. However, no statistical significance was detected in comparison with the baseline conditions (t(19) = -0.180, p = 0.859). Figure 47 shows the lane exceedance behavior and the percent of time off-lane obtained from the driving simulator dynamics.

Percent time off-lane
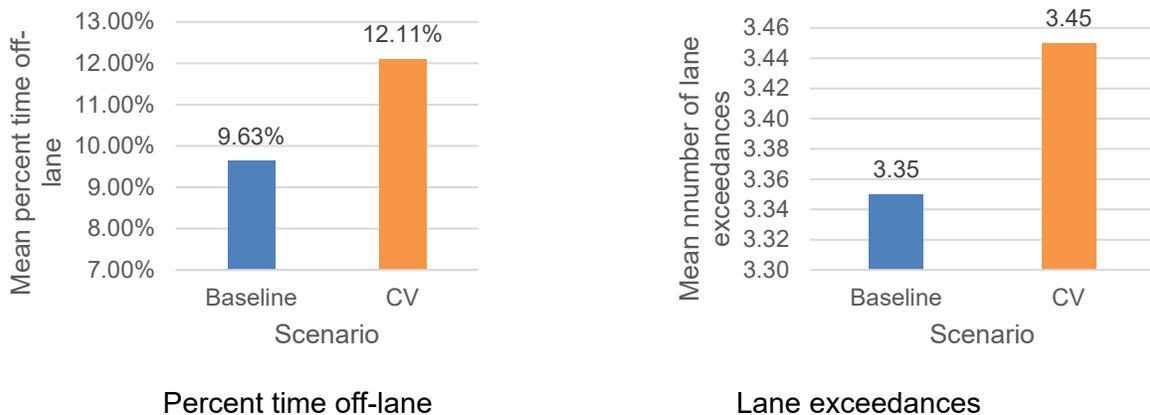
Lane exceedances

Figure 47. Lane Exceedance Behavior for Truck Drivers Experiment
Source: WYDOT

Speed trajectory analysis was conducted on the SWIW scenario. Figure 48 shows the speed profile of the subject vehicle operation under the CV and non-CV conditions averaged over the 23 participants. Mann-Whitney U test was conducted to statistically assess whether the two-speed trajectories are different or not. The results showed that the means of the speed profiles were not significantly different at the first section located between the first two Traveler Information Messages (TIM#1) and (TIM#2) (U=10368, P = 0.174).

This result depicted that the behaviors of the drivers for the two scenarios were similar before receiving the reduced speed limit, in which the average speed for the non-CV and the CV scenarios were 56.21 and 55.40 mph, respectively. Comparing the speed trajectories for the other TIMs, it was found that there was a statistically significant difference between the CV and the non-CV scenarios, which implies an enhancement is speed selection and reduction in speed variation within and between participants. This highlights the importance of the CV Pilot in Wyoming.

Furthermore, deviation from pathway, lateral speed, longitudinal acceleration, lateral acceleration, jerk, steering angle, roll, pitch, yaw, and yaw rate were assessed for CV and non-CV scenarios. These Surrogate Measures of Safety (SMoS) were analyzed when having slippery road surface conditions, especially at curves. The analysis shows a significant enhancement in the measured performances when encountering a slippery curve on the roadway alignment.
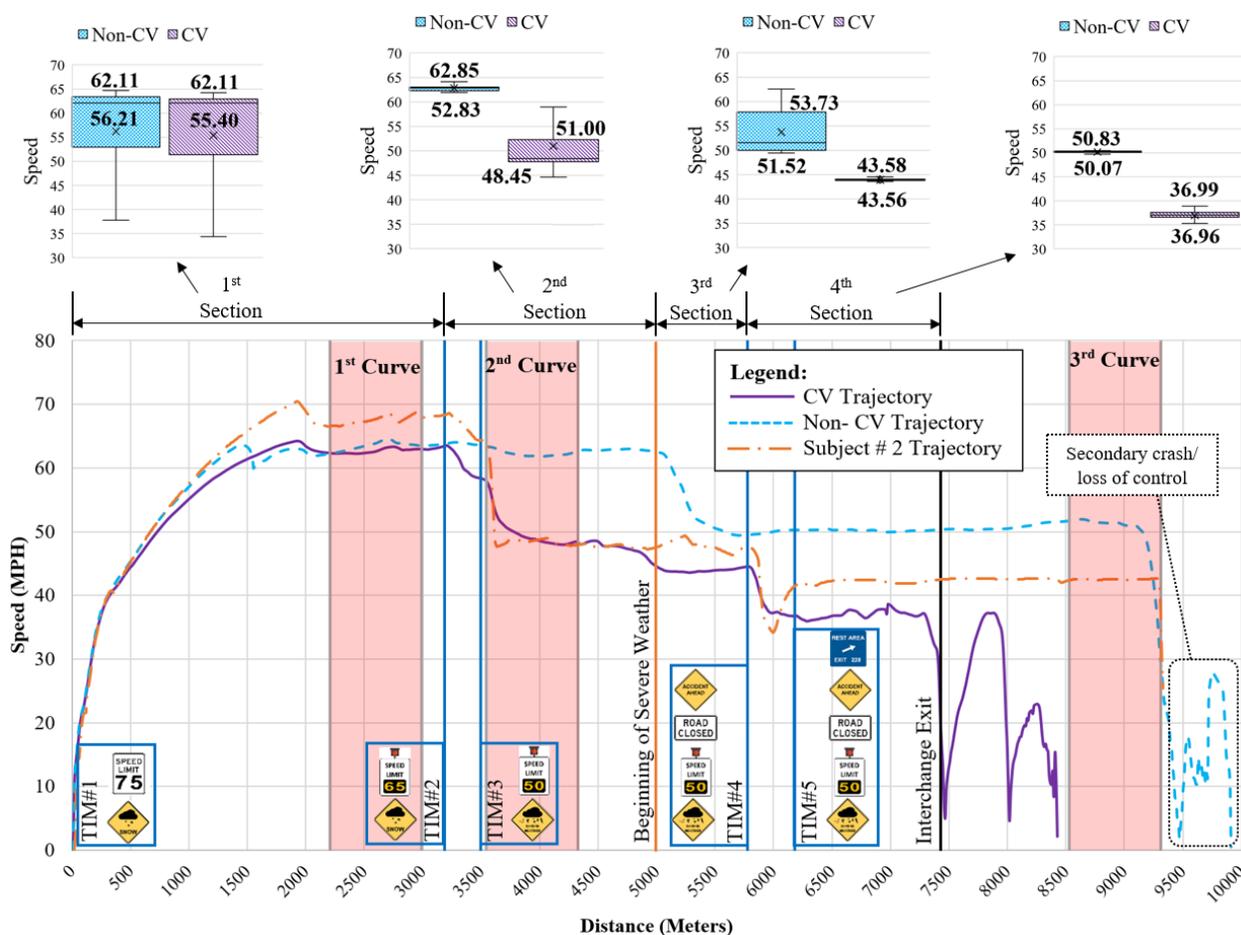
Figure 48. Subject Vehicle Trajectories for CV and non-CV Scenarios.
Source: WYDOT & (13)

5.2.1.2 Results of the Driving Simulator Vehicle Kinematics for Highway Troopers

To mitigate potential distraction introduced to HP equipped vehicles as a result of adding the WYDOT CV HMI, HP focus group was interviewed, ride-along completed, and training provided. Different CV warnings dissemination modalities were examined including included; 1) baseline with no CV warnings, 2) Enlarged HMI Icons with Beeps (EBeeps), 3) Enlarged Icons with Voice (EVoice), and 4) Small Icons with Beeps (SBeeps).

Speed performance was evaluated for the four modalities on a slippery curve location on the SWIW scenario. Slippery surface conditions were presented via Sensory feedback simulated through the steering/ breaking and a 3-degree of freedom motion base. In addition, icy surface conditions were visually simulated. Figure 49 shows the longitudinal speed profile averaged for the highway troopers on a simulated slippery horizontal curve.
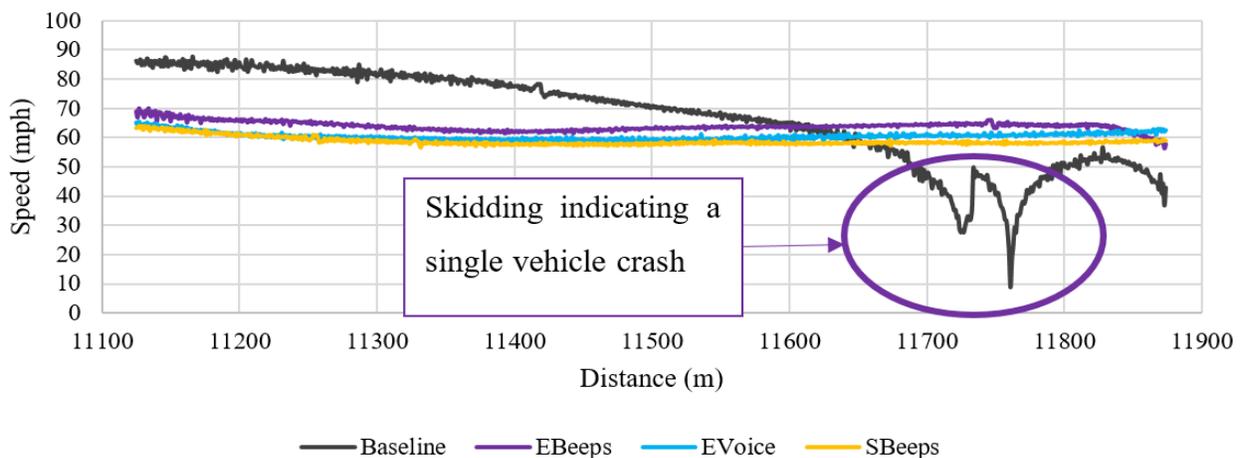
Figure 49. The Average Speeds of Highway Troopers for the four Modalities on a slippery Curve.
Source: WYDOT & (15)

The speed of the highway troopers entering the curve for the baseline modality was found to be significantly different than the CV modalities ($F_{(3,31)}$ =14.836; $p<0.001$). A Bonferroni post-hoc test revealed that the speed in the baseline scenario was significantly higher than each of the CV modalities. However, there was no significant difference in the entering speeds between any of the CV modalities. Lateral control, and brake activation showed similar results to the speed analysis.

The effectiveness of the Forward Collision Warning (FCW) was highlighted for the WZW scenario, in which it prevented the occurrence of a rear-end crash given the two warning stages. A five-second and twenty-second analysis showed that in each of the CV modalities, the participants braked smoothly following the cautionary and alert FCW. For the baseline, however, the participants braked at the very last moment and braked very hard trying to bring the vehicle to stop. For CV modalities, once the cautionary FCW yellow was provided, the participants slowed down, which made it easier for them to come to a complete halt when the alert FCW red went off.

5.2.1.3 Assessment of the Workload and Distraction Using Eye Tracking System – HP

One obvious concern is that the majority of the Pilot's CV applications rely on a visual HMI to display the content of the warnings, which leads to drivers diverting their visual attention away from the driving scene. An eye tracking system was used to assess the distraction for the CV HMI. The eye tracking system installed on the WyoSafeSim consisted of three Smart Eye Pro® eye tracking cameras. Two cameras were placed on the top of the dashboard and one camera was mounted to the right of the middle console, as shown in Figure 50. This allowed both the eyes to be tracked in almost all directions.

High resolution cameras
(Eye tracking system)

Figure 50. Smart Eye Cameras Mounting Locations - HP.
Source: WYDOT & (23)

To visualize the eye tracking data, heat maps were plotted for the two different scenarios: slippery road surface, and work zone. The heat maps show how the eye glances are distributed throughout the different driving simulator objects. The close world intersection points on world model for x and y directions were extracted for all the scenarios. Once the heat plots were obtained, they were overlayed on the real-life picture of the driving simulator using common reference points. Figure 51 shows the developed heat maps for the slippery road and the WZ scenarios for HP testing. More information on similar analysis performed for heavy truck drivers can be found in (22).

Slippery road surface scenario   Work zone scenario
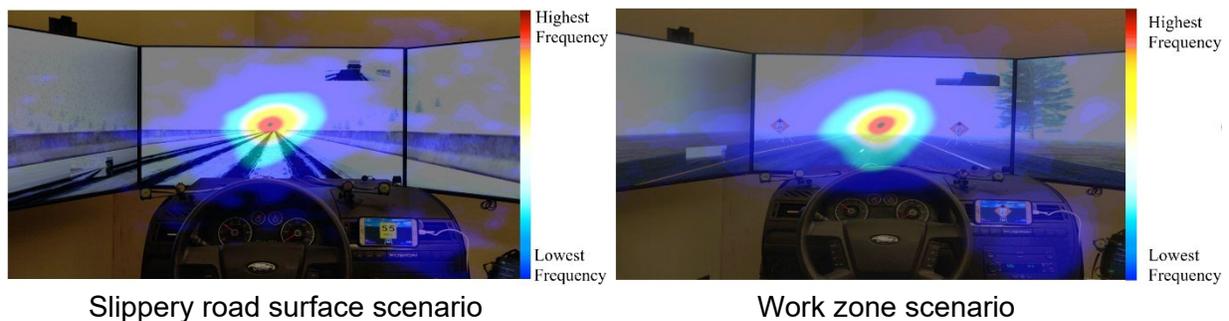
Figure 51. Heat map showing density of eye-tracking gaze points - HP.
Source: WYDOT & (23)

Table 42 represents the summary statistics of the glances in seconds for the SWIW and WZW scenarios for the HP.

Table 42. Summary of HMI Glances during for the tested CV modalities - HP

Scenario	Modality	Mean (s)	SD (s)	Maximum (s)
SWIW	EBeeps	0.55	0.38	2.35
	EVoice	0.59	0.33	1.76
	SBeeps	0.64	0.45	3.95
WZW	EBeeps	0.59	0.36	2.05
	EVoice	0.65	0.40	2.45
	SBeeps	0.69	0.47	4.17

A total of five cases of distraction were observed, where the distractions occurred with the Small Icons with Beeps modality. Multiple statistical tests were conducted to analyze the statistical significance of those distractions. The results are illustrated in Table 43.

Table 43. Visual Demand Metrics by CV Application - HP

CV app.	# of CV Notifs.	Mean HMI glance duration & (SD)	% time glancing to HMI (avg.)	Mean # of HMI glances per CV Notif.	Total HMI glance time per CV Notif.
SWIW	2	0.83s (0.26s)	8.87%	1.66	1.41
WZW	4	1.03s (0.26s)	9.11%	2.48	2.68

The comparison between the visual behavior induced by the SWIW and WZW applications using the following normalized metrics revealed that:

1) The average single glance duration to the HMI in response to a work zone warning was 0.20s longer than a single HMI glance duration due to a weather warning. Evidently, this marked difference in mean HMI glance duration between the two CV applications was found statistically significant using a paired t-test ($t_{(15)}$ = 2.52, p = 0.024).
2) The WZW application resulted in more glances to the HMI per single notification in comparison with the SWIW application. Statistical significance using the paired t-test was also established ($t_{(15)}$ = 4.35, p < 0.001). This result could be explained by fact that not only work zones are more challenging to navigate, but also the higher frequency of HMI information disseminated along the work zone section.
3) The total time spent glancing at the HMI in response to a single work zone notification was almost twofold of that of a weather notification. This result was also found statistically significant using a paired t test ($t_{(15)}$ = 4.34, p < 0.001). This finding also highlights that the work zone notifications involved substantially higher visual/cognitive workload demands to locate, recognize, and process the displayed information.

5.2.2 PM Evaluation Using Microsimulation Utilizing Driving Simulator Input

In response to the WYDOT CV Pilot Deployment Program "Performance Measurement and Evaluation Support Plan", traffic simulation modeling using VISSIM software is conducted for the

analysis of traffic safety performance measures. The use of microscopic traffic simulation modeling allows for the analysis of conflict-event safety surrogates such as time-to-collision, distribution of speeds, speed variation, number of lane changes, etc. It was anticipated that the CV deployment would result in changes to speed selection, lane changing and car following behavior for CV-equipped drivers that can be modeled in a microsimulation environment. Therefore, by using microsimulation, researchers can gain an insightful understanding of the impacts of the safety effectiveness of CV technology. In this regard, this system performance report proposes a VISSIM simulation framework for a 23-mile segment of the Cheyenne-Laramie (mileposts 317 to 340) Variable Speed Limit corridor to determine the suitability of adopting a microscopic simulation approach for evaluating the safety effectiveness of CV technology under various scenarios. The selected corridor represents the most challenging traffic situation along I-80 in Wyoming, such as high altitude, frequent adverse weather events, and steep vertical curves. Being limited by the available time and resources, it is not feasible to calibrate and simulate a 402-mile freeway corridor. In case of further evaluating the performance of the entire corridor, a sensitivity analysis was used to extrapolate the simulation results from the selected corridor to the 402-mile I-80 corridor in Wyoming. Non-CV "Baseline" Microsimulation Model. It is worth noting that driver behavior in response to the WYDOT CV Pilot applications from the Driving Simulator experiments, and driver behavior in adverse weather conditions from SHRP2 NDS were utilized to develop the microsimulation models.

5.2.2.1 Microsimulation Framework

The U.S. Federal Highway Administration (FHWA) defines Analysis, Modeling, and Simulation (AMS) as an evaluation process for assessing traffic operations along a corridor. Using AMS, researchers could identify key transportation challenges, and explore potential management strategies to be used to improve the operational performance of the corridor. Typically, an AMS framework contains three components:

1) Analysis, which requires investigation of the traffic and environmental conditions about the corridor.
2) Modeling, which refers to developing and calibrating a model or models to capture the real-world traffic and environmental conditions.
3) Simulation, which means using the developed model(s) to assess the performance of the corridor, and identify the operational issues as well as potential solutions to these issues.

The proposed AMS framework employs the VISSIM simulation with the Surrogate Safety Assessment Model (SSAM) for safety performance evaluation, as it is known that microsimulation software cannot directly simulate traffic crashes. The SMoSs used for safety evaluation were based on traffic conflicts (i.e., crash opportunities determined by safety assessment parameters such as TTC and Post-Encroachment Time (PET)) generated by the VISSIM simulation models. An overview of the proposed AMS framework is illustrated in Figure 52.
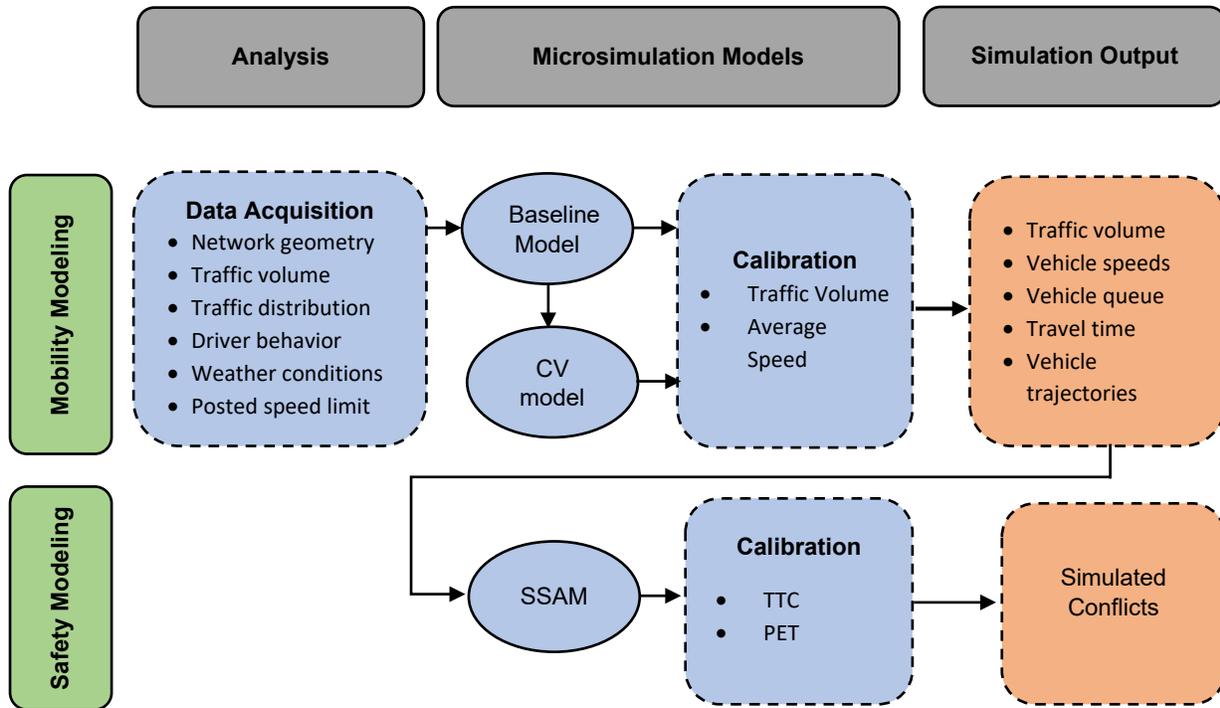
Figure 52. Overview of the proposed microsimulation modeling framework
Source: WYDOT

5.2.2.2 Safety Performance Assessment

A total of 18 microsimulation modeling scenarios (i.e., 3 traffic demand scenarios multiplied by 6 connected truck penetration rate scenarios) were designed to investigate the safety performance under various demand levels and connected truck penetration rates. Note that I-80 in Wyoming operates at Level of Service A or B with very low traffic demand, which is primarily affected by weather. Based on this, the three traffic demand scenarios reflect 3 weather conditions: 1) severe weather (very low traffic), 2) moderate weather (moderate traffic), and 3) clear (normal traffic).

For each scenario, 5 simulation runs were performed to eliminate the random errors of microsimulation. Afterwards, the simulated vehicle trajectory files were imported to SSAM for safety performance assessment. Since this research focused on a low-volume rural freeway corridor under adverse weather conditions, it was assumed that CV warnings would improve CV drivers' situational awareness. Among the SMoS used by SSAM, Time-To-Collision (TTC) was considered as most applicable for assessing the safety performance of the study rural freeway corridor, since vehicles had significantly lower lateral interactions in comparison with driving on urban freeways. Three different levels of TTC threshold were considered in the assessment analysis: high risk (1.5 s), medium risk (3.5 s) and low risk (9 s) to qualitatively compare the simulated conflicts under various traffic demand levels and CV penetration rates.

A comparison of the simulated number of conflicts for each scenario is presented in Figure 53. It is necessary to point out that the majority of the simulated conflicts from SSAM were rear-end conflicts, which is mainly due to the following two factors; 1) Under snowy weather condition, the majority of vehicles choose to drive on the right lane with a relatively lower speed and small

number of lane changing maneuvers, and 2) The simulated corridor was a rural freeway corridor with very large space interval between adjacent ramps, and under snowy weather condition, there was almost no on-ramp/off-ramp traffic. These factors resulted in very limited lane-changing maneuvers.

Simulated results indicated that the number of traffic conflicts increased significantly with the increase of traffic demand and decreased with the increase of connected truck penetration rate. Since the microsimulation models were developed for a 23-mi freeway corridor, the simulations resulted in large numbers of conflicts (e.g., up to 4,700 conflicts for baseline scenario under high demand levels). In the high-risk scenario, it was found that when the penetration of connected trucks was less than 10%, reduction in number of conflicts was not significant. In comparison, when the penetration of connected trucks was greater than 25%, there were remarkable reductions in conflicts. The reduction reached 85% for fully connected trucks scenarios, indicating that the CV applications developed by the WYDOT CV Pilot have the capability of improving traffic safety of this rural freeway corridor under snowy winter weather conditions. Generally, number of conflicts decreased roughly linearly as market penetration of CVs increased.
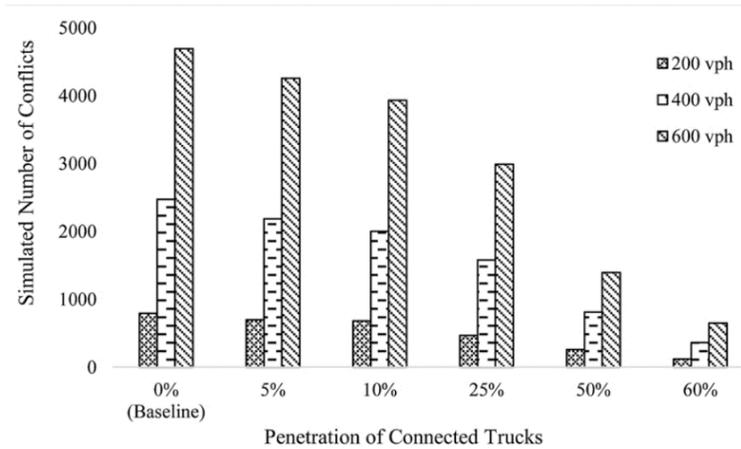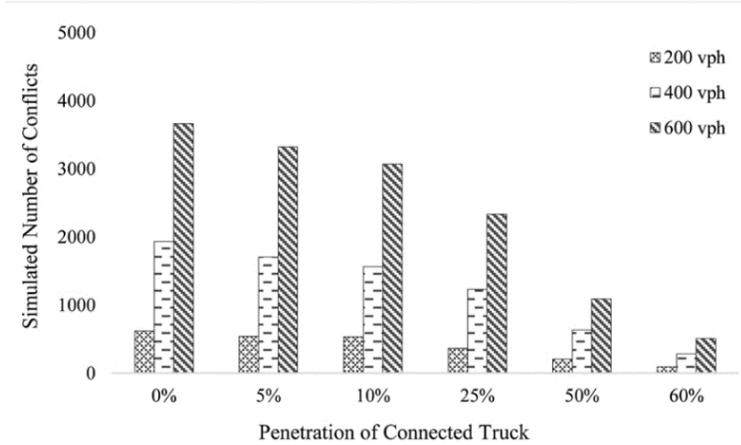
Figure 53. Sensitivity analysis of different TTC thresholds during winter snow weather condition under various demand levels and connected truck penetration rates.
Source: WYDOT

6 Operational Performance Analysis

This section describes system performance at the component level and explains challenges and limitations with respect to the listed components.

6.1 Pikalert

The Pikalert system was deployed across the state of Wyoming, including one-mile-long road segments in both directions (eastbound and westbound) of I-80. The system was installed in the cloud, allowing WYDOT to receive the necessary output data from the system and the system to receive upgrades. The cloud installation also provides 24/7 technical support in terms of uptime and reliability, which cannot be provided by the National Center for Atmospheric Research (NCAR). Working closely with WYDOT and the TMC, updates have been made to Pikalert through the lifetime of the project to address Wyoming's unique weather challenges and incorporate feedback on performance of the system.

As part of the WYDOT CVP, a blowover algorithm was added to Pikalert to provide a 0 to 1 blowover risk for four categories of vehicle: pickups with trailers, light high profile, heavy high profile, and a generic "all vehicles" category. Working across the team, previous research was leveraged with analysis of Wyoming blowover crashes to produce a fuzzy logic algorithm that alerts when an interest threshold for a category is reached (currently 0.7). Variables include wind gust speed, the difference between the wind gust speed and sustained wind speed, orientation of the wind direction relative to the roadway, and pavement slickness.

Pikalert output has been integrated in the TMC to provide operators with high resolution, rapidly updating road conditions across I-80. The TMC's Transportation Report and Action Console (TRAC) system compares current road conditions on a WYDOT segment to the worst case scenario conditions in the Pikalert segments along that stretch of road. If Pikalert assesses a condition different than the current hazard map, the TMC is given a task to accept or reject the update, along with a reason for the rejection. It is difficult to quantify the utility of the Pikalert data at this time because in addition to the performance of Pikalert itself, a cultural shift from the previous way of assessing road conditions in the TMC creates uncertainty in the validity of rejected alerts until more time has elapsed and more data are collected.

Results from this research were presented at the XVth International Winter Road Congress in February 2018. The paper, entitled "Use of the Pikalert® System in The Wyoming Department of Transportation Connected Vehicle Pilot Deployment", received the Best Paper award for its category. Subsequently, it was published in the World Road Congress's *Routes/Roads* magazine. A paper specifically about the blowover algorithm entitled "Generating Weather Alerts Including High Wind Blowover Hazards Using Pikalert® for the Wyoming Connected Vehicle Pilot Project" was presented at the 2019 Transportation Research Board (TRB) annual meeting. Presentations about Pikalert in the WYDOT CV Pilot and the blowover algorithm were also made during the project at the American Meteorological Society annual meetings. Importantly, much of the

development of the blowover algorithm was done by a protégé of the Significant Opportunities in Atmospheric Research and Science (SOARS) program, which is an undergraduate-to-graduate bridge program that seeks to broaden participation in the atmospheric and related sciences of historically underrepresented communities.

During the course of this work, the following challenges along with some resolutions were noted:

- **No vehicle data:** As discussed in the following section (6.2), vehicle-based observing equipment failed quickly after installation, resulting in no vehicle data being ingested by Pikalert shortly after its implementation. While able to operate with just weather data inputs, Pikalert was ultimately designed to ingest and use CV weather data from either an attached mobile weather sensor or through the vehicle's CAN-bus (air temperature, wiper status, etc.). This is especially difficult in complex terrain, such as I-80 in Wyoming.
- **Complex terrain:** Weather changes quickly in short horizontal distances in complex terrain. This renders the existing surface station network inadequate for capturing microclimates, even somewhere that is highly instrumented such as the RWIS station network on I-80 in Wyoming between Cheyenne and Laramie. Radars are also widely spaced in the western region of the US, and complex terrain further complicates this by blocking the radar beams, leaving many areas in the mountains outside radar coverage and subject to missed precipitation events due to blocking and overshooting the top of the precipitating cloud. The Pikalert team took steps to mitigate these issues, such as including WYDOT's RWIS network in the observation stream and using the hybrid scan product that accounts for beam blockage and partial filling of the beam, but inevitably without CV data, areas of precipitation and poor road conditions will be missed in complex terrain. Further, the Real Time Mesoscale Analysis (RTMA) product used as a background weather analysis for areas without surface station coverage was found to poorly correlate with surface observations in Wyoming's elevated and complex terrain.
- **RWIS reliability and integration:** RWIS station observations are key data sources, particularly in the absence of CV data. Especially in complex terrain, the data need to be quality controlled and reliably available. By default, Pikalert uses observations from the Meteorological Assimilation Data Ingest System (MADIS). Because some stations are missing from MADIS and the quality control is not to the level of the Clarus quality checks, the Weather Data Environment was utilized. However, being a research platform rather than operational, the uptime and availability of the data proved to be unreliable for the WYDOT CVP. NCAR provided WYDOT with simple quality checks developed specifically for their dataset, and RWIS observations are now provided directly from WYDOT.
- **Additional algorithm work:** While Pikalert has overall performed well, particularly given the lack of CV data, a major weather challenge seen on I-80 in Wyoming involved blowing and drifting snow causing pavement to become snowy and icy in otherwise clear weather conditions. While Pikalert contains a visibility hazard category pertaining to blowing snow and blowing snow conditions in the forecast engine, the current condition (tactical) alert horizon will require the addition of blowing snow-related logic to the pavement condition algorithm.

6.2 Weather Cloud

The WYDOT CVP installed 50 Weather Cloud environmental sensors to collect environmental data with the GroundTruth application along I80. This system was installed in the WYDOT Maintenance Vehicles using snowplows. The devices worked well at installation with the two sensor suites (Skypack and Roadpack) connecting via Bluetooth to the HMI Android tablet. This data was aggregated with the Lear OBU, transmitted over DSRC through an RSU to the TMC every five minutes with 10 groups of 30 second resolution data parameters. Once the data was received by the TMC, the data was moved to the Pikalert system for inclusion with the weather modeling. The overall system worked well together.

We noticed the data failing quickly after installation and validation. After inspection, the rigors of the snowplow environment were destroying the devices. Rapidly, the devices went offline and were found to be too fragile for continued operation. This was most prevalent in the Roadpacks.

It is recommended that future deployers look for systems with armored heavy duty wiring run in conduits or protected channels of the plows. Additionally, the sensors should not be plastic and open to the elements. The devices work well in the lab and limited testing on light duty vehicles, but do not seem ready for deployment on heavy duty vehicles. The CVP team was trained by the vendor on the installation and the vendor did selected installations on the snowplows to ensure they were properly installed. We did approach the vendor about replacements as they were under warranty, but the vendor was on to new product models and did not have replacement units available. Future installers may want to acquire addition devices to support field failures.

6.3 TMC Backoffice System

Early in the design phase for the CV Pilot project WYDOT made it clear that TMC Operators would not be able to support a new system interface that was built to just support the CV environment. With that as a primary parameter, the TMC Backoffice system was built out to integrate with the existing WYDOT Data Broker application. This system along with the USDOT Operation Data Environment (ODE) were built out to support the creation, updates, and distribution of TIMs to RSUs and the Situation Data Exchange (SDX). Incoming data was originally planned to be stored in the USDOT Situation Data Clearinghouse as well as an Oracle database housed on-premise by WYDOT.

The overall system design can be seen in Figure 54. After deploying the system into a test environment and beginning to push TIMs out, we noticed a few issues over the course of the production deployment. These issues and their resolutions are detailed below.

Overloading RSUs with TIM messages: The Lear RSUs only supported a 99 TIM max limit for broadcasting TIM messages. With each TIM containing a different ITIS code the number of TIMs could grow very quickly. For example, if a TMC operator updated road conditions for a road segment to contain Snow, Ice, Blowing Snow, and High Winds the Data Broker application would generate 4 different TIMs (one for each condition). When each RSU is broadcasting TIMs for multiple road segments and each condition is being broadcast in a separate TIM, the 99 number was quickly hit during winter months. The solution for this was to append multiple ITIS codes for a road segment into one TIM message. This drastically reduced the number of TIMS being

broadcast from the RSUs as well as increased efficiency in our code logic that managed the TIM messages.

Oracle Database Problems: The Oracle database was not able to sufficiently handle the volume of BSM data incoming efficiently. We had to convert our storage strategy from a relation database (Oracle) to a nosql database (MongoDB) in order to efficiently manage the storage and querying capability of the incoming BSM data.

TIM Inconsistency Issues: As the system began to go into production and vehicles were being outfitted with OBUs reports from drivers would come in claiming that the information they were seeing on the tablets in the vehicles was inconsistent with what the conditions in the field were. For instance, we saw a report come in that a driver was receiving a Snow TIM on a day that was sunny and 60 degrees outside. This was immediately identified as a top priority to resolve as it was paramount that drivers trust that the information they are receiving is accurate. The solution was to build a consistency check application that monitored the current road conditions being reported by the WYDOT 511 system and verified they were the same conditions that were being reported through the TIMs that were deployed. In cases where this was not the case, the errant TIM was removed and the WYDOT 511 road condition was added. This application continuously monitors and resolves any inconsistencies found on the RSUs and in the SDX.

Construction TIM Issues: During the summer months the bulk of the TIMs that were being deployed consisted of construction TIMs. Again, drivers began reporting instances where the TIMs being reported did not match with what was occurring in the field. In one instance a construction zone was set for striping operation that covered over 100 miles of I-80. The root cause of these inconsistent TIMs turned out to be operational as well as functional. Not much attention had been paid to the accuracy of construction zones prior to this project as drivers did not receive the information on the roadways previously. Now that CV drivers were receiving the messages on the roads, the WYDOT application (ConAdmin) used to manage the construction zones needed to allow for more accuracy. In addition to this, operators were retrained on inputting construction zones into the application to ensure more accurate construction zones were being reported.

RSU TIM Broadcasting Issues: During the production phase of the CV deployment, it was found that some RSUs were having issues where the RSU would become unresponsive to network commands including Simple Network Management Protocol (SNMP) and SCP requests. At the same time the RSU would continue to broadcast TIMs and the Consistency check applications would fail to update any TIMs on the RSU based on the network SNMP failure. It was found that rebooting the RSU would clear memory and restore network connectivity of the RSU. As part of the resolution a reboot script was built out to reboot the field RSUs after every 3 days or so. This resolution has cleared the bulk of the issues found.

Overall, the Backoffice system design was found to be effective at integrating a CV environment on the roads with no additional input from TMC operators to support the deployment. Our system also allowed for the expansion of TIMs Statewide without any additional TMC Operator input to the system. It did require integration and some input with existing systems but this was found to be a minimal effort on the WYDOT application development side.
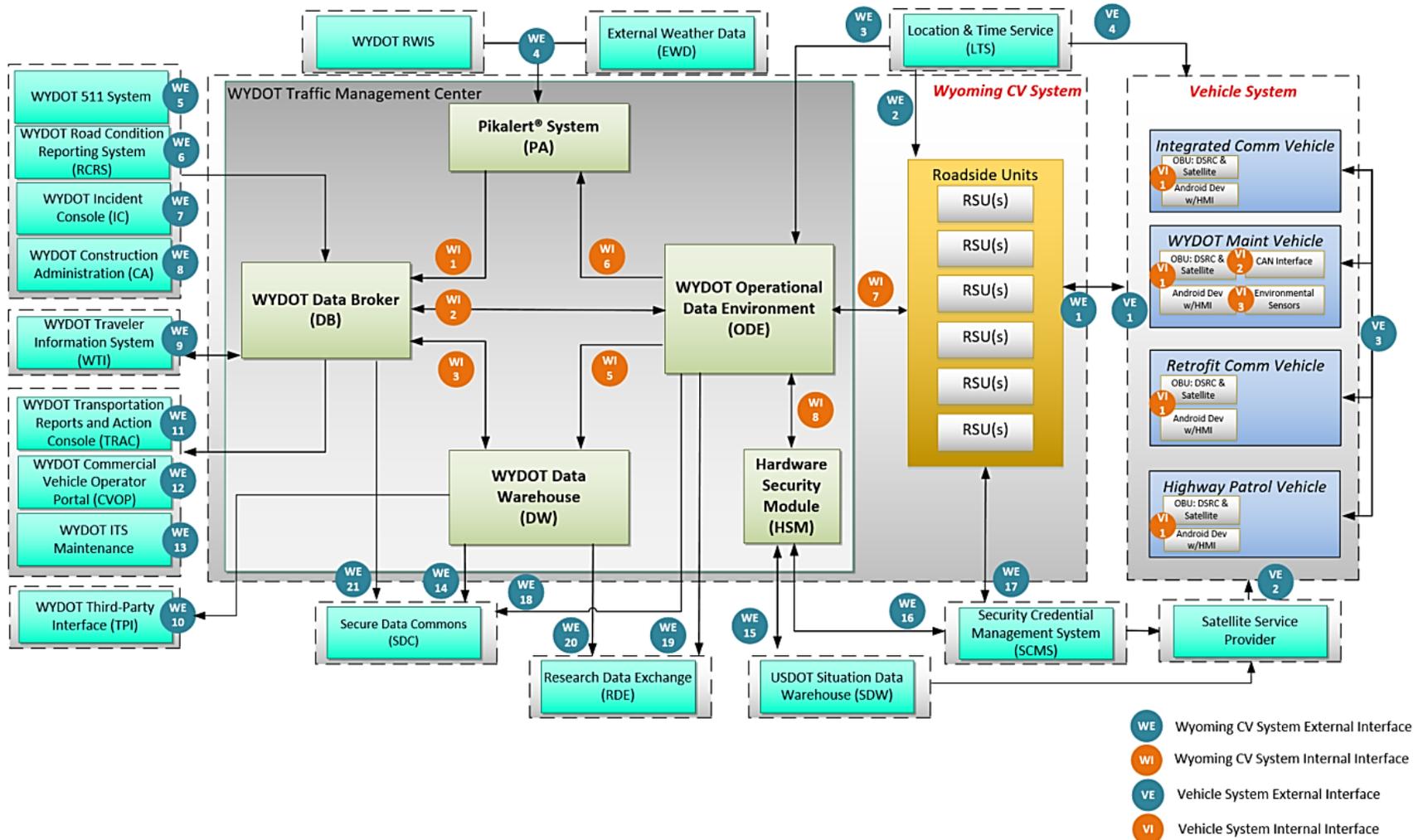
Figure 54. Physical View of WYDOT CV Pilot System Architecture with Numbered Interfaces.

NOTE: The Wyoming CV System Interface WI4 (PA→DW) was not implemented in the final system design.

6.4 Field Equipment

6.4.1 RSU

The WYDOT CVP used 76 Lear DSRC RSUs along I-80. The RSUs provided services for wave service announcements, TIM distribution, Distress Notification forwarding to the TMC (not implemented in this pilot), BSM logging, OBU log offloading via IPv6, Lear OBU certificated top offs, and Over the Air updates for Lear and SiriusXM OBUs. These RSU are enrolled in the ISS Secure Credential Management System (SCMS) for application certificates. For details on the applications please see the System Design Document[6] and Interface Control Document[7] for messaging.

Initially the deployment of the RSUs was smooth and worked well. At this point the SCMS was still coming online, so all communications were unsigned and did not leverage signature validations. The pilot quickly got each application and message set operational with the development team at Lear. After this was complete, the pilot did an onsite demonstration with USDOT that showed each of these capabilities.

As the proof of concept (PoC) SCMS was abandoned and the switch was made to ISS for the SCMS provider, Lear began integrating message signing and validation. It was discovered that Lear did not comply with the requirement of having an HSM, they felt the IM6 was adequate but it was not. As such, the RSUs were returned to Lear for retrofit with an HSM and re-hung over I-80. Test certificates were used during this timeframe to continue the testing with security. Lear struggled extensively with integrating SCSM certificates, this was an overwhelming effort for them and the pilot team for testing. Eventually, this was resolved, and testing was completed with all application using certificates. Follow on implementers are recommended to use certs from the beginning and select a vendor with deep capabilities using 1609.2(.1) and OmniAir certification.

In December 2020, Lear dropped DSRC entirely (OBUs and RSUs). They would not continue support, warranty, development, and repair for our deployment. There were existing bugs in the software and memory leaks with the SNMP engine. To move forward, the pilot created a reboot script that helped with stability and got a demo from ISS for the certificate management reporting. With these systems in place, the pilot has been able to keep the RSUs online and re-enrolled when necessary (as the SCMS integration was not adequately stable). Future implementors should consider multiple vendors for RSUs.

6.4.2 OBU

The WYDOT CVP implemented two types of OBUs, one from Lear and one from SiriusXM. Both OBUs had the ability to broadcast BSMs to include trailers information in part 2, receive and display TIMs with the full set of WYDOT ITIS codes via both RSUs and SiriusXM satellite, collect and send logs to the TMC via DSRC with IPv6, sign and validate messages with SCMS pseudonym certificates, receive and install over the air updates, and implement forward collision warning per SAE 2945/1. The Lear devices have the additional capability of implementing

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[6] Available at: https://rosap.ntl.bts.gov/view/dot/36241
[7] Available at: https://rosap.ntl.bts.gov/view/dot/42411

destress notification, sending Weather Cloud data to the TMC, and getting certificate top offs from the SCMS. For details on the applications please see the System Design Document and Interface Control Document for messaging. For quantities and types of vehicles deployed please see the Acquisition and Implementation Plan.[8]

Initially the deployment of the OBUs was smooth and worked well. At this point the SCMS was still coming online, so all communications were unsigned and did not leverage signature validations. The pilot quickly got each application and message set operational with the development team at Lear and SiriusXM. After this was complete, the pilot did an onsite demonstration with USDOT that showed each of these capabilities with both units. A subset of these tests focused on forward collision warning were successfully completed with the other two pilot sites at TFHRC for interoperability.[9]

As the PoC SCMS was abandoned and the switch was made to ISS for the SCMS provider, Lear and SiriusXM began integrating message signing and validation. It was discovered that Lear did not comply with the requirement of having an HSM, they felt the IM6 was adequate. It was not, the OBUs were returned to Lear for retrofit with an HSM and re-installed in the vehicles. Test certificates were used during this timeframe to continue the testing with security. Lear struggled extensively with integrating SCSM certificates, this was an overwhelming effort for them and the pilot team for testing. Eventually, this was resolved, and testing was completed with all application using certificates. SiriusXM properly implemented the HSM and integrated the SCMS certificates efficiently. Follow on implementers are recommended to use certs from the beginning and select a vendor with deep capabilities using 1609.2(.1) and OmniAir certification.

The pilot was planning to use Lear for most vehicles and use SiriusXM OBUs for only a few test vehicles. However, since Lear dropped the DSRC entirely the pilot switched to using SiriusXM for most vehicles. The SiriusXM OBUs proved to be more reliable, and the pilot received excellent support from the vendor to build a dual antenna solution for operation in tractor trailers. Future implementors should consider multiple vendors for OBUs.

6.5 Case Study: System Reaction to a Crash

On March 31, 2021, near Rock Springs a head-on collision crash occurred at around 3:17pm (coordinates: 41.61, -109.23) that closed all lanes in both directions for nearly 3 hours (see Figure 55).

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[8] Available at: https://rosap.ntl.bts.gov/view/dot/35425
[9] Details of the interoperability testing available at: https://rosap.ntl.bts.gov/view/dot/39009

Figure 55. Explosion after the crash occurred.
Source: WYDOT

- The Transportation Management Center (TMC) received information of the incident at 3:25pm.
- The RSU closest to the I-80 and US-191 interchange received the first TIM within a minute after the TMC became aware of the incident (at 3:26pm).
- The first TIM contained information advising travelers to 'prepare to stop'.
- Later at 6pm, the Wyoming Highway Patrol (HP) reported that westbound lanes were open, while the eastbound lanes remained closed—the HP notified this change in status to the TMC 10 minutes later. The eastbound road closure continued for another 1 hour and 40 minutes and the road opened at 7:42pm, for a total duration of nearly 4 hours and 25 minutes of lane(s) closure in that area.

The research team investigated the CVP system reaction to the crash by investigating the TIM, BSM and driver alert generation and transmission patterns.

While the number of vehicles in roadway with this technology is still low, equipped vehicles in the area were able to receive correct messages near the incident.

6.5.1 Traveler Information Message Analysis

Overall, there were three waves of TIM transmission at the vicinity of the interchange (within 5 miles radius):

1. Following to the first TIM at 3.26pm, the RSU closest to the incident area received 15 additional TIMs (with 'prepare to stop' advisory information) within the 1- minute timeframe.
2. The second wave of the TIMs contained a mix of 'prepare to stop' and 'incident' advisory information received by adjacent RSUs at 4:42pm.

3. The third wave of the TIMs transmission (with 'incident' advisory information) started at 5pm transmitted from TMC directly to the CV's OBU (450 TIMs), and between RSU to OBU (132 TIMs). The third wave ended around 8pm.

6.5.2 Basic Safety Message Analysis

Using this BSM data, limited trajectories (vehicles' path history) of the connected vehicles can be plotted on a map around events. Throughout the roughly 4.5 hours of the incident duration, between 3:15 and 7:45pm, the system generated 522,354 and 526,889 BSMs within a 5 and 25 miles radius of the crash location, respectively. At the beginning of the crash, only one CV was present at the vicinity of the incident, and it generated ~2,000 BSMs. The trajectories from these BSMs are shown in Figure 56.

