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Safe Integration of Automated Vehicles into Work Zones

Concept of Operations for the Safe Integration of Automated Vehicles into Work Zones (SI-AV-WZ) Project

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16. Abstract

This Automated Driving System Demonstration will evaluate the impact of improved connectivity, visibility, and mapping between automated vehicles and work zone objects to allow for the integration of automated vehicles into work zones. This document presents the Concept of Operations, which details the user-oriented operational description, user needs, system overview, operational and support environment, and operational scenarios. The purpose of this Concept of Operations is to clearly convey a high-level view of the system to be implemented from the viewpoint of each stakeholder. This document frames the overall system, sets the technical course for the project, and serves as a bridge between early project motivations and the technical requirements.

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1 INTRODUCTION

Pennsylvania has emerged as a leading region for on-road testing of Automated Vehicles (AVs) as AVs steadily advance toward practical use. Pennsylvania Department of Transportation (PennDOT) has supported these advances in automation through the deployment of connected infrastructure and advocating for uniform standards and practices. PennDOT has acted to sustain Pennsylvania's leadership in AV research, while simultaneously ensuring that the public safety remains the paramount priority. PennDOT proposed the idea of experimenting with AVs in work zones, which offers a unique opportunity for the AV industry and public sector to collaborate in resolving potential safety issues with Automated Driving Systems (ADS) technology.

The United States Department of Transportation (USDOT) ADS Demonstration Grants Program appropriated funding for a "highly automated vehicle research and development program" to fund planning, direct research, and demonstration grants for ADS and other driving automation systems and technologies. The demonstration grant included funds for testing the safe integration of ADS into our nation's on-road transportation system.

PennDOT applied for the USDOT ADS Grant Program and received funding of $8,409,444. PennDOT plans to utilize these funds for research and development, planning, testing, and demonstrating the safe integration of AVs in the work zones through this grant.

The intent of PennDOT's ADS Demonstration (hereinafter, the project) is to develop a consistent approach to enable AVs to safely operate in work zones. Knowing that there is unlikely to be a single technology solution, the project focuses on using a combination of connectivity, computer perception, and High-Definition (HD) mapping. To demonstrate the viability of these solutions, the project will perform simulations and demonstrations in a variety of work zone configurations with varying scale, complexity, and duration. PennDOT plans to take a systematic approach of working with testers to verify the proposed AV solutions. The simulations and demonstrations will be conducted in a controlled, closed-course environment. Eventually, upon successful testing, PennDOT will work with the project team to safely integrate the solutions into limited, small-scale, on-road live demonstrations.

1.1 Document Purpose and Scope

This Concept of Operations (ConOps) document serves as the first in a series of systems engineering documents that describes the ADS Demonstration environment, referred to as the AV Work Zone System, that will be developed for the *PennDOT Safe Integration of AVs into Work Zones* project. The purpose of this ConOps is to clearly convey a high-level view of the system to be designed and implemented from the viewpoint of each stakeholder. This document frames the overall system, sets the technical course for the project, and serves as a bridge between early project motivations and the technical requirements. The ConOps seeks to be technology-independent, focuses on the functionality of the proposed system, and forms the basis of the project. The ConOps also serves to communicate the users' needs and expectations for the proposed system. Finally, this document gives stakeholders the opportunity to provide input as to how the proposed system should function, which will help build consensus and create a single vision for the system moving forward.

The structure of this document is tailored from the American National Standards Institute (ANSI)/American Institute of Aeronautics and Astronautics (AIAA) G-043-1992 containing the following sections:

- **Chapter 1. Introduction** provides a high-level overview of the general concepts and nature of the project.

- **Chapter 2. Referenced Documents** identifies all documents referenced and interviews conducted in developing this document.
- **Chapter 3. User-Oriented Operation Description** describes the users and use cases of the system.
- **Chapter 4. Operational Needs** describes the features and user needs that the system aims to satisfy.
- **Chapter 5. System Overview** provides a high-level description of the proposed system resulting from the features described in Chapter 4.
- **Chapter 6. Operational Environment** describes both the operational environment and the physical environment within which the system will operate.
- **Chapter 7. Support Environment** describes the support concepts and support environment for the proposed system.
- **Chapter 8. Operational Scenarios** presents how the project is envisioned to operate from various perspectives.