Between 4:15 and 6:10pm (when both directions were closed), the CVs in the area transmitted more than 190,000 BSMs indicating their presence around the incident. During this timeframe, three Wyoming Highway Patrol and three fleet partner vehicles were present at the vicinity of the incident. The nearby CVs generated the majority of the BSMs (~330,000) between 6:10pm and 7:45pm when eastbound lanes were still close (but westbound opened). This is the period with heavy traffic at the interchange.

We also investigated the BSM data beginning 2 hours before the crash (at 1pm) and 3 hours after both lanes were open (11pm). We identified one vehicle traversing the interchange at 1:25pm and taking the US-191 south.

There were no other CV crossing the interchange prior to 3:00pm. At 3:40pm, one CV traversed through the interchange from US-191 south and took the I-80 east exit. Between 6:10pm and 7:45pm, more CVs started to cross the interchange. Later after the road was open, at 8:40pm and 9.30pm, an additional vehicle and one highway patrol vehicle traversed the interchange, respectively.

Arrows with different colors are showing connected vehicles' path trajectories. They are representing the route that invidual connected vehicles took in reaction to the congestion caused by a crash.

Accident location – concentration of Wyoming Highway Patrol at the crash site.

BSM shows highway patrol activity at the crash site and road closure on the eastbound direction. The picture also shows that other CVs are using alternate routes to avoid the incident.

Figure 56. Vehicle movement between 6:10 and 7:45 pm.
Source: WYDOT

6.5.3 Driver Alert

Within the timeframe of the crash, the system generated 52 driver alerts with ITIS codes of 268 (speed limit is 55 mph), 531 (incident), and 7186 (prepare to stop). Most of the alerts were generated within the 5 miles of the interchange and between 4 pm and 6pm.

6.5.4 System Performance Timetable

The below figure displays the system reaction to the crash at three (3) major time blocks:

- The first hour after the crash (3:15-4:15pm)
- The following two hours, which had both directions closed and wind gusts (4:15-6:10pm)
- The final timeframe up until the incident was fully cleared and both lanes were open (6:10-7:45pm)

15.17.26- crash occured / 15.25.41 - TMC was notified

16.12.31 - TMC researching wind gusts

17.59.41 - Westbound lane is open, eastbound lane is still closed / 18.09.41 - TMC was notified

19.41.08 - The road is open

Vehicles' path trajectory at Interchange

Within 5 miles radius

Time frame: 15:15:00 - 16:15:00
#BSM: 2,104
#unique vehicle ID: 1
#TIMs: 42
#Driver alerts: 0

Time frame: 16:15:00 - 18:10:00
#BSM: 191,184
#unique vehicle ID: 8
#TIMs: 74
Driver alerts: 48

Time frame: 18:10:00 - 19:45:00
#BSM: 329,066
#unique vehicle ID: 11
#TIMs: 357
#Driver alerts: 4

Within 25 miles radius

Time frame: 15:15:00 - 16:15:00
#BSM: 2,225
#unique vehicle ID: Static:1 HP; Dynamic: 1
#TIMs: 42
#Driver alerts: 0

Time frame: 16:15:00 - 18:10:00
#BSM: 193,708
#unique vehicle ID: Static: 3 HP & 2 TH ; Dynamic: 5
#TIMs: 93
#Driver alerts: 50

Time frame: 18:10:00 - 19:45:00
#BSM: 330,956
#unique vehicle ID: Static: 3 HP, 1 WY ; Dynamic: 7
#TIMs: 410
#Driver alerts: 4

Road is open

Figure 57. CVP system performance timeline.
Source: WYDOT

7 Achievements Beyond Original CV Pilot Deployment Scope

7.1 Misbehavior Detection Support

The WYDOT CVP has supported the testing of misbehavior detection (MBD) with the Noblis team. This is being conducted with the Integrity Security Services SCMS. The solution developed by Noblis is testing the BSM log files that contain the BSM data, metadata and the IEEE 1609.2 signature headers required for the misbehavior detection report. This solution leverages the misbehavior detection being defined by the SCMS manager working group. The solution is expected to be tested in Q2/Q3 2022.

In CV environments, the ability to trust messages is a foundational element of security. Trust is provided via a SCMS, which is a public key infrastructure (PKI) system that provides certificates to CV devices. Those CV devices then sign their messages with those certificates and anyone receiving that message will know it came from a trusted source. In order to maintain that trust though, there needs to be a capability to detect misbehaving devices and revoke their trust. This is accomplished through the MBD minimum viable product (MVP) system that USDOT developed and delivered in 2019.

The MBD MVP system utilizes BSMs that vehicles broadcast 10 times per second to detect misbehavior. These BSMs include basic data such as location (latitude, longitude, elevation), speed, acceleration, and brake status. The term "misbehavior" is loosely defined as any case in which the BSM has a value that is not representative of the corresponding vehicle's true behavior. Our technical criteria for misbehavior include the following:

1. Messages received with positioning data indicating the vehicle is much further away than is feasible (e.g. – BSM with position that is 5 miles from current location).
2. Messages that indicate a vehicle traveling at unrealistic speed (e.g. – 150 mph).
3. Messages including values that fall outside of pre-determined ranges specified in SAE J2735 Vehicle-to-Everything (V2X) Message Set standard or are not correctly formatted.
4. BSMs received from a single source at greater than 10 Hz (the hardware should not output messages any faster).

When the MBD algorithm detects one of these conditions it will flag that BSM and then create a misbehavior report that is sent to the SCMS Vendor. The SCMS Vendor will then apply its' own misbehavior report criteria (e.g., number of reports received for the same device), and if the device meets their criteria, all its' current and future certificates will be added to the certificate revocation list (CRL). The CRL is distributed to all CV devices and those devices will then ignore any messages signed with a certificate on the CRL.

Testing of the MBD MVP system has been conducted at Turner Fairbank Highway Research Center (TFHRC) in two first-of-their-kind field tests held in August 2019 and November 2019. The

August 2019 test focused on the basic open source MBD algorithm developed by USDOT. The November 2019 test focused on OBU and RSU vendor implementations of MBD as well as sending misbehavior reports to the SCMS and the generation of CRL updates. The high level results of testing included:

- Devices were correctly able to detect misbehavior based on speed, generate misbehavior reports and have those reports accepted. The SCMS could then generate a CRL updates based on the reports.
    - The vehicles traveling over the speed threshold were successfully detected by both the OBU and RSU.
    - The vehicles traveling under the speed threshold were not detected as misbehaving by OBUs and RSUs.
- Devices were able to detect misbehavior based on location, generate reports and have those reports accepted. The SCMS could then generate a CRL updates based on the reports.
    - An OBU was directly connected via coaxial cable to a GPS Spoofing device to generate positions within BSMs hundreds of miles from the testing location.
    - Both the OBU and RSU were able to detect these BSMs with the wrong location.

The USDOT has continued to support the open source MBD tools developed in 2019, developing a new module to generate misbehavior reports and a converting the tools to work within the USDOTs ODE. The MBD team continues to work with the WYDOT CV Pilot deployment to test the MBD capability with their ODE implementation. USDOT is also monitoring and participating in the MBD efforts within the SCMS Managers forum and within the different ITS standards development efforts (ETSI and SAE). These forums, supported by the automotive original equipment manufacturer (OEM) and vendor communities, have been using the concepts and documentation produced during the MBD MVP as the basis for their efforts.

7.2 Expansion of TIMs to State of WY

The Sirius XM partnership on the WYDOT CVP enables Wyoming to have 100% coverage of I-80 for CVs traveling in the corridor. WYDOT saw this as an opportunity to expand the coverage of TIMs in Wyoming to include all state and federal highways. In October 2019, the application development team began working with WYDOT to create representational state transfer (REST) enabled microservices that allowed WYDOT's existing application to easily create and distribute TIMs to the Trihydro SDX, where Sirius XM pulls the messages for distribution over their satellite infrastructure. These REST services communicate via Kafka topics to a WYDOT ODE to encode, sign, and generate the resulting CV TIM. Additionally, TIMs are stored on the WYDOT system in a MongoDB database and are added through listeners to pull data from ODE Kafka feeds.

The CV Application Development team worked with WYDOT application developers to design an easily-implemented application programming interface (API) for the microservices. During this project, the development team encountered numerous unforeseen obstacles. Some of these include missing milepost and roadway geographic information system (GIS) information, database performance problems querying WYDOT spatial roadway data, and inconsistent implementation methods between application developers.

The CV application development team resolved the performance and GIS data challenges by reevaluating the platform used to house the spatial data and moving the spatial data into a graph database. This allowed querying route information and build out path information related to the TIMs quickly and efficiently. The application development team also worked with the WYDOT management and development staff across the organization to standardize the route naming format for applications. Development went from conception to production for this system in under six months, enabling CV message delivery to the entire state with no additional hardware investment and limited software updates to the existing WYDOT applications.

The expansion of TIMs statewide for Wyoming now allows CV drivers to receive TIMs while on all state and federal highways instead of just Interstate 80. This allowed WYDOT to gather additional interest from fleet partners as well as provide communications to CV drivers statewide.

7.3 Alexa Skills

In an effort to expand the visibility of the WYDOT CV data, as well the feature set of the SDX, Trihydro reached out to WYDOT to see if there were other ways that the SDX could leverage the existing CV messages housed in the SDX to drivers not in CVs. WYDOT suggested making the data available through an Alexa Skill. Trihydro embraced the idea as a way to expand the visibility and effectiveness of the SDX for all DOTs.

Trihydro then began developing the Traveler Information Skill, which uses the SDX to identify the conditions along the roadways that drivers are planning to travel. During interstate travel, drivers can ask the Alexa Skill about road conditions from their existing location to a destination city. The Traveler Information Skill then queries the SDX for all TIM messages contained along the existing route to the drivers destination. Results are then filtered for relevant results and read back to the user. Users of the Skill can ask questions such as:

- "Alexa, ask Traveler Information about the roads to Cheyenne, Wyoming."
- "Alexa, open Traveler Information … How are the roads between Laramie, Wyoming and Cheyenne, Wyoming?"
- "Alexa, ask Traveler Information if the roads to Cheyenne, Wyoming are open."

7.4 Standards Improvements Support

As part of this project, the WYDOT pilot team has contributed to the following efforts:

- The SAE J2735 Trailer definitions and leveraging BSM part 2 for trailers standardized across the pilots. This is being documented with SAE J2945/1B.
- The upcoming SAE J2945/4 Road Safety Application spec in how work zones are defined in the replacement message for the TIM.

The pilot teams also worked with the SCMS Manager on:

- Misbehavior detection to help define realistic misbehavior from misconfiguration as well as setup testing for the misbehavior algorithms with the WYDOT CVP logs collected.

- End Entity protections to help define how secure updates can be structured and cryptographic protections needed to support 1609.2.1.

8 Lessons Learned Log

Table 44 summarizes the many lessons learned throughout Phases 2-3 of the project.

Table 44. Lessons Learned Log

#	Lesson Title	Issue Description that Generated the Lesson	Actions Taken (or in Hindsight, that Should Have Been Taken)
1.	**Utilize existing standards as a part of the system architecture and design process.**	The use of standards helped create a solid deployment effort in Phase 2, simplified technical documentation, and assisted with interoperability.	Pilot sites identified a set of common messages and relevant standards.
2.	**Reserve an appropriate amount of time in the schedule to account for testing, both test planning and test execution.**	Detailed test planning is dependent on many other factors including equipment availability, so the development of detailed test plans can be a lengthy process while numerous uncertainties are nailed down.	Testing is complex and takes time. Some of the testing may need more than one round of testing. In retrospect, more time for additional rounds of test planning and test execution would have been useful.
3.	**Detailed testing is required for OBU and RSU software and in most cases, every aspect of the tests must be re-run to ensure that end-to-end functionality is not affected by any firmware upgrades.**	Much of the software is not yet created or not created completely. As such, it is important to account for detailed testing of all software, and even the hardware.	Purchase proof of concept devices to begin testing and notify vendors of shortcomings.
4.	**Efficient data sharing with third party sources needs to be planned in the architecture.**	Updated flow from data broker-->third party interface to data warehouse-->third party interface. This was done by the development team for efficiency in sharing the data.	Consider data flow efficiency throughout the conceptualization of the system. This fixed entailed updates to the SAD and other relevant Phase 1 documents.

#	Lesson Title	Issue Description that Generated the Lesson	Actions Taken (or in Hindsight, that Should Have Been Taken)
5.	3rd party integration with OBUs is hard and subject to different levels of capabilities/constraints between vendors. For example, Bluetooth connection challenges between WeatherCloud and OBUs.	The use of the WeatherCloud Road Pack and Sky Pack to the Samsung Tab A has been unreliable for the ground truth application. It is important to have flexibility in connections and performance.	Working with WeatherCloud to update from BT 4.0 to 4.2 that may allow for more flexibility in connections and performance.
6.	Committing trucking partners is hard when equipment needs to be retrofitted and is not mature.	A trucking partner determined it did not have the assets or dispatch availability required to support the program. They expected to have 25 vehicles participate.\nIt is important to account for unrealistic willingness to participate from potential truck partners. They may be very enthusiastic and willing at the beginning, disregarding their realistic capability to handle the activities needed to install, operate and maintain the technology in their vehicles.	Continue outreach efforts to recruit additional trucking companies.
7.	Dealing with internal DOT Firewall issues is a critical part of the system installation and operations.	It is important to account for issues that may arise from using existing networks. Moving the Pikalert system from a cloud computing platform into the WYDOT computer network resulted in many challenges with connecting to required data sources due to firewall issues.	A contingency had been placed in the Phase 2 budget for Pikalert to allow for unexpected issues. Firewall issues were tackled through joint effort between NCAR, Trihydro, and WYDOT.
8.	Partnerships between different disciplines enhances system development.	Combining weather and vehicle crash expertise in the Pilot team expedited the background research process for blow over algorithm development.	NCAR, Gonzaga, and Vital Assurance worked together to combine expertise and prior research efforts to build foundation of the algorithm.
9.	Accurate RSU TIM delivery can be compromised by configuration issues.	We encountered issues with sending TIMs to vehicles. It is important to test the range of RSU to OBU communication.	Work with Lear to test and verify configuration.

#	Lesson Title	Issue Description that Generated the Lesson	Actions Taken (or in Hindsight, that Should Have Been Taken)
10.	Ensure early discussions on PSID and Channel allocations.	Work with other sites and USDOT to define interop goals with PSID and channel usage.	Document WYDOT usage and work with other pilot sites to align PSID and channel usage.
11.	Since some of the systems are still early in development, there is poor admin-related documentation.	We found a lack of user and admin documentation with SXM OBU.	We had vendor on site to do training.
12.	Use a System Design Document punch list to work through issues with our partners.	USDOT/Noblis review comments of SDD.	Meeting with review team to review level of detail expectation.
13.	Hardware Security Module for TMC TIM signing.	Work to develop solution for signing TIMs in the TMC.	Work with SafeNet to see if they have solution that will work with SCMS PoC.
14.	Research Data Exchange testing.	Began working with RDE to define how data would be processed.	Found it important to start early as the data dictionary as well as max/min values needed to be defined before we could start loading data
15.	Data reliability needs for CV-PEP/RDE.	Discuss with IE team how to QA/QC data.	Discover early how to do data validation for quantity as well as quality to data end points.
16.	IPv6 challenges on the backhaul.	Work with WYDOT ETS team to identify problems with reliability on the backhaul from the RSUs to the TMC.	Setup network monitoring of both IPv4 and IPv6 addresses as they both can have independent problem.
17.	Log offloading from OBU to TMC performance.	Testing speed of 100k log file offloading at highway speed, found sometime un-reliable.	Work with Lear to demonstrate the problem so they can work on fix.
18.	Presentation focus areas.	Develop presentations that address audience interests.	Ensuring each presentation is geared specifically to the audience and topic area.
19.	Large fleet vehicle antenna design.	Lear flew out to look at the Snow Plows to help design antenna system.	Got new cables and pole antennas to test, the antennas turned out to be good, the cables were not.
20.	Testing at Archer for USDOT Demo.	Could not get certificates from CAMP SCMS.	Were able to demonstrate FCW, DN, TIM (SAT and RSU).
21.	SSP for Distress Notification message.	Work on defining the SSP for DN message.	Write up and share with NY and THEA the WYDOT CVP SSP design.

#	Lesson Title	Issue Description that Generated the Lesson	Actions Taken (or in Hindsight, that Should Have Been Taken)
22.	Work with Areo Space to verify new SDW for Sat deliver of TIMs.	Helped Sirius XM and USDOT test new system for SDW.	Tested new SDW with TIMs deliver over SAT.
23.	SDD and ICD.	Work with Noblis on comments for resolution on SDD and ICD document.	Updated documents based on comments from Noblis.
24.	Signing of TIM through ISS application and using remote HSM over the Internet.	Setup Node.JS script to build proof of concept TIM signing using test certs.	Successfully got TIMs signed using test certs in prep of getting HSMs for onsite TMC use.
25.	Secure Data Commons integration with ODE and CVP data.	Initial testing of pushing data to S3 buckets for BSMs.	Got BSMs to AWS for data lake use but could not yet get data into Hadoop cluster.
26.	Work with Weather Cloud on data definition update.	Get input from Weather Cloud to like their data collection to the WYDOT CVP interface control document.	Updated resolution and frequency of data delivered to log file for IMO.
27.	Semi installation of OBU and antenna testing is unique to each truck type.	Initial testing of 53' box trailer configuration. Tested pole and Sharkfin antennas on semi out to 300 meters, got bad data results, cables or antenna look unreliable.	Got bad propagation of DSRC BSMs. Continue testing until finding solutions appropriate to each vehicle.
28.	Truck antennae need additional testing to make sure that the range of coverage is maintained. Antenna testing documentation is useful to other deployers as well.	Sent USDOT and Noblis our results for antenna testing.	Discussed possible options for updating design. Learned we should be using 3M DSRC sniffer for testing.
29.	Production certificate testing.	Enrolled RSUs and OBUs with GHS production certs for CV Pilots.	Got certs downloaded, but had to change cert template with Bill at GHS to get to pass with new HSM in Lear devices.
30.	Virtual participation plan for remote audiences.	Few attendees were present at the OCS due to travel difficulties, so options for virtual participation should have been offered.	Identify tactics to provide virtual participation, such as livestreaming the OCS presentation.
31.	Expand range of media contacts.	Media contacts were focused on local outfits, but this topic has national interest, so non-local media may have been interested in attending.	Send invitations to national media outlets, such as journals, magazines, and blogs, that cover transportation or technology topics. Do not limit invitations to local media.

#	Lesson Title	Issue Description that Generated the Lesson	Actions Taken (or in Hindsight, that Should Have Been Taken)
32.	**Recommend TRL assessment for CV hardware elements.**	Using Technology Readiness Levels (TRL) to assess the development level for CV hardware.	It would have been useful to accurately assess the CV hardware primarily the OBUs and RSUs as to where they were on the Technology Readiness Level (TRL) scale. This assessment would have indicated the larger scope and cost of testing that we encountered. In hindsight, the initial TRL of the CV hardware was in the 5 -7 range, and our required TRL for the hardware in this project is 8 - 9. The general rule of thumb for development is that the development/test costs grow exponentially as you move up the scale and peak at TRL 8.
33.	**Standards need to catch up especially around truck-related issues. We noticed this in SDD and ICD.**	Tractrix use of trailer location and pose for BSM part 2.	Tractrix was a stretch goal to get accurate trailer dynamics integrated into BSM Part2. Looks like this will not be possible with this project. We have worked with David Kelly (author of J2735) and he agrees with Dominic from Lear that this needs to be addressed in the J2945/x standards, but currently is not defined. We will not include the tractrix with our pilot, due to the current maturity of the ecosystem. We will have the part 2 for use to define trailers and pivot points (per our requirements).
34.	**Manage growth of log files, as there's been issues of log files expanding to consume all system memory on RSUs.**	Due to failure of the certificate top-off processing on the RSUs, the certificates expire and result in high rate error message logging. Log files grow so rapidly with error messages that the log files consume all available memory and the RSU processes fail from memory exhaustion.	Lear reviewed the behavior but was not able to isolate/confirm the root cause of the certificate top-off failure. Lear did generate a new RSU firmware release PR12.06.18 (delivered 2020-12-16). This firmware release reduced the error logging rate to slow the log file size growth and included a fix to the certificate top-off process. Lear was not sure if the certificate top-off fix was related to the certificate top-off problems we were seeing in the RSU. The firmware release was installed on test RSUs (2020-12-20) The firmware operated on test RSUs verified BSM receipt, RSU logging, log offload and SXM OTA updates (2021-01-12) Rollout of PR12.06.18 firmware to production RSUs (started 2021-01-13)
35.	**Technical lesson - Keep up on production updates.**	Update production RSUs to PR12.06.18.	Update initial subset of production RSUs with PR12.06.18 with 1 week monitoring period.

#	Lesson Title	Issue Description that Generated the Lesson	Actions Taken (or in Hindsight, that Should Have Been Taken)
	Update production RSUs to PR12.06.18.		Upon successful completion of monitoring period update remaining production RSUs with PR12.06.18. It is important to note that Lear does no longer provides supports for its equipment as they are out of the DSRC line of business.
36.	**Technical lesson - Keep as-built documentation to to date. For example, we have had to update SXM OBU installation documentation to reflect changes in production OBUs.**	Due to changes in the production OBUs relative to the engineering unit OBUs the SiriusXM installation documentation was out-of-date.	Identified changes and updates required in the OBU installation documentation and communicated those to SiriusXM. SiriusXM revised their OBU installation documentation per the requested updates and provided the the new OBU installation manual to the WYDOT project team (delivered 2020-12-14).
37.	**Allow for greater ability to turn off OBU functionality over the air. For example, we had to develop a firmware release to disable BSM transmission due to the FCC ruling.**	Due to the FCC ruling potentially eliminating DSRC transmission on the 5.9 GHz band by December 2021, the project requested a firmware update from SiriusXM that would turn off BSM broadcast over DSRC.	SiriusXM confirmed that it was technically possible to have a firmware update that would turn off BSM broadcast over DSRC. The firmware upgrade would be possible to distribute via OTA updates. SiriusXM created a production release firmware AURIGA_186_WY upgrade to implement the BSM broadcast shut off. The production release firmware and OTA upgrade package were delivered to the WYDOT project (2020-12-09). The firmware and OTA upgrade were tested and confirmed successful at disabling the BSM broadcast over DSRC. TIM reception via satellite and TIM display were confirmed operating after the BSM broadcast was turned off (2020-12- 11).
38.	**Lesson learned- 3rd party sensor integration to OBUs WeatherCloud files not transferring to OBU.**	On some OBUs the WeatherCloud files are collecting on the tablet and not transferring to the OBU.	Lear confirmed that a problem was introduced in firmware PR12.06.14 which may require a file to be created in the /var directory to properly handle the weathercloud files. Lear provided a firmware fix to automatically create a Weather_cloud_files folder with correct permissions. This fix is implemented in the firmware release PR12.06.16 (delivered 2020-08-10)
39.	**OBU implementation of standards is subject to interpretation. For example,**	Production systems were all switched to using relative path TIMs per the J2735 standard 2020-05-18. Lear OBUs are not correctly processing the relative path TIMs and not	Lear confirmed that their OBU firmware through the current release (PR12.06.14) did not support relative path TIMs. Lear will add this capability in the next firmware release. Lear provided a new firmware release with the capability to

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	OBUs fail to display relative path TIMs.	displaying the TIMs when traversing the TIM path.	handle relative path TIMs PR12.06.16 (delivered 2020-08-10). WYDOT team installed the new firmware in 5 test vehicles and confirmed proper handling of multiple types of relative path TIMs (completed 2020-09-17).
40.	**Driver preferences may not mesh with standard user interface. Need flexibility. For example, several users complained about display screen is too bright for nightime operation.**	WY Hwy patrol report that display screen is too bright for nighttime operation.	SXM identifies that they cannot directly alter the screen brightness, screen supplier has already set brightness to lowest possible value. SXM proposes altering the color scheme for the CV display pages to a dark theme. SXM develops dark theme color palette for CV display pages (e.g., maps and roadway) SXM provides new firmware release AURIGA_185_WY implementing the dark color theme (delivered 2020-10-23).
41.	**Drivers (especially new installations) might have strong user interface preferences that we cannot control. For example, several of our new users in the highway patrol noted that Maps not converting to dark color scheme and not able to zoom-in while others have not identified this as an issue.**	About 50% of initial delivery of Siemens sourced SXM OBUs appear to be missing the display map files. This causes the map display to not use the new dark color theme, also the map display cannot be zoomed in for high-resolution view.	SXM identifies this as a failure in the Siemens configuration process, map files were not added during the device initial configuration. SXM provides to the WYDOT team the set of map files that should have been loaded onto the OBU (delivered 2020-11-02) WYDOT team develops plan and documentation for WYDOT installers to update map files in existing deployed WY Hwy patrol vehicles WYDOT team updates pre-delivery testing to check for and repopulate missing map files (completed 2020-11-13)
42.	**Have a plan for errors in OBU equipment. Issues noted in some OBUs included No sound generated for driver alerts from speaker connect to RCA jack.**	About 50% of initial delivery of Siemens sourced SXM OBUs appear to have their RCA jack disabled. This causes no sound to be generated from the OBU for driver alerts.	SXM identifies this as a failure in the Siemens configuration process, a cleanup script that resets several parameters after initial device testing appears to have not been run. SXM provides to the WYDOT team the cleanup script that can be run on new uninstalled OBUs (delivered 2021-01-18). SXM provides to the WYDOT team a modified clean up script that can be run on installed OBUs (delivered 2021-02-01). WYDOT team develops plan and documentation for WYDOT installers to run clean up script on existing OBUs

#	Lesson Title	Issue Description that Generated the Lesson	Actions Taken (or in Hindsight, that Should Have Been Taken)
			in deployed WY Hwy patrol vehicles. WYDOT team updates pre-delivery testing to execute clean up script for all new OBUs (completed 2021-02-01). SXM indicates that they will develop a OTA firmware update that will reset the parameters of concern (2021-01-25).
43.	Have a plan for errors in OBU equipment. Users noted OBU starts a repetative "dinging" sound upon vehicle shutdown.	This behavior was traced to the Installation Wizard application that was running on the OBU. This application was not shutting down after the OBU configuration process, and while it was running, it did not allow the unit to transition into standby mode when the ACC power stopped (vehicle key turn off). Besides generating the "dinging" sound the continuously running application caused a small increase in parasitic current draw, which resulted in battery draw down in some fleet vehicles that were idle for several weeks in cold weather.	The Installation Wizard application can be shutdown, by using Android OS user interaction actions to stop the application. Instructions for shutting down the Installation Wizard application provided to Fleet partner Dooley (2021-01-07). Configuration instructions for fleet partner installations were updated to ensure the Installation Wizard application is shut down after unit configuration. WYDOT team added a check for the Installation Wizard running for WYDOT installers when they update existing deployed WY Hwy patrol vehicles. Trihydro implemented a check of the existing fleet vehicles with SXM OBUs installed.
44.	Build in software alerts and canary functions to notify system ownwers when expected data transfers do not occur. We noted that log file write to local Oracle database fails due to a 3-day pause.	Writing of log file data into the local WYDOT Oracle DB was interrupted for a period of 3 days due to an error with the logger-kafka-consumer. The error caused the log file writes to the Oracle database to be suspended, but after a 3 day pause, the error somehow cleared and the log file writes resumed. Log file writes to other repositories were not affected (i.e., s3 deposits to SDC and writes to the MongoDB).	Reviewed log files and made sure all data available is there and correctly recorded. Failure of Kafka-consumer was traced to Docker container startup error. Software operation alerting was updated to flag Docker container failures.
45.	Malfunctioning OBUs. Because OBUs are in the "wild" once installed, we need to be able to see odd behavior and account for them. For example, we've noted multiple driverAlert log file instances created	Several Lear OBUs deployed in WYDOT snow plows are generating many driverAlert log files for a single driver alert event (e.g. TIM display, blind spot warning, etc.). There are some instances when over 1600 driverAlert log files have been generated from a single driver alert event.	This is an ongoing issue that will need to be resolved at the data analysis level.

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	for a single driver alert event.		
46.	**Widespread check of spectrum availability.**	A general lesson learned is the need to have early in the development and deployment process a comprehensive and integrated process to check for the spectrum, instead of ad hoc "micro-checks".	
47.	**Plan for installation on Leased Vehicles.**	Many freight fleets actually lease the vehicles. So installation of any equipment that may impact the vehicle's original condition (e.g., making holes to install antennas) is something that needs to be discussed early on to make sure the fleet owner/operator understands and approves these modifications.	Engaged in further discussion with fleet operators and owners to clarify the requirements of participating in the Pilot.
48.	**Train the trainers. Installation Training for fleets needs to be on their schedule and their staff.**	Train people and then they do installation different than how they were tought. Audio and video are being turned off due to faulty installation.	Sadly, not much can be done at this stage. Once the partner is trained, it is their responsibility to correctly installed the equipment. WYDOT has little capability to check on the installation, unless the partner itself reaches out to WYDOT for assistance.
49.	**O&M of the system especially around TIM accuracy is an ongoing tasks. Need to monitor TIM generation, delivery lest wrong message shown to drivers. Have to rely on friendly partner fleet reports to see if any odd TIMs are being noted.**	TIMs are not being received correctly by Drivers, the message itself does not match what was sent by the TMC. It seems that the TIM's messages are either being changed at some point after they leave the TMC (e.g., at the ODE or at the OBU)	We have identified several instances of this error. The development team is running tests to clearly stablish the reason for this and develop a solution. This issue was opened in response to a few erroneous TIMs displayed as reported by WYDOT field equipment maintenance teams. The TIM issues they reported, and which were subsequently resolved, are described in subsequent specific TIM error lessons learned. There were two key actions taken based on these initial reported errors. 1) Encourage the WYDOT field maintenance personnel to report the erroneous TIMs as they encountered them. Since the field maintenance personnel were consistently driving the I-80 corridor they provided high coverage of the deployed TIMs. Since they were familiar with WYDOT roadway alert procedures, they could quickly identify anomalous TIMs. 2) Provide a tracking process to collect a standard set of information for each reported error. Collecting this

#	Lesson Title	Issue Description that Generated the Lesson	Actions Taken (or in Hindsight, that Should Have Been Taken)
			consistent set of data for each reported error provided information needed to uncover the root cause of the TIM errors. Having an active, knowledgeable reporting team was the most critical element in identifying and ultimately resolving inaccurate/erroneous TIMs.
50.	Related to previous lessons - have to handle differences in implementation/display by OBUs between Advisory vs Regulatory TIMs.	Same TIMs are being sent out differently from RSUs and Satellite, one being regulatory messages but for the other being advisory.	Currently being studied to ID the cause of this. Advisory instead of regulatory TIMs on the SDX was traced to an issue with the TIM refresh logic that was updating the speed limit TIMs on the SDX as advisory instead of their original regulatory type. This logic error was fixed (2021-05-26).
51.	See previous lesson - Work Zone TIMs not showing	Drivers are not receiving TIMs that relate to work zone in specific areas. Problem could be the use of the ITIS code.	Currently being studied to ID the cause of this, looking into geo fence issues and other potential causes. These particular instances of workzone TIMs not appearing, were traced to the WYDOT workzone definition as a single point. See lesson "construction zones that have a location at a single point" for the resolution.
52.	Ensure automation to verify data availability in SDC. We've had situations where WYDOT has missing PM data in SDC.	Processed Speed data missing for specific days in March/April/May and failure to generate the PM queries 5,6,11.	Changed the generation of PSD script to generate the csv file and populate the S3 bucket and then process the data into local wydot.processed speed data table after creation of csv file, then continue to generate query 5,6,11. Also generate a script re-try logic for when connection to the database is lost, the re-try will generate on the following day. Added additional extensive logging for the scheduled task to track issues generating the scripts/csv files.
53.	Including redundancy to recover from poor equipment and maturity issues of applications. We've seen significant Lear application stability issues. Luckily we had a second vendor that we were able to transition to as a result of vendor-related issues with our original OBU vendor.	Vehicle installations and RSU installation are delayed due to Lear application stability; December 2018 update by DBPeel: still experiencing firmware issues, which has delayed deployment. January and February 2019 update by DBPeel: continued firmware issues further delaying RSU and OBU production deployment. March 2019 update by DBPeel: continued firmware issues further delaying Lear equipment deployment, continued IPv6 communication issues in the	February update: new code has been tested from 1/25/2019 and still has problems with OTA updates and WSA being inconsistent. March Update: new code has been tested from 3/25/2019 and still has problems with OTA updates and WSA being inconsistent. April/May Update: new code has been tested from 5/10/2019 and still has problems with OTA updates. June/July/August update: new code has been tested with success.

#	Lesson Title	Issue Description that Generated the Lesson	Actions Taken (or in Hindsight, that Should Have Been Taken)
		field (being addressed by State of Wyoming ETS) and ongoing issue of needing to reboot RSU to clear IPv6 problem - reported to Lear. April 2019: Issue continues. May 2019: Issue continues. August 2019: Update by DBPeel: continuing firmware issues further delaying Lear equipment deployment. October 2019 update by DBPeel: continued delays due to faulty Lear firmware. January 2020: Issues remain constant.	
54.	**Need to constantly monitor status of RSU certificates.**	Problems noted with RSU certificates - cascading effect causing RSU crashes. Problems getting initial OBU certificate download via RSU. Various OBU problems preventing testing in the field.	September 2019: Various OBU problems preventing testing in the field. & RSU firmware upgrade (PR12.06.11) slowly proceeding. October 2019 update by DBPeel: pursuing randomized vehicle ID issue, working with Lear and Trihydro on RSU configuration failures. January 2020: Deploying Lear firmware update to PR12.06.14 and appstart_final script to RSUs to mitigate configuration failures, identifying problem OBUs in the field and attempt to fix. will return to OBU and WeatherCloud installations. September 2021: The RSU reboot script deployed July 2021 has been rebooting the RSUs every Mon, Wed, Fri. This periodic reboot appears to have eliminated the repeated certificate update failures on the RSUs and related RSU crashes. Feb 2022: rebooting may be needed daily, and RSUs should be revised after each reboot to check if reboots fixed issues.
55.	**SXM OBU Transition**	Planning for a rapid transition to vendors is not easy with supply-chain constraints even if we want to move ahead aggressively. Moving to SXM OBUs for light and heavy vehicles was contingent on a complex web of supplier, reseller, manufacturer communications and schedule management.	Held weekly calls to understand schedule dependencies and resolve issues. April 2020: First order of 50 placed. June 2020: first order of 50 received, Second order of 50 light duty vehicles for delivery mid Aug. July 2020: 200 truck platform SXM OBU's ordered due late Sept and arrived in late October.
56.	**Antennae configuration and wiring between trucks is unique. Since we are only installing at very low-**	Configuring a truck at a when at a fleet partners garage, we typically see a need to develop a custom approach to wiring and mounting of the on-board system. In the short-term we have	Test on a pilot vehicle. Develop mounting design and wiring needs. Install on a first vehicle and conduct a test. Based on that machine more mounting kits.

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	volumes, the hardware for antennae mounting kit can't be purchased off the shelf.	been able to machine these kits but retrofitting these devices in a large-scale deployment will be difficult.	
57.	Accuracy and information quality for work zones	It is important to start a cultural shift with contractors to provide more accurate information on work zone location and duration. This has become a critical issue since we are now pushing that information directly to vehicles.	
58.	Mongo database logs consumed too much memory	Mongo database logs consumed too much memory filling the file system and resulting in the database shutdown. A contributing problem was that the ip monitor for the Mongo server failed to alert for the developing low memory situation. Approximately 3 days (2,3,4 July 2021) of vehicle log data were not recorded in the Mongodb. Log file writes to SDC were not affected.	Mongodb was restarted along with the logging configuration update. (2021-07-05) Issue opened with WYDOT support regarding why ip monitor failed to alert for the developing low memory conditions.
59.	SXM display issues.	Two displays for SXM OBUs installed in Fleet Partner trucks (Sinclair) have failed. The screens were working after being installed, but after several weeks of operation, the screens went dark. The OBUs appear to be operating (the OBUs still make the TIM alert sound when driving in areas where TIMs are known to be present) but the screen remains dark.	Walked though some basic troubleshooting steps with the Fleet Partner installer, usb and HDMI cable connections at the display and at the OBU were checked for security. Installer also replaced the usb and HDMI cables between the OBU and display, but to effect. Two new display screens were shipped to the Fleet Partner (2021-07-15). Fleet Partner installed the new screen on one unit and it powered up and it displayed correctly. He noticed the screen brightness setting was low and he went into Android settings and increased the screen brightness. He then reinstalled the original display screen and it was operating fine again (2021-07-21). WYDOT received two screens from Fleet Partner, one was completely dead the other worked (2021-09-07), but Fleet Partner had changed out the working one citing display problems when it was installed in the truck (display kept going dark).

#	Lesson Title	Issue Description that Generated the Lesson	Actions Taken (or in Hindsight, that Should Have Been Taken)
60.	**Incorrect speed-limit TIMs along Work Zones.**	Incorrect speed-limit TIMs were displayed for drivers traversing a construction zone. A 75 mph limit was displayed on their OBUs, but the construction zone was posting a 65 mph limit. The incorrect 75 mph TIM was traced to a VSL on that section of road that had been turned off and "bagged" as part of the construction process. Turning off the VSL sign did not update the last speed setting for that VSL in the CV system - thus the last known speed for the VSL was broadcast.	A review meeting with WYDOT (2021-06-09) confirmed that when VSL signs were turned off for construction, there was no update for the CV system as to the status change for that sign. An additional "offline" property was added to the JSON request for VSL signs updates. The TIM Wrapper code was updated and the offline property was used to remove TIMs for any VSLs that go offline.
61.	**Road closed TIMs were not being cleared for some highways.**	Road closed TIMs were not being cleared for some highways. Particularly some mountain pass roads that are closed for the winter season did not have their "road closed" TIM cleared when the roads were reopened in the spring. The root cause was found that some of the "all clear" requests that were issued to the CV system did not include an ITIS code. The TIM wrapper was expecting a "dry road" ITIS code within the all clear request and when it did not find one, the all clear request failed and the existing "road closed" TIM was left in place.	Since the "all clear" request is made to a specific end-point, the additional "dry road" ITIS code is not required. The TIM Wrapper software was updated to remove the dependency on the ITIS code for the "all clear" request (2021-07-19). A review with WYDOT is planned to identify why some "all clear" requests included the dry road ITIS code and other "all clear" requests did not. WYDOT meeting (2021-07-22) confirmed that "all clear" requests for road opening after a seasonal closure did not include a dry road ITIS code. Given the previously described TIM Wrapper software update, the missing ITIS code is no longer an issue.
62.	**TIMs that indicated a time delay were displayed in vehicles without any units for the time period.**	TIMs that indicated a time delay (e.g., construction zone may include a 10 min delay) were displayed in vehicles without any units for the time period. A time delay TIM includes 3 ITIS codes: 1) delay (1537) 2) time value (e.g. 12579) 3) time units (e.g. 8728 minutes) It was found that the TIMs being broadcast did not include the 3rd ITIS code, and thus the displayed TIM appeared as "delay 10" with no time units. The root cause was found as the ITIS code for	The missing "minutes" ITIS code (8728) was added to the database.

#	Lesson Title	Issue Description that Generated the Lesson	Actions Taken (or in Hindsight, that Should Have Been Taken)
		"minutes" was missing from the CV database. When the TIM refresh logic ran to renew the broadcast TIMs, no code was found to match the time units so the refreshed TIMs did not include it.	
63.	When a construction TIM is deleted any "buffer" TIMs that were associated with the construction TIM are not getting deleted.	When a construction TIM is deleted any "buffer" TIMs that were associated with the construction TIM are not getting deleted. A "buffer" TIM is created and associated with a construction TIM if the construction zone is defined with optional buffer zones. For example, a construction zone with a 25 mph speed limit buffer would cause an additional "reduced speed ahead 25 mph" buffer TIM to be created and located just upstream from the original construction zone. These buffer TIMs were not getting deleted when the original construction TIM was deleted. The TIM removal logic for construction zones was updated to properly clear all buffer TIMs created for a construction zone (2021-07-19).	51 "orphaned" buffer zone TIMs were identified in the CV system and deleted (2021-07-15). Review of the TIM delete logic found that the client_ids of the buffer zone TIMs were not being properly matched to the client_ids of their parent construction zone. When the parent construction zone was deleted, any associated buffer zone TIMs were not found, and thus not deleted. The TIM delete logic was modified to find all TIMs related to a given construction zone and remove them (2021-07-19)
64.	Construction zones that have a location at a single point (not a path), are not getting TIMs generated for them.	Construction zones that have a location at a single point (not a path), are not getting TIMs generated for them. A small percentage of construction zone requests are made for a construction zone at a single point location as opposed to a construction zone for a segment of roadway with start and end points. Requests for a construction zone at a single point included a start point, but did not include an end point. The TIM Wrapper logic currently is rejecting construction zone requests that have no end point and no TIMs are built for those construction zones. A review was held with WYDOT regarding how single point construction zones were being created WYDOT confirmed a change in their practice, so that all construction zones would	In a review with Wyoming Dot (2021-07-22), they confirmed that they were creating some construction zones with a single point location. Wyoming DoT determined that all defined work zones should have a minimum length of 1/10 mile. This policy, requiring a minimum length for work zones, was adopted by WYDOT and all new work zones defined using the WYDOT construction administration system (after 2021-08-01) will have a min length of 1/10 mile.

#	Lesson Title	Issue Description that Generated the Lesson	Actions Taken (or in Hindsight, that Should Have Been Taken)
		have a start and end point at a minimum 1/10 mile apart (2021-08-09).	
65.	It is important to account for the complexity of long, multi-segment TIMs when developing them as errors can be made.	Drivers were seeing intermittent "delay" TIMs as they drove NB I-25 around mp 50 and 113. Check of TMC data showed no delay for NB I-25, but there was a delay on SB I-25 from mp 182 to mp 16.	Review of the vehicle driver alert data identified that drivers were seeing the TIM set up for the SB I-25 direction. Further analysis uncovered that the SB delay TIM had included incorrect direction masks thus allowing the NB drivers to occasionally appear to be in SB TIM. A check of the TIM generation logic identified an error when constructing very long, multi-segment TIMs (this one was 166 miles long with 4 segments) which generated incorrect direction masks for these long multi-segment TIMs. The logic fixing this TIM generation error was revised, tested and deployed (2021-05-11).
66.	Deployment need to be flexible and quick to act in order to provide partners with customized hardware that would have the least impact possible on their vehicles.	Fleet Partner was reluctant to proceed with installation of the CV equipment on their trucks due to concerns about the equipment installations on their trucks.	Project supported a pre-installation visit to the fleet partner truck maintenance terminal and the installation team was able to design an installation configuration tailored for the partners trucks. Based on this design the project produced customized antenna mounts and worked with SiriusXM (OBU supplier) to modify the antenna cable length for the fleet partner trucks. With the modified CV installation, the fleet partner agreed to proceed with the installation. The ability of the team to build custom antenna mounts and have the OBU supplier modify the CV equipment were the key actions that enabled the fleet partner to proceed with the customized install.
67.	Plan for errors that may occur after deployment, particularly with software bugs that may take longer to appear.	Sporadic receipt of TIMs in vehicles, prompted an investigation of TIM generation and delivery. This investigation uncovered that TIMs were being signed with invalid signatures.	ISS was informed and their analysis identified a bug with the TMC Authority HSM software using incorrect keys to sign messages. Per ISS, "the likelihood of this error occurring increases over a TMCA's life". ISS "reset" the WYDOT TMCA (2022-04-07), this should enable correct signing for the near future, but a complete fix for this bug is required for long term stable operation.
68.	Implement a robust test environment that automatically and routinely runs through the generation of a series of TIMs.	Speed Limit TIMs for some VSL zones were showing incorrect speed limits compared to the speed limits posted on the VSL signs (e.g., TIM in vehicle shows 65 mph, VSL sign displays 75 mph). Investigation showed that the update	Changes were made to the ODE code to enforce the id variable type as String. This update will also be submitted as a change request for the US DOT ODE (2022-04-13). The ODE change with the Jackson deserialization library was tested in the WY test environment, but a limited

#	Lesson Title	Issue Description that Generated the Lesson	Actions Taken (or in Hindsight, that Should Have Been Taken)
		TIMs (from 65 to 75 mph) for the effected VSL zones had failed to be generated. Further analysis showed that a prior change in the ODE deserialization library from Gson to Jackson resulted in some TIMs failing during generation, resulting in the failed TIMs not being posted. The previous library change caused the TIM generation to fail when certain String ids in the TIM were incorrectly interpreted as numeric values. The IDs in the TIMs were randomly generated, and only specific sequences of characters caused the failed interpretation, so the failures were random and sparse.	number of TIMs were manually generated to test the code, and these test TIMs did not trigger the failed id interpretation. A more robust test environment with the ability to automatically run through generation of a defined series of test TIMs may be desired capability.
69.	**Have frequent test drives to test TIM dissemination through all means.**	In vehicle test drives, it was identified that OBUs were not receiving any TIMs from RSUs. A follow up check identified that TIMs were not being deposited on the RSUs. Additional analysis identified that the updated ODE (with Jackson library) also was not handling additional data in the TIM messages for RSUs (lat and lon of RSU) and RSU TIMs were failing to get generated. Satellite TIMs were not affected by this bug.	A fix for this bug is under development (2022-04-13). These issues stem from the conversion to the Jackson library for deserialization of all TIM messages (previously both Gson and Jackson were used). The Jackson library was incorrectly resolving some IDs to numeric values when they should have been strings. Jackson was sensitive to additional data included in some TIMs, causing it to fail deserialization when this additional data was present. These two failures led to the failure in generating TIMs for RSUs. This fix was implemented in production (2022-03-31) However, it should be noted that TIM dissemination from RSUs will stop starting July, 2022—an update is already being deployed to OBUs to discontinue DSRC communications.
70.	**Have frequent checks on credentials and signatures, as these may limit the distribution/acceptance of messages across devices.**	A sharp drop in TIMs recorded as received in vehicle OBUs started on 9 Mar 2022 and is still ongoing as of 13 Apr 2022. The drop in TIMs received in vehicle was confirmed to be caused by invalid signatures on the TIMs.	ISS identified that the HSM was not generating valid signatures for the TIMs and therefore the OBUs were rejecting the TIMs as invalid. ISS identified the problem and reset the HSM to start generating valid signatures. ISS has not developed a fix for the root cause of this problem (2022-04-18) but the HSM reset is a temporary fix that allows generation of valid signatures going forward for at least several months.

Appendix A. References

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Appendix B. Acronyms

Table 45 provides a list of acronyms used in this report.

Table 45. List of Acronyms.

Acronym	Description
AMS	Analysis, Modeling, and Simulation
ANOVA	Analysis of Variance
API	Application Programming Interface
BSM	Basic Safety Messages
CMF	Crash Modification Factors
CMP	Crash Prediction Models
CO	Colorado
CV	Connected Vehicle
CVP	Connected Vehicle Pilot
CVOP	Commercial Vehicle Operator Portal
CV-VSL	Connected Vehicle Variable Speed Limit
DB	Data Broker
DMS	Dynamic Message Signs
DN	Distress Notification
DSRC	Dedicated Short-Range Communication
DW	Data Warehouse
FCW	Forward Collision Warning
FHWA	Federal Highway Administration
GIS	Geographic Information System
HMI	Human Machine Interface
HP	Highway Patrol Vehicles
HSM	Hardware Security Module
ID	Identifications
IPV6	Internet Protocol Version 6
ITS	Intelligent Transportation Systems
I2V	Infrastructure-to-Vehicle
JPO	Joint Program Office
MADIS	Meteorological Assimilation Data Ingest System
MBD	Misbehavior Detection
MP	Milepost
MPH	Miles Per Hour
MPRs	CV Market Penetration Rates
MVMT	Million Vehicle Miles Traveled

MVMTT	Million Vehicle Miles Traveled by Truck
NCAR	National Center for Atmospheric Research
NHTSA	The National Highway Traffic Safety Administration
OBU	Onboard Units
ODE	Operational Data Environment
PKI	Public Key Infrastructure
PM	Performance Measures
PET	Post-Encroachment Time
REST	Representational State Transfer
RMVMT	Work Zone Crash rate per Million Vehicle Miles Traveled
RMVMTT	Work Zone Crash rate per Million Vehicle Miles Traveled by trucks
RSU	Roadside Units
RTMA	Real-Time Mesoscale Analysis
RTRA	Real-Time Risk Assessment
RWIS	Road Weather Information Stations
SA	Situational Awareness
SDC	Secure Data Commons
SDX	Situation Data Exchange
SCMS	Secure Credential Management System
SLVA	Speed Limit Violation Alerts
SMoS	Surrogate Measures of Safety
SOARS	Significant Opportunities in Atmospheric Research and Science
SPFs	Safety Performance Functions
SQL	Structured Query Language
SSAM	Surrogate Safety Assessment Model
SWIW	Spot Weather Impact Warning
SVA	Stationary Vehicle Alert
TH	Trihydro Vehicles
TIM	Traveler Information Messages
TMC	Transportation Management Center
TRB	Transportation Research Board
TTC	Time-To-Collision
TFHRC	Turner Fairbank Highway Research Center
USDOT	U.S. Department of Transportation
UW	University of Wyoming
VISSIM	Microscopic Multi-modal traffic flow simulation modeling software
VSL	Variable Speed Limits
VMT	Vehicle Miles Traveled
VMTT	Vehicle Miles Traveled by Truck
V2I	Vehicle To Infrastructure
V2V	Vehicle To Vehicle
WY	Wyoming

WYDOT	Wyoming Department of Transportation
WZW	Work Zone Warning

Appendix C. Road Condition Ratings

Table 46 lists the different road condition ratings used by WYDOT.

Table 46. Road condition ratings.

Condition	Impact	Text Page Column Name
Surface Conditions		
81 (dry)	L	Conditions
82 (wet)	L	Conditions
83 (slick)	H	Conditions
84 (slick in spots)	M	Conditions
85 (drifted snow)	M	Conditions
86 (closed)	C	Conditions
86 (closed - seasonal)	E	Conditions
Atmospheric Conditions		
91 (favorable)	No Impact	Conditions
92 (snowfall)	L	Conditions
93 (rain)	L	Conditions
94 (strong wind)	M	Conditions
94 (dangerous wind w/EBOR or C2LHPV)	H	Conditions
95 (fog)	M	Conditions
96 (blowing snow)	H	Conditions
97 (reduced visibility)	H	Conditions
Advisories		
BI (Black Ice)	H	Advisories
NUT (No Unnecessary Travel)	H	Advisories
EBOR (Extreme Blow Over Risk)	H	Advisories
NTT (No Trailer Traffic) March 25 - November 22	H	Advisories
NTT (No Trailer Traffic) November 23 - March 24	E	Advisories
ANLT (Advise No Light Trailers)	M	Advisories
FR (Falling Rock)	L	Advisories
Restrictions		
CL1/CL2 (Chain Law 1 & 2)	H	Restrictions
C2LHPV (Closure to Light, High Profile Vehicle)	C	Restrictions

Appendix D. Drivers Behavior Under High Wind Alert

This section summarizes multiple drivers' reaction to a high wind event that occurred on June 22, 2021. The cases B.1 – B.4 explains a driving event under the high wind and drivers' reaction as far as speed and acceleration adaptation is concerned.

Case B.1. High Wind Event

A connected vehicle was traveling eastbound on I-80 near milepost 335 near Buford (Figure 58) and began to experience high winds at 22:39:56, as indicated by sudden lateral and yaw acceleration jumps possibly caused by wind gusts.

Figure 58. Case B.1 - CV trajectory at the time of the event.
Source: WYDOT

Driver response to the event

The driver drastically slowed speed as a result of this wind, until they received a high wind alert at 22:40:12. At that time, the driver decided it was prudent to pull off the road and **stop the vehicle**—see Figure 59 and Figure 60.
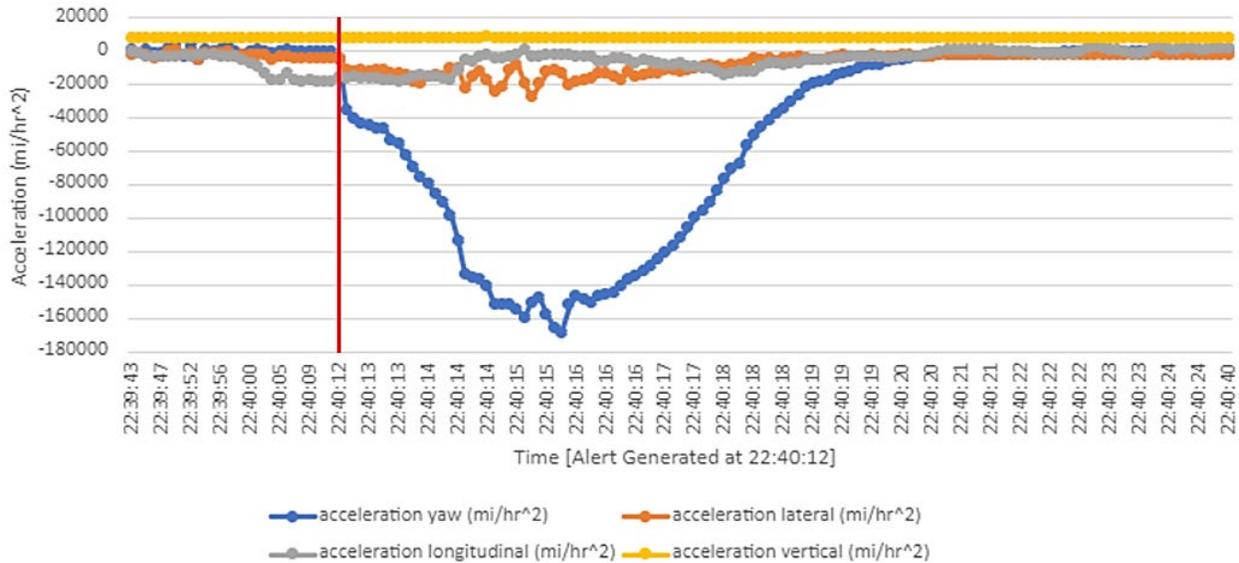
Figure 59. Case B.1 -- Acceleration (miles/hour^2) v. Time: Action: Vehicle Stopped.
*Source: WYDOT*
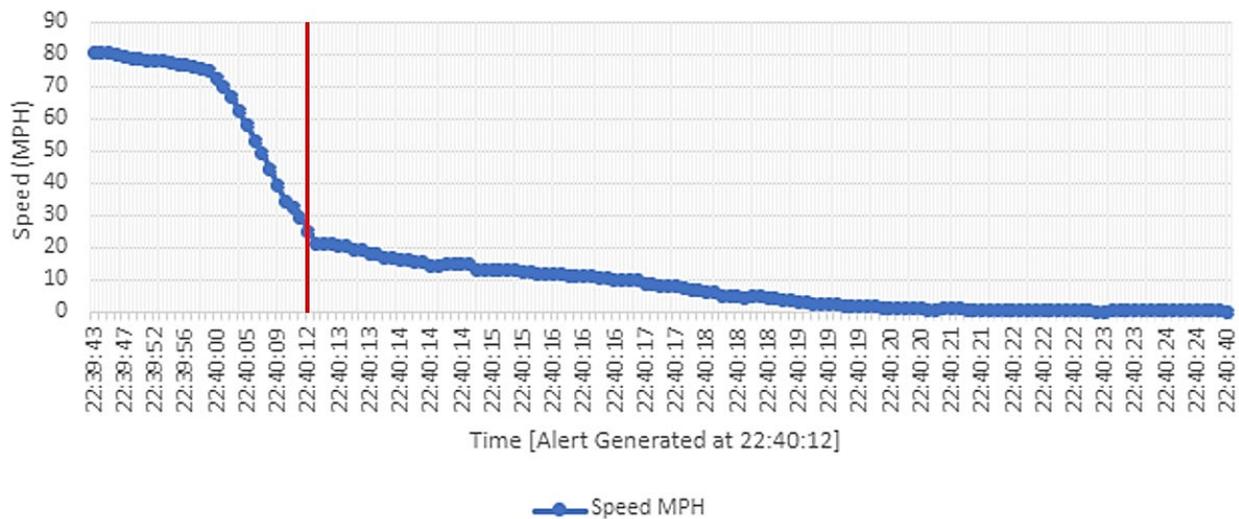
Figure 60. Case B.1 -- Speed (MPH) v. Time. Action: Vehicle Stopped.
Source: WYDOT

This proved to be a sound decision, as the vehicle experienced severe lateral and yaw accelerations for several seconds during slow down. The truck's negative acceleration reached a maximum of over –170,000 miles/hour^2 at 22:40:15, and the truck parked completely at 22:40:19. The vehicle then remained parked for some time. The nearby RWIS (Buford East) showed wind speeds around 40 mph and wind gust speeds reaching 71 mph near the time of the event. Winds were from the West (250-degrees) at the time of the crash.

Case B.2. High Wind Event

The driver was traveling westbound on I-80 near milepost 335 near Buford (Figure 61). After experiencing high wind-related yaw, lateral, and longitudinal accelerations at time 22:41:04.

Figure 61. Case B.2 - CV trajectory at the time of the event.
Source: WYDOT

Driver response to the event

As wind-related accelerations increased to their extreme maximums and minimums, **the driver received a high wind warning alert at 22:41:07 and began to slow down more rapidly.** Although the winds had significantly diminished by 22:41:20, as expressed by accelerations returning to near-zero levels, the driver still chose to pull off the Interstate and stop for safety. The driver remained stopped through the end of the analysis period—see Figure 62 and Figure 63.
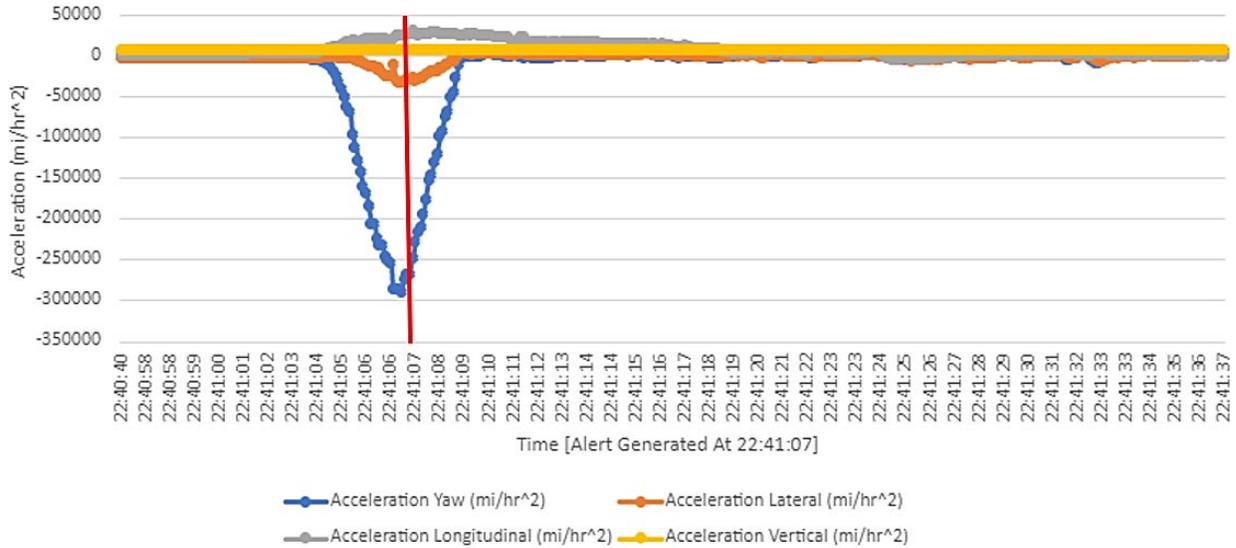
Figure 62. Case B.2 -- Acceleration (miles/hour^2) v. Time. Action: Vehicle Stopped.
Source: WYDOT

The nearby RWIS (Buford East) showed wind speeds around 40 mph and wind gust speeds reaching 71 mph near the time of the event. Winds were from the West (250-degrees) at the time of the event.
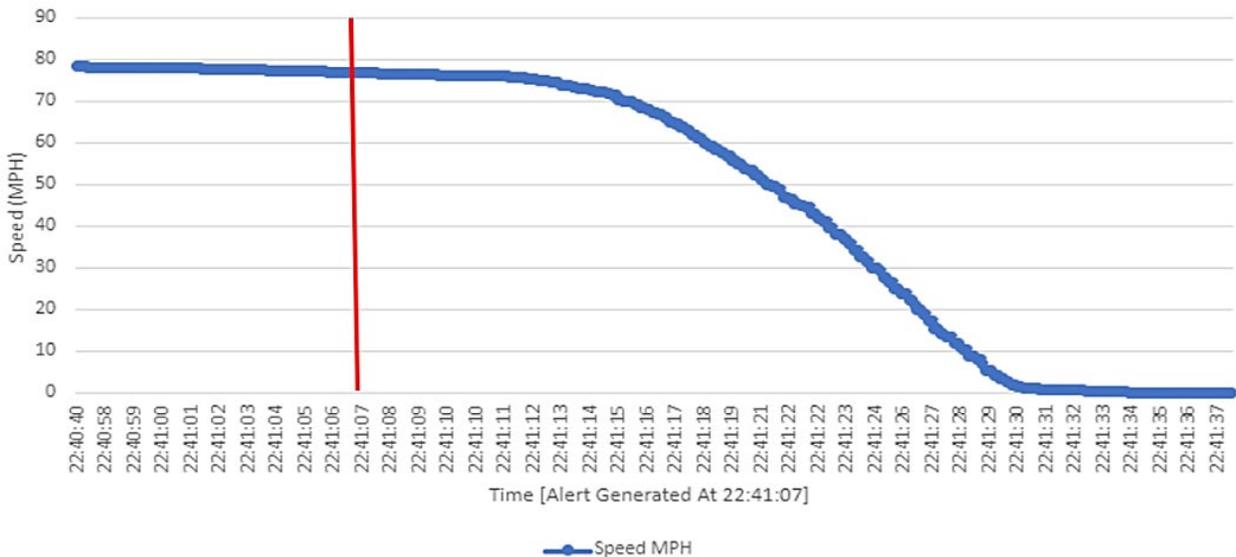
Figure 63. Case B.2 -- Speed (MPH) v. Time. Action: Vehicle Stopped.
Source: WYDOT

Case B.3. High Wind Event

A connected vehicle was traveling westbound on I-80 near milepost 335 near Buford (Figure 64). The driver received a high wind alert generated at 22:21:30.

Figure 64. Case B.3 - CV trajectory at the time of the event.
Source: WYDOT

Driver response to the event

Experiencing minor initial wind events, the driver was already in the process of reducing speed from 80 MPH to 70 MPH when a high wind warning alert was generated at 22:21:30.

Feeling that the winds had remained steady, **the driver continued to slowly reduce speed down to as low as 60 MPH in response to the alert.** Then, winds suddenly picked up at 22:21:49, causing impressive yaw accelerations in the positive direction (22:21:49 – 22:21:52) and then in the negative direction (22:21:56 – 22:22:01).

As wind gusts continued to threaten to shove the truck off the Interstate, pushing and pulling the vehicle left and right, the driver made the prudent decision to rapidly reduce speed down to 15 MPH by the end of the reporting window—see Figure 65 and Figure 66.
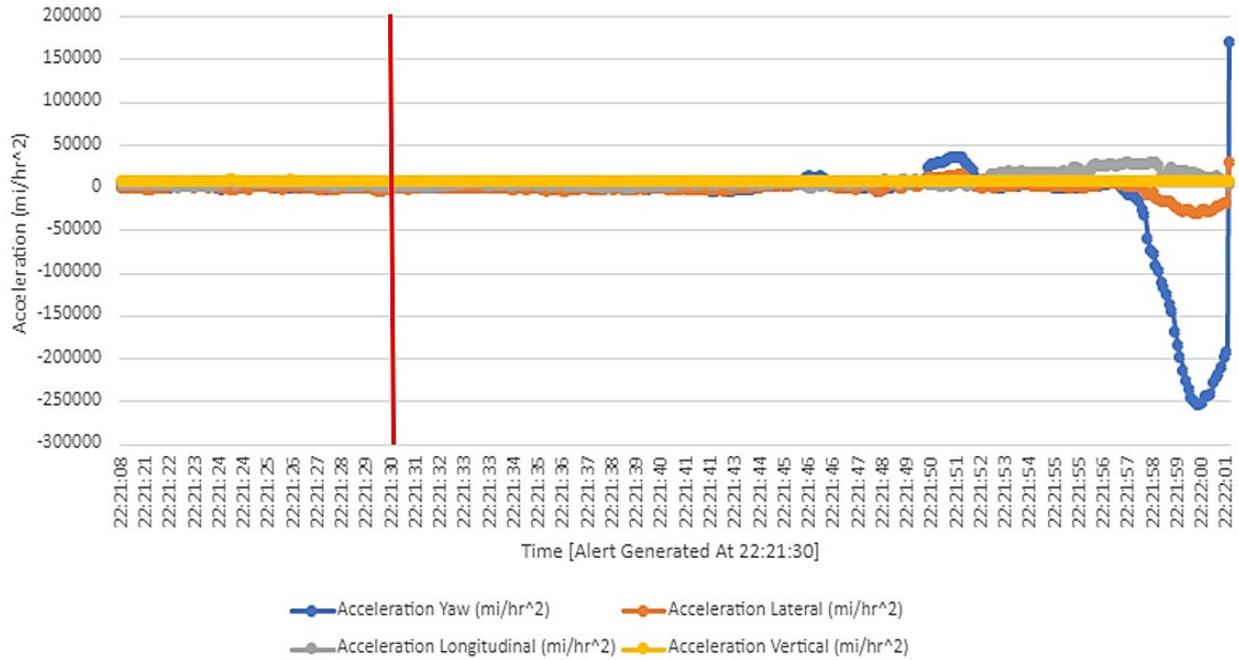
Figure 65. Case B.3 -- Acceleration (miles/hour^2) v. Time. Action: Vehicle Reduced Speed.
Source: WYDOT
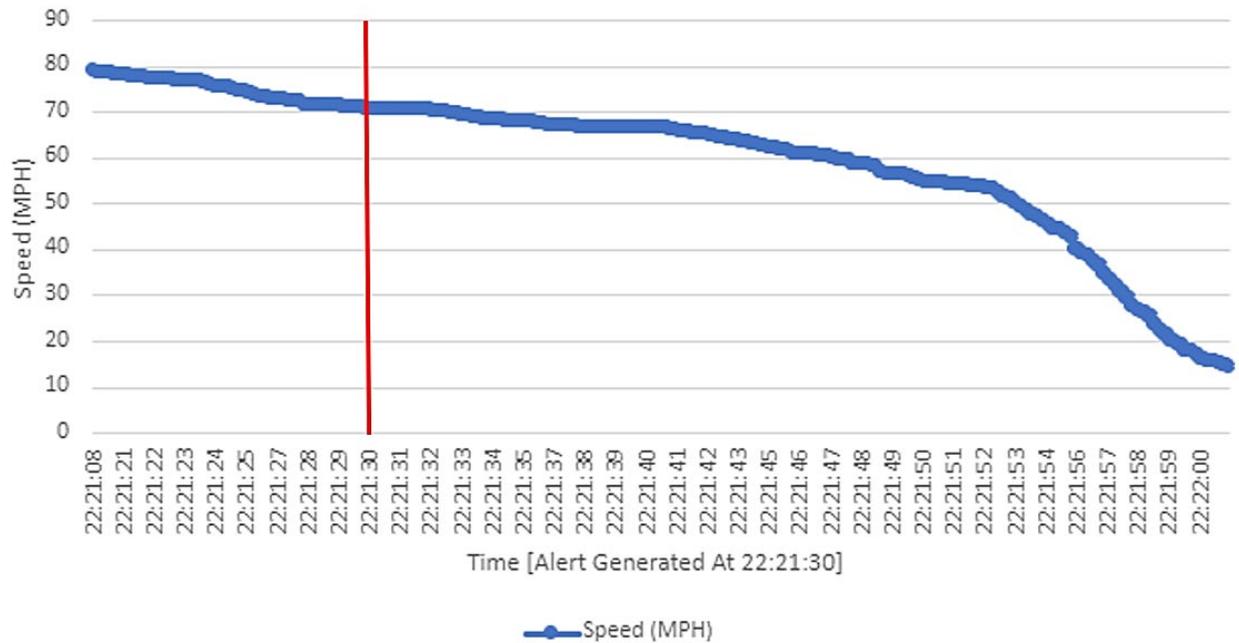
Figure 66. Case B.3 -- Speed (MPH) v. Time. Action: Vehicle Reduced Speed.
Source: WYDOT

The driver may have even stopped at a time shortly after 22:22:01, compelled to do so by physical wind events more so than the driver alert itself. The nearby RWIS (Buford East) showed wind speeds around 40 mph and wind gust speeds reaching 67 mph near the time of the event. Winds were from the West (255-degrees) at the time of the event.

Case B.4. High Wind Event

The driver was traveling on a country road with access to Little Snake River Valley, passing by a parking lot (Figure 67). At 21:29:11, the driver was already speeding up in preparation to rejoin I-80 around mile marker 187 and head westbound, but suddenly intense winds influenced the truck with extreme negative and then positive yaw accelerations from 21:29:47 to 21:30:42.

Figure 67. Case B.4 - CV trajectory at the time of the event.
Source: WYDOT

Driver response to the event

The driver rapidly slowed down to 10 MPH on the onramp and remained at only 30 MPH when they received a CV alert warning about continued high winds at 21:30:56. Nevertheless, since they were already on the onramp, the driver slowly increased speed back to 70 MPH and commenced travel on I-80, continuing west. Then, the driver maintained speed until the end of the observation window.

Thus, the driver slowed down due to high wind activity, which was confirmed by the CV alert; however, the CV alert did not necessarily influence the driver's decision to reduce speed—see Figure 68 and Figure 69.
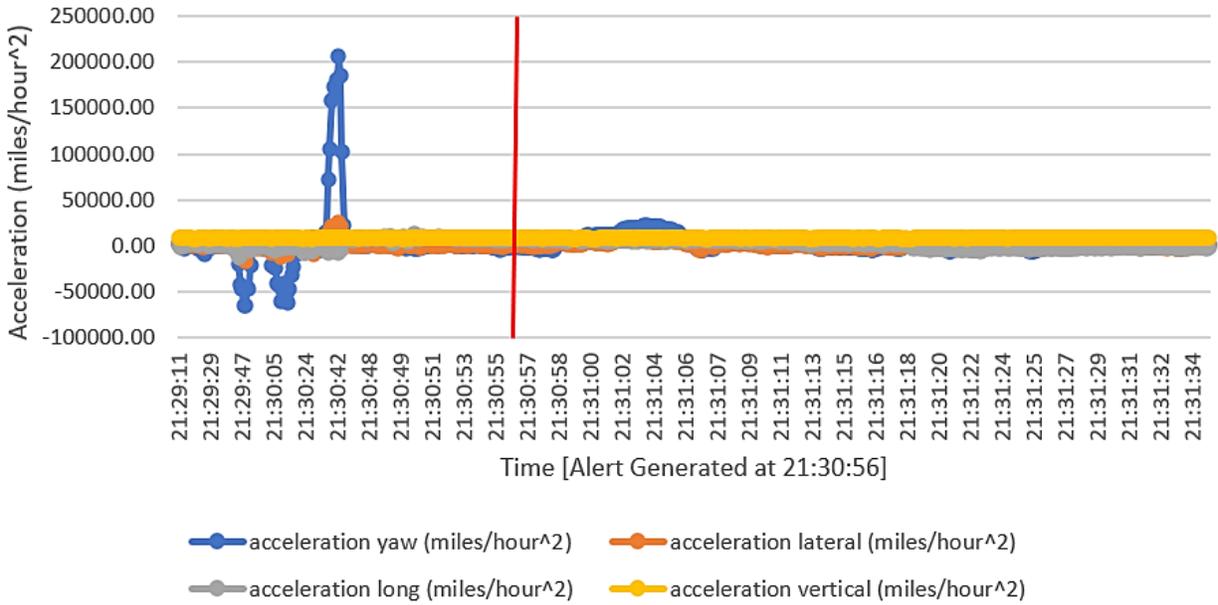
Figure 68. Case B.4 -- Acceleration (miles/hour^2) v. Time. Action: Vehicle Reduced Speed.
Source: WYDOT
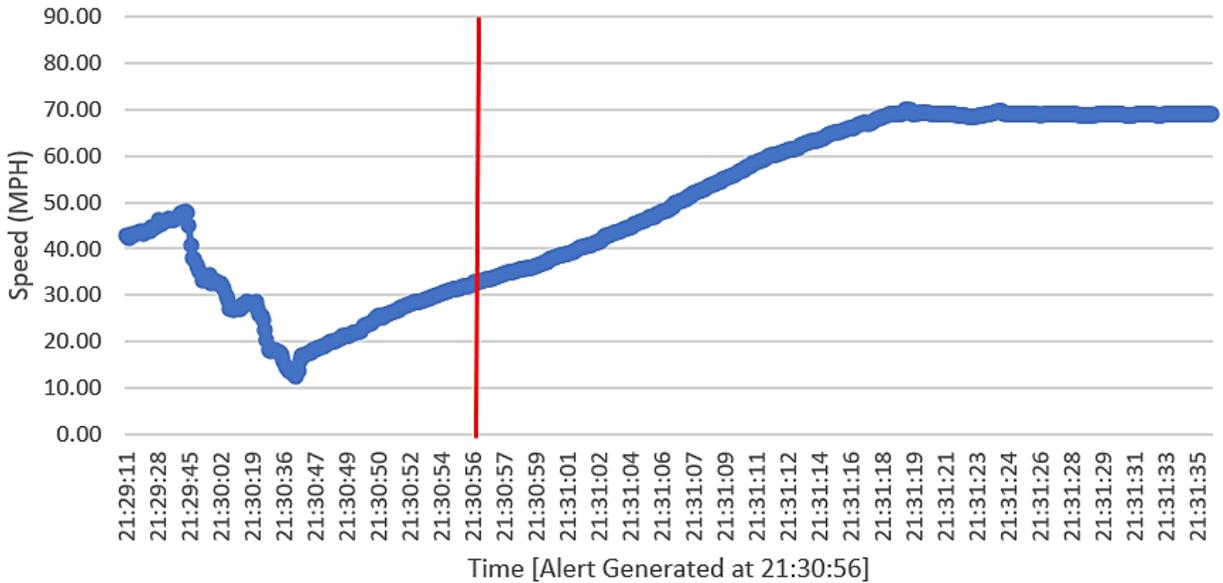
Figure 69. Case B.4 -- Speed (MPH) v. Time. Action: Vehicle Reduced Speed.
Source: WYDOT

Appendix E. Drivers Behavior Under Work Zone Alert

Performance measures 16 is based on determining the action the driver took after receiving an in-vehicle alert. For this analysis, driver alert data for events on the I-80 corridor were compiled for the month of June. From the comprehensive driver alert dataset, a list of 6,994 CV alerts with an ITIS code of 1025 were identified, representing construction zone alerts.

These alerts were imported into Google Earth for spatial referencing. While the alerts were spread along the 400-mile Wyoming corridor, in the Google Earth software it became evident that many of these events were concentrated around a few select construction zones. Specifically, four locations stood out as regions of major activity; these sites were identified for potential further analysis—see Figure 70 through Figure 73. These four locations were cross-referenced with listed summer construction projects on the WYDOT Construction Console database that provides the basis for generating Work Zone TIMs (Table 47). This process reduced the number of construction alert events from 6,994 to 653, divided between each active construction project as follows: 42 instances associated with project No. 49; 15 instances associated with project No. 34; 427 instances associated with project No. 40, and 167 instances associated with project No. 6. The latter two projects (40 and 6 from Table 47) were selected for further review given the larger number of events associated with them.

Table 47. Work Zones Selected for Further Analysis

| No.	Project Key	Perm ID	PK	Route	From MP	To MP	Surface	Start Date Key	End Date Key	Description
49	28692	28690	31533	ML80B	5	6	Paved	20210706	20211031	I-80 WB MP 6 AM to 5 PM Road Work in Driving Lane
34	24896	24916	30604	ML80B	96.95	97.05	Paved	20210414	20220731	Mechanical Surface Removal
40	25985	25983	28483	ML80B	252	258	Pavement Removed	20210524	20211031	I-80 MP 252-258 Paving to Elk Mountain
6	21414	21393	32083	ML80B	372	382	Paved	20200427	20211031	I-80 MP 372-382 Hillsdale Bridge Replacement Redirect
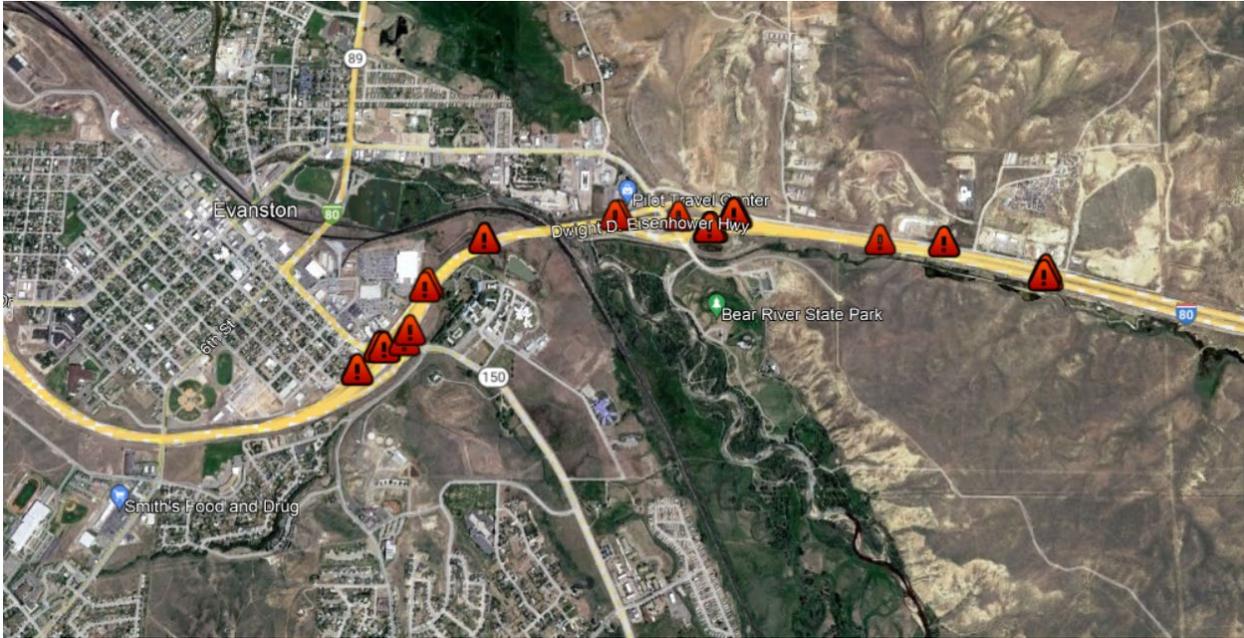
Figure 70. Work Zone 49: Evanston Roadwork (MP 5-6)
Source: WYDOT
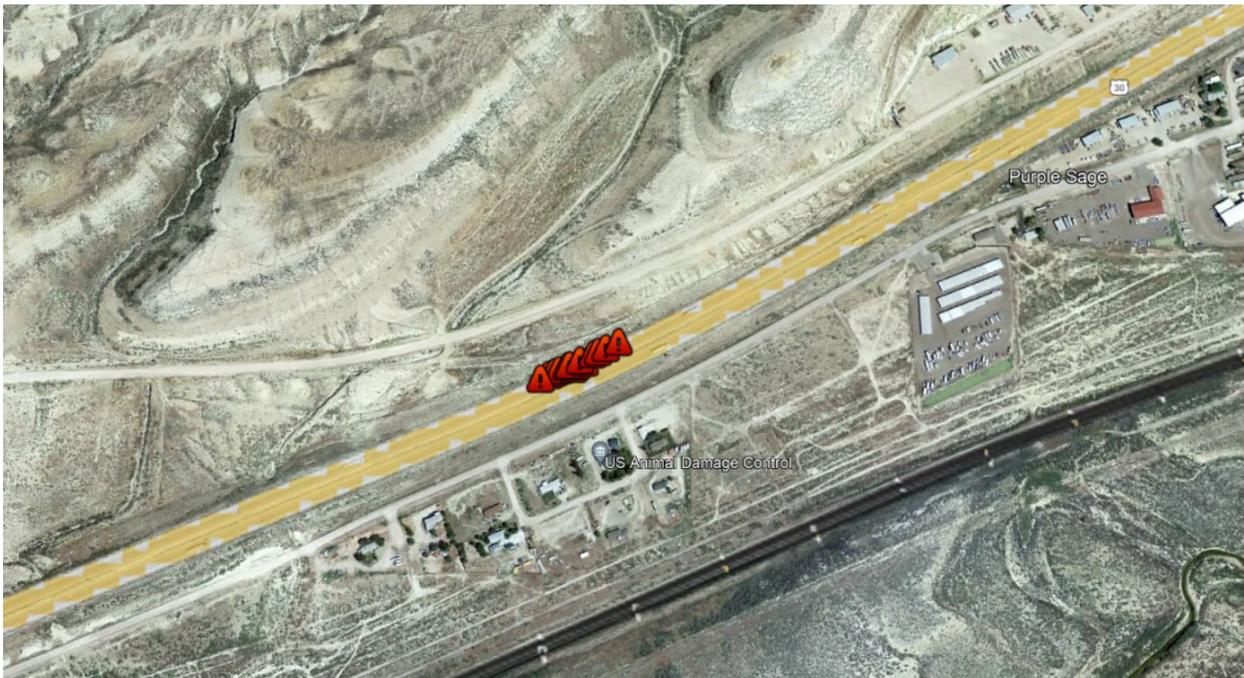
Figure 71. Work Zone 34: Between Green River and Rock Springs Surface Removal Project, (MP 97)
Source: WYDOT
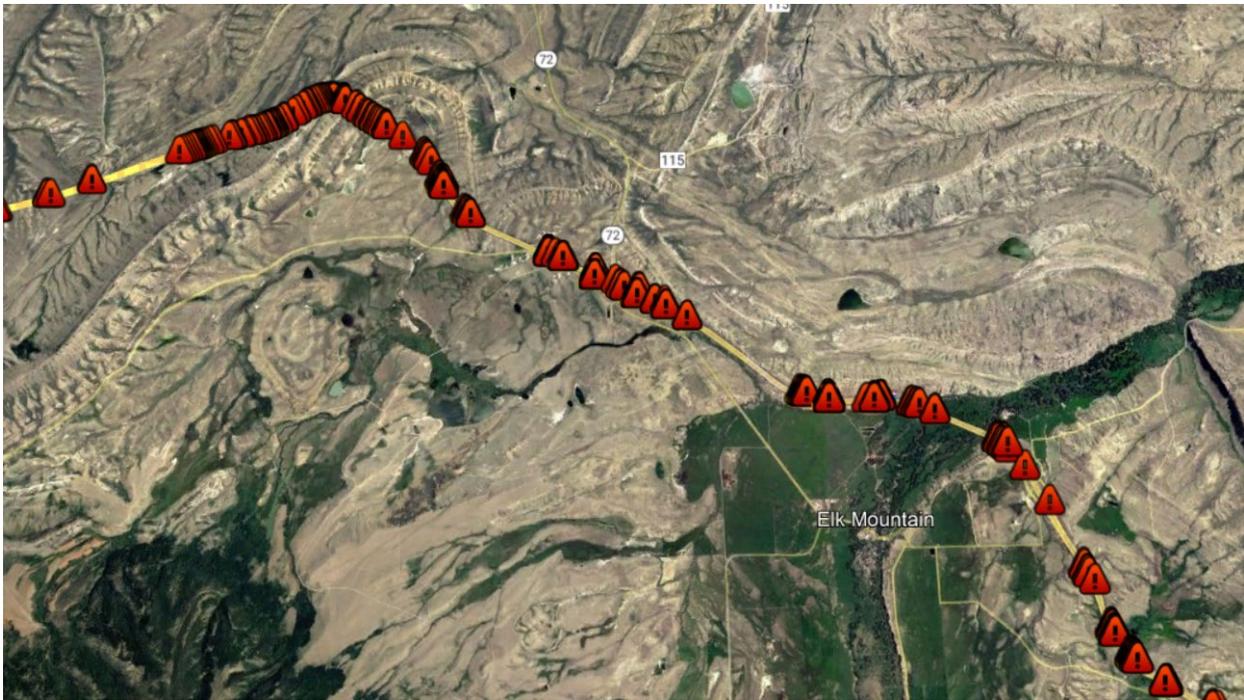
Figure 72. Work Zone 40: Elk Mountain Paving Project (MP 252-258)
Source: WYDOT

Figure 73. Work Zone 6: Hillsdale Bridge Replacement East of Cheyenne (MP 372-382)
Source: WYDOT

The WYDOT Construction office was then contacted for more information about the two projects, and detailed construction plans were obtained. The Resident Engineers (REs) in charge of each of those projects were also contacted directly, and it was determined that Project 6, the Hillsdale Bridge Replacement Project, was the best candidate for comprehensive analysis, as it was a fully

active project throughout the month of June. The Hillsdale work zone was set up to direct all traffic to the eastbound lanes utilizing temporary median crossovers, so the resulting traffic was one lane in each direction through the work zone, which bridge replacement work occurred on the westbound lanes.

The next step for data analysis was to compile the BSM data for each of the work zone driver alerts in June that were located near or in the Hillsdale work zone area in eastern Wyoming. A geofence for the area of interest was created as the basis for a spatial query of the BSM data for the month of June. It was noted in the driver alert table that many of the events were likely associated with the same vehicle as the time and location were similar or identical. This was confirmed in the BSM data by reviewing the time, location, vehicle ID, and Bundle ID values. BSMs associated with highway patrol and WYDOT maintenance vehicles were removed from the analysis as well, and these vehicles were easily identified since they do not exhibit standard speed behavior. These steps resulted in 16 unique events for work zone alerts associated with the Hillsdale Bridge Replacement Project work zone.

For each of the sixteen events, the BSM latitude and longitude data were mapped in Google Earth to see the vehicle path during the event. The BSM algorithms are set to store high-resolution data (one observation every 1 second) for 10 seconds before and after a driver alert is given. Additionally, low-resolution data (one observation every 30 seconds or longer) is seen outside of this window. For most of the events, the vehicle received multiple work zone alerts, so the data for each event showed periods of both high- and low-resolution BSM data as it traveled through the work zone. High resolution data recorded BSM values every 10th of a second and low resolution data every 30 seconds. The system was designed to record data every 10th of a second (10 Hz) but was allowed to only retain one observation every 30 seconds if no alerts were received during that window.

The speed data from the BSM algorithms were converted to miles per hour and graphed with the time of the driver alert noted. The BSM data also contained vehicle acceleration data including longitudinal, vertical, lateral, and yaw accelerations. Of these, longitudinal (braking and gas application) accelerations were graphed, also in units of MPH (specifically miles per hour^2).

A narrative around each alert event was created based on analysis of the driver behavior postulated from the graphed data. One of four driver actions was given to each event by the analyst.

- **Vehicle Reduced Speed** was assigned to events where a notable speed reduction was witnessed after the driver alert was given.

- **Vehicle Stopped** was assigned for events where the analyst found the vehicle speed came to zero after the driver alert was given but the driver remained on the roadway, either in the lane or shoulder areas.

- **Vehicle Exited** was assigned for events where the analyst found the vehicle exited after the driver alert was given.

- **No Action** taken was assigned for events where the analyst found no evidence of deceleration, stopping, or exiting.

From the 16 events that were analyzed, seven vehicles (44%) took no action; eight (50%) reduced speed; and one (6%) vehicle exited following the alert (Table 48).

Table 48. Summary of Driver Actions for Construction Alert Events

Event	Number of Alerts	Time of First Alert	Time of Last Alert	Driver Action
1	8	6/17/2021 21:38:24	6/17/2021 21:50:43	Vehicle Exited
2	6	6/17/2021 22:30:29	6/17/2021 22:58:26	No Action
3	2	6/23/2021 14:12:03	6/23/2021 14:21:38	No Action
4	6	6/24/2021 14:02:31	6/24/2021 14:54:38	Reduced Speed
5	1	6/24/2021 22:44:57		Reduced Speed
6	6	6/24/2021 23:31:36	6/24/2021 23:36:06	Reduced Speed
7	1	6/26/2021 18:24:46		Reduced Speed
8	2	6/26/2021 20:09:41	6/26/2021 20:10:02	Reduced Speed
9	2	6/28/2021 10:54:30	6/28/2021 10:57:55	Reduced Speed
10	1	6/28/2021 11:07:14		No Action
11	6	6/28/2021 13:59:00	6/28/2021 14:11:29	Reduced Speed
12	1	6/28/2021 16:36:55		Reduced Speed
13	3	6/28/2021 16:42:38	6/28/2021 16:47:18	No Action
14	3	6/28/2021 18:03:23	6/28/2021 18:03:31	No Action
15	1	6/28/2021 18:13:12		No Action
16	4	6/28/2021 22:43:18	6/28/2021 22:49:39	No Action

All times in this report are in local Wyoming time, reported in military Hours:Minutes:Seconds on the dates indicated on each graph.

Event 1

Traveling eastbound into the construction zone (Figure 74), the driver received an initial 1025 ITIS alert ("Active Construction Zone") at around 21:38, possibly causing them to reduce speed slightly from approximately 80 to approximately 75 miles per hour (Figure 75). Then, as the driver proceeded into the main active part of the work zone, the driver needed to slow down to an even lower speed as he traversed a lane-crossover and followed the instructions of a messaging signs, ultimately reducing speed to a crawl (2 miles per hour), and momentarily to a complete stop at 21:42. The driver's necessary speed reduction was also communicated by a trio of alerts between 21:41 and 21:42 that may have helped them to reduce speed further and forewarn of the

slowdown. Finally, at 21:43, as the driver began to exit the work zone, a final alert reminded them to maintain a low speed. The driver never had to slam on their brakes or speed up too quickly, as is shown by the relatively smooth and steady acceleration graph. The analysis showed the **vehicle exited**, although it is impossible to know if they were doing that in reaction to the alert or needed to stop for other reasons.