1.2 System Overview

Through this demonstration, PennDOT and the project team aim to solve the challenge of safe integration of AVs into most work zones by examining if improved connectivity, computer perception, and HD mapping will improve AVs operations to safely travel the work zones.

PennDOT has assembled a comprehensive team of project partners and subject matter experts including representation from state and local government, metropolitan planning organizations, academic partners, equipment manufacturers, data management specialists, and members of industry to successfully conduct the research. It was important to PennDOT to have this breadth of collaboration to harness the collective expertise, ingenuity, and knowledge of multiple stakeholders.

The team will demonstrate how the operation of AVs in work zones can be tested, improved and standardized in three phases as shown in **Figure 1**:

- Phase I – Planning
- Phase II – Deployment
- Phase III – Post-Deployment

Figure 1: Project Work Breakdown Structure

Phase I Planning		Phase II Deployment	Phase III Post-Deployment
I.1 Project Management	I.7 Deployment Plan	II.1 Data Management System	III.1 Final Evaluation
I.2 Risk Management	I.8 O&M Plan	II.2 Simulation	
I.3 Systems Engineering Management Plan	I.9 Data Privacy and Data Management Plan	II.3 Closed Track Testing	
I.4 Concept Of Operations	I.10 Project Evaluation Plan	II.4 Live-On Road Testing	
I.5 Systems Requirements/Test Plan	I.11 Human Use Approval		
I.6 System Architecture and Standards Plan	I.12 Coordination, Communication, & Outreach		
	I.13 Data Management System Sandbox		

SOURCE: ADS DEMONSTRATION PROJECT MANAGEMENT PLAN

During Phase I, the team will (a) plan for the deployment of the testing and analysis phase using the project management and systems engineering approaches, and (b) develop appropriate planning documentation.

During Phase II, the team will implement and deploy the plan developed as part of Phase I. Based on PennDOT's experience, the team has identified 17 common work zone scenarios/configurations in different urban, rural, and suburban settings, as well as on limited access facilities and urban arterials, typical in not only Pennsylvania but also other states. Each work zone scenario setup will include the lane configuration and traffic control devices as identified in PennDOT's *Publication 213 - Temporary Traffic Control Guidelines*[1]. In addition, connectivity equipment including Vehicle-to-Everything (V2X) communications will be added to the appropriate traffic control devices, construction workers and vehicles (collectively called work zone objects[2]). Pavement markings and work zone objects will be enhanced with special coatings developed by PPG Industries, Inc. (PPG) to improve visibility specifically for the AVs.

For each of the 17 work zone scenarios, the team will conduct simulation and closed-track testing at the PSU test track as applicable. In addition, the team will conduct live on-road testing for at least three (3) of the work zone scenarios including one (1) long-term, one (1) short-term, and one (1) mobile work zone.

The simulation and testing processes include detailed mapping of the work zone with PSU's enhanced mapping vehicle, making the map accessible to CMU's AV and operating the AV through simulated and

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[1] http://www.dot.state.pa.us/public/pubsforms/publications/pub%20213.pdf
[2] Note: Work zone objects – traffic control devices, construction workers, and vehicles – that are not equipped with V2X radios are referred to as "work zone objects", while work zone objects that are equipped with V2X radios are referred to as "V2X Work Zone Objects" – a subsystem of the project described further in **Section** Error! Reference source not found..

staged work zones in the closed track and live on-road environment. PSU's vehicle has enhanced capabilities to produce accurate, 3rd party work zone mapping. Throughout the simulation and testing process, mapping data, vehicle data, connectivity ecosystem data, operational data and safety performance data will be collected and stored in a cloud-based Data Management System (DMS) for open access by the United States Department of Transportation (USDOT) and, (with approval from the USDOT), by the public. In addition to data collection, the team will attempt to standardize the map information so that it can be disseminated in real-time to the AV.

During Phase III, the team will evaluate the performance of the demonstration project by following the procedures identified in the *Project Evaluation Plan*, developed during Phase I.

The vision, mission, goals, and objectives of the project are as follows:

Vision – Enable AVs to safely operate in work zones without human intervention.

Mission – Reduce traffic fatalities and increase mobility for all Americans in work zones through AVs.