Figure 74. Google Earth Image of Construction Event 1.
*Source: WYDOT*
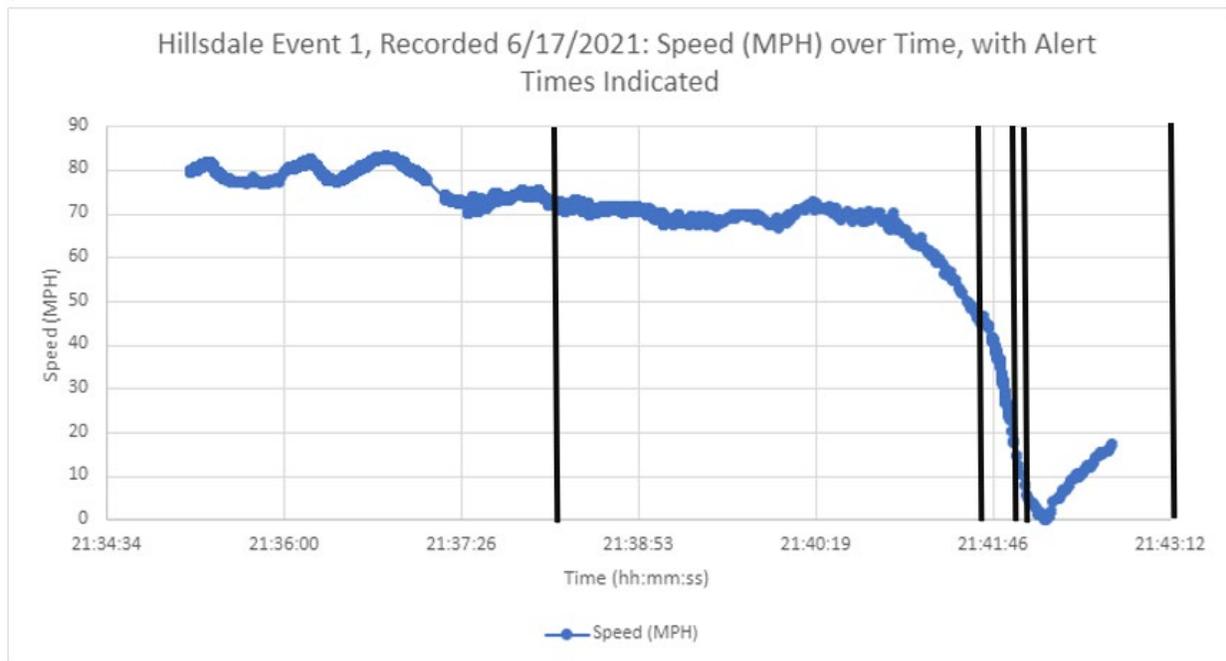
Figure 75. Event 1: Speed Profile.
*Source: WYDOT*
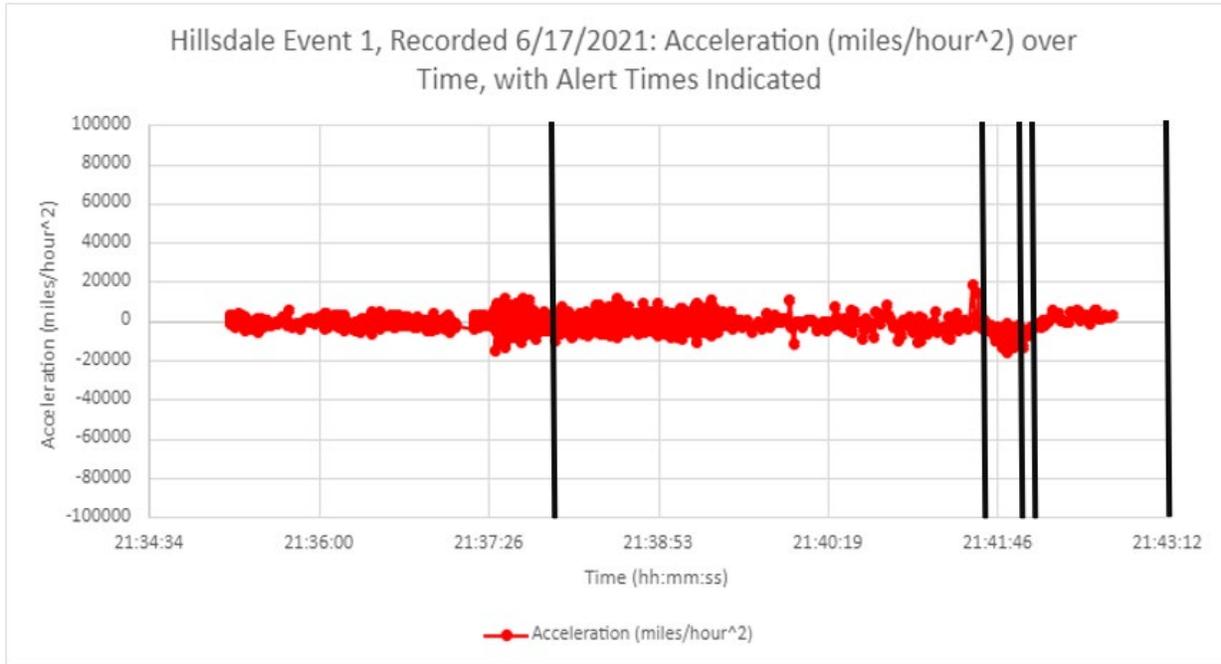
Figure 76. Event 1: Acceleration Profile.
Source: WYDOT

Event 2

An eastbound traveling vehicle approached the Hillsdale Construction Zone (Figure 77). Perhaps impatient after waiting in bottlenecked traffic to enter the construction zone, the driver began to accelerate rapidly around 22:30 after the median crossover zone (Figure 79). The vehicle rapidly sped up from 20 miles per hour to 60 miles per hour in spite of two work zone alerts at 22:30 (Figure 78). The driver ignored or did not see these warnings, as well as two more sent at around 22:35; instead, the driver continued to speed up to approximately 83 miles per hour, which was maintained, through the work zone until 22:54. Then, the driver experienced another construction related slow down as the vehicle crossed back into the usual lane of travel, and the driver reduced speed back to 60 mph. The driver was warned twice more about the construction zone around 22:59, but choose to speed up to a 120 miles per hour and leave the work zone and choose to remain at this high speed. On the acceleration graph, two anomalies occur when the driver chooses to speed up; but does not indicate any instances where rapid declaration occurred. From this analysis, it was determined that the driver **took no action**.
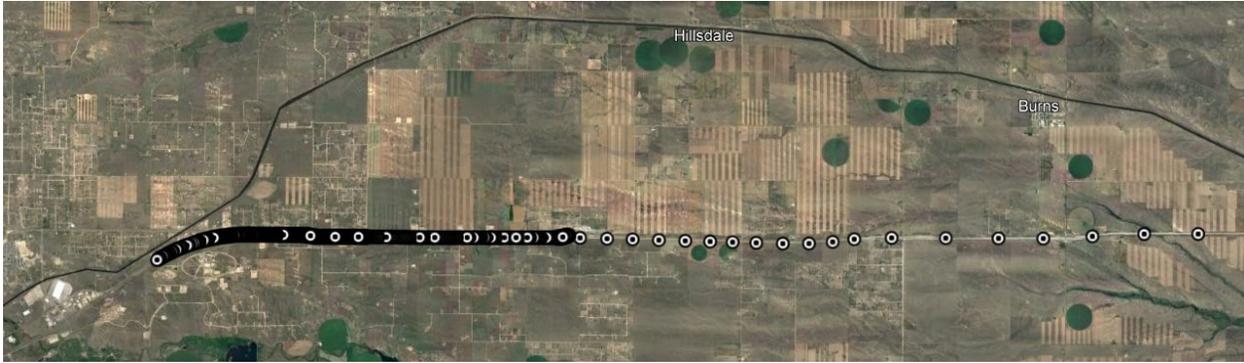
**Figure 77. Google Earth Image of Construction Event 2.**
Source: WYDOT
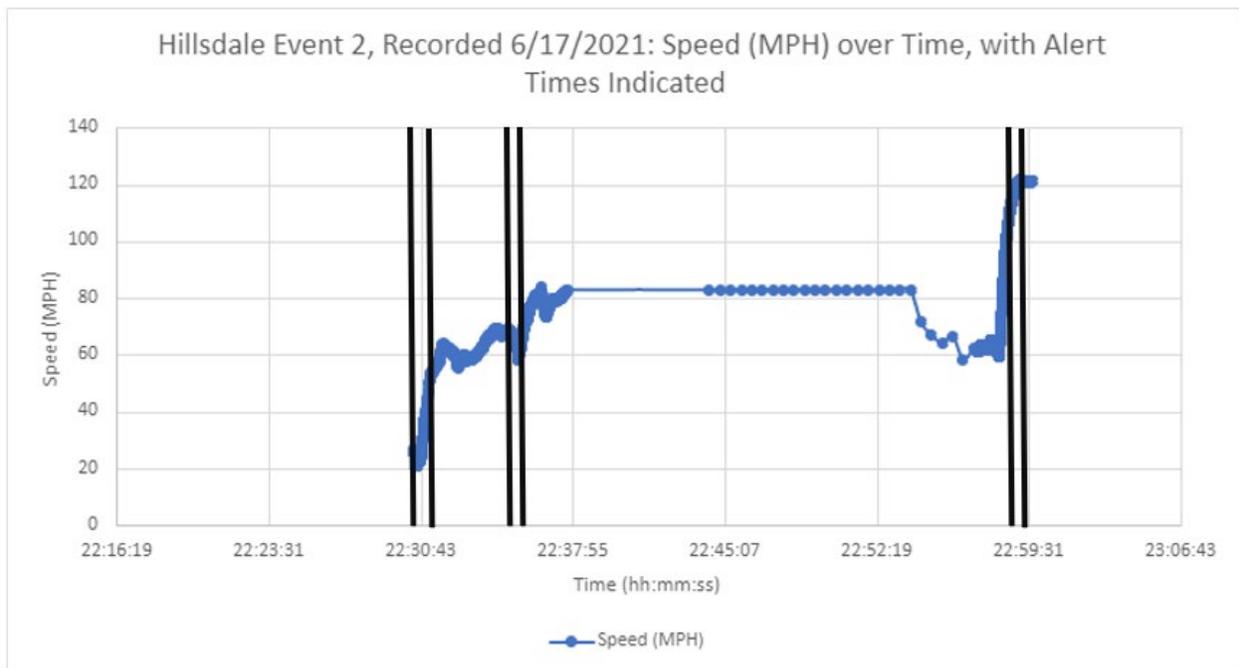
Figure 78. Event 2: Speed Profile.
Source: WYDOT
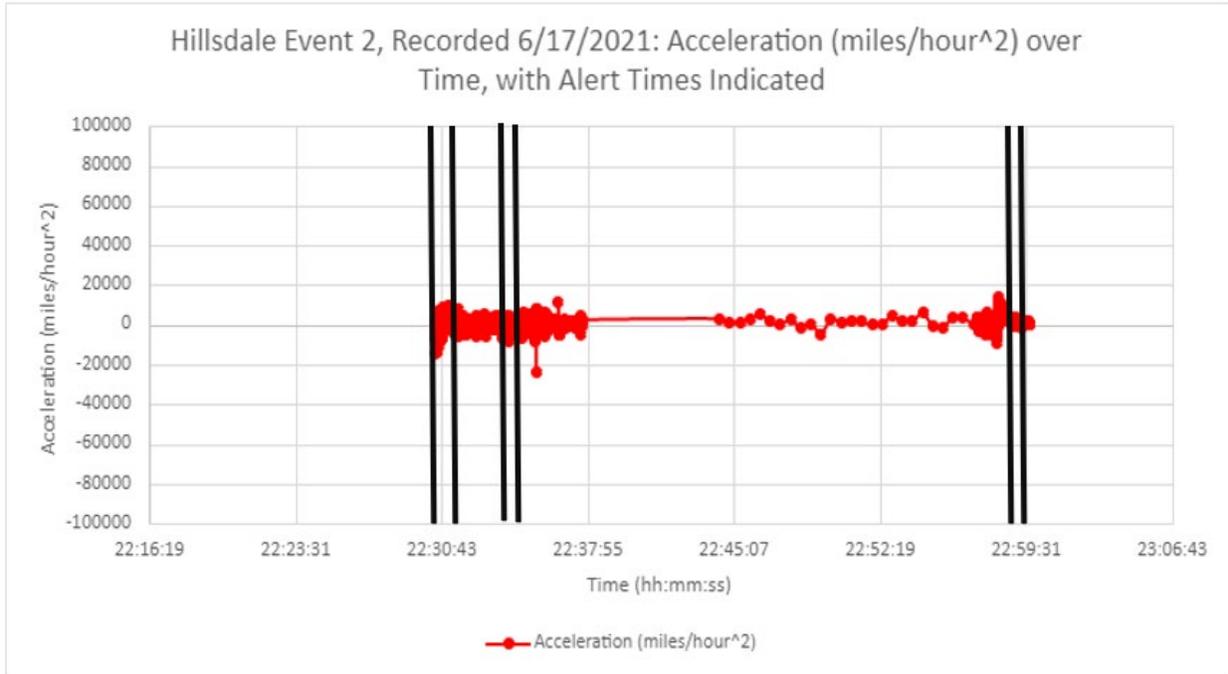
Figure 79. Event 2: Acceleration Profile.
*Source: WYDOT*

Event 3

The driver was traveling westbound at 80 miles per hour at 14:10 when they reached the end of the queue to enter the work zone (Figure 80). The driver reduced speed to 55 miles per hour before receiving the alert at 14:12 (Figure 81). Then, the vehicle speed varied between 45 and 80 miles per hour until a reminder alert concerning the construction zone was received at 14:22. The instantaneous outlier shown on the speed graph of 85 MPH at 14:16 was considered erroneous, as there is no corresponding jump in acceleration (Figure 82). From this analysis, it was determined that the driver **took no action**.

Figure 80. Google Earth Image of Construction Event 3
Source: WYDOT
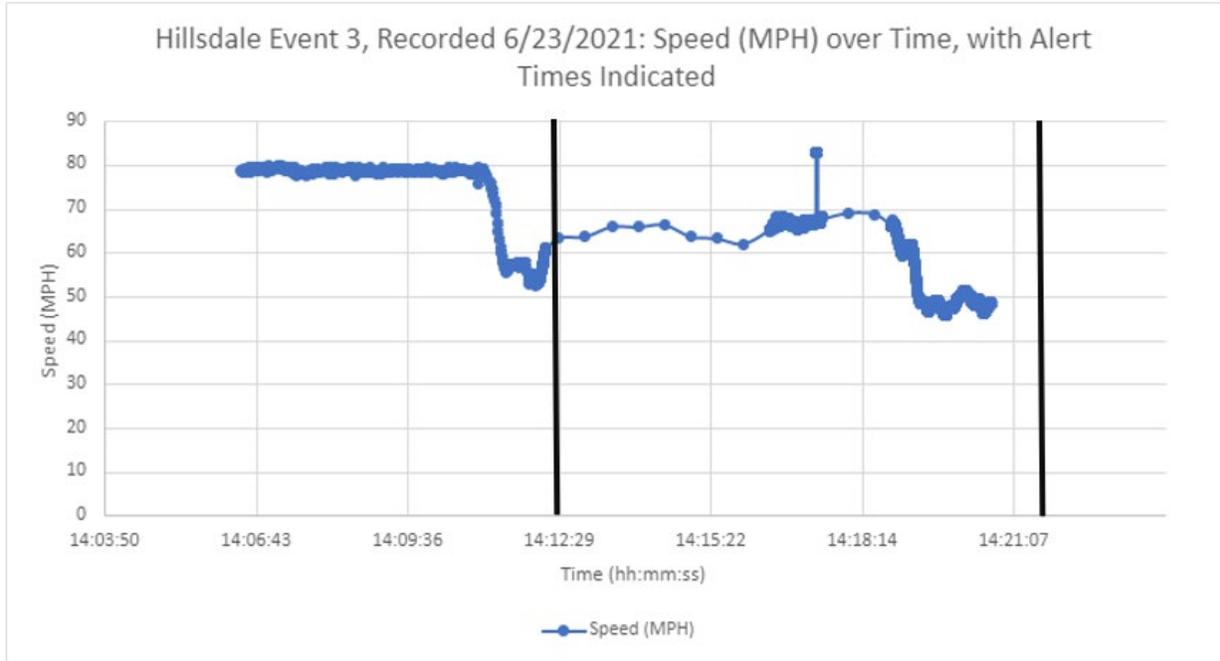
Figure 81. Event 3: Speed Profile.
Source: WYDOT
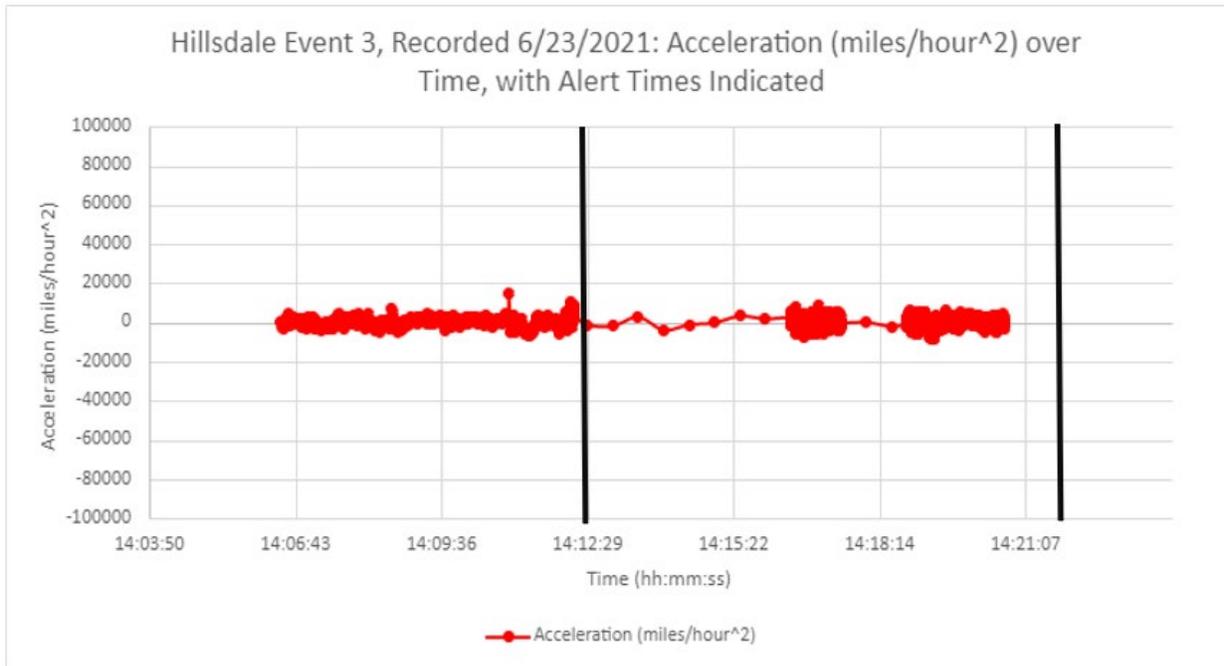
Figure 82. Event 3: Acceleration Profile.
Source: WYDOT

Event 4

The vehicle was proceeding westbound at approximately 65 mph, having already received two early alerts at 14:02 and 14:06 (Figure 83). On arriving at the start of work zone, the driver applied the brakes, as can be seen in the acceleration report (Figure 85), and continued applying them lightly from 14:28 to 14:34, reducing speed to 42 MPH at 14:33 (Figure 84). Another construction alert was received at 14:34. The driver began to increase speed to 60 MPH speed, not applying the brakes again until two more alerts were received about construction at 14:42 and 14:44. Possibly in response to the alerts, speed was then rapidly reduced to only 10 MPH, and this was maintained until exiting the construction zone at 14:54, following one final alert. The fact that acceleration (braking) data aligns with alerts, with periods of no braking between alerts, may suggest that the driver was influenced by the alerts into making decisions to slow down for construction. It is unclear why data was missing between 14:45 and 14:53. From this analysis, it was determined that the driver **reduced speed**.

**Figure 83. Google Earth Image of Construction Event 4.**
Source: WYDOT
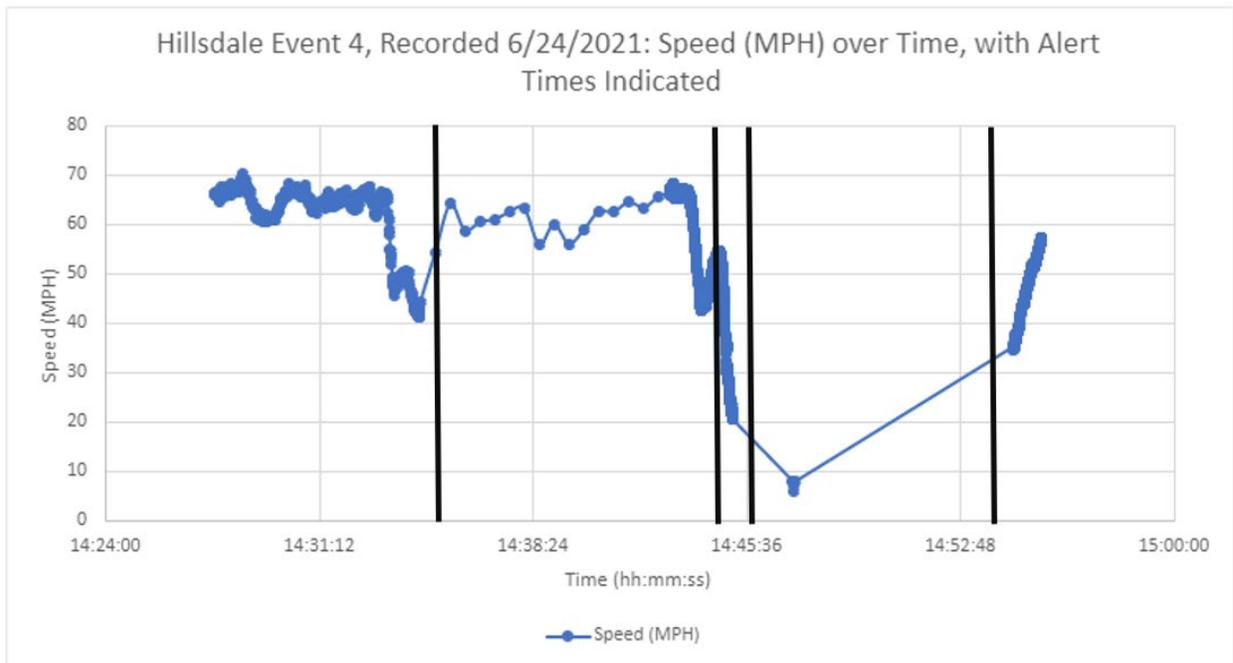
Figure 84. Event 4: Speed Profile.
Source: WYDOT
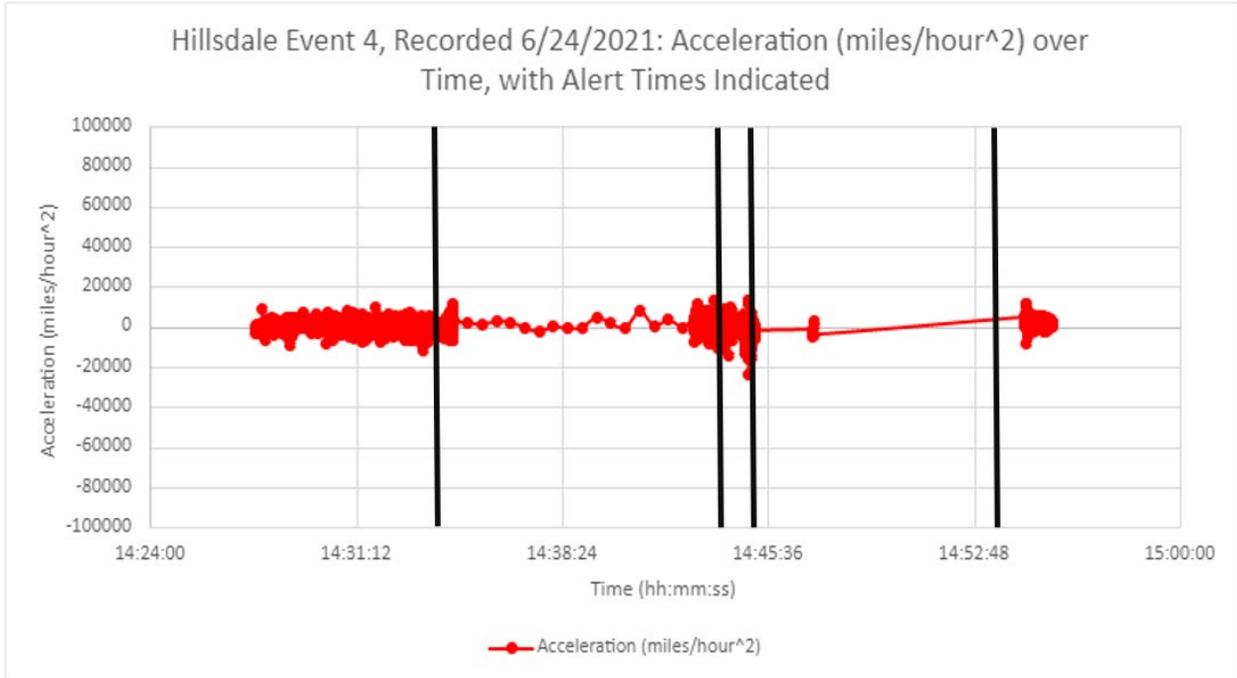
Figure 85. Event 4: Acceleration Profile.
Source: WYDOT

Event 5

The vehicle was traveling eastbound through the work zone, with speeds fluctuating between 69 and 84 MPH (Figure 86). As the driver approached the most active part of the work zone, they applied the brakes beginning at 22:44:45 (Figure 88), and reduced speed to 22 MPH (Figure 87). As the driver was reducing speed, a 1025 ITIS alert was received, and the driver reduced speed further. From this analysis, it was determined that the driver **reduced speed**.

**Figure 86: Google Earth Image of Construction Event 5.**
*Source: WYDOT*
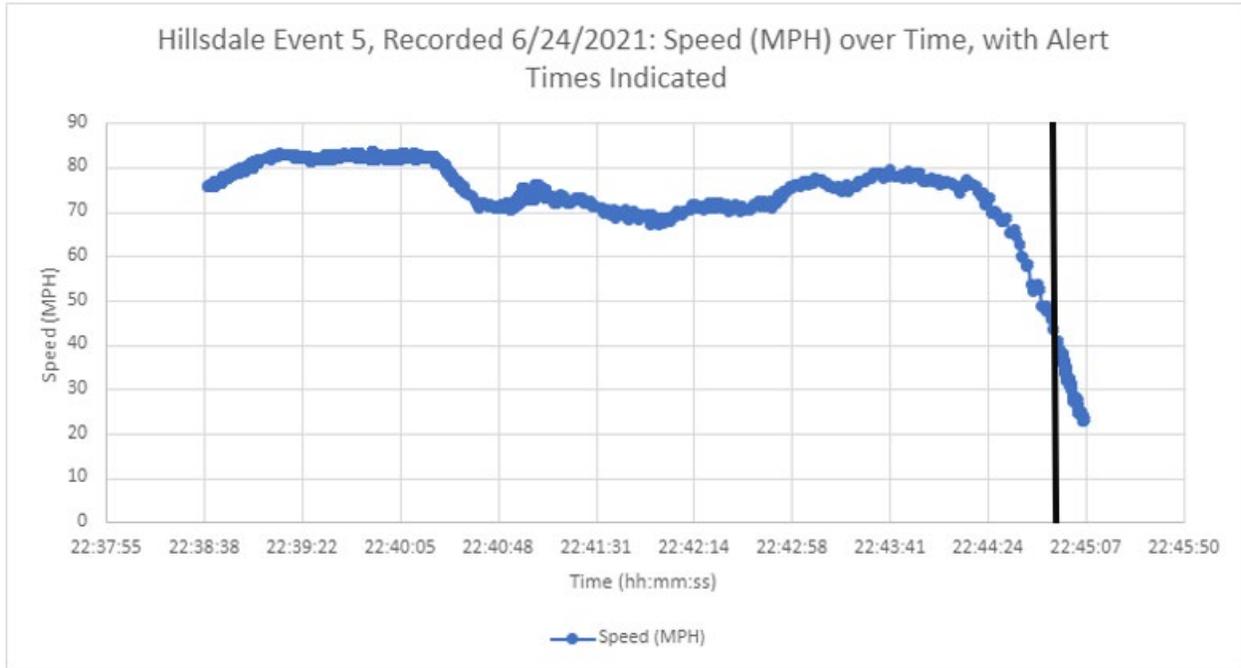
Figure 87. Event 5: Speed Profile.
Source: WYDOT
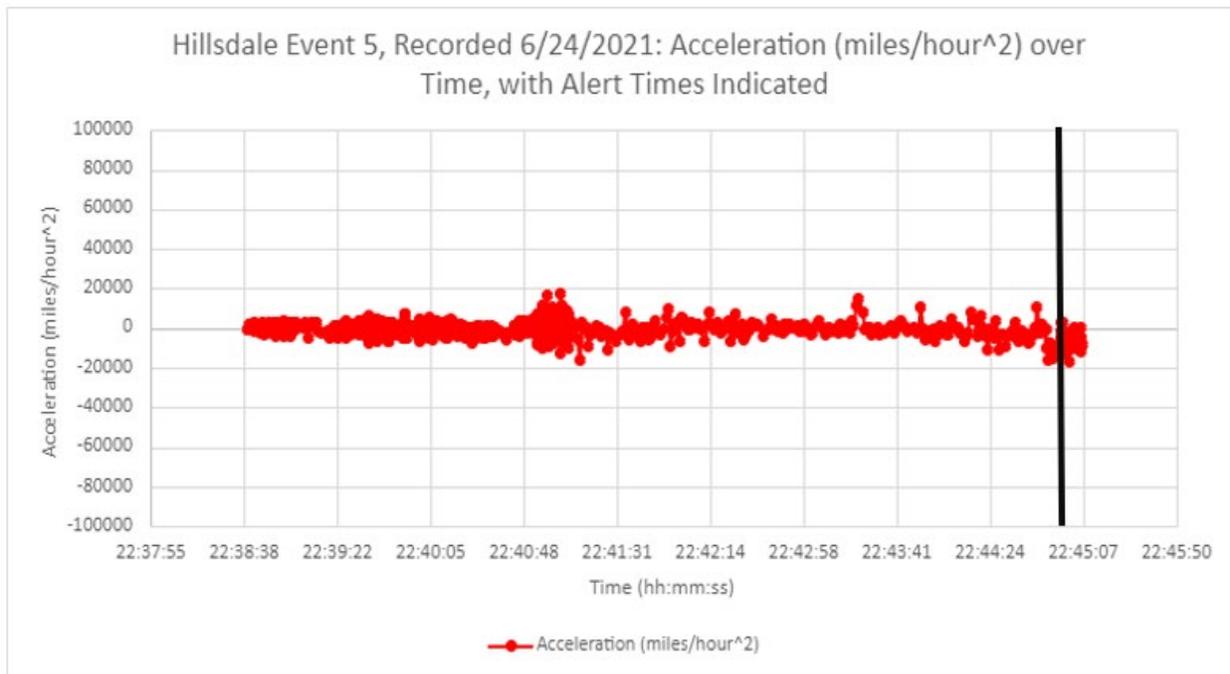
Figure 88. Event 5: Acceleration Profile.
Source: WYDOT

Event 6

At the beginning of the analysis period, the vehicle was traveling westbound 30 MPH, possibly waiting in congested traffic from the approaching work zone (Figure 89). The vehicle received an alert at 23:31:30 and the vehicle continued to reduce speed down to 15 MPH (Figure 90). The vehicle received two additional alerts in quick succession while the vehicle increased speed to 75 MPH. Another speed decrease occurred at 23:35 with the driver hitting the brakes, as can be seen by on the acceleration graph (Figure 91), and the vehicle reduced speed to 40 MPH as a final alert was received. The vehicle left the construction corridor and increased speed up to 75 MPH again. From this analysis, it was determined that the driver **reduced speed**.

Figure 89. Google Earth Image of Construction Event 6.
Source: WYDOT
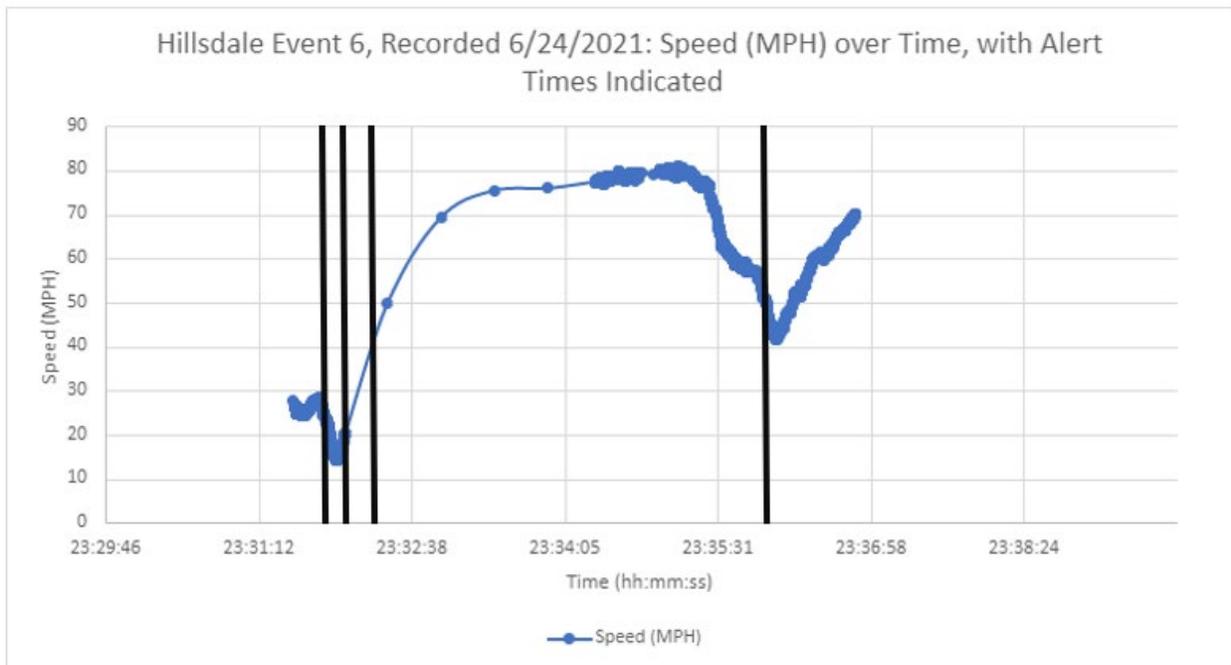
Figure 90. Event 6: Speed Profile.
Source: WYDOT
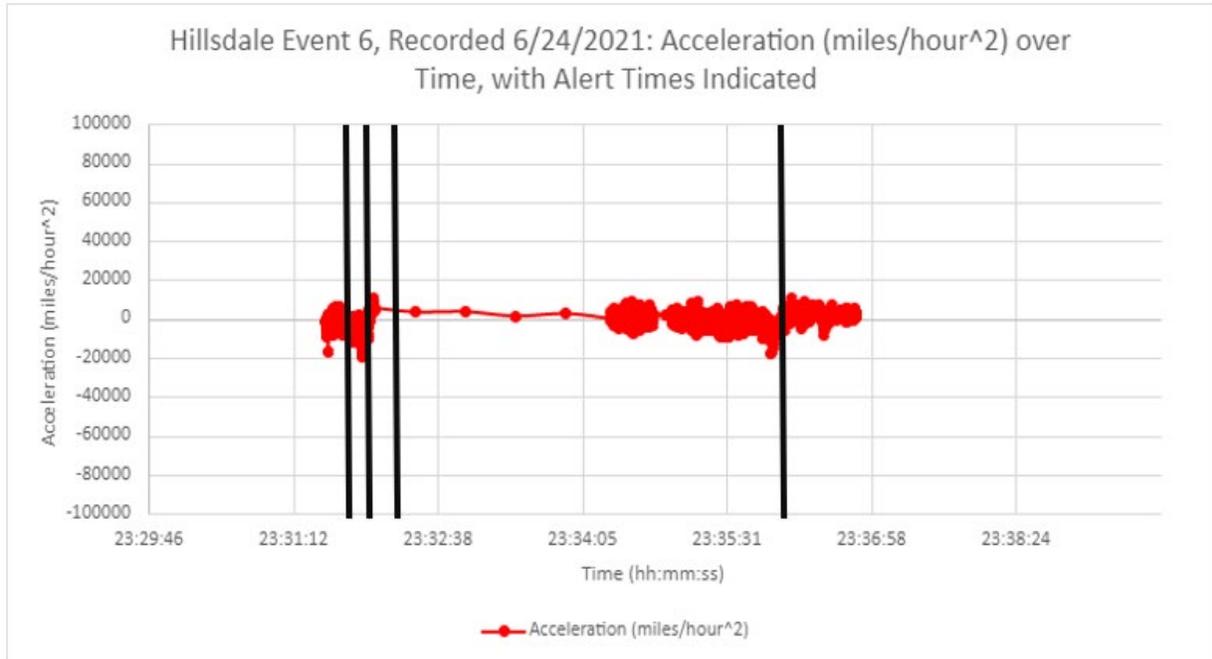
Figure 91. Event 6: Acceleration Profile.
Source: WYDOT

Event 7

The driver was traveling westbound just below the 65 MPH and begun to reduce speed when the construction alert was received (Figure 92). Possibly in response to this alert at 18:49:55, the driver applied the brakes and dramatically reduced speed to 22 MPH (Figure 93). For unknown reasons, BSM data is missing for the next few moments (Figure 94), but it is likely that the driver slowly increased speed up from 22 as they continued through the corridor, again achieving 40 MPH by 18:33 and full 65 MPH speed by 18:34. From this analysis, it was determined that the driver **reduced speed**.

**Figure 92. Google Earth Image of Construction Event 7.**
Source: WYDOT
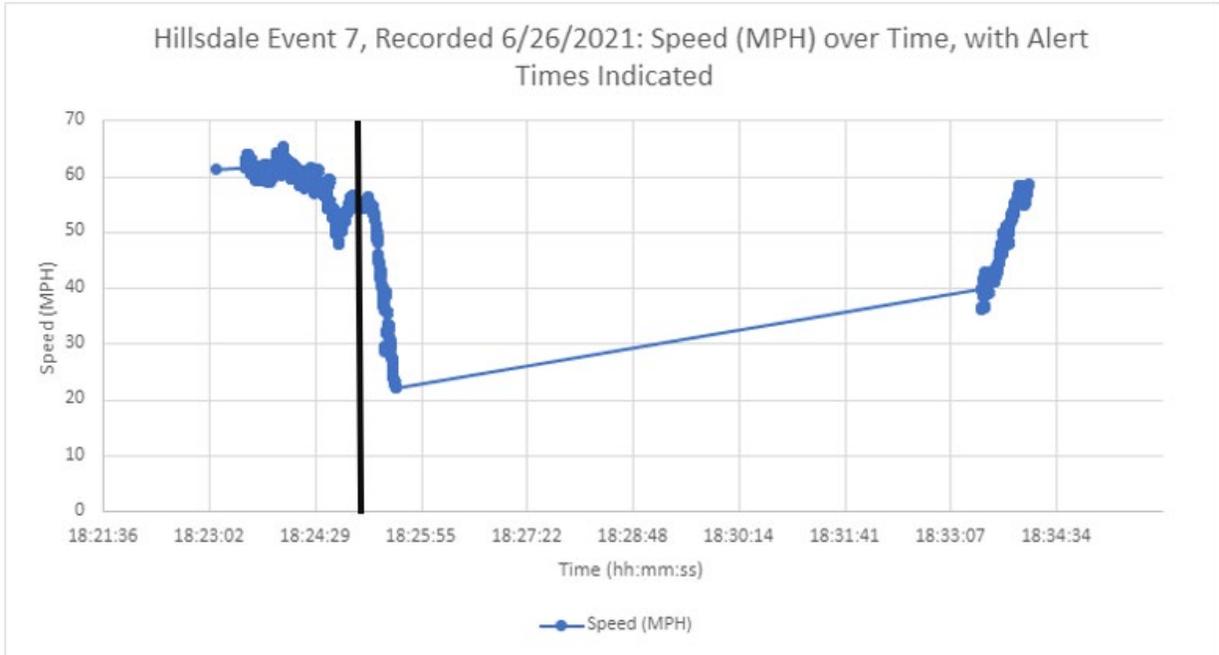
Figure 93. Event 7: Speed Profile.
Source: WYDOT
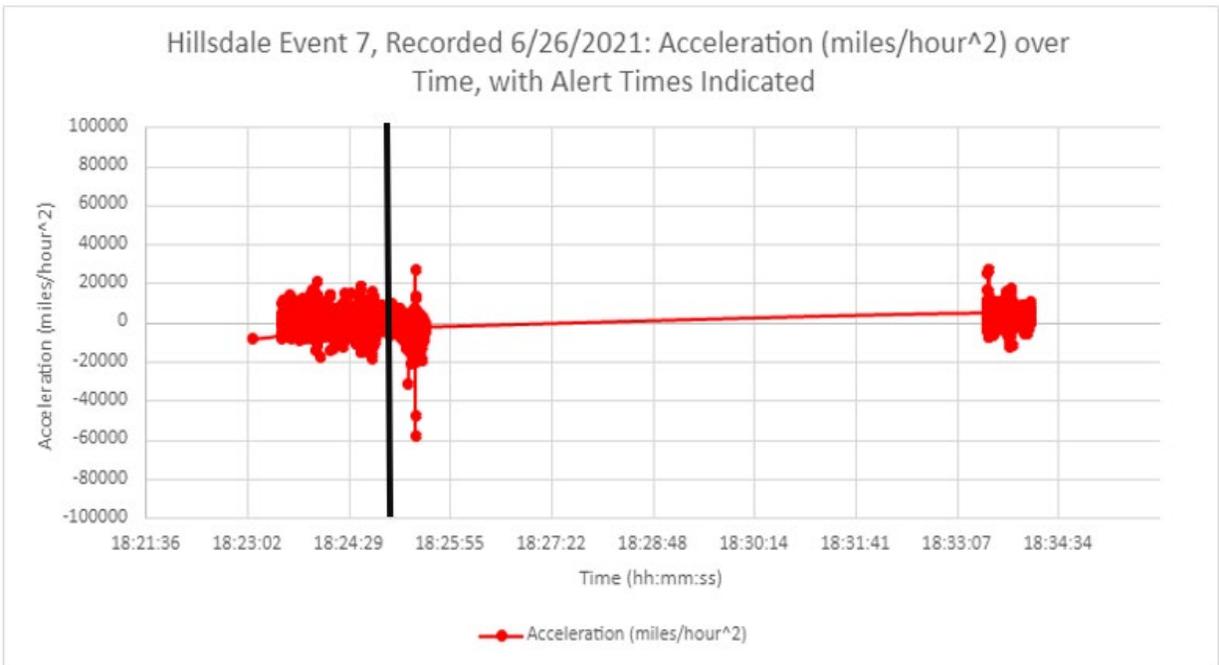
Figure 94. Event 7: Acceleration Profile.
Source: WYDOT

Event 8

The vehicle entered the interstate traveling westbound, accelerating from 17 MPH to 60 MPH (Figure 95). Two construction alerts were received (Figure 96), one just before and one just after 20:10. The driver sped up slowly while entering the construction zone as seen by the low deviations of the acceleration graph (Figure 97), perhaps in response to the construction alerts. The driver kept a low speed for a while, eventually reaching a maximum speed of 60 MPH. Given the slow acceleration rates, it was determined that the driver selected speeds that were lower than behavior typically observed when entering an interstate. From this a driver action of **reduced speed** was assigned to this event.

Figure 95. Google Earth Image of Construction Event 8.
Source: WYDOT
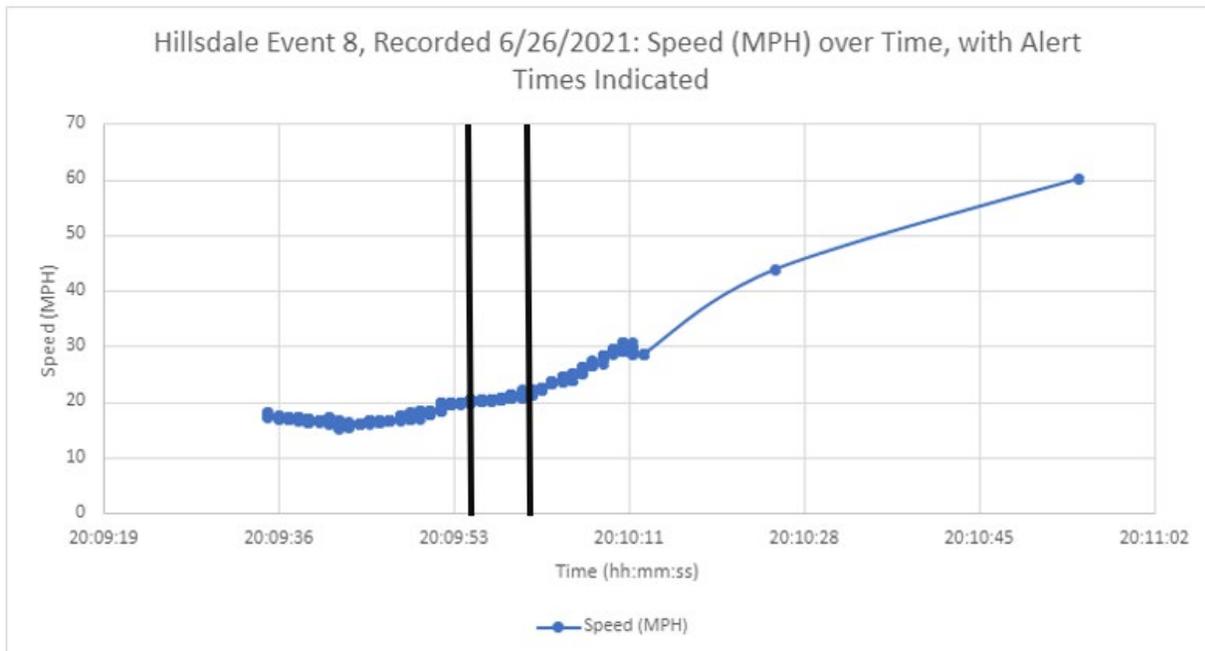
Figure 96. Event 8: Speed Profile.
Source: WYDOT
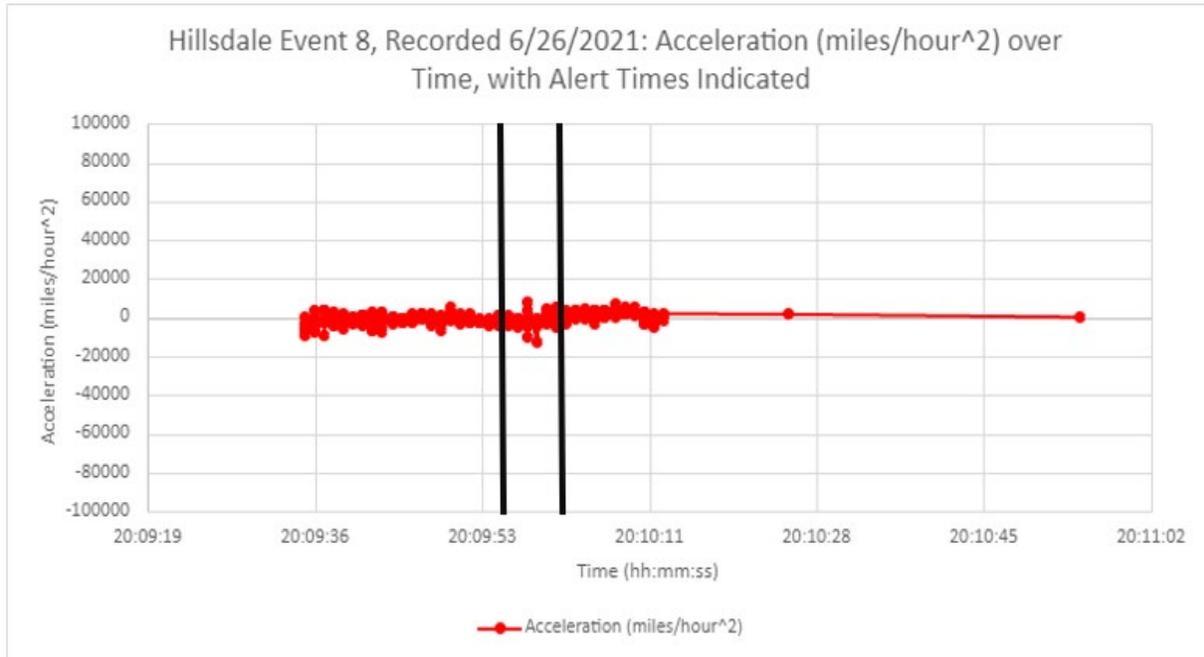
Figure 97. Event 8: Acceleration Profile.
Source: WYDOT

Event 9

The vehicle was heading westbound at approximately 77 MPH when it approached the construction zone prior to the median crossover location (Figure 98). The vehicle had already reduced speed to approximately 58 MPH by the time it entered the active construction zone (Figure 99), receiving an alert at 10:57:55 to this effect. The vehicle then proceeded at a reduced speed between 60 and 65 MPH through the work zone without further incident (Figure 100). From this analysis, it was determined that the driver **reduced speed**.

Figure 98. Google Earth Image of Construction Event 9.
Source: WYDOT
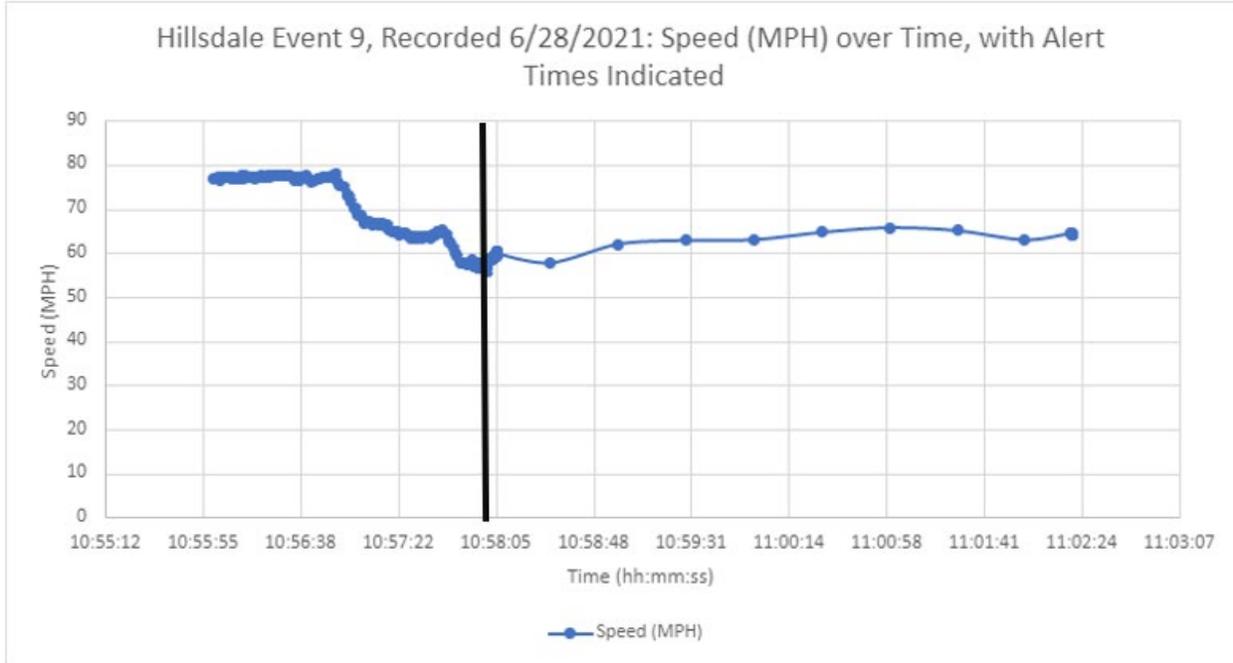
**Figure 99. Event 9: Speed Profile.**
Source: WYDOT
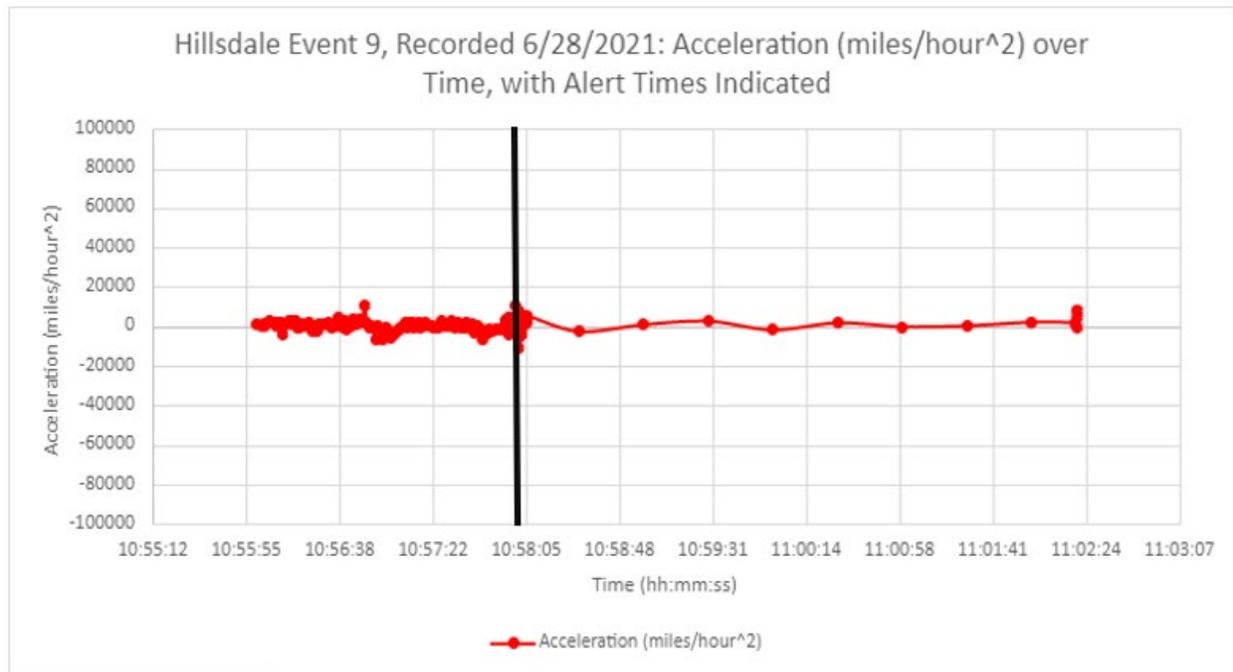
Figure 100. Event 9: Acceleration Profile.
Source: WYDOT

Event 10

The vehicle was traveling westbound through the construction zone at an already reduced speed of between 54 and 60 MPH (Figure 101). As the vehicle completed the second cross over to return to the proper westbound lane of travel, an alert was received by the vehicle. The driver completed the median crossover and began speeding back up to the normal speed limit around the time of the alert, achieving and maintaining a speed of 75 MPH as the vehicle exited the work zone (Figure 102). Unlike the vehicles involved in most other events analyzed, the vehicle in this event only received one alert, which was quite late into the construction zone and therefore of less use to the vehicle operator (Figure 103). From this analysis, it was determined that the driver **took no action**.

Figure 101. Google Earth Image of Construction Event 10.
Source: WYDOT
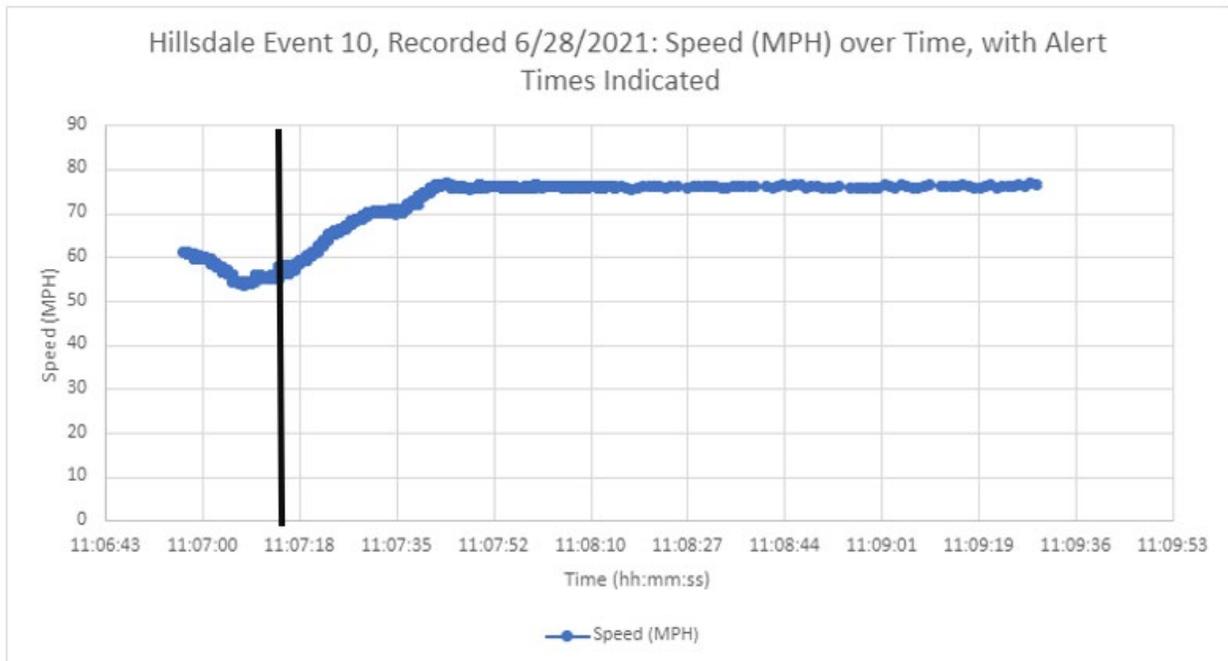
Figure 102. Event 10: Speed Profile.
Source: WYDOT
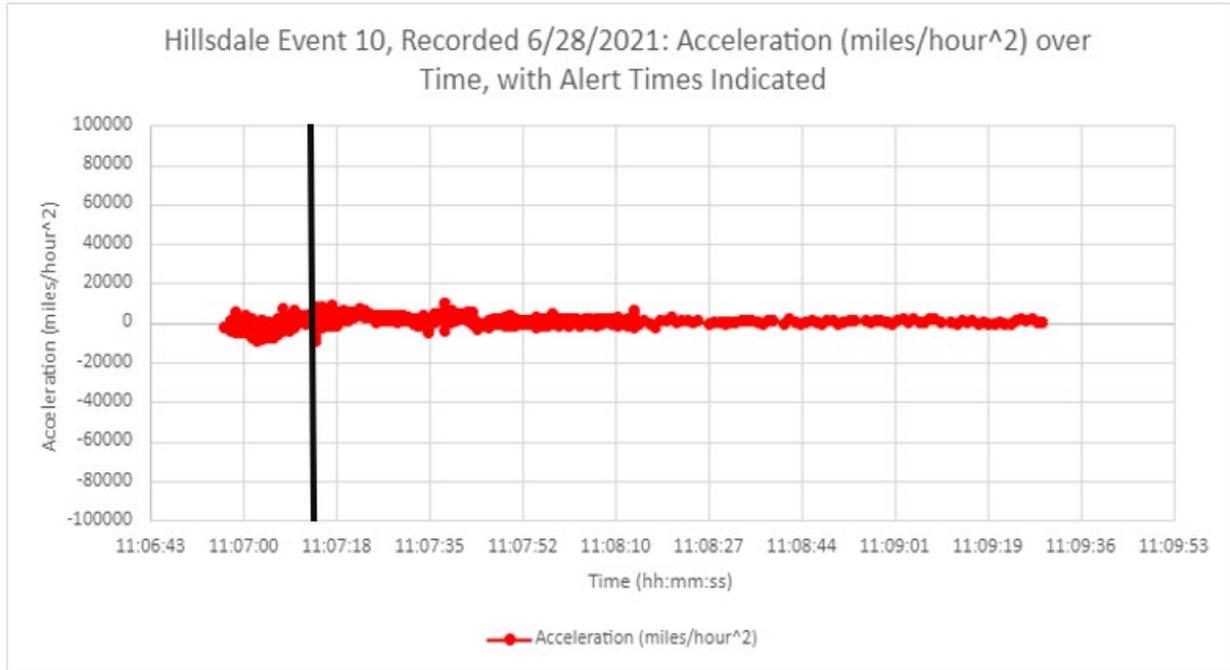
Figure 103. Event 10: Acceleration Profile.
Source: WYDOT

Event 11

Traveling eastbound, this driver approached the work zone around 75 MPH (Figure 104). The driver received three alerts concerning upcoming construction conditions in rapid succession at 13:59:00, 13:59:05, and 14:00:17, and reduced speed from 75 to 62 MPH, possibly in response to these alerts (Figure 105 and Figure 106). The driver crossed over the median and entered the opposing side of traffic, based on construction conditions, and received another alert at 14:01:04, at which time the vehicle was already in the active area of the construction zone. The driver proceeded through the bridge replacement zone at around 65 MPH, and the vehicle received two more alerts several minutes later (not depicted on the graph), including one when the vehicle crossed back to the original interstate side of travel, and another when the vehicle exited the overall work zone. A total of six alerts were received in all, which appear to correlate with the driver's actions and responses. From this analysis, it was determined that the driver **reduced speed**.

**Figure 104. Google Earth Image of Construction Event 11.**
*Source: WYDOT*
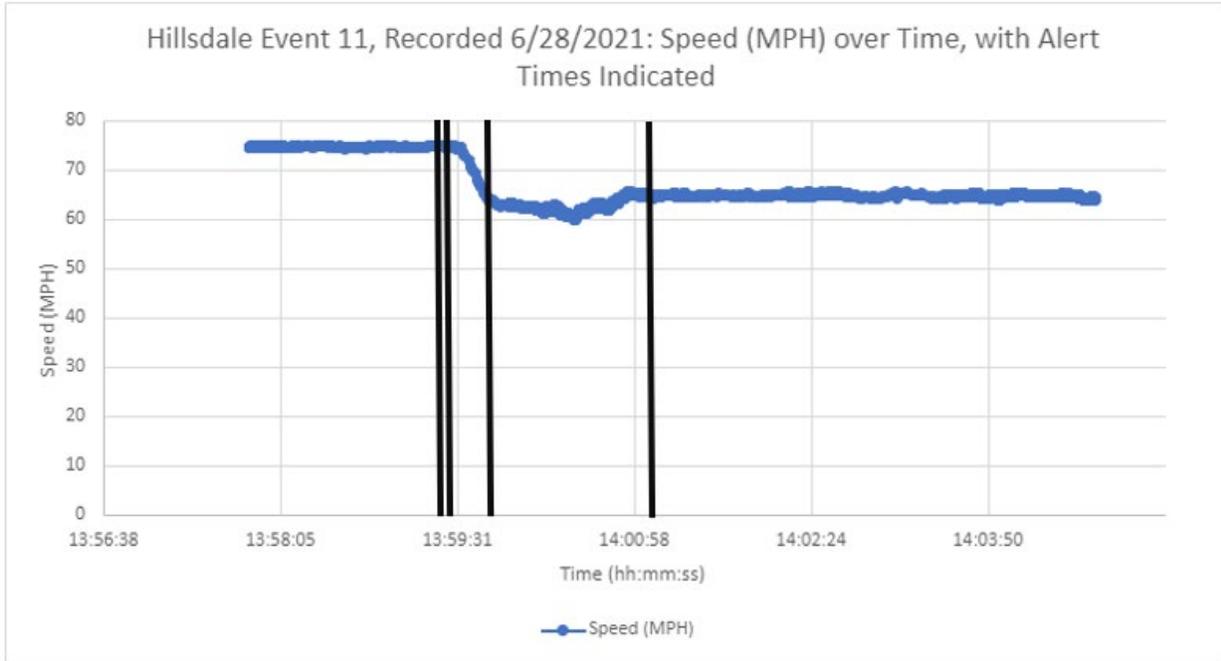
Figure 105. Event 11: Speed Profile.
Source: WYDOT
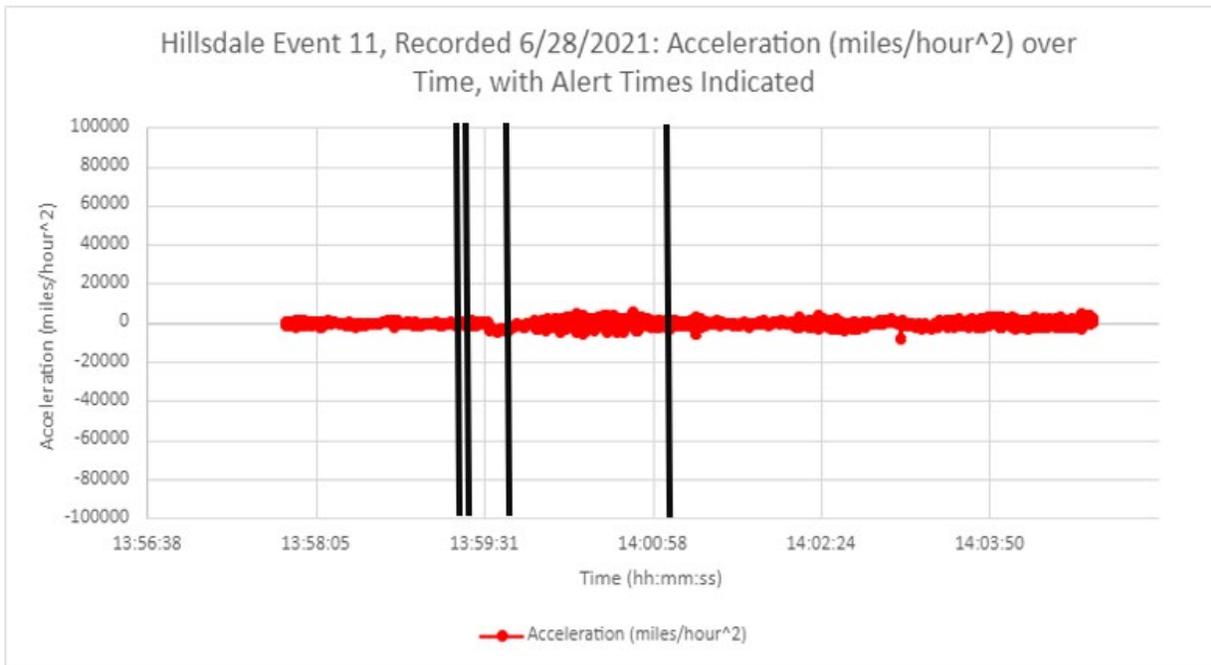
Figure 106. Event 11: Acceleration Profile.
Source: WYDOT

Event 12

The vehicle was traveling westbound at approximately 83 MPH in a speed limit was 75 MPH (Figure 107). The driver approached the construction work zone at 16:36 and had to reduce speed to 40 MPH (Figure 108 and Figure 109). A single construction alert was received by the vehicle about thirty seconds later. Possibly in response to this initial warning, the driver maintained low speeds between 30 and 50 MPH through the work zone; however, the vehicle did not receive any additional construction alerts. From this analysis, it was determined that the driver **reduced speed** given the low speed that was maintained through the construction zone.

Figure 107. Google Earth Image of Construction Event 12.
Source: WYDOT
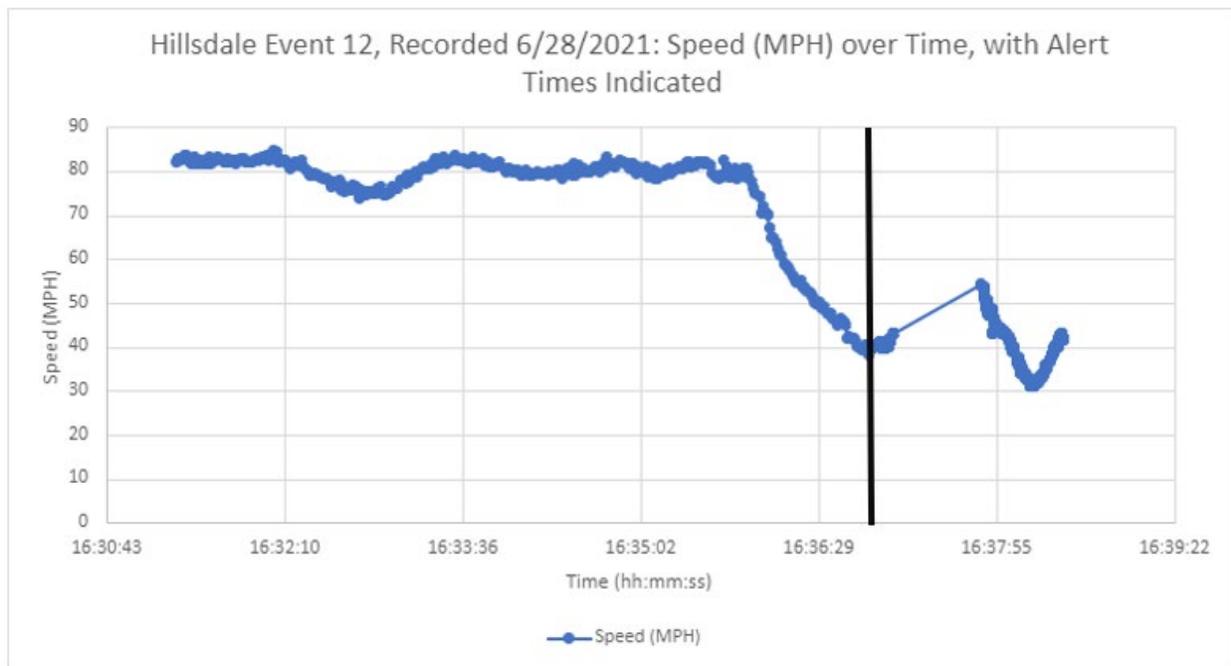

Figure 108. Event 12: Speed Profile.
Source: WYDOT
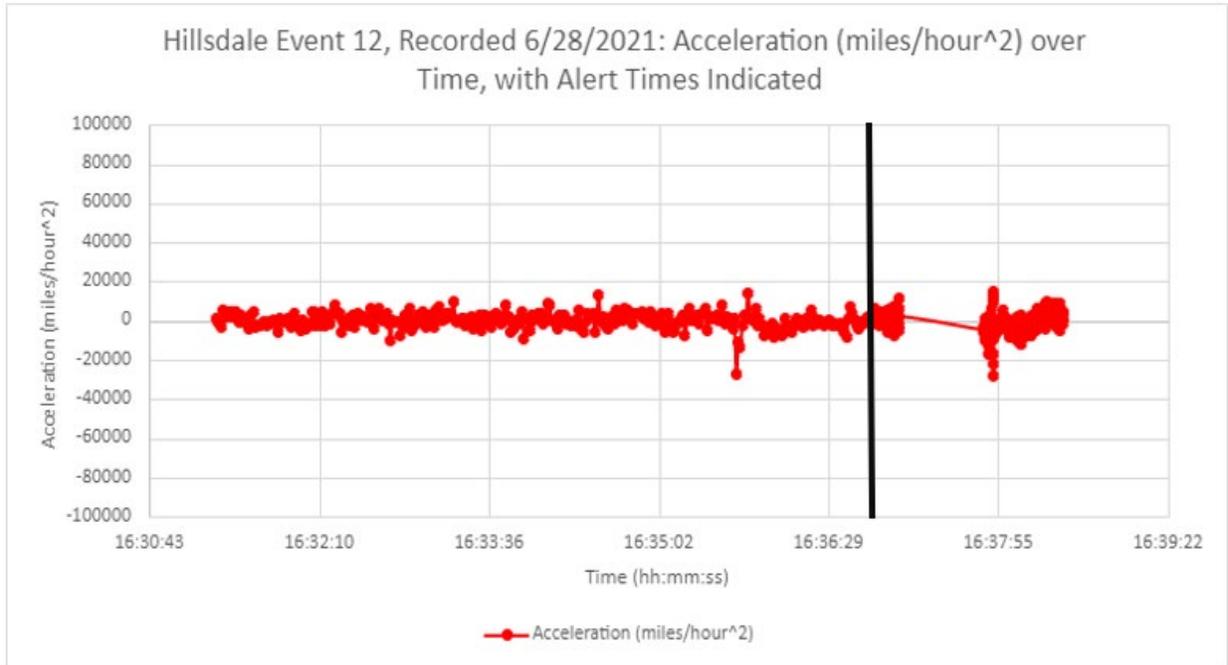
Figure 109. Event 12: Acceleration Profile.
Source: WYDOT

Event 13

The westbound traveling vehicle had slowed down while approaching the construction zone when the vehicle received two construction alerts at 16:42 just after the vehicle had completed the median crossover (Figure 110). Then, continuing westbound, the vehicle did not receive another warning until the vehicle was exiting out of the construction zone around 16:47. At that point, the driver was again speeding up to resume travel at 65 MPH (Figure 111 and Figure 112). Approximately three minutes of data is missing between these two analysis constraints, but it is not clear that any action was taken by the driver in response to the construction alerts. From this analysis, it was determined that the driver **took no action**.

Figure 110. Google Earth Image of Construction Event 13.
*Source: WYDOT*
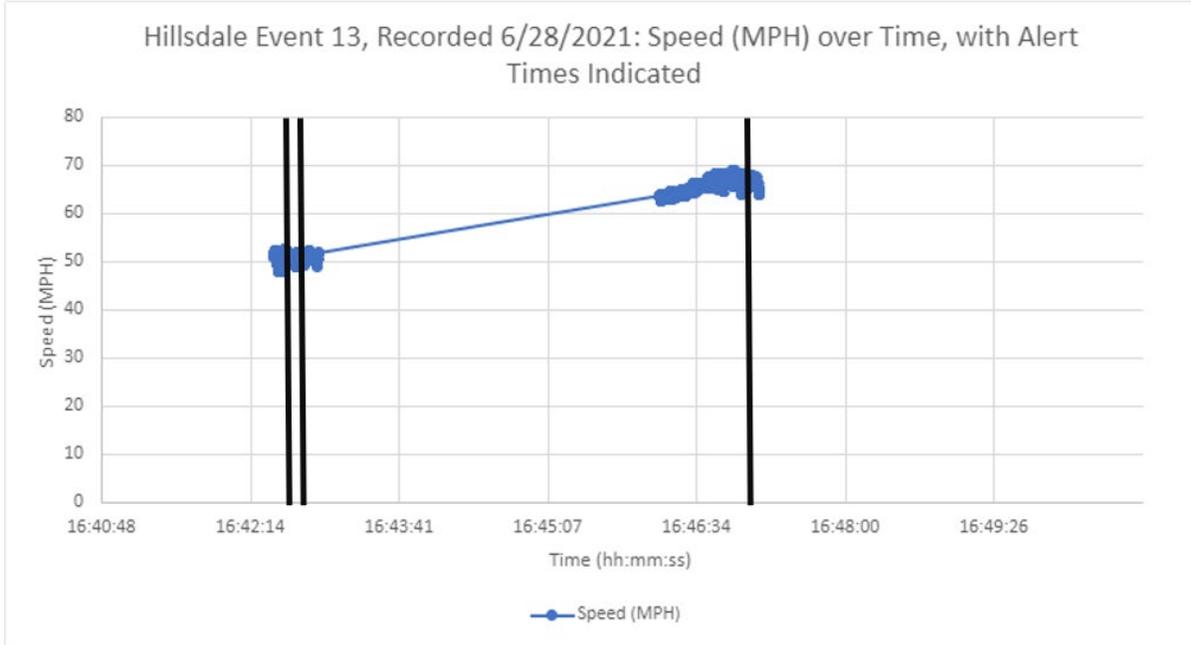
Figure 111. Event 13: Speed Profile.
Source: WYDOT
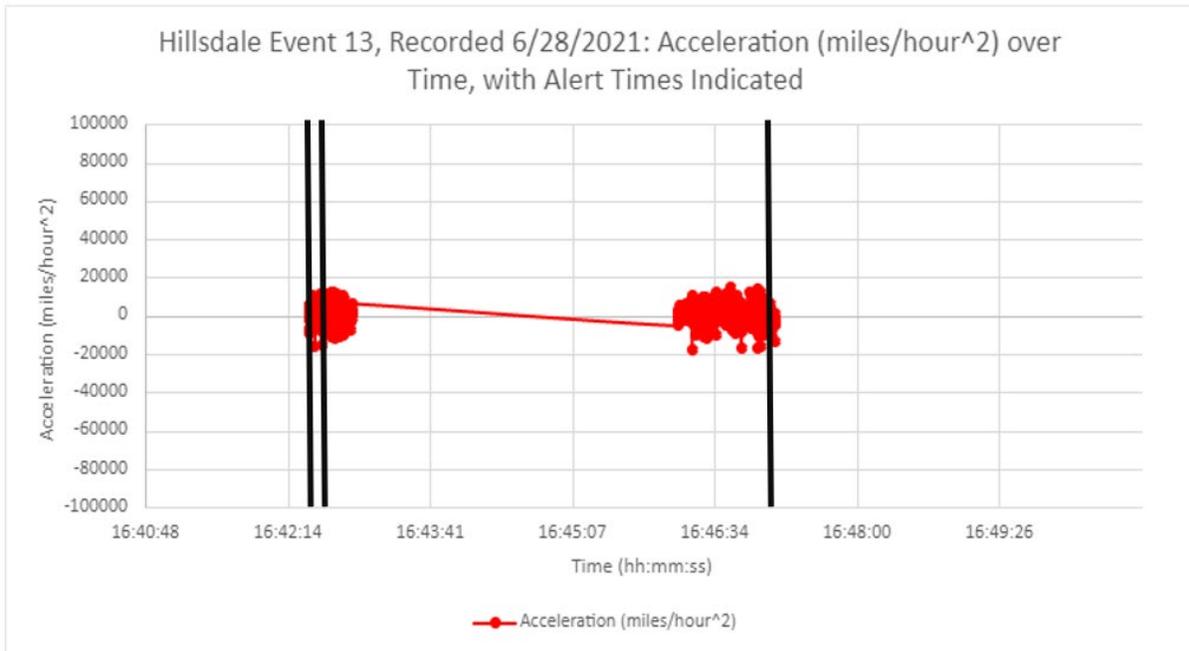
Figure 112. Event 13: Acceleration Profile.
Source: WYDOT

Event 14

The vehicle was traveling westbound when it encountered a construction zone median crossover (Figure 113). Just prior to the crossover, the driver received three construction alerts, and the driver maintained a reduced speed at approximately 55 MPH through the zone (Figure 114 and Figure 115). However, this is the course of action that the driver was already maintaining, and it is unclear that the driver decisions were influenced by the CV alerts. From this analysis, it was determined that the driver **took no action**.

Figure 113. Google Earth Image of Construction Event 14.
Source: WYDOT
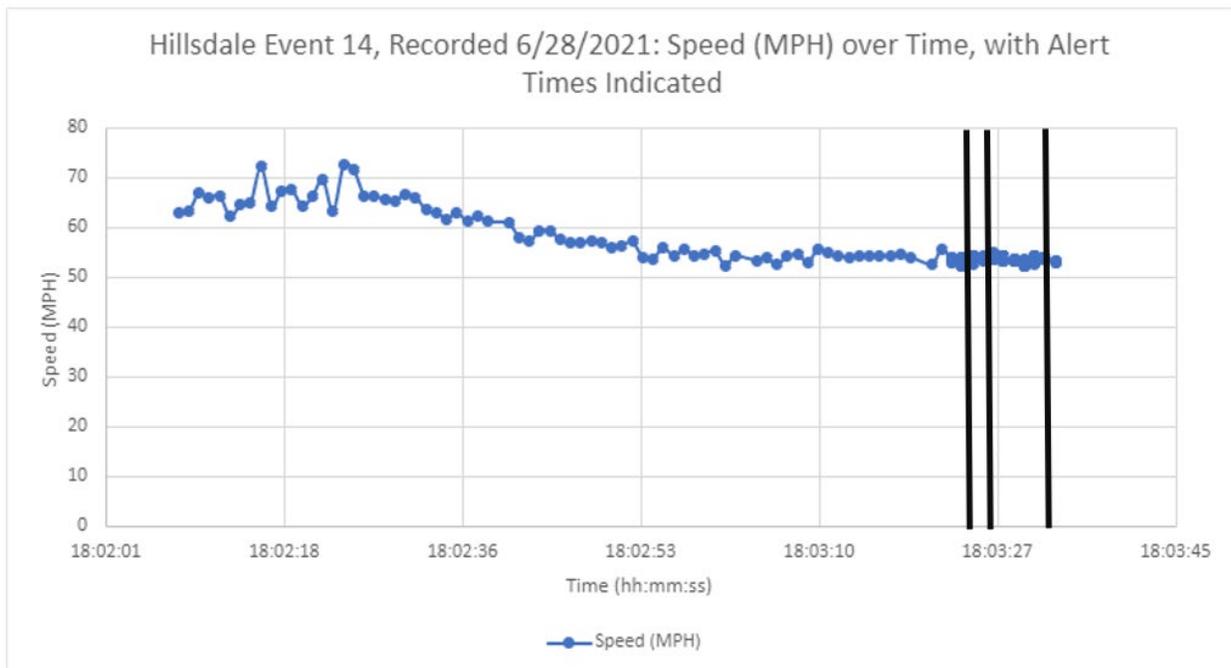
Figure 114. Event 14: Speed Profile.
Source: WYDOT
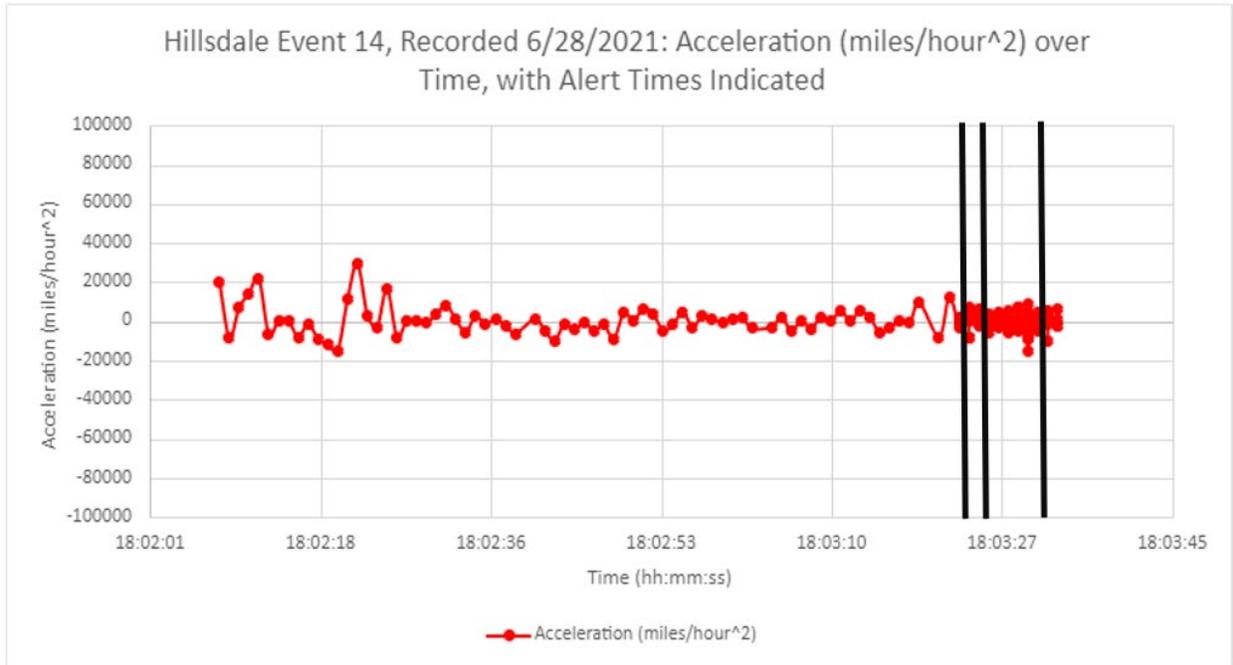
Figure 115. Event 14: Acceleration Profile.
Source: WYDOT

Event 15

Already traveling in the construction zone, the driver was heading westbound at 60 MPH (Figure 116). The vehicle reduced speed yet further to 50 MPH in order to complete a median crossover back to the normal lanes of travel (Figure 117 and Figure 118). At this time, the driver received a single ITIS construction zone alert that was somewhat late. So, the vehicle resumed travel at 67 MPH through the end of the construction zone, unrelated to the alert. From this analysis, it was determined that the driver **took no action**.

Figure 116. Google Earth Image of Construction Event 15.
Source: WYDOT
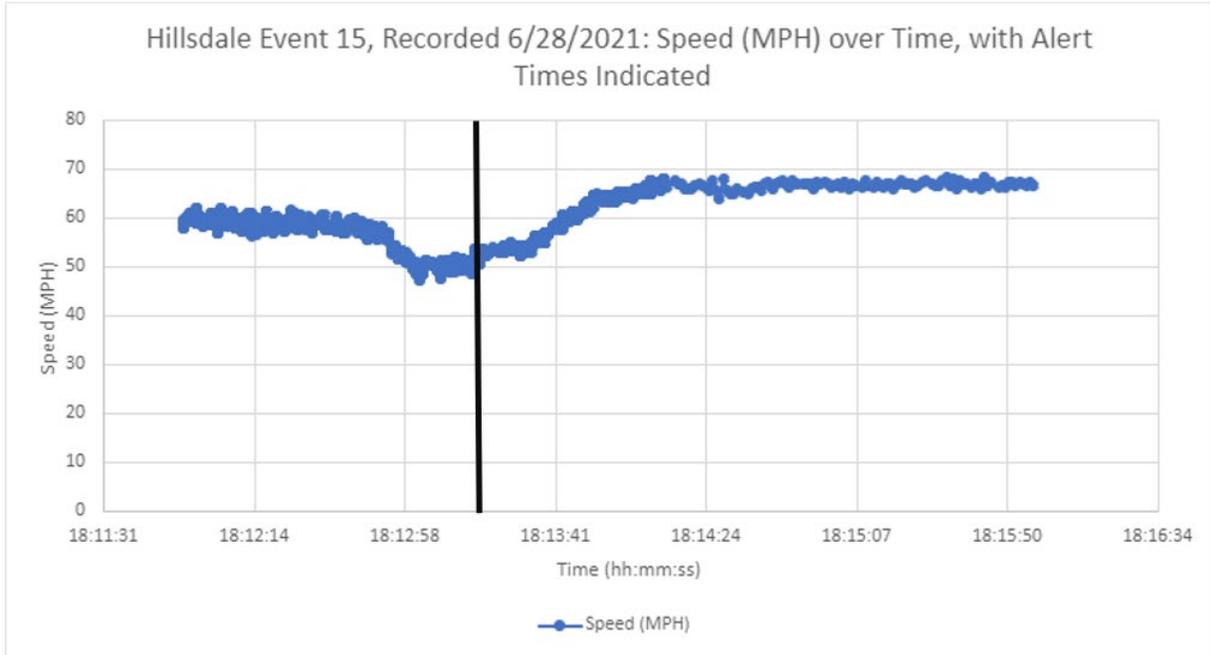
Figure 117. Event 15: Speed Profile.
Source: WYDOT
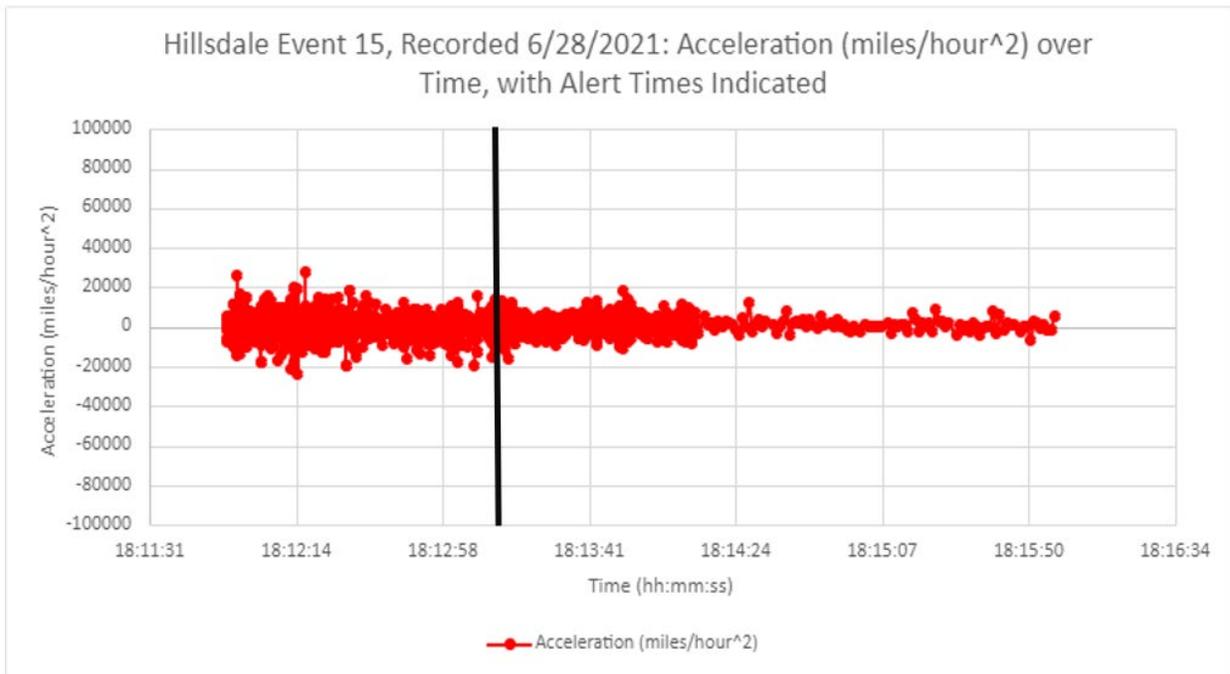
Figure 118. Event 15: Acceleration Profile.
Source: WYDOT

Event 16

Traveling eastbound at 75 MPH, the vehicle received an alert about the upcoming construction conditions (Figure 119). Thirty seconds later, the driver reduced speed to approximately 65 MPH, either in response to the alert or in response to the physical conditions of the construction zone and its associated crossover. The vehicle maintained a slightly reduced speed of 65 MPH through the construction zone and received three additional alerts between 22:48 and 22:50 as it left the work zone (Figure 120 and Figure 121). Finally, the vehicle exited the interstate just after the construction zone, and it proceeded south. Some safety action was taken by the driver in the construction zone, but the delay in timing does not clearly indicate that it was associated with the CV alert system's messages. From this analysis, it was determined that the driver **took no action**.

**Figure 119. Google Earth Image of Construction Event 16.**
Source: WYDOT
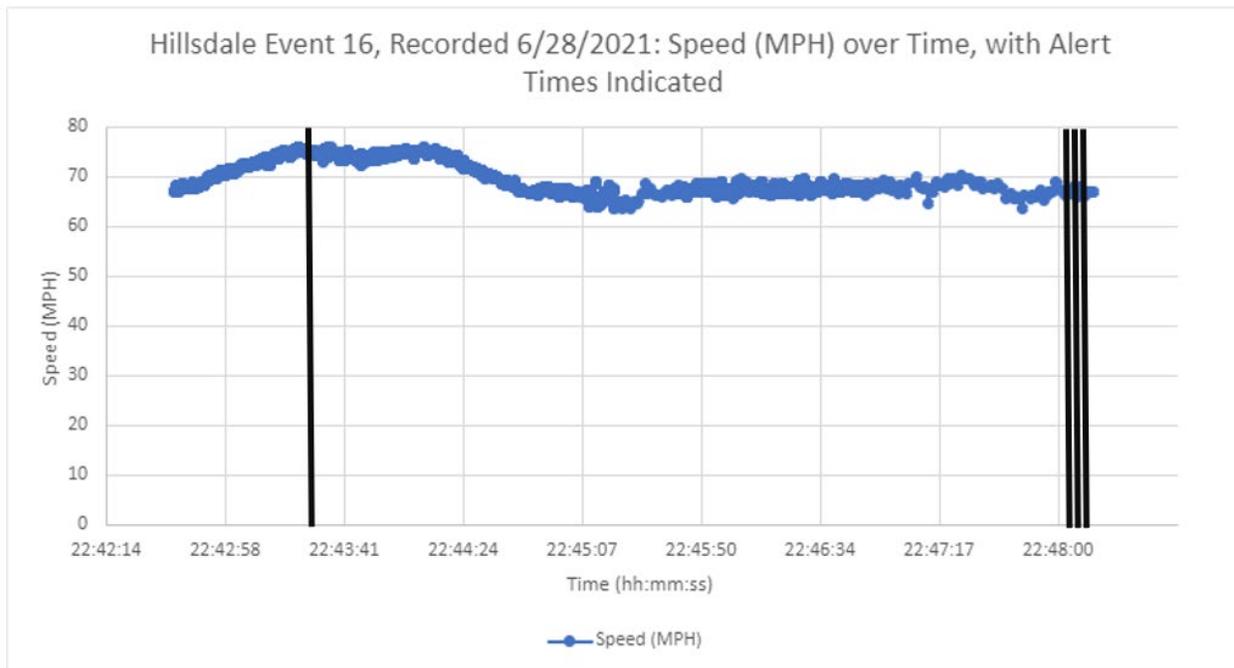
**Figure 120. Event 16: Speed Profile.**
Source: WYDOT
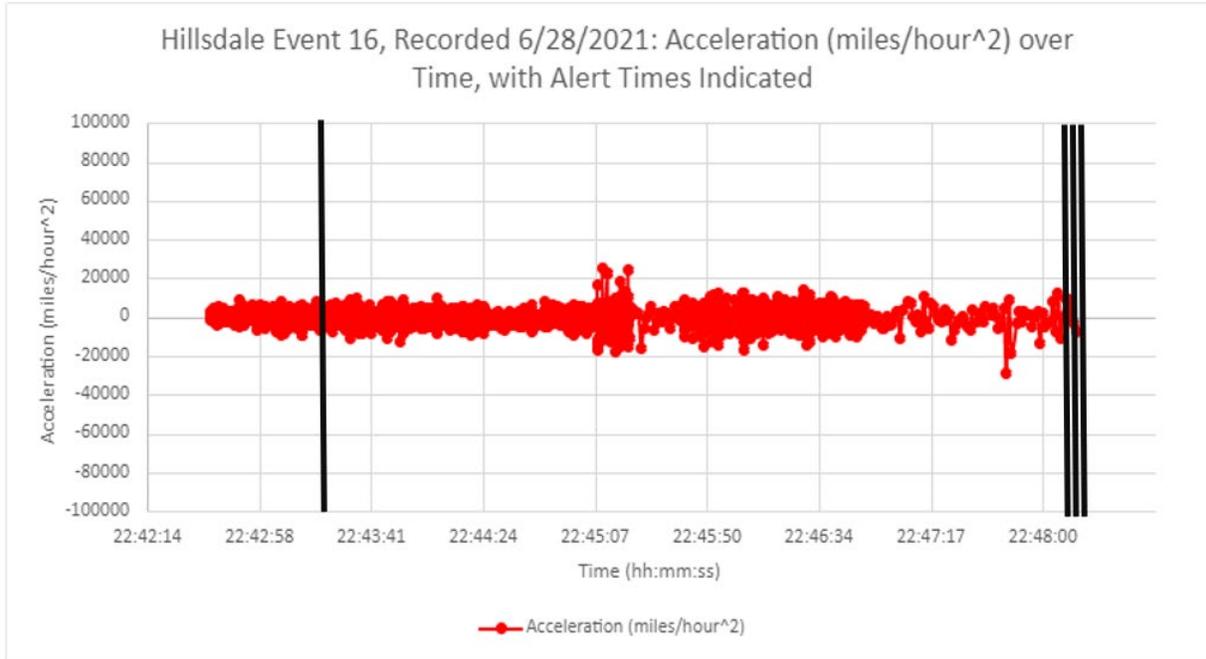
Figure 121. Event 16: Acceleration Profile.
*Source: WYDOT*

Appendix F. Drivers Behavior Under Winter Storm Alert

This appendix presents the results from an analysis of CV drivers experiencing alerts associated with a winter storm on February 2, 2022 on the I-80 in Wyoming. All times in this appendix are in UTC reported in military Hours:Minutes:Seconds on the dates indicated in each narrative (2/2/2022).

Overview of February 2, 2022 Winter Storm

A low-pressure storm event occurred in Wyoming from Tuesday, February 1st through Thursday, February 3rd. Periods of moderate snow led to slick and snow packed roads with portions of black ice. The temperatures dropped near the end of the storm. Southeastern Wyoming was the hardest hit by the storm, but all areas of I-80 were impacted. Figure 122 shows the forecasted impacts of the storm in a YouTube video prepared by WYDOT to inform travelers of the upcoming storm. Note that CV pilot data is stored in UTC time and the times in the impact video are in local time, which is Mountain Standard Time or six hours behind UTC.
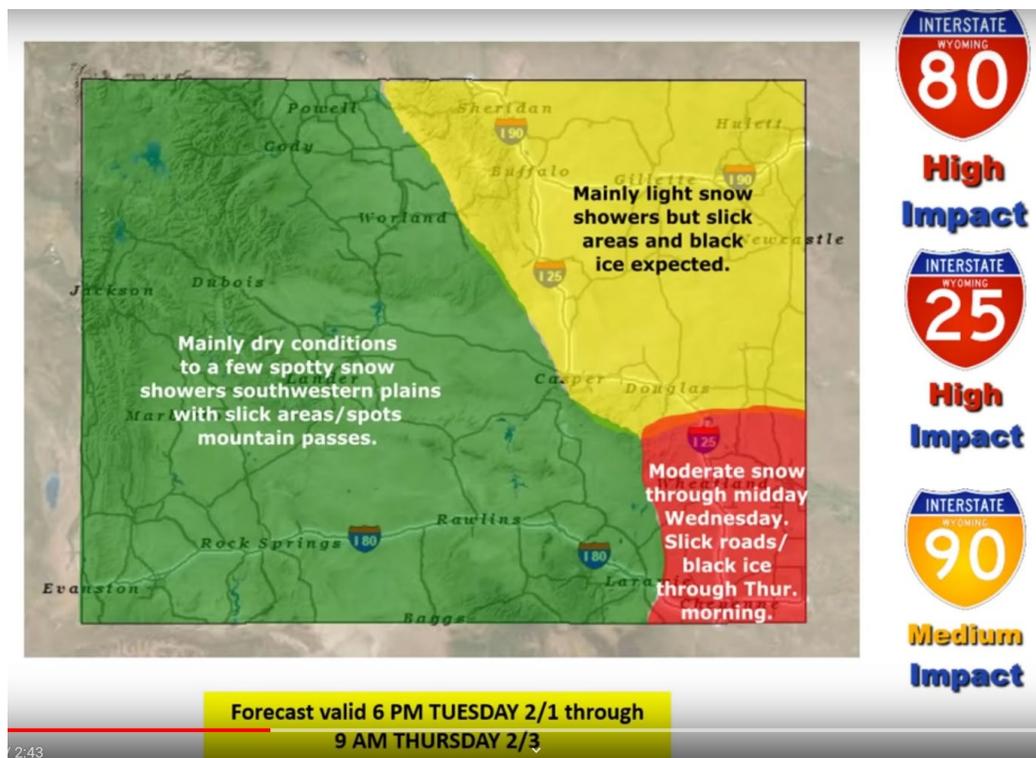
Figure 122. Forecasted Impacts for February Winter Storm Event
Source: WYDOT YouTube Channel https://youtu.be/D4WlfctRNfA

Driver alerts for February 2nd were compiled and 1,930 driver alerts were found once speed limit violation alerts (SLVA) and forward collision warning (FCW) were removed. Table 49 summarizes these alerts by ITIS code.

Table 49. Summary of Driver Alerts for February 2, 2022.

ITIS Code	Count	Code Description
2	7	Accidents / Incidents
268	665	Speed limit
1025	74	Construction
4868	**518**	**Snow**
5127	9	Strong Winds
5383	**40**	**Visibility Reduced**
5385	**119**	**Blowing Snow**
5895	92	Wet Pavement
5906	**186**	**Ice**
5907	**116**	**Icy Patches**
5908	**60**	**Black Ice**
5927	**8**	**Snow drifts**
6011	13	Dry Pavement
6156	7	Snow Tires or Chains Required
7443	16	Reduce Your Speed
1,930		Sum of all alerts
1,047		**Sum of Key Winter Storm Related Alerts** *(highlighted rows)*

Seven of the ITIS codes were identified as being most relevant to the winter storm event. There were 1,047 of these alerts, which were then mapped in Google Earth (Figure 123). Three clusters of alerts located outside of the urban areas were selected for analysis, listed in Table 50.

Figure 123. Mapping of February 2nd Winter Strom Driver Alerts
Source: WYDOT

Table 50. Analysis Corridors for Winter Storm Driver Alerts

Corridor	MP Range	# of Alerts	Description
A	139-159	366	East of Point of Rocks and West of Red Desert/Wamsutter
B	322-326	71	Summit Area, East of Laramie
C	334-344	31	East of Buford

The first corridor is in the central part of the I-80 corridor between Rock Spring and Rawlins in an area west of Point of Rocks. The heavy concentration of 366 driver alerts in this 20-mile corridor can be seen in Figure 124. The second corridor had 71 driver alerts and is a four-mile corridor located just east of Laramie in an area known as the Summit (Figure 125), where Interstate 80 tops out at an elevation of 8,640 feet. The last analysis corridor is a 10-mile segment located just east of the Buford exit and had 31 driver alerts on February 2nd (Figure 126).

Figure 124. Winter Storm Driver Alerts in Corridor A
Source: WYDOT
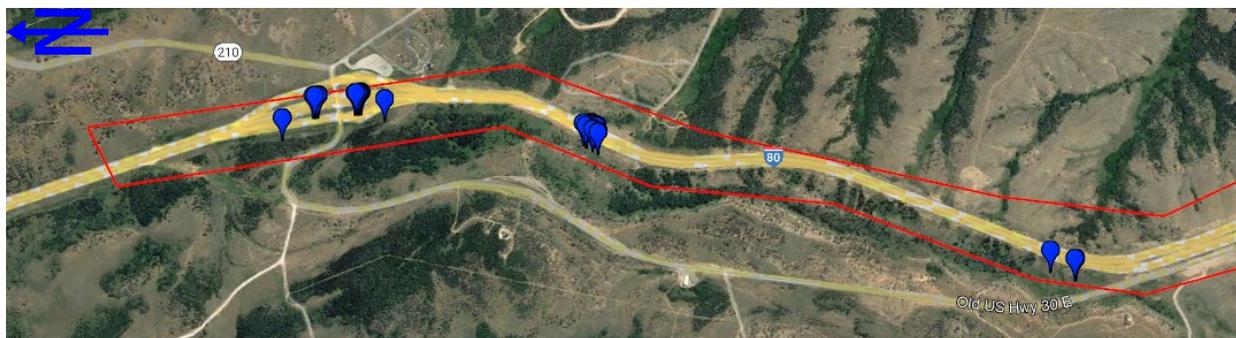
Figure 125. Winter Storm Driver Alerts in Corridor B.
Source: WYDOT

Figure 126. Winter Storm Driver Alerts in Corridor C
Source: WYDOT

The BSM data for each of these corridors were queries for February 2nd. The BSM data for all static ID associated with snowplows and highway patrol vehicles were removed from the dataset since these vehicles are excluded from the driver action analyses given their unique driver behaviors. Since the alert data does not contain vehicle IDs as part of the system design to protect privacy, the alert and BSM data has to be matched based on time and spatial data.

For Corridor A (Figure 124), there were 16,810 BSM records after the snowplow and highway patrol records were removed. From the alert data, it was found that the winter storm associated alerts in the corridor began around 16:33 UTC time and the last alert for the day was at 22:09 UTC time. Almost half of the BSM records (8,565) occurred before the first winter storm alert, indicating they were associated with an alert-type that was not part of this analysis. Note that these 8,565 BSM records were associated with two unique vehicle events. An event with 3,841 BSM records matched alerts records for the time period between 20:01 and 20:19 UTC time but when viewed spatially the alerts were found to be in the westbound lane, while the BSM records were in the eastbound lane. There was also a few minutes time lag between the two data types indicating that a westbound vehicle (likely a snow plow or highway patrol) was receiving alerts, while the eastbound vehicle was not. This could be because the eastbound vehicle received the alerts outside of the geofence that the BSM data was queried from or that the conditions in the two directions of the interstate warranted different weather TIMs. The remaining BSM observations weren't found to match with the alert data resulting in **no candidate events from this corridor**.

For Corridor B (Figure 125), there were 6,371 BSM records after snowplow and highway patrol vehicles were removed. The BSM records were found to contain three unique vehicle events that

corresponded to 9 of the corridor B winter storm alerts. Event B1 had 1,666 BSM records associated with five alerts. Two of these alerts were "Icy Patches" and the remaining alerts were for "Snow", "Blowing Snow" and "Ice". Event B2 had 1,717 BSM records associate with two "Snow" alerts. Events B3 and B4 had 2,988 BSM records combined associated with a "Snow" and an "Icy Patches" alert.

For Corridor C (Figure 126), there were 3,107 BSM records after snowplow and highway patrol vehicles. All these records occurred after the last winter storm alert at 21:29:02 indicating that the winter storm alerts were likely given to snowplow and highway patrol vehicles. Therefore, **no qualifying events were found in this corridor**.

A narrative around each alert event was created based on analysis of the driver behavior postulated from the graphed data. One of four driver actions was given to each event by the analyst.

- **Vehicle Reduced Speed** was assigned to events where a notable speed reduction was witnessed after the driver alert was given.
- **Vehicle Stopped** was assigned for events where the analyst found the vehicle speed came to zero after the driver alert was given but the driver remained on the roadway, either in the lane or shoulder areas.
- **Vehicle Exited** was assigned for events where the analyst found the vehicle exited after the driver alert was given.
- **No Action** taken was assigned for events where the analyst found no evidence of deceleration, stopping, or exiting.

From the four events that were analyzed, 2 (50%) vehicles reduced speed; and 2 (50%) vehicles took no action directly responding to the alert. No vehicles exited the highway or stopped as a response to the alert, though in one case the vehicle had previously been stopped just prior to the alert. (Table 51). Therefore, it was determined that 50% of vehicles took some action.

Table 51: Summary of Driver Actions for Winter Storm Alert Events

Event	Number of Alerts	Time of First Alert	Time of Last Alert	Alert Types	Driver Action after Alert
B1	5	2/2/2022 14:35:23	2/2/2022 14:36:03	Icy Patches (2), Snow, Blowing Snow, Ice	Vehicle Reduced Speed
B2	2	2/2/2022 21:33:51	2/2/2022 21:34:40	Snow (2)	Vehicle Reduced Speed
B3	1	2/2/2022 22:37:30	N/A	Snow	No Action
B4	1	2/2/2022 22:42:52	N/A	Icy Patches	No Action

Event B1

While traveling westbound east of the Summit Rest Area (Figure 127), the vehicle gained speed as it powered uphill, reaching a maximum speed of approximately 80 MPH. Then, as the vehicle proceeded towards the high impact weather zone, the driver received a series of three alerts [icy patches, snow, blowing snow] around 14:35:23. Accordingly, the driver reduced speed to approximately 65 miles per hour on the subsequent downhill section (Figure 128). The driver then received two more alerts about dangerous weather conditions [ice, icy patches] around 14:36:03, and continued to **reduce speed**. Throughout this time, no major fluctuations in vehicle longitudinal acceleration were observed, suggesting that the driver always remained in control of the vehicle.

Figure 127: Google Earth Image of Winter Storm Event B1.
Source: WYDOT
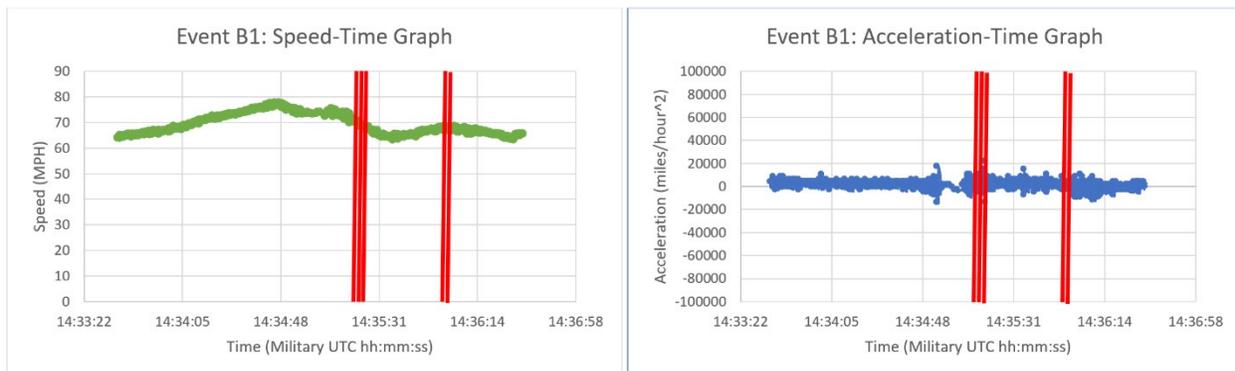
Figure 128. Event B1 Speed and Acceleration Time Graphs.
Source: WYDOT

Event B2

While traveling eastbound in Corridor B (Figure 129), the driver was experiencing windy and snowy conditions and was fluctuating speed between 55 and 70 MPH. The driver received an alert about the winter storm conditions [snow] at 21:33:51, and, traveling downhill in these conditions, decided to **reduce speed** yet further to about 50 MPH, which was then maintained (Figure 130). A second alert [heavy snow] appeared at 21:34:40, and the driver continued driving

at a reduced speed for two more minutes before reaching the bottom of the hill and beginning to speed up.

Figure 129. Google Earth Image of Winter Storm Event B2
Source: WYDOT
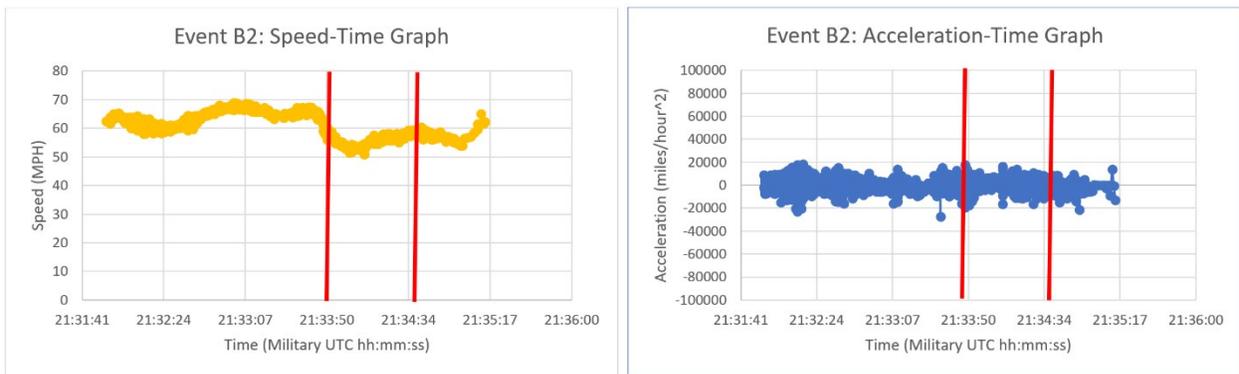
Figure 130. Event B2 Speed and Acceleration Time Graphs.
Source: WYDOT

Event B3

The vehicle was traveling westbound on Corridor B (Figure 131) near the Summit Rest Area at slightly reduced speeds between 63 and 70 MPH. A "snow" alert was received at 22:37:30 just as the vehicle crested the summit and began the decent into Laramie. The driver continued at the original (reduced) speed with only a slight speed reduction (Figure 132). Because the driver was already proceeding cautiously prior to the alert, it was determined that **no action was taken** in response to the winter storm alert.
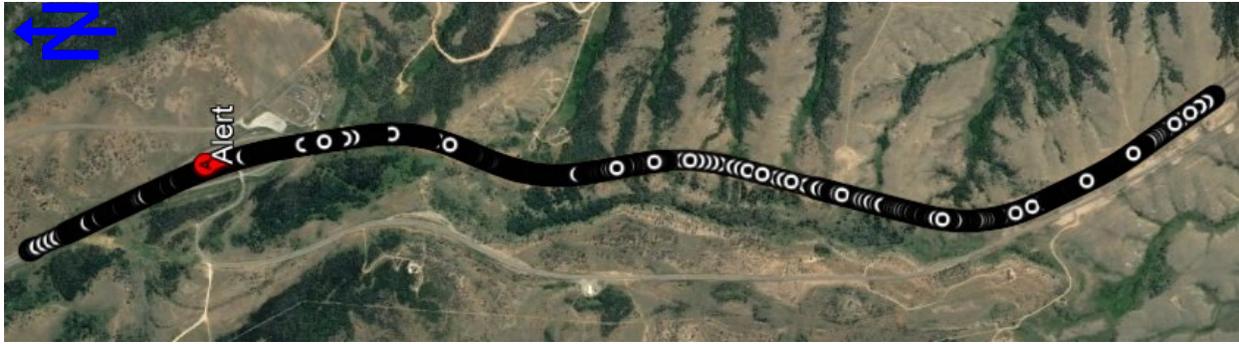
Figure 131. Google Earth Image of Winter Storm Event B3.
Source: WYDOT
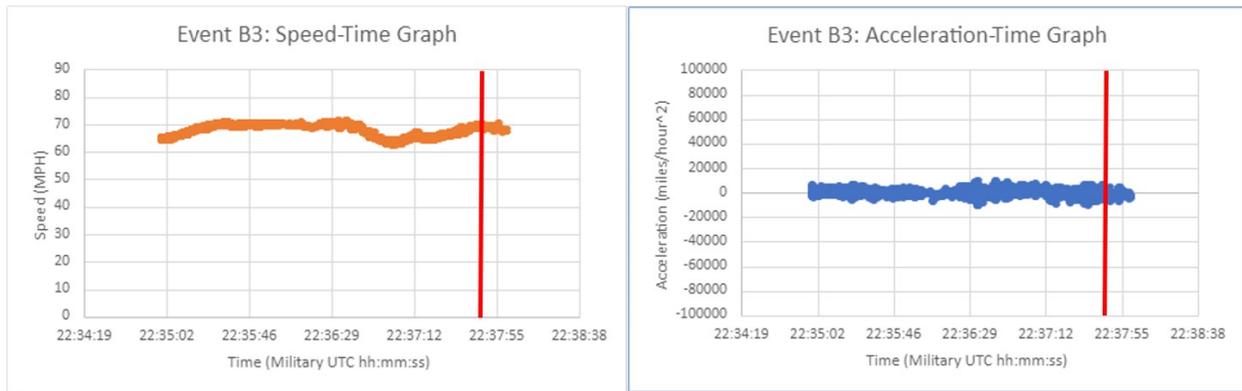
Figure 132. Event B3 Speed and Acceleration Time Graphs
Source: WYDOT

Event B4

The driver was proceeding eastbound through the Summit area (Figure 133). After cresting the Summit at slow speeds of 30 to 45 MPH, the driver reduced speed at the summit of the hill and passed the Rest Area interchange and truck parking area. The driver pulled the vehicle onto the shoulder of the road and came to a complete stop for approximately two minutes (Figure 134), possibly adjusting snow chains or other gear (the reason is uncertain). Then, the driver pulled back onto the highway and steadily accelerated, approaching a speed of 50 MPH by the time an alert was received indicating "icy patches." The driver **took no action** in response to this alert, instead continuing to increase speed to 70 PMH. Acceleration abated momentarily, but the driver chose to continue increasing speed to 80 MPH by the end of the observation window.

Figure 133. Google Earth Image of Winter Storm Event B4.
Source: WYDOT
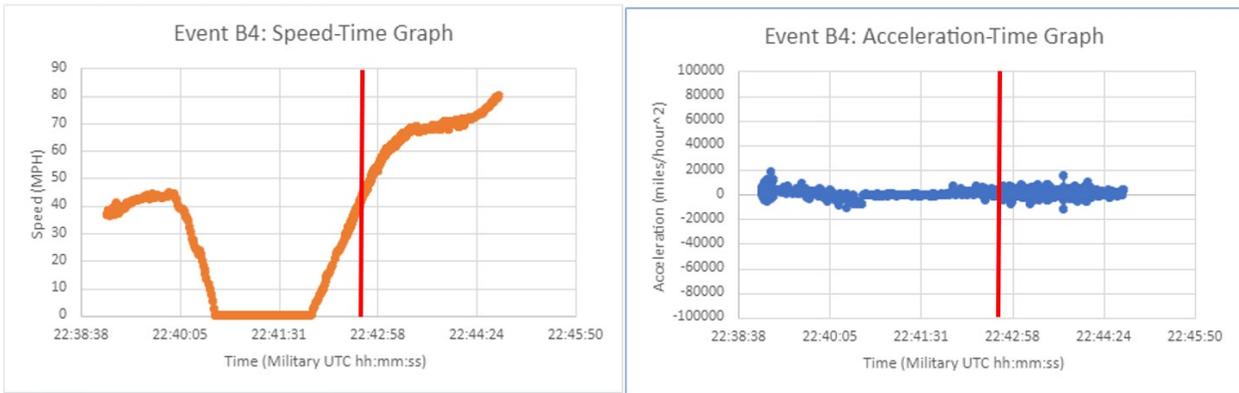
Figure 134. Event B4 Speed and Acceleration Time Graphs.
Source: WYDOT

Appendix G. Analysis of Forward Collision Warning Alerts

Event A

Event A involved two vehicles EB traveling vehicles near MP 67 about 1 mile west of the Little America exit. Both vehicles had dynamically assigned vehicle IDs, therefor neither were a highway patrol or snow plow vehicle. Event A involved 39 separate FCW alerts over a span 8 seconds and about 850 feet, shown by the white markers in Figure 135.

Figure 135. Google Earth Image of FCW Event A showing Location of Alerts.
Source: WYDOT

The lead vehicle (red) was about 4 seconds ahead of the following vehicle (blue), both of which were in the right lane at the beginning of the event (Figure 136). The majority of the alerts (37 of the 39) occurred within first over a 3.5 second span and then two more alerts occurred about 4 second later. Looking at the time and location data, it became clear that the following vehicle passed the lead vehicle with the passing maneuver happening near the beginning of the alerts. Around the time of the last two alerts the vehicles were in the middle of the passing maneuver.

Figure 137 shows the speeds of the two vehicles with the lead vehicle (bottom line) traveling around 26.5 meters per second at the time of the initial alerts. This vehicle can be seen gradually decelerating at the beginning of the analysis period, prior to the alerts, and from the BSM elevation data, it was found that the vehicles were on a mild upgrade. The following vehicle at the beginning of the analysis (top line) is shown to be traveling at higher speeds, decelerating when it

approaches the lead vehicle and then beginning to increase speed as it prepared to pass the lead vehicle. The 39 alerts are shown as vertical lines in the graph. At the time of the initial alerts it is estimated that the following vehicle was about 200 feet behind the lead vehicle.

The final two alerts that occurred about 4 seconds after the initial ones are associate with a sudden deceleration by the vehicle being passed. It is unclear which vehicle received the alert but it is likely that it was the received by the vehicle being passed, indicating that the driver received the alert and **reduced speed**.

Figure 136.Google Earth Image of FCW Event A showing Location of Alerts and Vehicle BSM Data
Source: WYDOT
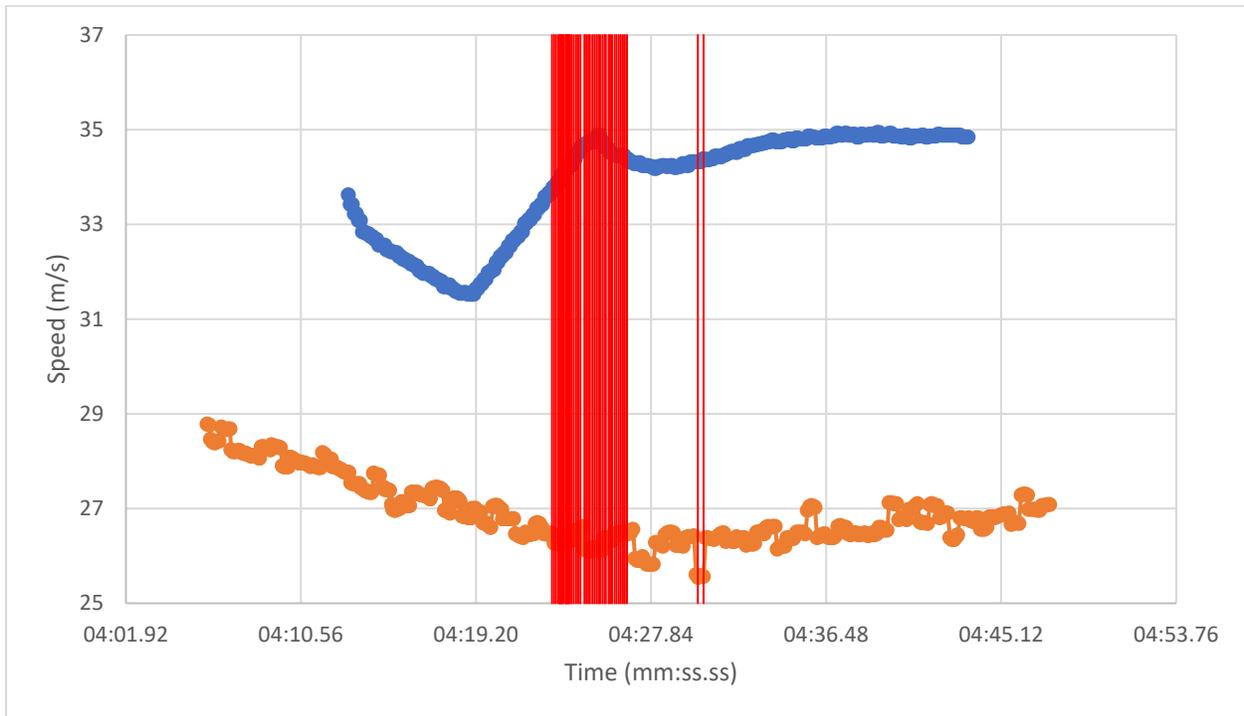
Figure 137. Speed Graph of FCW Event A.
Source: WYDOT

Event B

Event B involved two highway patrol vehicles near MP 209 about a half mile east Johnson Road Exit (Flying J), which is approximately 1.5 miles of Rawlins West Interchange (Figure 138). One patrol vehicle (blue) was parked at roadside and a second patrol vehicle (red) approached the first vehicle from a median crossover. Three FCW alerts were recorded (#28, #30, and #29) with the first alert occurring about 680' feet from the stationary vehicle. **Driver reaction was not analyzed** for this event since the second patrol vehicle was likely fully aware of the first during this event so slowing cannot be attributed to the driver alert.
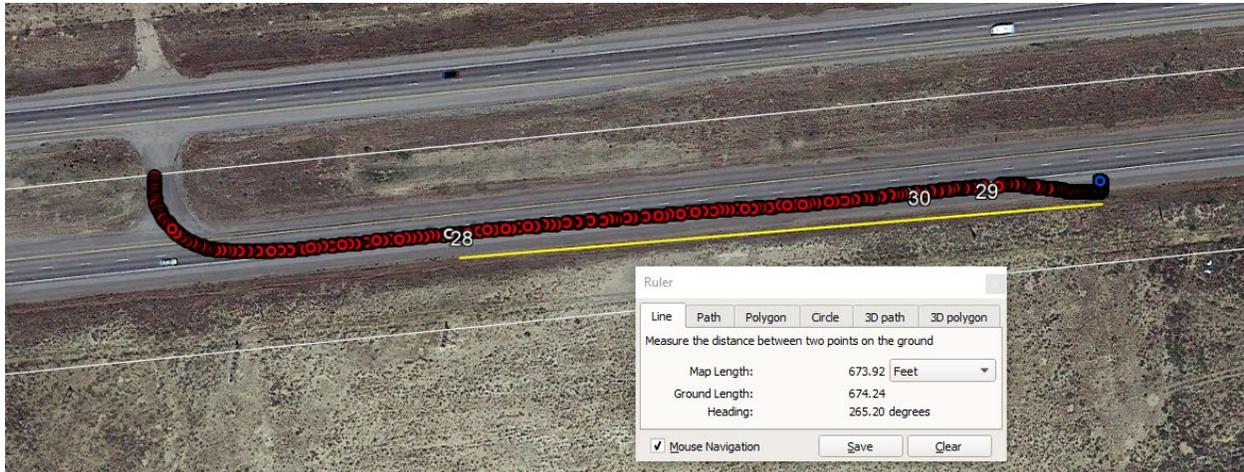
Figure 138. Google Earth Image of FCW Event B
Source: WYDOT

Event C

Event C involved a single Highway Patrol vehicles traveling westbound near MP 211 close Rawlins West Interchange WB onramp (Figure 139). Vehicle was in median area before entering I-80 WB and received FCW shortly after (white #42). No other connected vehicles were found in the BSM records at that time and location. **Driver reaction was not analyzed.**

Figure 139. Google Earth Image of FCW Event C
Source: WYDOT

Event D

Event D involved two highway patrol vehicles traveling EB near MP 214 about half mile east of Central Rawlins interchange (Figure 140). The lead vehicle (blue) was being following by a second patrol car (red) with less than a 1 second time headway at similar speeds. A FCW alert (white #43) was given. **No driver reaction was analyzed** given that these were two highway patrol cars that were likely traveling together.

Figure 140. Google Earth Image of FCW Event D.
Source: WYDOT

Event E

Event E involved a single Highway Patrol vehicle was traveling westbound near MP 215 about 1 mile east of Rawlins East Interchange (Figure 141). Vehicle was WB on I-80 and received an FCW (white #36). No other connected vehicles were found in the BSM records at that time and location. **Driver reaction was not analyzed.**

Figure 141. Google Earth Image of FCW Event E.
Source: WYDOT

Event F

Event F involved a single Highway Patrol vehicle was traveling westbound near MP 215 about 1 mile east of Rawlins East Interchange (Figure 142). Vehicle was WB on I-80 and received an FCW (white #31) and then another (#32) about 4 seconds later. No other connected vehicles were found in the BSM records at that time and location. **Driver reaction was not analyzed.**
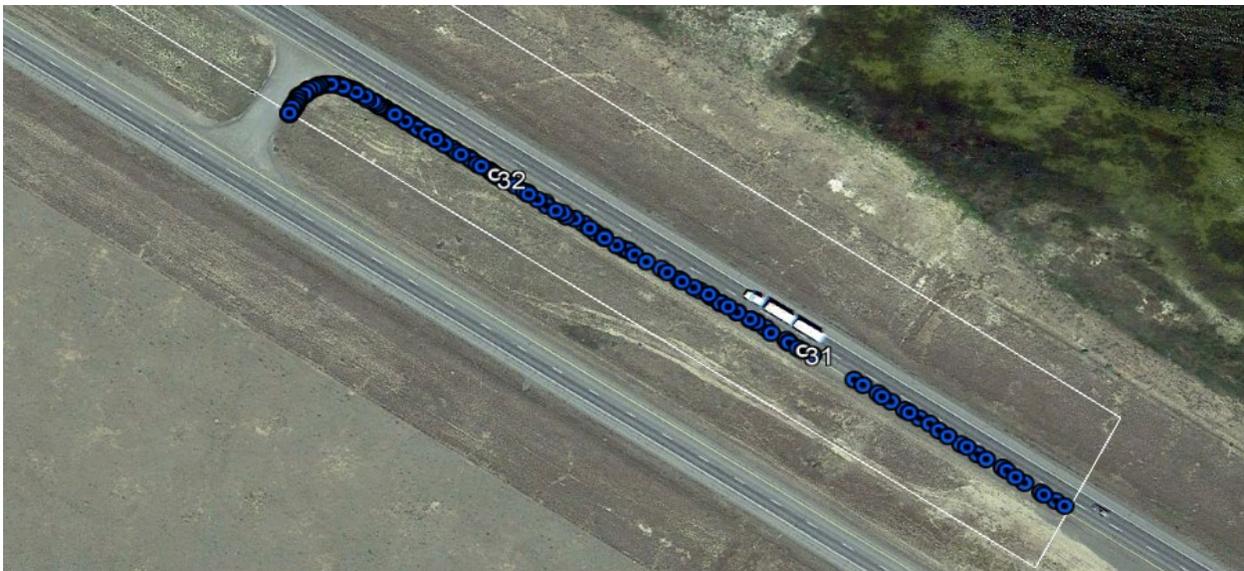
Figure 142. Google Earth Image of FCW Event F.
Source: WYDOT

Event G

Event G involved two highway patrol vehicles near MP 296 about ¾ of a mile west of Herrick Lane overpass (Figure 143). One patrol vehicle (red) was parked at roadside and a second patrol vehicle (blue) approached the first vehicle from a median crossover. An FCW alert was delivered (white #33) when the arriving patrol car was about 220 feet from the stationary vehicle. **Driver reaction was not analyzed** for this event since the arriving patrol vehicle was likely fully aware of the first during this event so slowing cannot be attributed to the driver alert.
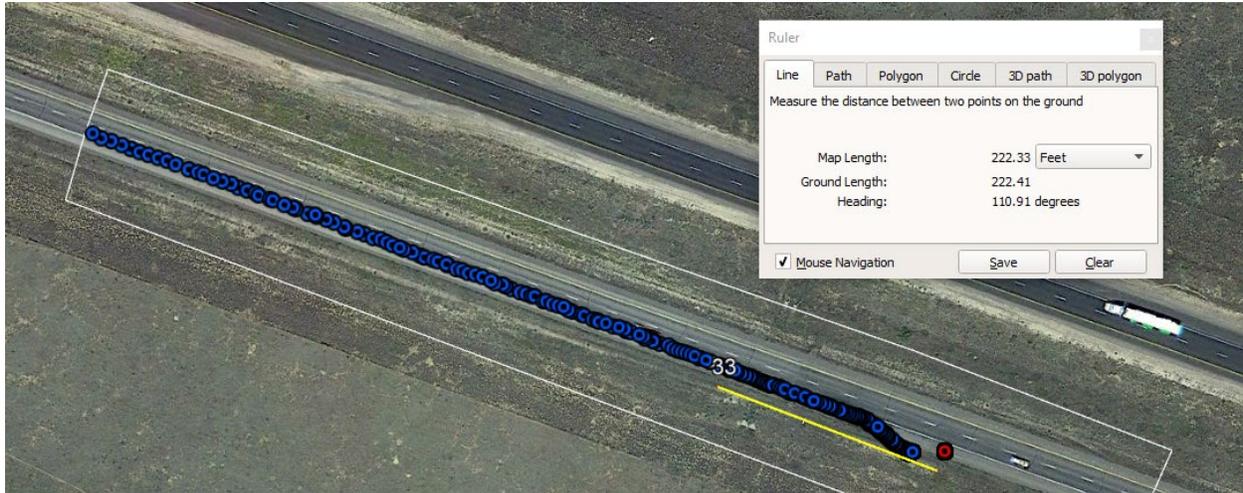
Figure 143. Google Earth Image of FCW Event G.
Source: WYDOT

Event H

Event H involved two highway patrol vehicles traveling EB near MP 297 near the Herrick Lane crossing (Figure 144). The lead vehicle (blue) was about 17 seconds ahead of the second patrol car (red). The lead vehicle came to a stop and as the second vehicle approached, two FCW alerts (white #23 and 24) were given. The first (24) occurred when the approaching vehicles was about 405 feet from the lead vehicle and the other about 270 feet away. **No driver reaction was analyzed** since the second patrol vehicle was likely fully aware of the first during this event so slowing cannot be attributed to the driver alert.
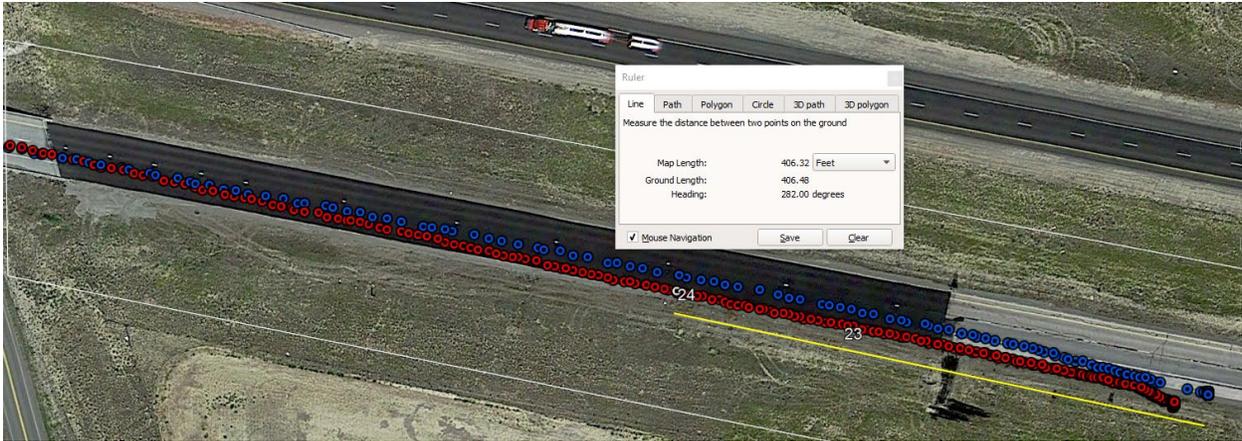
Figure 144. Google Earth Image of FCW Event H.
Source: WYDOT

Event I

Event I involved two highway patrol in the WB direction near MP 310 about a half mile east (south) of Curtis Road interchange in Laramie (Figure 145). One patrol vehicle (blue) was parked at roadside and a second patrol vehicle (red) approached the first vehicle from the south. An FCW alert was recorded (#22) 300' feet from the stationary patrol vehicle. **Driver reaction was not analyzed** for this event since the second patrol vehicle was likely fully aware of the first during this event so slowing cannot be attributed to the driver alert.
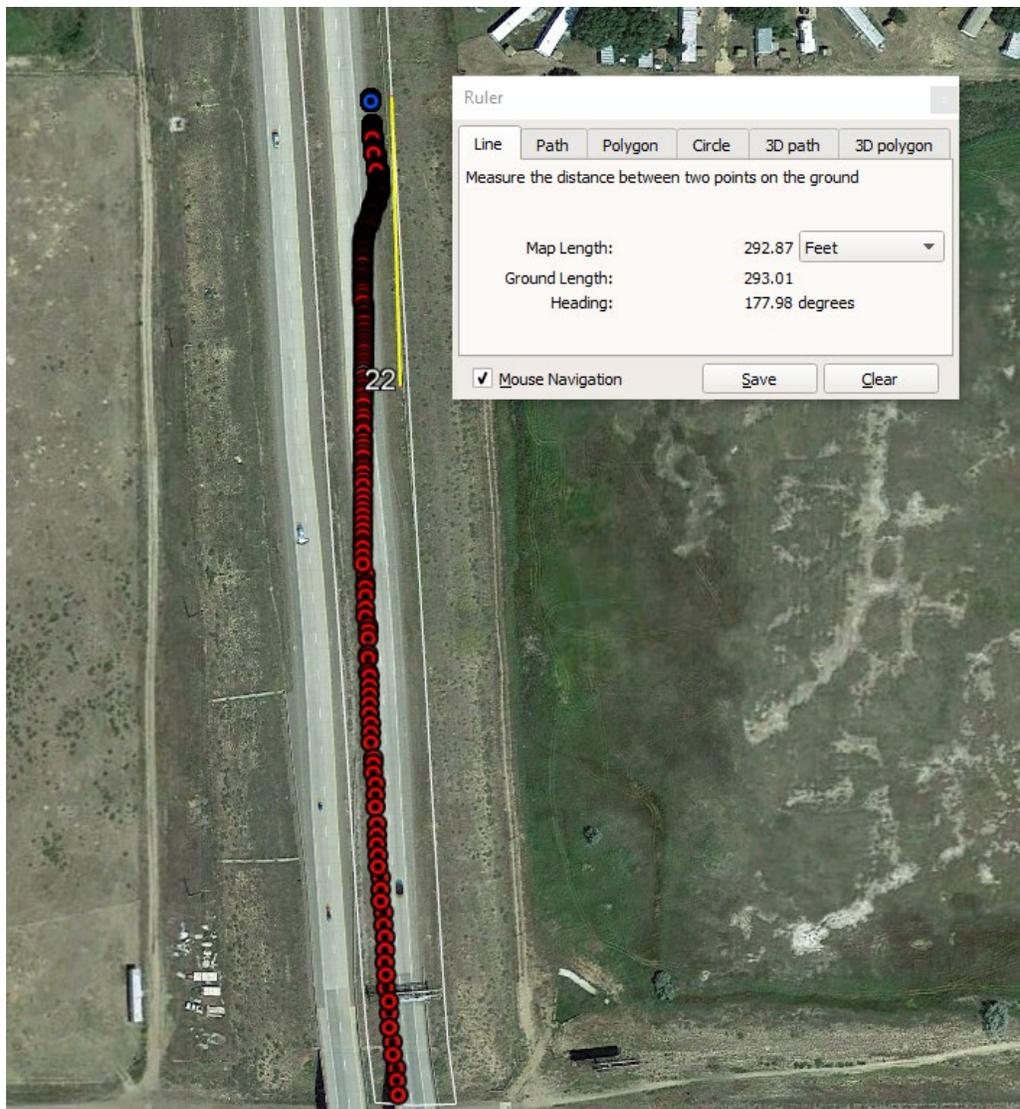
Figure 145. Google Earth Image of FCW Event I.
Source: WYDOT

Event J

Event J involved a single Highway Patrol vehicle was traveling westbound near MP 314 about one mile east or Laramie's 3rd Street Interchange (Figure 146). Vehicle was WB on I-80 and received an FCW (white #20) and then another (#19) about 3 seconds (160 feet) later. No other connected vehicles were found in the BSM records at that time and location. **Driver reaction was not analyzed.**
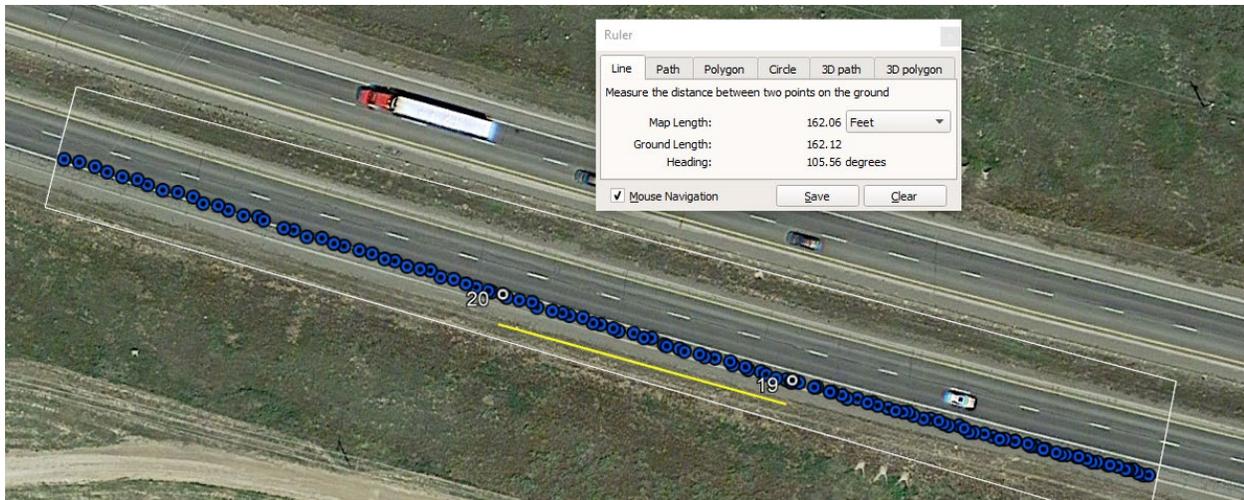
Figure 146. Google Earth Image of FCW Event J.
Source: WYDOT

Appendix H. Simulation Analysis of Driver Behavior

Considering traffic safety concerns and challenging driving conditions on I-80 in Wyoming, the USDOT FHWA selected Wyoming to develop, test, and deploy a suite of CV applications. The WYDOT CV Pilot utilizes real-time communication technologies to provide warnings and advisories of various road conditions to heavy trucks and light vehicles. One of the ultimate goals of this pilot is to alleviate traffic safety and improve travel reliability of the 400-mile I-80 freight corridor utilizing CV technology. Hence, the safety performance assessment of the pilot is essential for the WYDOT and the FHWA strategic goals.

The University of Wyoming led the effort to provide a new traffic safety perspective for the safety performance evaluation of the WYDOT CV Pilot utilizing advanced statistical modeling, Machine Learning, Data Mining applications, safety data visualization, high-fidelity driving simulator experiments, and traffic microsimulation modeling. To this aim, the procedure and the analytical inference for developing a pre-deployment baseline, and Analysis, Modeling, and Simulation (AMS) framework to assess the safety efficacy of the pilot are presented in several peer-reviewed journal publications using two distinct but complementary approaches; 1) conducting a before/after analysis to explore contributing factors to crashes and their severity during CV pre-deployment as a baseline, and 2) the AMS framework in with/without analyses to quantify drivers' behavioral alteration under the effect of various WYDOT CV applications.

Results from the first approach identified statistically significant real-time traffic and environmental factors contributing to crashes and critical crashes during CV pre-deployment. In the with/without analysis and based on the calibrated and validated AMS framework, the results affirmed promising safety benefits of the WYDOT CV applications. The quantified impact of several CV applications including Spot Weather Impact Warning (SWIW), Distress Notification (DN, not implemented in the pilot), Situational Awareness (SA), Work Zone Warning (WZW), Forward Collision Warning (FCW), and rerouting applications showed a positive alteration of drivers' behavior under at a trajectory-level. Moreover, the Surrogate Measures of Safety (SMoS) analysis utilizing microscopic simulation indicated an enhanced traffic safety performance under varying CV Market Penetration Rates (MPRs).

Pre-deployment Baseline Safety Assessment

Reducing the frequency and rate of traffic crashes has been considered as the ultimate performance measure in the safety assessment of CVs. The explored crash causations are expected to be affected under various CV applications during the CV post-deployment. Hence, a procedure for the baseline safety assessment have been conducted to identify crash contributing factors on I-80 during CV pre-deployment. The baseline safety assessment was conducted in two levels of analyses; 1) Aggregate level analysis, in which Safety Performance Functions (SPFs) were developed for the CV pilot deployment corridor, as well as assessment of the efficacy of

existing safety countermeasures, and 2) Disaggregate level analysis, in which real-time safety assessment were conducted to identify traffic-related contributing factors to crashes.

Data Acquisition and Processing

Datasets used in the baseline analyses are maintained by the WYDOT. Roadway geometry features, traffic data, cross sectional elements, and implemented countermeasures were accessed via the online roadway data portal. Crash data and speed sensor data, which are considered the main datasets for the baseline analysis, were requested and obtained from the WYDOT. Weather data was extracted from the National Oceanic and Atmospheric Administration (NOAA) website.

Multiple datasets collected were visualized to provide initial insights about the I-80 corridor. Roadway homogenous segmentation method was adopted for the aggregate analysis to account for the variation in the roadway geometry. Matched-Case Control Design (MCCD) was followed to explore real-time traffic-related crash contributing factors by predicting crashes based on analyzing crash precursors and comparing them with normal traffic patterns before non-crash instances within the same timeframe. This technique was adopted to control for confounding factors such as roadway geometry, driver population, seasonal traffic variation, and to some extent, weather conditions.

Aggregate Level Analyses

Aggregate crash analyses are required to unveil the statistical linkage between the crash probabilities and the environmental factors, roadway geometry, and crash characteristics. As a result of such analysis, crash prediction models, known as safety performance functions (SPFs) are developed. SPFs are statistical models predicting the likelihood of crashes on a certain roadway facility. In addition, they investigate the effect of various variables on crash occurrence. Using the developed SPFs, crash modification factors (CMF) could be calculated for the countermeasures and roadway treatments implemented on the investigated roadway facility. To this aim, parametric, non-parametric, and spatial statistical modeling techniques were utilized to develop pre-deployment baselines for I-80. Additionally, CMFs for the WYDOT weather-based variable speed limit (VSL) corridors were estimated.

Development of Crash Prediction Models

Three statistical approaches were adopted to conduct a comprehensive assessment for I-80 in Wyoming (1). Negative binomial model (NB) was used as the parametric approach, as it accounts for the overdispersion nature of the crash data. However, this approach does not account for the effect of the neighbor roadway segments that might influence crash prediction and/or causation. Accordingly, spatial autoregressive (SAR) model were employed to investigate the effect of adjacent roadway segment in affecting the probabilities of crashes. Furthermore, multivariate adaptive regression splines (MARS) model as a nonparametric model was used. Nonparametric approaches provide more flexibility compared to traditional approaches as they do not have underlying assumptions for the datasets. Although this flexibility could increase crash prediction accuracy, it could complicate the identification of the crash causal factors as well as the interpretations of the developed models.

To conduct the analyses, the corridor was divided into mountainous sections, and flat and rolling sections. Moreover, sections with VSL were separated from non VSL sections. This segmentation approach was followed to accurately account for the effect of these factors on crash probability. Eventually, the 400-mile corridor was divided into total of three sections; 1) Mountainous sections with VSL, 2) Flat and rolling with VSL, and 3) Flat and rolling without VSL. Figure 147 shows the different sections considered in the study, roadway geometric features per 5 miles, number of snowy, windy, and rainy days, and crash counts.

Total crashes, fatal and injury (F+I) crashes, and truck crashes were the three crash severities and types considered in the analysis. A total of 27 SPFs were generated for the considered statistical approaches, corridor sections, crash types, and crash severities. Figure 148 shows the 27 developed SPFs for the I-80 corridor. In addition to the SPFs developed for the corridor subdivision, general corridor SPFs were generated using the same statistical approaches for the different crash severities and types, resulting in an additional nine general SPFs.

Transferability analysis was conducted to investigate the generalizability of the developed SPFs. The analysis clarified that the SPFs developed using a certain portion of the roadway cannot be transferred to the full corridor. This asserts the need of developing separate site-specific SPFs for better prediction accuracy, especially, when having significant change in roadway geometry, and traffic and environmental conditions.

The results of the study showed that MARS models provided better prediction accuracy, however, it is not easy to interpret causal factors when involving more than two variables in the developed basis function. On the other hand, NB and SAR models provided much easier to interpret crash causal factors, with a lower crash prediction accuracy compared to the MARS models.

Figure 147. The Observed crash counts, geometric characteristics, and weather conditions on I-80 from 2012 to 2016
Source: WYDOT & (1)

Developed Models

Mountain Section with VSL

MARS
- Total: 5.19+26.92×(LogVMT-3.26)+0.023(MedWidth-416)
- F+I: 1.75+14.23×(LogVMT-3.76)-2.72×(3.76-LogVMT)+0.04×(Winday-10)
- Truck: 2.32+9.69×(LogVMT-3.21)+0.023×(MedWidth-416)

SAR
- Total: -53.20+18.93×LogVMT-2.40×MedType(0)   ρ=0.03
- F+I: -9.94+3.6×LogVMT-0.50×MedType(0)   ρ=0.32
- Truck: -21.65+7.57×LogVMT   ρ=0.06

NB
- Total: -4.32+1.96×LogVMT-0.30×MedType(0)
- F+I: -6.71+2.01×LogVMT-0.28×MedType(0)+0.02×Winday
- Truck: -5.70+1.97×LogVMT-0.38×MedType(0)+0.01×Snowday

Flat and Rolling with VSL

MARS
- Total: 8.64+24.57×(LogVMT-3.46)-9.73×(3.46-LogVMT)+22.37×(Tper-0.45)
- F+I: 2.12+3.52×(LogVMT-3.54)-1.92×(3.54-LogVMT)+2.05×(BrgCount-1)
- Truck: 1.59+10.95×(LogVMT-3.45)-4.35×(3.45-LogVMT)+23.77×(Tper-43)

SAR
- Total: -48.23+15.12×LogVMT+9.43×Tper+2.97×BrgCount   ρ=0.04
- FI: -9.82+2.89×LogVMT+2.58×Tper+0.84×BrgCount-0.4×MedType(0) ρ=0.07
- Truck: -28.07+6.99LogVMT+15.59Tper+0.85×BrgCount   ρ=0.05

NB
- Total: -5.73+2.10×LogVMT+0.99×Tper+0.31×BrgCount
- F+I: -6.38+1.86×LogVMT+0.44×BrgCount+0.41×MedType(0)
- Truck: -9.70+2.36×LogVMT+5.47×Tper

Flat and Rolling without VSL

MARS
- Total: 7.70+141.19×(LogVMT-3.97)-6.23×(3.97-LogVMT)+0.08×(74-MedWidth)+3.38×(BrgCount-1)-1.62×(1-BrgCount)+56.20×(Tper-0.50)+3.24×(0.5-SRS)
- F+I: 1.48+20.66×(LogVMT-4.00)-1.07×(4.00-LogVMT)+0.01×(Snwday-17)-0.39×(1-BrgCount)+0.26×(Rnday-101+0.55×(0.75-SRS)
- Truck: 2.89+54.57×(LogVMT-4.11)-2.79×(4.11-LogVMT)+79.22×(Tper-0.50)-69×(0.5-Tper)+2.40×(BrgCount-1)+1.20×(0.5-SRS)

SAR
- Total:-42.97+1.65×Gcat(2)+ 23.39×Gcat(3)+0.39×DOC-0.01×medwdth+17.66×Tper+11.46×LogVMT-2.27×SRS+0.09×snwday+1.24×Factyp+23.04×Brgcount   ρ=0.05
- F+I: -7.85+0.15×Gcat(2)+0.82×Gcat(3)+0.11×DOC+2.39×LogVMT-0.42×SRS+0.01×Rnday+0.61×Brgcount   ρ=0.65
- Truck: 52.10-8.33×Gcat(2)-19.15×Gcat(3)+0.26×DOC-138.12×Tper-17.39×LogVMT-0.96×SRS+0.03×snwday-0.30×Brgcount+2.71×LogVMT×Gcat(2)+6.078581×LOGVMT×Gcat(3)+45.78×Tper×LOGVMT0.06×snwday×Brgcount   ρ=0.01

NB
- Total:-7.20+0.07×Gcat(2)+0.44×Gcat(3)+0.08×DOC-0.25×medtyp-0.003×medwdth+0.018×wtot+3.08×Tper+1.92×LogVMT-0.28×SRS+0.02×Snwday+0.24×Factyp+0.28×Brgcount
- F+I: -11.82+0.12×Gcat(2)+0.40×Gcat(3)+0.53×DOC+3.07×LogVMT-0.37×SRS+0.01×Rnday+0.18×Winday+0.28×Brgcount-0.01×DOC×Rnday-0.05×LogVMT×Winday
- Truck: -12.49+0.30×Gcat(2)+0.53×Gcat(3)+0.10×DOC-0.24×medtyp+7.43×Tper+2.68×LogVMT-0.37×SRS+0.08×Snwday+0.25×Factyp+0.28×Brgcount-0.02×LogVMT×Snwday

Figure 148. The Developed SPFs for the I-80 Subdivisions
Source: WYDOT & (1)

Development of CMFs for the Weather Based VSL

Crash modification factors for the weather based VSL corridor was calculated using a before–after study with Empirical Bayes (EB) method (*2*). The EB method is considered a rigorous approach to calculate CMFs as it accounts for the regression to the mean (RTM) bias. Several SPFs were developed using NB and MARS models for the I-80 corridor before the implementation of the VSL. Total crashes, F+I, PDO, and Truck crashes were considered. Observed, predicted and expected crashes were utilized to calculate the effectiveness of the VSL in reducing crashes. Table 52 shows the calculated CMS for the multiple crash types and severities. Additionally, standard errors, 95% confidence intervals, and safety effectiveness for each calculated CMF are provided. The results shows that the VSL is highly effective in reducing truck crashes, which reached a 28.66% to 33.78% reduction in truck crashes.

Table 52. Developed CMFs for VSL using NB and MARS Models

	CMFs using NB				CMFs using MARS			
	Tcrash	F+I	PDO	Truck	Tcrash	F+I	PDO	Truck
CMF	0.7832	0.7844	0.8549	0.7134	0.7194	0.7204	0.8752	0.6622
SE (CMF)	0.0097	0.0092	0.0121	0.0130	0.0088	0.0085	0.0093	0.0099
Min. 95%CI	0.7642	0.7664	0.8312	0.6879	0.7022	0.7037	0.8570	0.6428
MAX. 95%CI	0.8022	0.8024	0.8786	0.7389	0.7366	0.7371	0.8934	0.6816
Safety Effectiveness	21.68%	21.56%	14.51%	28.66%	28.06%	27.96%	12.48%	33.87%

Note. CMF = Crash Modification Factor; VSL = Variable Speed Limit; NB = Negative Binomial; MARS = Multivariate Adaptive Regression Splines; F+I = Fatal and Injury Crashes; PDO = Property Damage Only Crashes; CI = Confidence Interval.

Source: (*2*)

Disaggregate Level Analysis

Real-time Crash Prediction Models (CPMs) are required to unveil the statistical linkage between traffic flow characteristics and the probability of crashes. In the Real-Time Risk Assessment (RTRA) arena, it is known that traffic crashes can be predicted by investigating crash precursors during a period preceding crash occurrence. Under RTRA, most previous analyses investigated RTRA in a particular section of a corridor or limited length of a segment. However, the safety performance assessment of disruptive technology such as CVs on I-80 in Wyoming required looking into a long corridor. Accordingly, this analysis dealt with two main problems in conducting a unique CPM on the 402-miles I-80. First, it was essential to deal with nonlinear predictors due to a remarkable variation in traffic patterns throughout the 402-miles I-80 corridor. Secondly, the study has to account for the small number of real-time traffic observations within a predefined time window crash precursors on I-80 with comparatively less traffic volume.

Real-time Crash Prediction Models

In total, nine CPMs were conducted based on a combination of three types of statistical modeling and three feature selection techniques (*3*, *4*). The best model was selected based on the predictive performance for the within-sample and out-of-sample.

The CPMs were developed using two phase procedure; 1) determining the important predictors, in which Mean Decrease Accuracy (MDA), Mean Decrease Impurity (MDI), and Corrected-Impurity Importance (CII) were used as the feature selection techniques offered by Random Forest (RF), and 2) development of CPMs, where the important predictors obtained from the first phase were utilized. In the second phase, under Logistic regression, three types of statistical modeling, namely Generalized Linear Model (GLM), Generalized Non-linear Model (GNM), and Generalized Additive Model (GAM), were employed to deal with nonlinear predictors. Akaike Information Criterion (AIC) and area under the curve (AUC) were used to compare the prediction accuracy of the nine developed models. The results showed that the combination of CII and GAM outperformed the other models by achieving the lowest AIC value and the largest AUC. In total, 29 variables were used to enable the model to cluster crash and non-crash cases.

Table 53 present the description of the continuous and categorical variables used in this study. The obtained results confirmed the better performance of the combined CII and GAM in terms of achieving the highest accuracy, the minimum error rate, and detecting the maximum number of significant features. Table 54 shows the results of the nine real-time developed Crash Prediction Models (3, 4).

Table 53. Description of Explanatory Variables.

Continuous Variables [a]	Description			S.D.	Mean	Min.	Max.
T_SpMean	Spatial Difference in Mean Speed of Total Traffic Volume in both Lanes			7.09	-0.10	-34.88	35.52
T_SpVar	Spatial Difference in Speed Variance of Total Traffic Volume in both Lanes			58.05	-11.78	-578.05	458.17
T_SpVARoMEAN	Spatial Difference in Speed Variance Divided by Mean Speed for Total Traffic Volume in both Lanes			1.21	-0.16	-17.27	9.79
T_SpSlop	Spatial Difference in the Slop of Speed Regression (from Speed Profile) for Total Traffic Volume in both Lanes			0.02	0.00	-0.03	0.26
T_SpVarDiff	Spatial Difference in Subtraction of Speed Variance in HSL[b] from Speed Variance in LSL[c]			100.79	12.63	-1227.42	533.89

T_Volume	Spatial Difference in Total Traffic Volume			28.45	10.90	-88.00	138.00
T_TrP	Spatial Difference in Truck Proportion in Total Traffic Volume in both Lanes			0.17	0.01	-0.57	0.57
T_TrPDiff	Spatial Difference in Subtraction of Truck Proportion in HSL from Truck Proportion in LSL			0.29	-0.04	-1.00	0.84
T_VolumeDiff	Spatial Difference in Subtraction of Traffic Volume in HSL from Traffic Volume in LSL			19.05	6.12	-75.00	72.00
HSL_SpMean	Spatial Difference in Mean Speed in HSL			11.55	1.59	-32.85	84.07
HSL_SpVar	Spatial Difference in Speed Variance in HSL			77.20	1.04	-752.67	537.92
HSL_SpVARoMEAN	Spatial Difference in Speed Variance Divided by Speed Mean in HSL			1.47	0.01	-19.68	10.59
HSL_SpSlop	Spatial Difference in Slop of Speed Regression (from			0.18	-0.01	-3.80	0.27

	Speed Profile) for HSL					
HSL_Volume	Spatial Difference in Traffic Volume in HSL			14.22	-0.23	-54.00	111.00
HSL_TrP	Spatial Difference in Truck Proportion in HSL			0.30	-0.01	-1.00	1.00
LSL_SpMean	Spatial Difference in Speed Mean in LSL			17.7	4.17	-35.20	79.50
LSL_SpVar	Spatial Difference in Speed Variance in LSL			65.67	-11.59	-576.08	475.12
LSL_SpVARo MEAN	Spatial Difference in Speed Variance Divided by Mean Speed in LSL			1.30	-0.18	-17.07	10.52
LSL_SpSlop	Spatial Difference in Slop of Speed Regression (from Speed Profile) for LSL			0.02	0.00	-0.14	0.24
LSL_Volume	Spatial Difference in Traffic Volume in LSL			23.86	11.13	-70.00	99.00
LSL_TrP	Spatial Difference in Truck Proportion in LSL			0.27	0.06	-0.45	1.00

Categorical Variables [a]	Description	Number of Positive (Pct.)	Number of Negative (Pct.)
D_ T_SpVARoMEAN	Dummy Variable Representing T_SpVARoMEAN (1: Negative (Reference Level), 0: Positive)	297 (60.9 %)	190 (39.1 %)
D_ T_SpSlop	Dummy Variable Representing T_SpSlop (1: Negative (Reference Level), 0: Positive)	251 (51.5 %)	236 (48.5 %)
D_T_SpMean	Dummy Variable Representing T_SpMean (1: Negative (Reference Level), 0: Positive)	240 (49.2 %)	247 (50.8 %)
D_ T_VolumeDiff	Dummy Variable Representing T_VolumeDiff (1: Negative (Reference Level), 0: Positive)	205 (42.1 %)	282 (57.9 %)
D_HSL_SpSlop	Dummy Variable Representing HSL_SpSlop (1: Negative (Reference Level), 0: Positive)	244 (50.1 %)	243 (49.9 %)
D_HSL_SpMean	Dummy Variable Representing HSL_SpMean (1: Negative	212 (43.5 %)	275 (56.5 %)

	(Reference Level), 0: Positive)		
D_ LSL_SpSlop	Dummy Variable Representing LSL_SpSlop (1: Negative (Reference Level), 0: Positive)	248 (50.9 %)	239 (49.1 %)
D_LSL_SpMean	Dummy Variable Representing LSL_SpMean (1: Negative (Reference Level), 0: Positive)	217 (44.5 %)	270 (55.5 %)

a Each of the Continuous variables (C) was measured at Upstream (U) and Downstream (D). Afterward, for all of the observations, the corresponding values of the continuous variables were calculated by subtracting U from D (i.e., C=D ₋ U). If a continuous variable was negative, the corresponding dummy variable took the value of one; otherwise, it took the value of zero.
b HSL: High-Speed Lane/ (i.e., Left Lane)
c LSL: Low-Speed Lane/ (i.e., Right Lane)

Table 54. Results of the nine developed models.

Step 1.	Mean Decrease Accuracy (MDA)								

Step 2.	Highly Correlated Variables (VIF>10):		T_SpVARoMEAN, T_Volume			HSL_SpVar,	LSL_SpVARoMEAN,		
	Non-linear variables [a]:		T_SpVar, HSL_TrP, HSL_SpMean						

Step 3.	CPM 1- GLM			CPM 2- GNM			CPM 3- GAM		
Variable	Est.	p-value	Sgfnt.	Est.	p-value	Sgfnt.	Est.	p-value	Sgfnt
Intercept	-0.425	0.010	*[b]	-0.585	0.001	*	-0.346	0.041	*
T_SpMean	-0.026	0.230		-0.032	0.149		-0.090	0.004	*
HSL_SpSlop	-2.051	0.290		-2.600	0.404		-2.578	0.200	
LSL_SpVar	0.008	0.005	*	0.009	0.003	*	0.015	0.000	*
LSL_Volume	0.006	0.278		0.005	0.363		0.002	0.704	
HSL_SpVARoMEAN	-0.011	0.911		-0.093	0.365		0.019	0.861	
T_SpSlop	9.154	0.444		9.561	0.464		10.725	0.420	
D_T_SpVARoMEAN	-0.732	0.009	*	-0.701	0.013	*	-0.610	0.037	*
LSL_SpMean	-0.035	0.017	*	-0.030	0.039	*	-0.030	0.076	
LSL_TrP	2.159	0.029	*	1.878	0.058		1.381	0.229	
T_TrP	-0.994	0.383		-0.748	0.511		0.878	0.579	
T_SpVar	-	-	-	0.000	0.798		EDF=1	0.031	*

Variable	Est.	p-value	Sgfnt.	Est.	p-value	Sgfnt.	Est.	p-value	Sgfnt.
HSL_TrP	-	-	-	1.027	0.107		EDF=1.12	0.079	
HSL_SpMean	-	-	-	0.001	0.013	*	EDF=1	0.001	*

Step 1. **Mean Decrease Impurity (MDI)**

Step 2.	Highly Correlated Variables (VIF>10):	T_SpVarDiff, T_Volume, T_SpVARoMEAN, HSL_SpVar, LSL_SpVar, LSL_TrP
	Non-linear variables:	T_SpVar, HSL_TrP, HSL_SpMean

Step 3.

	CPM 4- GLM			CPM 5- GNM			CPM 6- GAM		
Variable	Est.	p-value	Sgfnt.	Est.	p-value	Sgfnt.	Est.	p-value	Sgfnt.
Intercept	-0.720	0.000	*	-0.880	0.000	*	-0.587	0.000	*
T_SpMean	-0.039	0.049	*	-0.046	0.022	*	-0.087	0.001	*
HSL_SpSlop	-1.929	0.361		-3.035	0.416		-2.470	0.258	
LSL_SpSlop	-1.848	0.793		-2.327	0.760		-4.716	0.683	
HSL_Volume	0.003	0.679		0.004	0.646		0.007	0.412	
HSL_SpVARoMEAN	-0.088	0.360		-0.156	0.112		-0.004	0.970	
T_SpSlop	10.324	0.377		12.360	0.397		14.910	0.396	
T_VolumeDiff	-0.010	0.229		-0.004	0.611		-0.007	0.441	
T_TrPDiff	0.123	0.774		0.450	0.310		-0.751	0.276	

Variable	Est.	p-value	Sgnt.	Est.	p-value	Sgnt.	Est.	p-value	Sgnt.
LSL_SpMean	-0.009	0.336		-0.002	0.829		-0.018	0.104	
LSL_SpVARoMEAN	0.268	0.044	*	0.333	0.017	*	0.835	0.002	*
LSL_Volume	0.010	0.168		0.006	0.412		0.002	0.794	
T_TrP	0.845	0.164		0.859	0.163		2.437	0.009	*
T_SpVar	-	-	-	0.000	0.712		EDF = 2.7	0.030	*
HSL_TrP	-	-	-	0.987	0.136		EDF = 1	0.020	*
HSL_SpMean	-	-	-	0.001	0.008	*	EDF = 1	0.000	*

Step 1.	Corrected-Impurity Importance (CII)	
Step 2.	Highly Correlated Variables (VIF>10):	T_SpVar, LSL_SpVar
	Non-linear variables:	HSL_SpMean, HSL_TrP, T_TrP
Step 3.	CPM 7- GLM	CPM 8- GNM	CPM 9- GAM

Variable	Est.	p-value	Sgfnt.	Est.	p-value	Sgfnt.	Est.	p-value	Sgfnt.
Intercept	-1.044	0.000	*	-1.096	0.000	*	-0.858	0.004	*
T_SpMean	-0.059	0.019	*	-0.057	0.028	*	-0.108	0.000	*
HSL_SpSlop	-1.961	0.355		-3.380	0.433		-4.314	0.306	
T_SpSlop	2.261	0.859		3.253	0.805		9.424	0.476	
D_T_SpMean	0.141	0.624		0.111	0.705		0.034	0.914	

T_TrPDiff	0.151	0.721		0.381	0.380		-0.887	0.193	
D_HSL_SpSlop	0.382	0.109		0.355	0.153		0.308	0.231	
LSL_SpVARoMEAN	0.742	0.012	*	0.570	0.050	*	0.872	0.006	*
T_SpVarDiff	0.001	0.602		-0.001	0.728		0.000	0.988	
T_SpVARoMEAN	-0.635	0.023	*	-0.459	0.106		-0.861	0.005	*
LSL_SpMean	-0.008	0.310		-0.004	0.635		-0.020	0.045	*
HSL_SpMean	-	-	-	0.001	0.013	*	EDF=1	0.001	*
HSL_TrP	-	-	-	0.814	0.256		EDF=1	0.013	*
T_TrP	-	-	-	-0.396	0.889		EDF=5.55	0.002	*

Results of the nine developed models (Continued)

	CPM-1	CPM-2	CPM-3	CPM-4	CPM-5	CPM-6	CPM-7	CPM-8	CPM-9
	MDA			MDI			CII		
	GLM	GNM	GAM	GLM	GNM	GAM	GLM	GNM	GAM
AIC	604.04	596.22	589.8	614.94	605.74	594.48	608.6	602.12	579.64
AUC	0.63	0.65	0.66	0.61	0.63	0.66	0.63	0.65	0.72
# of Sgfnt. Predictors	2	3	5	2	3	6	3	3	7
Mean of OOB	0.37	0.36	0.35	0.38	0.36	0.34	0.39	0.36	0.33

a Y=X² was used to transform all the nonlinear predictors in GNM from MDI, MDA, and CII to achieve linearity.

b * Represents statistically significant predictors under 95% Confidence Interval.

Real-time Crash Causal Factors

The causal effects of crash contributing factors can be found in Table 55 (*5*), where the result of the selected CPM during CV pre-deployment is presented. It is worth mentioning, GAM is a non-parametric statistical approach. Accordingly, smoothing functions in GAM led to the estimation of Effective Degree of Freedom (EDF) for nonlinear predictors, which is difficult to interpret although the high prediction accuracy. Accounting for this limitation, post-hoc analysis was conducted to provide interpretable results.

Table 55. Causal Effect of Real-Time Traffic-Related Factors on the Crash Likelihood.

Combined CII and GAM (AIC: 579.64, AUC: 72%)					
Variables	Est.	Z value	χ^2	p-value	Sig.
(Intercept)	-0.942	-3.149	-	0.002	*a
T_SpMean	-0.108	-3.495	-	<0.000	*
HSL_SpSlop	-4.314	-1.023	-	0.306	
T_SpSlop	9.424	0.713	-	0.476	
D_T_SpMean	0.034	0.108	-	0.914	
T_TrPDiff	-0.887	-1.302	-	0.193	
D_HSL_SpSlop	0.308	1.197	-	0.231	
LSL_SpVARoMEAN	0.872	2.758	-	0.006	*
T_SpVarDiff	0.000	0.015	-	0.988	
T_SpVARoMEAN	-0.861	-2.798	-	0.005	*
LSL_SpMean	-0.020	-2.007	-	0.045	*
HSL_SpMean	EDF= 1.000	-	11.403	0.001	*
HSL_TrP	EDF= 1.000	-	6.235	0.013	*
T_TrP	EDF= 5.553	-	22.114	0.002	*

Note: Description of variables can be found in table 2; CII = Corrected Impurity Importance; GAM = Generalized Additive Model; AIC = Akiake Information Criterion; AUC = Area Under Curve; EDF = Effective Degree of Freedom

a Nonlinear Predictor

* Statistically significant predictors under 95% Confidence Interval.95%

Post-Hoc Analysis

Post-hoc analysis needs to develop another independent model, as a shallow model, to interpret an existing model. In fact, the post-hoc interpretability can be considered as a distillation process from the highest accurate prediction model to the highest interpretable model by providing a global vision in a post-hoc manner. To conduct the post-hoc analysis, two steps were followed; 1) Developing CPM to detect statistically significant real-time traffic-related crash contributing factors, and 2) Developing Crash Interpretation Model (CIM), as a shallow model for CPM, to interpret and visualize the effect of crash contributing factors on crash risk.

Figure 149 depicts the causal effects of significant variables on the crash likelihood throughout the 402-mile of I-80 in Wyoming. Accordingly, a reliable baseline has been conducted to explore the causal effect of real-time traffic-related factors on the crash likelihood before piloting CV technology on the I-80 corridor in Wyoming. The patterns of these causal effects on the crash likelihood are expected to be changed and affected due to the impact of CVs' speed adherence and harmonization during post-deployment. This pattern recognition could be attained by following the same approach and conducting real-time CPM during CV post-deployment once CVs reach notable MPRs. The comparison of causation patterns between CV pre-and post-deployment would reveal how CV technology can affect the crash likelihood on the I-80 corridor in Wyoming.

Figure 149. Causality Effect Visualization of Crash Contributing Factors on the Crash Probability.

Source: WYDOT and (5)

Analysis, Modeling, and Simulation (AMS)

A two-prong approach was accomplished to evaluate the effectiveness of the CV pilot utilizing several Performance Measures (PM). The first approach was utilizing the University of Wyoming (UW) driving simulator lab, WYOSAFESIM, while the second approach was incorporating the changes in driving behaviors observed at the driving simulator in a microsimulation model using VISSIM microsimulation models. Additionally, safety assessment were conducted for the microsimulation modeling using Surrogate Safety Assessment Model (SSAM) (*6*, *7*).

The pilot developed five on-board CV applications to provide key information to the drivers of equipped vehicles (*8*):

1) Forward collision warning (FCW),
2) Infrastructure to vehicle situational awareness (I2V SA),
3) Distress Notifications (DN)—ultimately not implemented and later replaced by Stationary Vehicle Alert (SVA),
4) Work zone warnings (WZW),
5) Spot weather information warnings (SWIW).

Through the on-board CV applications, WYDOT aimed to improve on road messaging on the corridor, especially when adverse weather and work zones are present.

The WYDOT Pilot team has identified performance measures, incorporated within performance categories—see Section 3. The major performance categories represent the primary activities and outcomes of the WYDOT CV pilot system. These categories focus on improvements to efficiency, safety, and mobility. Quantitative and qualitative measures were proposed to evaluate the WYDOT CV project with a focus on understanding the extent and impact of the benefits. Performance measures related to reduction in vehicle crashes were investigated using Analysis, Modeling, and Simulation (AMS).

Evaluation Using the UW Driving Simulator

The WyoSafeSim provided a controlled environment, in which critical events that mimic real life conditions were simulated in multiple scenarios. The CV hands-on training and evaluation module was performed using two high-fidelity truck driving simulator as well as the passenger vehicle driving simulator located at the University of Wyoming. The two simulators have open architecture software with a complete source code of the simulation creator tools. The open architecture offers a flexible tool that allows development of driving scenarios and building of roadways that replicate actual environments. The motion-based truck driving simulator has a freight truck open cockpit cab (i.e., a 2000 Sterling AT9500 18-wheeler semi-trailer), while the passenger vehicle open cockpit cab is a 2004 Ford Fusion. Both simulators are mounted on a three-degree-of-freedom D-Box motion platform, comprising four electromechanical linear actuators, as illustrated in Figure 150. The motion base provides two rotational and one translational degree of freedom (roll, pitch, and heave). The provided motion cues immerse the driver in a real driving experience with kinematic changes in velocity and acceleration. The HMI was mounted on the center console of the driving simulator to deliver the received CV warnings to the participants. Additional upgrades and integration of a Mobile Data Terminal (MDT) was included for the passenger vehicle to provide a realistic driving environment for the highway troopers.
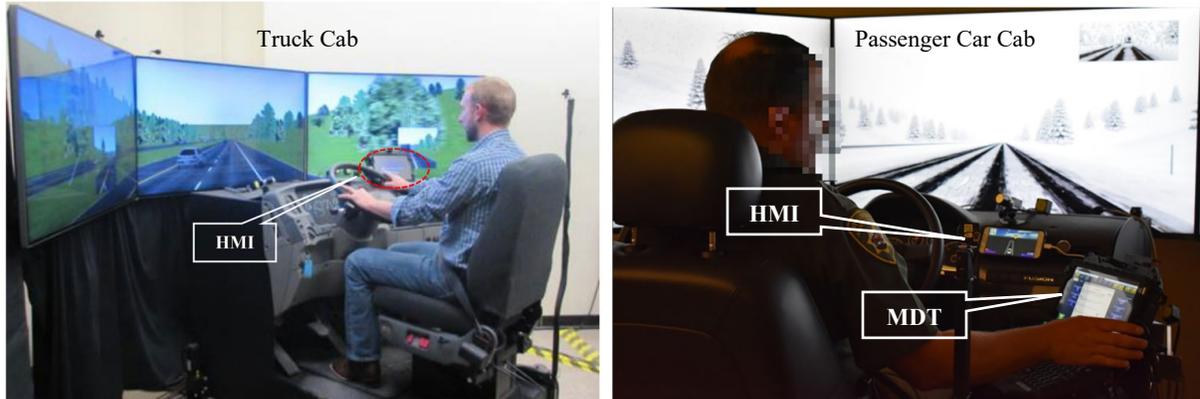
Figure 150. University of Wyoming WyoSafeSim truck and passenger car driving simulators.
Sources: WYDOT & (9, 10)

Initially, baseline scenarios were developed to compare the change in driving behavior as well as the performance of the vehicle kinematics. The baseline scenarios included critical events while removing the CV technology (Muted CV Scenarios). Afterwards, the experiment testes the effect of introducing the CV technology to observe the change/enhancement in the investigate PMs. Two driver populations participated in this driving simulator study; 1) Commercial truck drivers, and 2) Wyoming highway patrol. Distinct scenarios were developed for both populations to account for the variation the driving performance and regular tasks conducted on daily bases. Within the five on-board CV applications, multiple CV warnings and notifications were designed to notify road users with upcoming hazardous events. Source*: WYDOT*

Table 56 provides a summary of the developed CV warnings and notifications (11).

Table 56. Summary of the Developed CV Warnings and Appropriate Responses.

CV Warning	Sign of Warning	Messages Delivered	Appropriate Response
Forward Collision Warning (FCW)		An impending front-end collision with a connected vehicle ahead in the same traffic lane and direction of travel.	An immediate breaking is required to avoid rear ending the vehicle in front.
Spot weather		A spot weather condition such as rain, snow, fog, strong wind, or severe weather ahead.	Driver should be alerted to the forthcoming weather condition, keep the vehicle on the right lane without overtaking any leading vehicle, and drive with caution.
Road Surface Notifications		An icy or slick spot road surface will be encountered on the roadway while driving.	Driver should be alerted to the forthcoming slippery road surface condition and drive with extreme caution.

CV Warning	Sign of Warning	Messages Delivered	Appropriate Response
Road Closures and Restrictions		A road closure to all types of vehicles, or road closed to certain vehicle types such as light trailers or light high profile vehicles.	Drivers need to exit the road, park in the nearest parking area, or cancel the trip.
Work Zones		Work zone ahead, lane closure, and speed limit.	Driver should keep the vehicle on the left lane without overtaking any leading vehicle.
Other advisories		An accident will be encountered on the roadway while driving.	Driver should be alerted to the forthcoming accident situation and drive with extreme caution to avoid secondary crashes.
Speed Limits		Regulatory Speed Limits and VSL: Enforceable by law. Advisory Speed Limits: Non-regulatory but inform drivers of a safe driving speed.	Regulatory and VSLs should always be followed no matter what. Advisory speed limits should be followed as far as possible.

Participants in the Driving Simulator Study

Two distinct groups participated in this study. The first tested group consisted of 18 professional commercial truck drivers, i.e., snowplow drivers from WYDO. All the participants were males and their ages ranged from 21 to 61 years (*11–14*). Among the 18 participants, 13 graduated from high school, 4 have a college degree, and 1 has a postgraduate degree. All participants had a valid CDL and had been driving for an average of 12.5 years (0.5 to 35 years). The participants reported having driven an average of 20,000 miles in the preceding year (minimum 5,000 and maximum 30,000). All the participants reported that they had encountered reduction in visibility because of snow, blizzards, fog, smoke, or heavy rain while driving on the I-80, in Wyoming, from November 2016 to May 2017.

The second group participated in the CV pilot was highway patrol troopers from Wyoming Highway Patrol (HP). A total of 10 HP troopers completed the training and participated in testing the CV applications (*15*). The participating troopers were all males, between the ages of 26 to 60 years. The troopers had been working for an average of 7.8 years for the HP (minimum 1 year and maximum 23 years). They reported their average annual mileage over the past 5 years to be above 30,000 mi. All the participating troopers stated they perform secondary tasks on a regular basis while driving such as talking on the radio, scanning road traffic condition, and interacting with the MDT. All of them reported to be using I-80 corridor more than 4 times a week, with each

trip being an average of 200 mi. All the participants reported that they had encountered reduction in visibility because of snow, blizzards, fog, smoke, or heavy rain while driving on the I-80 corridor. Two of the troopers reported that they had been involved in a crash on I-80 while on duty. One of the crashes was during inclement weather condition and resulted in a personal injury.

Driving Simulator Framework

The framework of the CV training program is presented in Figure 151. Institutional Review Board (IRB) approved the study and allowed the use of human subjects in the CV training and testing. The approval procedure conformed to the U.S. Department of Health and Human Service regulations and policies for the protection of human subjects' rights and welfare. The training started with an introduction of the background of the training program; then, participants were asked to read and sign a consent form, which detailed the general purpose of the study, training procedure, potential risks during driving simulator training, and confidentiality of personal and training data. In the next step, responses to a pre-training questionnaire were collected including demographics, driving experience, crash history, and experience with existing Advance Driver Assistance Systems (ADAS). Subsequently, an e-learning module was completed by all participants. A total of six driving scenarios illustrated to participants the basic components of the Wyoming CV system, the concept and function of each CV warnings, and the proper response they should implement. Several quizzes were included in the e-training module to evaluate participants' understanding of the training material. It was assumed that a participant needs to correctly answer a minimum of 75% of the questions before he or she can move to the hands-on driving simulator training. The hands-on driving simulator training aimed to provide participants with a simulated environment where they could experience the CV applications which were introduced in the e-learning module. After the driving simulator training, a post-training questionnaire was employed to collect the participant's assessment of the CV applications, such as user acceptance of the CV applications, how useful the CV applications would be in the real world, desirability and efficiency of each CV application. Additional discussions about the participant's understanding of the CV warnings displayed on the HMI and recommendations to the training approach and materials were performed through face-to-face conversations with the participants.
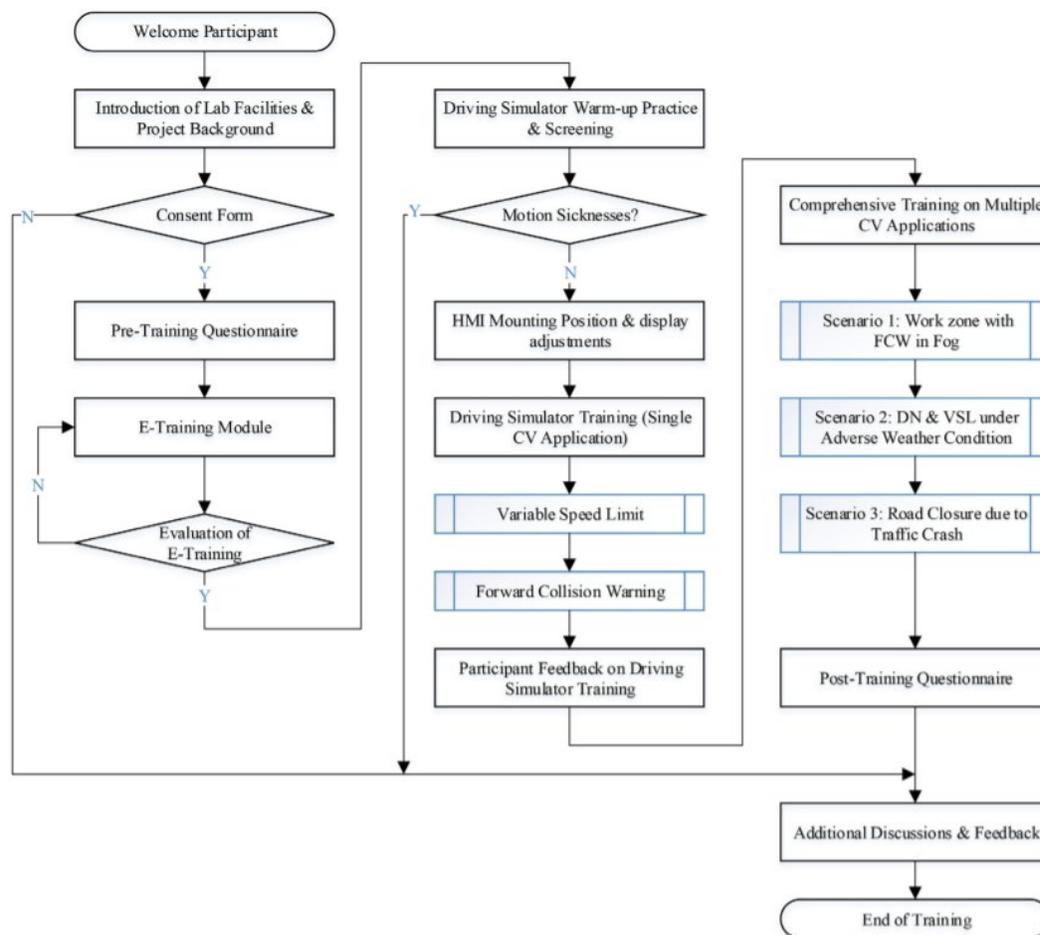
Figure 151. Flow chart of the developed Wyoming CV training framework.
Source: WYDOT & (16)

Driving Simulator Test Scenarios

Each participant drove each developed scenario twice, during which, minor changes that would not affect the driving performance was provided to eliminate any learning effect. The first driving simulation had the HMI deactivated (baseline scenario) and no CV warnings were communicated, during the second simulation the HMI was activated to communicate the CV warnings (CV scenario). A total of six driving scenarios were tested, where the driving order of the scenarios was randomly assigned to minimize potential learning and adaptation effects.

For the truck experiment, all notifications were communicated in the form of audible signals (double beeps) and visual displays on the HMI. Vocal instructions were not tested, as vocal notifications could be easily masked out with the truck cab loud environment. However, the vocal modality, as well as other modalities, were tested with the highway patrol experiment. The design of the HMI visual and auditory displays conformed with the NHTSA human factors design guidelines for heavy-vehicle user interface (*17*). In addition, all visual displays were standard warning signs obtained from the MUTCD (*18*), as per the FHWA's guidelines recommending the use of familiar messages and standard MUTCD signs for in-vehicle safety systems (*19*).

The experiment involved the testing of two distinct applications; the SWIW and the WZW, in addition to the rerouting application that was only tested with the truck driving experiment. Figure 152 shows the layout of the three developed testing scenarios with commercial truck drivers, where part (A) represents the WZW scenario, part (B) shows the SWIW scenario, and part (C) is the layout of the rerouting scenario. WZW and SWIW scenarios were the only two scenarios provided to the highway patrol, as the rerouting application does not apply for them. Additional dispatch messages and increased work load was provided, in which subjects were requested to engage a dispatched event. Figure 153-A is the layout for the SWIW scenario and Figure 153-B shows the layout for the WZW scenario for the highway patrol scenarios.
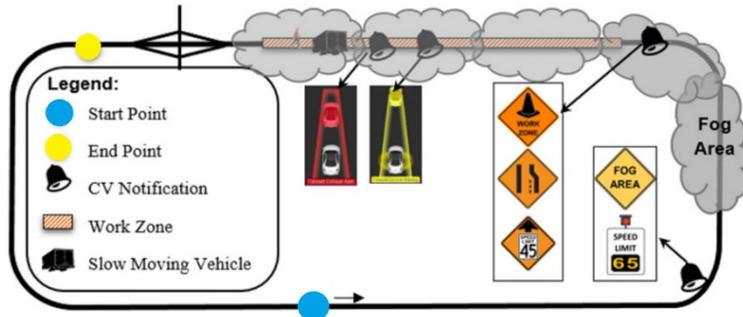
A- Truck Driving Simulator layout for the Work Zone Scenario
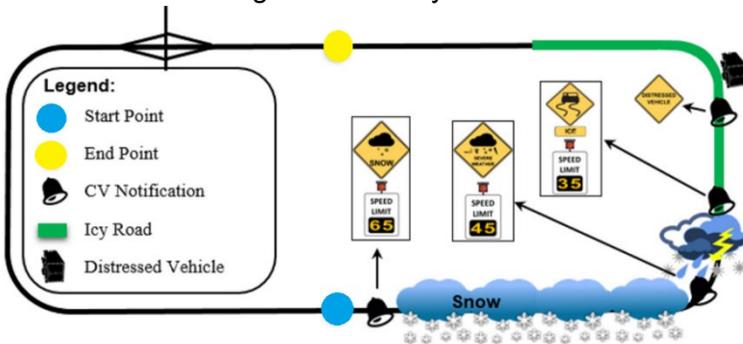
B- Truck Driving Simulator layout for the Slippery Road Scenario
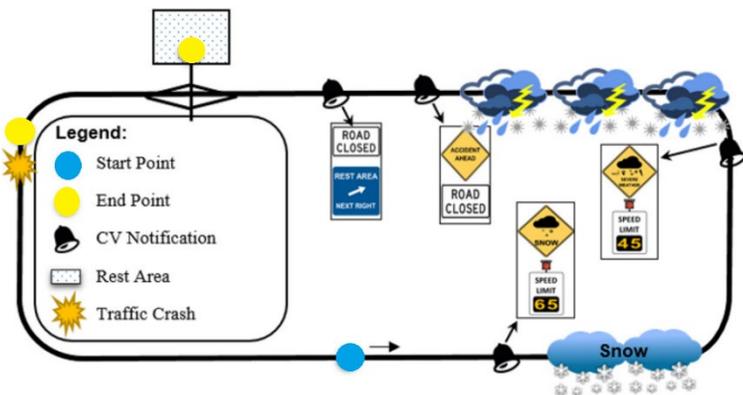
C- Truck Driving Simulator layout for the Rerouting Scenario

Figure 152. CV Scenario Layouts for the Truck Experiment.
Source: WYDOT & (20–22)
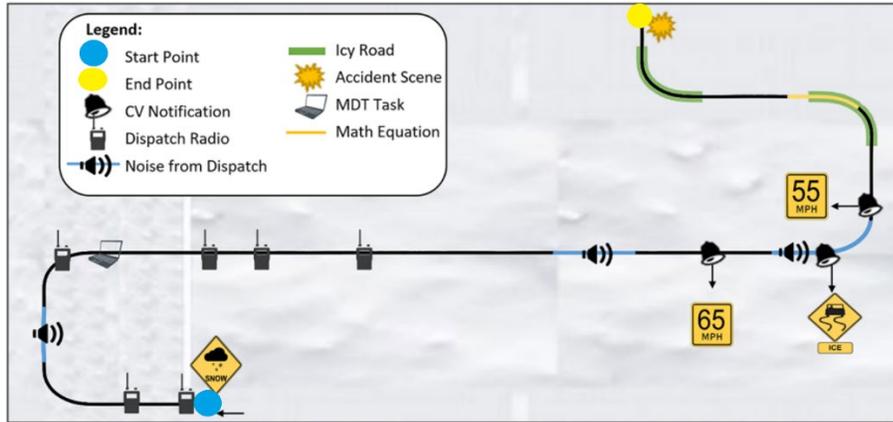
A- Slippery Roadway Scenario

B- Work Zone Scenario

Figure 153. CV Scenario Layout for the Highway Patrol Experiment.
Source: WYDOT & (15)

Results of the Driving Simulator Vehicle Kinematics for Truck Drivers

Driving simulator vehicle trajectories and speed analyses for CV and Baseline scenarios were conducted to compare the participants' performance with and without the CV technology. The data analyses was developed to serve two main objectives: 1) assess the successive impact of exposure to the notifications within the CV scenario, and 2) compare the driver behavior and performance change, between the CV scenario and the baseline scenario where the CV notifications are muted. To assess the behavioral effects of the CV warnings on longitudinal control of the vehicle, several behavioral measures were used for both applications comprised of mean speeds, speed standard deviations, mean accelerations, maximum decelerations, and percent of participants activating brakes.

Drivers in the baseline scenario, when encountered a severe weather event, a sudden reduction in speeds was observed. This increases the speed variability within the corridor, increasing crash probabilities. Table 57 provides the summary statistics for the effects of the CV weather notifications on longitudinal control within the WZW scenario for truck drivers (22).

Table 57. Summary statistics of the longitudinal control analysis.

Space-Time interval	Prior to fog warning		After fog warning		After 55 advisory speed notification		When encountered with fog	
Scenario	CV	Baseline	CV	Baseline	CV	Baseline	CV	Baseline
Mean velocity (m/s) / (mph)	30.61 / 68.46	30.55 / 68.33	30.34 / 67.87	30.79 / 68.88	27.81 / 62.10	30.82 / 68.94	24.58 / 54.98	26.37 / 58.99
Mean acceleration (m/s^2)	-	-	-0.10	-0.02	-0.50	-0.04	-0.29	-0.69
Average maximum deceleration (m/s^2)	-	-	-0.23	-0.11	-1.18	-0.16	-0.54	-1.81
Percent participants activating brakes	-	-	5%	0%	50%	0%	15%	65%

Lateral control was also investigated for the WZW scenario for truck drivers. The exposure to the CV advance warning area notifications was found to slightly increase the number of lane exceedances experienced in the WZ advance warning area. However, no statistical significance was detected in comparison with the baseline conditions (t(19) = -0.180, p = 0.859). Figure 154 shows the lane exceedance behavior and the percent of time off-lane obtained from the driving simulator dynamics.
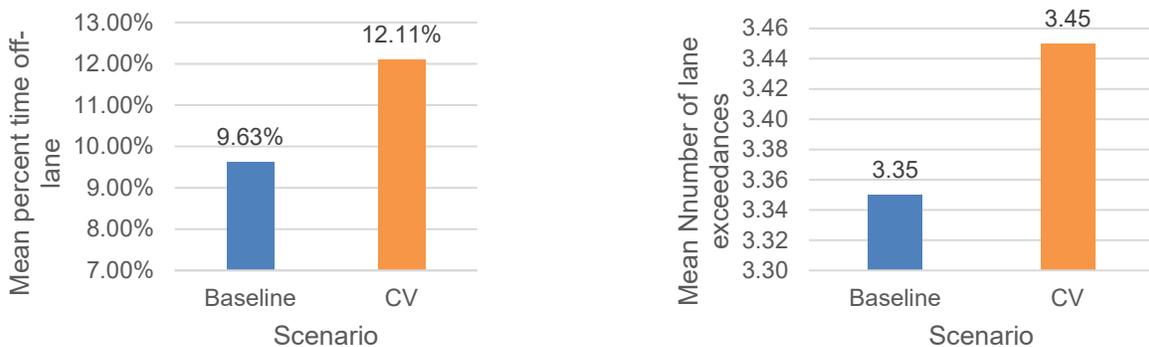
Percent time off-lane   *Lane exceedances*

Figure 154. Lane Exceedance Behavior for Truck Drivers Experiment
Source: WYDOT

Speed trajectory analysis was conducted on the SWIW scenario. Figure 155 shows the speed profile of the subject vehicle operation under the CV and non-CV conditions averaged over the

23 participants. It was expected to have an insignificant difference in operating speed for the CV and the non-CV at the first section of the developed scenarios, which is located between the first two Traveler Information Message (TIM#1) and (TIM#2). Mann-Whitney U test was conducted to statistically assess whether the two-speed trajectories are different or not. The nonparametric test was selected because the two-speed profiles were not normally distributed. The results showed that the means of the speed profiles were not significantly different at the first section located between TIM#1 and TIM#2 (U=10368, P = 0.174). This result depicted that the behavior of the drivers for the two scenarios were similar before receiving the reduced speed limit, in which the average speed for the non-CV and the CV scenarios were 56.21 and 55.40 mph, respectively.
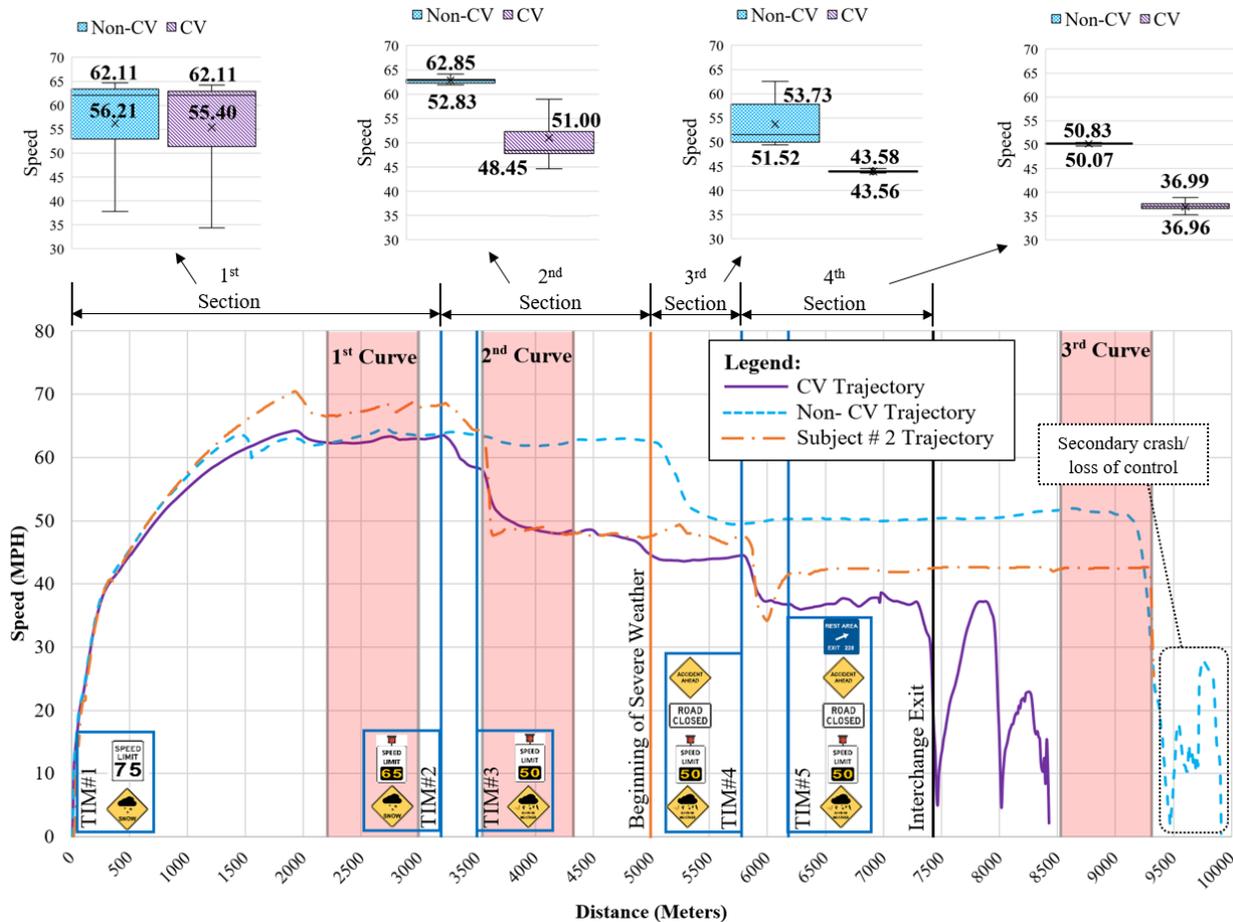
Figure 155. Subject Vehicle Trajectories for CV and non-CV Scenarios.
Source: WYDOT & (13)

Comparing the speed trajectories for the other TIMs, it was found that there was a statistically significant difference between the CV and the non-CV scenarios, which implies an enhancement is speed selection and reduction in speed variation within and between participants. This highlights the importance of the CV Pilot in Wyoming.

Furthermore, deviation from pathway, lateral speed, longitudinal acceleration, lateral acceleration, jerk, steering angle, roll, pitch, yaw, and yaw rate were assessed for CV and non-CV scenarios. These Surrogate Measures of Safety (SMoS) were analyzed when having a slippery road surface

conditions, especially at curves. Table 58 presents the statistical description of the kinematic-based SMoS corresponding to CV and non-CV scenarios on regular and slippery curves (12).

Table 58. Statistical Description of Kinematic-Based SMoS.

		Connected Vehicles				Non-Connected Vehicles			
	Variable	Min	Max	Mean	SD.	Min	Max	Mean	SD.
Curve A (Regular Pavement Condition)	Deviation from Pathway (m)	-2.21	2.09	-0.48	0.47	-2.26	0.90	-0.48	0.50
	Longitudinal Speed (mph)	41.59	67.20	57.68	4.93	47.63	73.15	60.78	5.88
	Lateral Speed (m/s)	-0.16	0.36	0.07	0.09	-0.13	0.68	0.13	0.14
	Longitudinal Accel. (m/s^2)	-2.63	1.20	-0.07	0.25	-2.11	-0.02	0.53	0.16
	Lateral Accel. (m/s^2)	-2.47	0.21	-1.28	0.58	-4.14	0.21	-1.43	0.67
	Instantaneous Accel. (m/s^2)	0.01	2.92	1.32	0.55	0.00	4.14	1.44	0.65
	Jerk (m/s^3)	-13.14	28.84	0.01	1.55	-15.17	20.37	0.00	1.78
	Steering Angle (Radians)	-1.64	0.33	-0.46	0.48	-2.12	0.38	-0.56	0.57
	Roll (degree)	-4.60	0.33	-3.39	1.39	-4.61	0.34	-3.33	1.38
	Pitch (degree)	-0.73	0.31	-0.27	0.19	-0.71	0.37	-0.27	0.19
	Yaw (degree)	-0.90	53.01	31.20	20.54	-0.49	49.07	21.62	22.77
	Yaw Rate (degree/s)	-12.99	22499.76	2.34	332.70	-21176.42	22499.71	3.97	412.17
Curve B (Slippery Pavement Condition)	Deviation from Pathway (m)	-1.53	2.30	0.22	1.35	-4.93	5.63	0.66	1.77
	Longitudinal Speed (mph)	37.62	58.15	46.82	3.83	0.04	70.74	52.37	10.04
	Lateral Speed (m/s)	-0.34	0.25	-0.05	0.09	-0.49	0.52	0.62	2.81
	Longitudinal Accel. (m/s^2)	-1.00	0.54	-0.03	0.15	-3.11	4.52	-0.04	0.39
	Lateral Accel. (m/s^2)	-2.20	0.87	-0.84	0.37	-8.14	2.55	-1.07	0.68
	Instantaneous Accel. (m/s^2)	0.00	2.22	0.87	0.34	0.00	8.33	1.16	0.64

Appendix H. Simulation Analysis of Driver Behavior

Jerk (m/s^3)	-14.16	10.82	0.01	1.07	-56.58	89.81	0.01	1.81
Steering Angle (Radians)	-1.66	1.12	-0.13	0.23	-2.49	2.12	-0.06	2.09
Roll (degree)	-4.88	0.24	-3.57	1.47	-17.62	17.01	-3.26	2.40
Pitch (degree)	-0.76	0.31	-0.25	0.18	-16.97	7.24	-0.51	1.84
Yaw (degree)	-0.65	52.39	44.86	29.82	-179.59	179.99	91.62	36.68
Yaw Rate (degree/s)	-13.60	6.40	-2.31	1.26	-53.05	21151.72	-2.62	95.46

Central tendency and dispersion analysis for the selected vehicle kinematics parameters were conducted to quantify the percent enhancement in the parameters. Table 59 shows the results obtained from the Central Tendency and Dispersion Analysis, which shows a significant enhancement in the measured performances when encountering a slippery curve on the roadway alignment (12).

Table 59. Central Tendency and Dispersion Analysis of Kinematic-Based SMoS.

Curve-A (Regular Pavement Condition)

	Median			Central Tendency Analysis			Dispersion Analysis		
				Wilcoxon Signed-Rank Test			Median Absolute Deviation		
Kinematic-Based SMoS	Non-CVs	CVs	% of Enhancement [a]	Test Stats. (W)	p-value	Sig.	Non-CVs	CVs	% of Reduction
Dev. from Pathway	-0.47	-0.46	2.01	164388	0.971		0.18	0.14	22.40
Steering Angle	-0.59	-0.58	1.59	164435	0.976		0.21	0.14	30.46
Ins. Accl.	1.59	1.57	0.60	163211	0.831		0.26	0.17	34.57
Lateral Speed	0.09	0.08	6.58	163336	0.846		0.04	0.03	16.56

Curve-B (Slippery Pavement Condition)

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Kinematic-Based SMoS	Median			Central Tendency Analysis			Dispersion Analysis		
	Non-CVs	CVs	% of Enhancement	Wilcoxon Rank Test		Signed-	Median Absolute Deviation		
				Test Stats. (W)	p-value	Sig.	Non-CVs	CVs	% of Reduction
Dev. from Pathway	0.33	0.16	51.97	71830	<0.001	*	0.95	0.28	70.69
Steering Angle	-0.25	-0.17	31.90	144015	0.002	*	0.39	0.09	77.65
Ins. Accl.	1.32	1.01	23.30	40	<0.001	*	0.21	0.09	53.99
Lateral Speed	0.42	0.01	98.97	416	<0.001	*	0.52	0.03	95.19

[a] Enhancement is defined as the relative proportion of shifting in the central tendency of SMoS toward the zero.

* Representative of statistically significant differences under 95% Confidence Interval (CI).

Results of the Driving Simulator Vehicle Kinematics for Highway Troopers

It is known that the highway troopers had a very unique driving environment that poses an increased driving workload. Therefore, three different communication approaches, resulting into four modalities, has been tested to communicate the CV warnings with the highway troopers with the aim to minimize the potential distraction introduced by the added Human Machine Interface (HMI). The different modalities tested could be concluded as; 1) baseline with no CV notifications, 2) Enlarged Icons with Beeps (EBeeps), 3) Enlarged Icons with Voice (EVoice), and 4) Small Icons with Beeps (SBeeps).

Speed performance was evaluated for the four modalities on the slippery curve location on the SWIW scenario. Figure 156 shows the longitudinal speed profile averaged for the highway troopers on a simulated slippery horizontal curve.
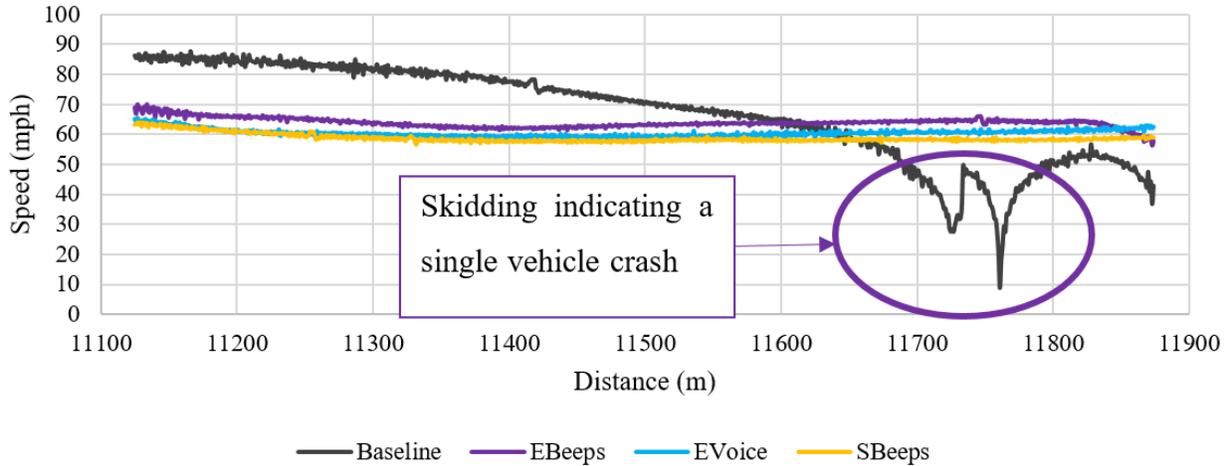
Figure 156. The Average Speeds of Highway Troopers for the four Modalities on a slippery Curve.
Source: WYDOT & (15)

The speed of the highway troopers entering the curve for the baseline modality was found to be significantly different than the CV modalities ($F(3,31) =14.836$; $p<0.001$). A Bonferroni post-hoc test revealed that the speed in the baseline scenario was significantly higher than each of the CV modalities. However, there was no significant difference in the entering speeds between any of the CV modalities. Lateral control, and brake activation showed similar results as the speed analysis.

The effectiveness of the Forward Collision Warning (FCW) was highlighted for the WZW scenario, in which it prevented the occurrence of a rear-end crash given the two warning stages A five-second and 20 second analysis showed that in each of the CV modalities, the participants braked smoothly following the cautionary and alert FCW. For the baseline, however, the participants braked at the very last moment and braked very hard trying to bring the vehicle to stop. For CV modalities, once the cautionary FCW yellow was provided, the participants slowed down, which made it easier for them to come to a complete halt when the alert FCW red went off.

Assessment of the Workload and Distraction Using Eye Tracking System

One obvious concern stem from the fact that the majority of the Pilot's CV applications rely on the visual HMI to display the content of the warnings calling drivers to divert their visual attention away from the driving scene. Accordingly, potential introduced distraction was assessed to ensure a safe driving setting while adding the HMI as an in-vehicle safety system. An eye tracking system was used to assess the distraction for the CV HMI. The eye tracking system installed on the WyoSafeSim consisted of three eye tracking cameras from Smart Eye Pro. Two cameras were placed on the top of the dashboard and one camera was mounted to the right of the mid console, as shown in Figure 157. This allowed both the eyes to be tracked in almost all the directions.

Figure 157. Smart Eye Cameras Mounting Locations.
Source: WYDOT *& (23)*

To visualize the eye tracking data, heat maps were plotted for the two different scenarios. The heat maps show how the eye glances are distributed throughout the different driving simulator objects. The close world intersection points on world model for x and y directions were extracted for all the scenarios. Python coding was done to obtain the heat maps. To obtain a smooth heat map a Gaussian kernel density estimation was performed with dispersion = 32 sigma. Once the heat plots were obtained, they were overlapped on the real-life picture of the driving simulator using certain reference points. Figure 158 shows the developed heat maps for the slippery road and the WZ scenarios. Table 60 represents the summary statistics of the glances in seconds for the SWIW AND WZW scenarios.

Slippery road surface scenario   Work zone scenario
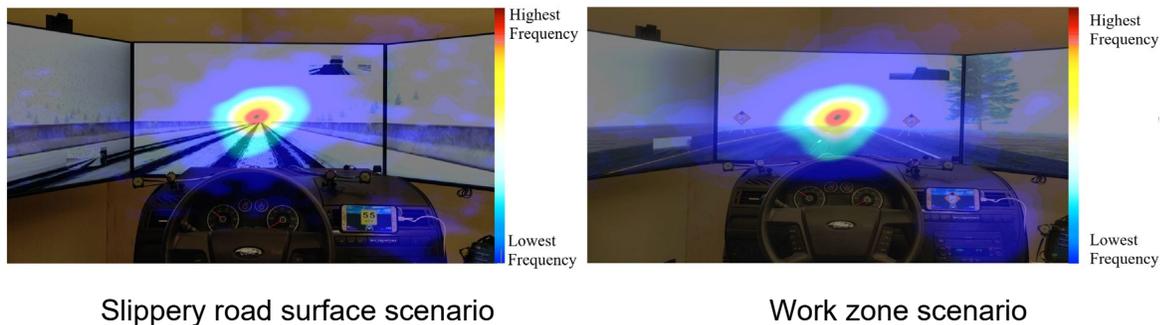
Figure 158. Heat map showing density of eye-tracking gaze points.
Source: WYDOT & (23)

Table 60. Summary of HMI Glances during for the tested CV modalities

Scenario	Modality	Mean (s)	SD (s)	Maximum (s)
SWIW	EBeeps	0.55	0.38	2.35
	EVoice	0.59	0.33	1.76
	SBeeps	0.64	0.45	3.95
WZW	EBeeps	0.59	0.36	2.05
	EVoice	0.65	0.40	2.45
	SBeeps	0.69	0.47	4.17

Mean glance duration and glances counts were used to assess the distraction introduced by the CV HMI, in which the NHTSA threshold of 2 seconds was considered as a reference to evaluate distraction (*24*). A total of five cases of distraction were observed, where the distractions occurred with the Small Icons with Beeps modality.

A one-way ANOVA test was conducted on the whole scenario to compare the mean HMI glance duration, standard deviation of glance duration on HMI and number of glances on HMI for the different modalities. The showed that there was no statistical significance between the four modalities in the mean glance time, standard deviation of glance time, and number of glances. This result was observed for the SWIW scenario as well as the WZW scenario.

A focused analysis was conducted on specific warnings within the simulated scenarios. For the WZW notifications, a significant difference was found between the glance duration on HMI ($F_{(2,23)}$ =4.032, p=0.032). A Bonferroni post hoc showed that both EBeeps and EVoice modalities invoked significantly lower glance duration on HMI than the SBeeps modality. According to the eye tracking analysis and the survey responses, the SBeeps module was the least preferred communication modality.

Distraction and Workload was also assessed for the truck drivers study. The SWIW consisted of two weather notifications communicated in clear weather conditions. During the weather notifications area (i.e., from the moment participants received the first weather warning until the moment of entering the reduced visibility area), the 16 participants on average spent 8.9% of the total time driving with their eyes directed/being directed towards the HMI. Each of the SWIW notification invoked on average 1.66 glances to the HMI (x 2 notifications) where the average single HMI glance duration took approximately 0.83s to complete. This is the equivalent of 1.41s total glance time per a single notification, on average.

On the other hand, the WZW application consisted of four work zone notifications communicated in the work zone advance warning area (i.e., the reference area for the WZW application). On average, the display of the work zone warnings prompted the participants to spend 9.1% of the total driving time in the reference area glancing to the HMI. Moreover, the display of a single WZW notification on average induced 2.48 glances to the HMI (x 4 notifications) where each glance lasted approximately 1s to complete. This is the equivalent of 2.68s total glance time per single notification. These results are illustrated in Table 61.

Table 61. Visual Demand Metrics by CV Application.

CV app.	# of CV Notifs.	Mean HMI glance duration & (SD)	% time glancing to HMI (avg.)	Mean # of HMI glances per CV Notif.	Total HMI glance time per CV Notif.
SWIW	2	0.83s (0.26s)	8.87%	1.66	1.41
WZW	4	1.03s (0.26s)	9.11%	2.48	2.68

The comparison between the visual behavior induced by the SWIW and WZW applications using the following normalized metrics reveals that: 1) the average single glance duration to the HMI in response to a work zone warning was 0.20s longer than a single HMI glance duration due to a weather warning. Evidently, this marked difference in mean HMI glance duration between the two CV applications was found statistically significant using a paired t-test ($t_{(15)}$ = 2.52, p = 0.024). 2) The WZW application prompted participants to effect more glances to the HMI per single notification in comparison with the SWIW application. Statistical significance using the paired t-test was also established ($t_{(15)}$ = 4.35, p < 0.001). This result demonstrates that the display of a work zone notification required more glances to the HMI to extract and process the communicated information. 3) The total time spent glancing at the HMI in response to a single work zone notification was almost twofold of that of a weather notification. In other words, the display of a single work zone notification required nearly twice as much glance time in comparison with a weather notification. This result was also found statistically significant using a paired t test ($t_{(15)}$ = 4.34, p < 0.001). This finding also highlights that the work zone notifications involved substantially higher visual/cognitive workload demands to locate, recognize, and process the displayed information.

PM Evaluation Using Microsimulation Utilizing Driving Simulator Input

In response to the WYDOT CV Pilot Deployment Program "Performance Measurement and Evaluation Support Plan", traffic simulation modeling using VISSIM software is conducted for the analysis of traffic safety performance measures. The use of microscopic traffic simulation modeling allows for the analysis of conflict-event safety surrogates such as time-to-collision, distribution of speeds, speed variation, number of lane changes, etc. It was anticipated that the CV deployment would result in changes to speed selection, lane changing and car following behavior for CV-equipped drivers that can be modeled in a microsimulation environment. Therefore, by using microsimulation, researchers can gain insightful understanding of the impacts of the safety effectiveness of CV technology. In this regard, this system performance report proposes a VISSIM simulation framework for a segment of the Cheyenne-Laramie (mileposts 317 to 340) Variable Speed Limit corridor to determine the suitability of adopting a microscopic simulation approach for providing insight into the safety effectiveness of CV technology under various scenarios. The selected corridor represents the most challenging traffic situation along I-80 in Wyoming, such as high altitude, high adverse weather events, and steep vertical curves. Being limited by the available time and resources, it is not feasible to calibrate and simulate a 402-mile freeway corridor. In case of further evaluating the performance of the entire corridor, a sensitivity analysis could be used to extrapolate the simulation results from the selected corridor to the 402-mile I-80 corridor in Wyoming. Non-CV "Baseline" Microsimulation Model.

Microsimulation Framework

The U.S. Federal Highway Administration (FHWA) defines Analysis, Modeling, and Simulation (AMS) as an evaluation process for assessing traffic operations along a corridor. Based on while, researchers could identify key transportation challenges, and explore potential management strategies to be used to improve the operational performance of the corridor. Typically, an AMS framework contains three components; 1) Analysis, which requires investigation of the traffic and environmental conditions about the corridor, 2) Modeling, which refers to developing and calibrating a model or models to capture the real-world traffic and environmental conditions, and 3) Simulation, which means using the developed model(s) to assess the performance of the corridor, and identify the operational issues as well as potential solutions to these issues.

The proposed AMS framework employs the VISSIM simulation with the Surrogate Safety Assessment Model (SSAM) for safety performance evaluation, as it is known that microsimulation software cannot directly simulate traffic crashes. The SMoSs used for safety evaluation were based on traffic conflicts (i.e., crash opportunities determined by safety assessment parameters such as TTC and Post-Encroachment Time (PET)) generated by the VISSIM simulation models. High-resolution traffic flow data were collected from field (baseline scenario) and truck driving simulator experiment (CV scenario) and feed into the developed microsimulation models to more accurately capture the real-world traffic operation condition and driver behavior (25, 26). An overview of the proposed AMS framework is illustrated in Figure 159.
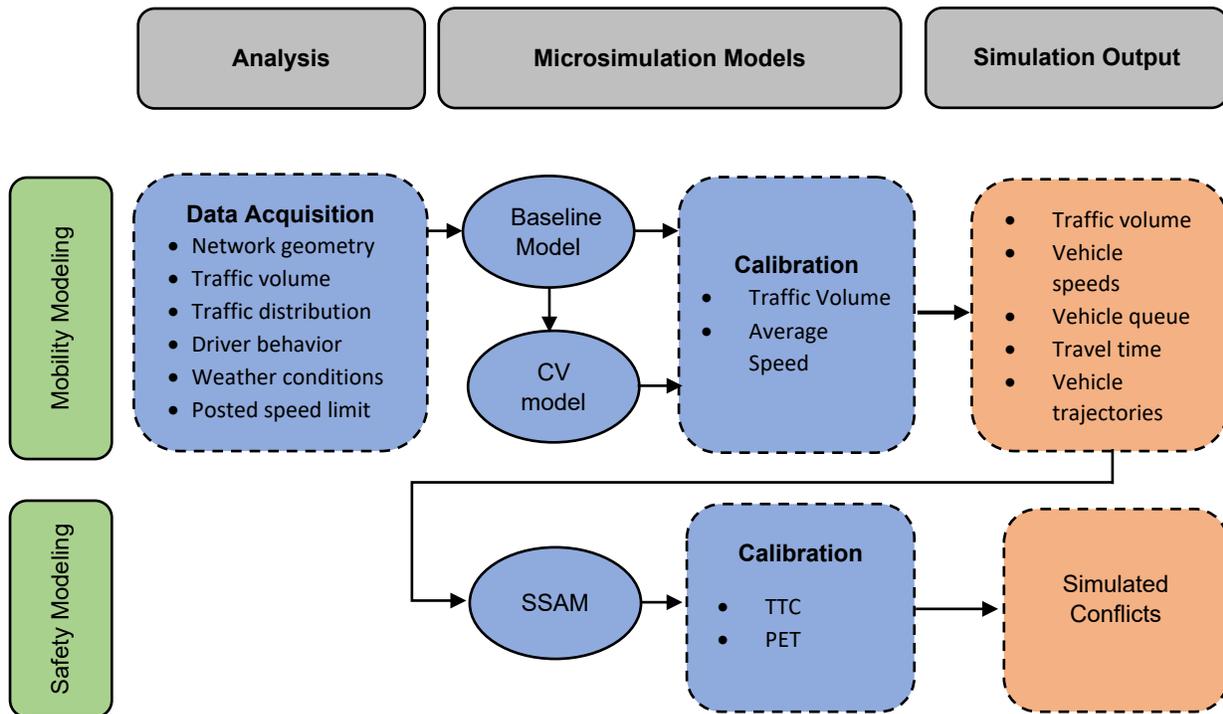
Figure 159. Overview of the proposed microsimulation modeling framework.
Source: WYDOT

It is known that microsimulation software cannot directly simulate traffic crashes. In current practice, using Surrogate Measures of Safety derived from data output by traffic simulation

models has been proved as an efficient method for safety evaluation. This safety performance simulation employed the VISSIM simulation with the Surrogate Safety Assessment Model (SSAM) for safety performance evaluation. The surrogate measures developed for safety evaluation are based on the traffic conflicts (crash opportunities determined by safety assessment parameters such as Time-to-Collison, TTC) generated by the VISSIM simulation model. A default TTC threshold (usually range from 1.5 to 5 seconds) was used during the initial simulation. Then, the model calibration process used field data to identify the appropriate TTC threshold. For pre-deployment period, traffic flow and speed data were collected by the WYDOT's roadside Wavetronix sensors installed the corridor. For post deployment period, the micro-level driver behavior data were obtained from a high-fidelity driving simulator at the University of Wyoming Driving Simulator Lab (WyoSafeSim).

In order to assess the suitability of simulation modeling for providing insight into the safety effectiveness of CV technology, a Baseline VISSIM model was built for a selected freeway segment on the Cheyenne-Laramie (mileposts 317 to 340) Variable Speed Limit corridor. The basic corridor network was uploaded from the standard map data in VISSIM; then, the roadway geometric data, including number of lanes, roadway segment lengths and grades, location of lane additions and drops, locations of rest and/or parking areas, etc., have been manually coded in VISSIM. Additional detailed traffic control parameters have been incorporated into the VISSIM network to better reflect existing operational conditions. Key traffic parameters include traffic composition, vehicle dynamics data, posted speed limits, presence of work zones (including location, length, lane closure condition, etc.), amongst other.

The driver behavior in VISSIM is modeled through car-following and lane-changing models. The driving behavior is linked to each link by its link type and the mechanical capabilities of the driver's vehicle. For each vehicle class, a different driving behavior parameter set is defined. The behavior model for the driver involves a classification of reactions in response to the perceived relative speed and distance with respect to the preceding vehicle. For the car following model, since this study focuses on performance evaluation on a freeway corridor, driving behavior settings include standstill distance, headway time, safe distance, look ahead and back distances, temporary lack of attention, etc. For the lane-changing model, the following driving behavior parameters is considered: lane utilization, acceleration/deceleration profiles, minimum headway, lane-changing gap acceptance, waiting time before diffusion, safety distance reduction factor, etc.

The impact of adverse weather on freeway operations could be simulated by changing the driving behavior parameters. Weather-responsive microsimulation modeling is a substantial task and the PM team hopes to leverage ongoing research efforts from a SHRP2 Naturalistic Driving Study (NDS) project that is being done on this topic at the University of Wyoming. As part of this project, driving behavior models are calibrated to represent driving behavior in various adverse weather conditions. It is proposed that the observed behavioral changes of drivers, as identified from the SHRP2 NDS project, will be used to inform the development of driving behavior models for the CV Pilot microsimulation modeling. Driver behavior from SHRP 2 will need to be assessed and adjusted to Wyoming I-80 conditions. Given the timeline of the NDS and CV Pilot study, it was proposed that a simulation model utilizing currently available driver behavior models be developed in Phase 2 and that incorporation of weather responsive driver behavior and CV technology components be done in Phase 3. In case of road closure due to severe weather or accident, since in reality there is no alternative routes (or very limited access to alternative routes) along the selected I-80 corridor in Wyoming, it is assumed that truck drivers will cancel the current trip, exit

the freeway from the nearest exit, and reschedule the trip after road re-open. The waiting time is treated as delay in the mobility analysis.

Development and calibration of VISSIM models

A VISSIM simulation model was developed for a 23-mile segment of the Cheyenne-Laramie VSL corridor (mileposts 317–340) to determine the suitability of adopting a microscopic simulation approach for providing insights into the safety effectiveness of the WYDOT CV Pilot. The selected corridor represents the most challenging traffic situation along I-80 in Wyoming, such as high altitude, severe weather events, and steep vertical grades. The basic corridor network was uploaded from the standard map data in VISSIM; then, the roadway geometric data, including number of lanes, roadway segment lengths and grades, location of lane additions and drops, etc., have been manually coded in VISSIM Version 11.

For the baseline microsimulation model, this research adjusted the microsimulation model's default Wiedemann 99 car-following model and lane-changing parameters based on the traffic flow and speed data collected by the WYDOT's Wavetronix sensors and the SHRP2 Naturalistic Driving Study conducted by the University of Wyoming (*27–31*). Two default vehicle types in VISSIM (Car and Truck) were used to define traffic composition. For each vehicle type, detailed vehicle classification and corresponding percentages were obtained from the WYDOT TMC traffic database. A single vehicle category shares the same vehicle performance attributes, which include vehicle lengths maximum speed, acceleration and deceleration capabilities, weight, power, and other mechanical features. Simulation results were compared against field observed data to check the errors between simulation inputs and outputs. The two commonly used microsimulation model calibration and validation tests, Geoffrey E. Havers (GEH) statistic test and Mean Absolute Percentage Error (MAPE) statistic test, were employed to verify the errors between simulated and the observed traffic volume and speed profiles, respectively. Results showed that both the GEH test results and the MAPE test results for all the four sensor locations are within an acceptable range (26).

For internally modeling of CV, since VISSIM has the capability of defining vehicle class-specific driving behaviors for each link in the network, different vehicles can behave differently on the same link. This allows the user to simulate CV driving behavior by defining a dedicated CV class and calibrate the default driver behavior parameters based on field collected or tested CV driver behavior data. Since the WYDOT CV Pilot focuses on truck safety, at this stage only commercial trucks, WYDOT snowplow trucks, and the Wyoming Highway Patrol (HP) vehicles were equipped with CV system. Therefore, this research defined three vehicle categories: regular car, non-connected trucks, and connected trucks. According to the user instruction provided by the PTV Group, key methodologies used for internally modeling of Connected and Autonomous Vehicles (CAVs) in VISSIM are described as follows (Cisco, 2017):

- Keep smaller standstill distance (i.e., change CC0 parameter in VISSIM Wiedemann 99 model),

- Keep smaller distances at non-zero speed (i.e., change CC0, CC1, CC2 parameters in VISSIM Wiedemann 99 model),

- Accelerate faster and smoothly from standstill (i.e., change acceleration functions and CC8, CC9 parameters in VISSIM Wiedemann 99 model),

- Follow other vehicles with smaller oscillation distance oscillation (i.e., change CC2 parameter in VISSIM Wiedemann 99 model),

- Perform more co-operative lane change as lane changes could occur at a higher speed co-operatively (i.e., switch cooperative lane change; change maximum speed difference; change maximum collision time),

- Smaller lateral distances to vehicles or objects in the same lane or on adjacent lanes (i.e., change default behavior when overtaking on the same lane),

- Drive as CAV on selected routes and as conventional human controlled vehicles on other routes (i.e., Use different link behavior types and driving behavior for vehicle classes; and/or depending on complexity of CAV behavior).

Based on the descriptive features of CAV behavior and in accordance with the quantified changes of driving behavior under CV environment (such as a 10 percent reduction in average speed and smaller variations of speeds) obtained from the driving simulator experiment, the CV microsimulation model was developed and re-calibrated by adjusting the desired speed distribution and driving behavior data of the calibrated baseline microsimulation model, as listed in Table 62 (26).

Table 62. Calibrated Driving Behavior Data for Baseline and CV Scenarios.

Driver Behavior Parameter		Regular Car	Non-Connected Truck	Connected Truck
Car Following	CC0 (Standstill Distance) (ft.)	18.2	25.8	30
	CC1 (Headway Time) *	3-4	4-8	6-10
	CC2 (Following Variation)	32.2	37.30	43.70
	CC8 (Standstill Acc. (ft/s^2)	8.3	4	2
	CC9 (Acc. With 50mph) (ft/s^2)	4	1.5	0.1
	Look ahead distance (ft.)	500	600	800
	Look back distance (ft.)	300	350	410
	Observed Vehicle	1	2	3
Lane Changing	General Behavior	Free lane change	Right lane rule	Right lane rule
	Safety distance reduction factor	0.5	0.6	0.7
	Advanced Merging	No	No	Yes
	Cooperative lane changeing	No	No	Yes

	Maximum deceleration (ft/s^2)	-15	-15	-13

Note: * Headway followed a normal distribution pattern; regular car non-connected truck were included in the baseline model; regular car, non-connected truck, and connected truck were included in the CV model.

Safety Performance Assessment

A total of 18 microsimulation modeling scenarios (i.e., 3 traffic demand scenarios multiplied by 6 connected truck penetration rate scenarios) were designed to investigate the safety performance under various demand levels and connected truck penetration rates. For each scenario, 5 simulation runs were performed to eliminate the random errors of microsimulation. Afterwards, the simulated vehicle trajectory files were imported to SSAM for safety performance assessment. Since this research focused on a low-volume rural freeway corridor under adverse weather conditions, it was assumed that CV warnings could improve CV drivers' situational awareness. Among the SMoS used by SSAM, Time-To-Collision (TTC) was considered as most applicable for assessing the safety performance of the study rural freeway corridor, since vehicles had significantly lower lateral interactions in comparison with driving on urban freeways. Three different levels of TTC threshold were considered in the assessment analysis: high risk (1.5 s), medium risk (3.5 s) and low risk (9 s) to qualitatively compare the simulated conflicts under various traffic demand levels and CV penetration rates.

A comparison of the simulated number of conflicts for each scenario is presented in Figure 160. It is necessary to point out that the majority of the simulated conflicts from SSAM were rear-end conflicts, which is mainly due to the following two factors; 1) Under snowy weather condition, the majority of vehicles choose to drive on the right lane with a relatively lower speed and small number of lane changing maneuvers, and 2) The simulated corridor was a rural freeway corridor with very large space interval between adjacent ramps, and under snowy weather condition, there was almost no on-ramp/off-ramp traffic. These factors resulted in very limited lane-changing maneuvers.

Simulated results indicated that the number of traffic conflicts increased significantly with the increase of traffic demand and decreased with the increase of connected truck penetration rate. Since the microsimulation models were developed for a 23-mi freeway corridor, thus the simulations resulted in large numbers of conflicts (e.g., up to 4,700 conflicts for baseline scenario under high demand levels). In the high risk scenario, it was found that when the penetration of connected trucks was less than 10%, reduction in number of conflicts was not significant. In comparison, when the penetration of connected trucks was greater than 25%, there were remarkable reductions in conflicts. The reduction reached 85% for fully connected trucks scenarios, indicating that the CV applications developed by the WYDOT CV Pilot have the capability of improving traffic safety of this rural freeway corridor under snowy winter weather condition. Generally, number of conflicts decreased roughly linearly as market penetration of CVs increased.
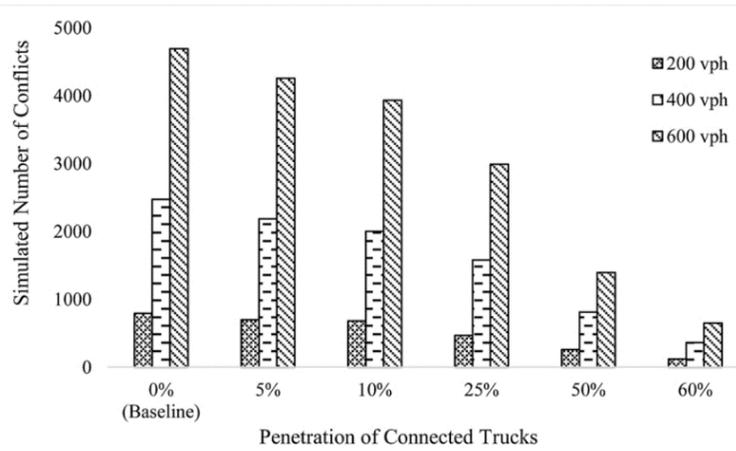
(a) High risk (TTC = 1.5s)
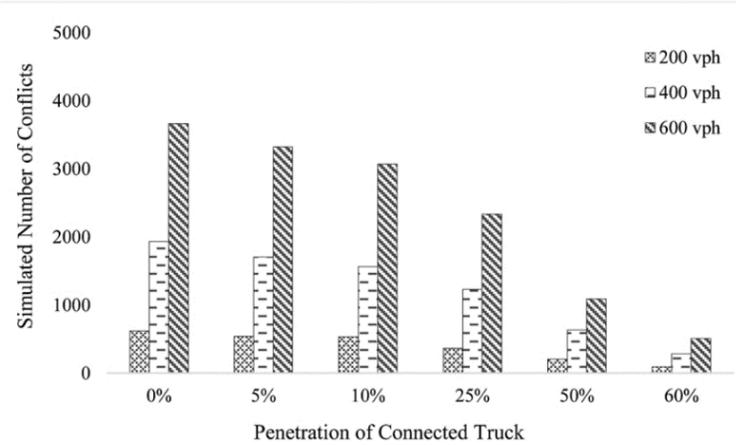
(b) Medium risk (TTC = 3.5s)
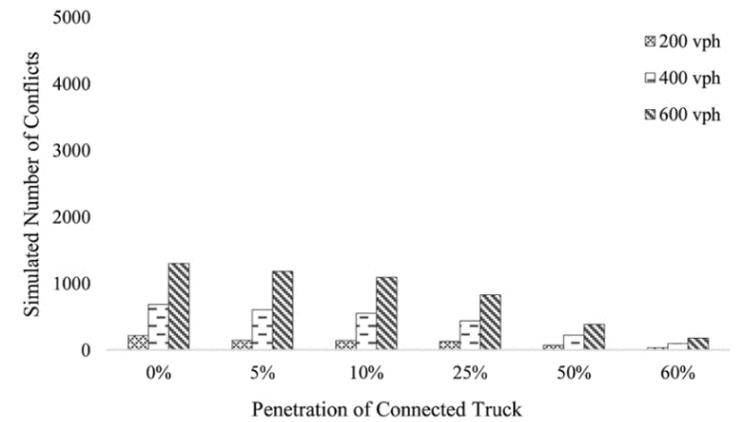
(c) Low risk (TTC = 9s)

Figure 160. Sensitivity analysis of different TTC thresholds during winter snow weather condition under various demand levels and connected truck penetration rates.
Source: WYDOT

Appendix I. Overview of Pre-Deployment Measures of Performance

This appendix provides further details about the initial and updated set of metrics, and how they relate to each other. Table 63 lists both sets of metrics and the justification for change. Most of the changes can be explained by the fact that the initial set of measures was set prior to the full design and deployment of the system. As such, assumptions were made on the data available and how it would be collected.

Table 63. Comparison of pre- and post-deployment set of PMs

Pre-deployment PM	Changed in Post-deployment?	Change Justification
PM 1. Number of road weather condition reports per road section/day pre and post CV Pilot	No.	N/A
PM 2. Number of road sections with at least one reported road condition per hour pre and post CV Pilot	No	N/A
PM 3. Average refresh time of road condition reports in each section pre and post CV Pilot	No	N/A
PM 4. Pikalert™ generated motorist alert warnings (MAWs) that were rejected by TMC operators as inaccurate	Not included in the Phase 3 report.	The Pikalert system presented issues during its deployment and the pilot was not able to collect the necessary data for the purpose of this PM. See Section 6.1 for more details.
PM 5. Number of messages sent from the TMC that are received by the RSU	Yes	The new indicator for this PM is **PM 4**. For this measure, it was later discovered that, while the data was mostly available to obtain an accurate percentage of success transmission of TIMs to each individual RSU, the process to obtain the data and estimate this value could not be fully automized and it would require intense manual efforts. Based on this, this measure was edited to account for the percentage of TIMs received by at least one RSU.
PM 6. Number of messages sent and received between the RSU and WYDOT fleet vehicle's OBU	Yes	Similar to the previous measure (initial PM5), it was later determined that the data was not readily available, and it would require intense manual effort to

Pre-deployment PM	Changed in Post-deployment?	Change Justification
		estimate this measure. As a proxy, this measure was broken down into three new PMs: **PM 5**. Percentage of TIMs received by at least one OBU on I-80 through satellite. **PM 6**. Percentage of TIMs received by at least one Friendly vehicle from RSUs. **PM 7**. Percentage of TIMs received by at least one OBU, through either satellite or RSU.
PM 7. Connected vehicles that likely took action following receipt of an alert	Yes	This measure changed in the list order to **PM 16**. This measure was also limited to a certain number of case studies, given the intense manual effort needed to assess each driver behavior.
PM 8. Commercial vehicle managers are satisfied with information provided by the TMC	Not included in the Phase 3 report.	This PM was excluded from the analysis due to lack of response from managers. The team made several rounds of survey with minimal response rate, not yielding enough information to assess this measure. It should be noted though that the baseline for this measure was already very high, at around 96%. As such, the pilot did not expect to have a significant positive impact on this.
PM 9. Number of operational changes made by fleet managers due to information from TMC	Not included in the Phase 3 report.	This PM was excluded from the analysis due to lack of response from managers.
PM 10. Commercial vehicle drivers' benefits experienced due to CV technology during major incidents and events on I-80	Not included in the Phase 3 report.	This PM was excluded from the analysis due to lack of response from drivers.
PM 11. Number of V2V messages properly received in surrounding vehicles from sending vehicle	Yes	Assessment of the V2V interactions was explored via **PM 17** and case study "Analysis of Forward Collision Warning Alerts" in Appendix G.
PM 12. Connected vehicles that likely took action following receipt of a V2V alert	Yes	This measure changed in the list order to **PM 17**. This measure was also limited to a certain number of case studies, given the intense manual effort needed to assess each driver behavior.
PM 13. Number of emergency notifications that are first	Not included in the Phase 3 report.	The PM was excluded from the scope of the study. Due to changes in design and OBU equipment, Distress Notifications

Pre-deployment PM	Changed in Post-deployment?	Change Justification
received in the TMC from connected vehicles		were no longer supported by the vast majority of OBUs. The project team concluded that lack of this capability does not negatively impact safety performance or the success of the WYDOT CV Pilot and therefore agreed to proceed without this capability in all OBUs. This resulted in no DNs ever activated, so there was no data to report on.
PM 14. Total vehicles traveling at no more than 5 mph over the posted speed	Yes	This measure changed in the list order to **PM 8.** No other change beyond this one.
PM 15. Total vehicles traveling within +/- 10 mph of the Posted Speed	Yes	This measure changed in the list order to **PM 9.** No other change beyond this one.
PM 16. Speed of applicable connected vehicles are closer to posted speed when compared to non-connected vehicles	Yes	This measure changed in the list order to **PM 10.** No other change beyond this one.
PM 17. Number of connected vehicles involved in a crash	Yes	This measure changed in the list order to **PM 11.** No other change beyond this one.
PM 18. Reduction of the number of vehicles involved in a crash	Yes	This measure changed in the list order to **PM 12.** No other change beyond this one.
PM 19. Reduction of total and truck crash rates within a work zone area	Yes	This measure changed in the list order to **PM 13.** No other change beyond this one.
PM 20. Reduction of total and truck crash rates along the corridor	Yes	This measure changed in the list order to **PM 14.** No other change beyond this one.
PM 21. Reduction of critical total and truck crash rates in the corridor	Yes	This measure changed in the list order to **PM 15.** No other change beyond this one.

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