Goals – Achieve safe navigation of AVs on par with non-distracted, human-operated vehicles within work zones.

Objectives –

1. Evaluate the impact of improved connectivity between an AV and the work zone objects using V2X
2. Evaluate the impact of increased visibility (machine vision) of pavement markings and work zone objects on AVs through innovative coatings.
3. Evaluate the impact of providing HD mapping of work zone objects (including cones, barrels, workers, vehicles).
4. Improve the map information dissemination process from the mapping providers and/or infrastructure owners/operators to the AV through standardization of digital mapping information for work zones.

The goals and objectives are further integrated into a process-based evaluation plan as part of the *Project Evaluation Plan* development.

1.3 Long-Term Vision

PennDOT envisions that in the coming years SAE Level 4 AVs will be operating on limited or all roads under most conditions. In order to operate under nearly all conditions, vehicles will need to be able to operate in work zones in autonomous mode.

Using smart roadside infrastructure, an AV will receive notice of nearby construction work zones in the vicinity. The AV will be responsible for determining if a work zone is in it's planned path. If so, the AV will send a request for a HD map of the work zone in its route. The request will be received either by the RSU or through wide-area wireless communications and sent to a cloud-provisioned DMS, who will then return an HD map of the corresponding zone to the AV. The AV will read, integrate, and use the new map to navigate the path along the work zone.

The work zone map format would be a standardize format that is used universally so that all AVs would be receiving the same data, regardless of where the work zone is located. The work zone map functionality would likely be built into the ATMS or another central data system and policies would be in place to facilitate the mapping for all work zones.

Alternatively, or in conjunction with map updates, V2X Work Zone Objects will be able to send their location to an RSU, which will aggregate the locations and send them to the AV, allowing the AV to understand the work zone layout and navigate through. The use of enhanced coatings on work zone objects may augment the AV's ability to navigate through the work zone as well.

To achieve this vision, the high level needs of the Commonwealth are as follows:

- The DMS needs to be able to receive, process, validate, store and transmit work zone map data.
- The Mapping Van needs to ble able to map the work zone and upload the data to the DMS for processing.
- The V2X Work Zone Objects need to be able to send their location to the HPC/RSU for aggregation, then send to AVs.
- The Work Zone Operators need to be able to set up and configure V2X Work Zone Objects.
- Processes and policies need to be in place to facilitate the mapping of work zones and transmission of the data to the AVs.
- Communications need to be in place to enable the transmission of data between system elements.
- WZDx system needs to be in place, which is currently being developed by PTC.

1.4 Procurement

PennDOT has established procurement processes to handle the various professional, technical, and construction services and equipment to be acquired during the demonstration. PennDOT's Engineering and Construction Management System portal will be used for all procurement. All project team members have contracts in place to assist with the project.

Most of the subsystems of this project are already owned by the stakeholders. The development of this project will require that the subsystems that already exist be integrated. Various components of the incomplete subsystems may require that items or services be procured as part of this project. For these procurements, PennDOT will follow the *Buy America Act*. An exception under the Buy American Act or an exception to the terms of the Notice of Funding Opportunity Clause at Section F, Paragraph 2.J. entitled BUY AMERICAN AND DOMESTIC VEHICLE PREFERENCES is currently not anticipated for new procurement.

Further discussion on procurement can be found in the *Project Management Plan*.

2 REFERENCED DOCUMENTS

Table 1 lists resources (documents, online information, and standards) relevant to the AV Work Zone System.

Table 1: AV Work Zone System Resources

Title	Publication Date
PennDOT Publication 213 – Temporary Traffic Control Guidelines http://www.dot.state.pa.us/public/pubsforms/publications/pub%20213.pdf	March 2021
ANSI/AIAA G-043-1992 – Guide for the Preparation of Operational Concept Documents https://webstore.ansi.org/Standards/AIAA/0431993	January 1993
Safe Integration of AVs into Work Zones (ADS Demonstration Grant Proposal) https://www.transportation.gov/sites/dot.gov/files/docs/policy-initiatives/automated-vehicles/351461/36-penndot.pdf	March 2019
Pennsylvania Code http://www.pacodeandbulletin.gov/Home/Pacode	February 2021
PennDOT AV Testing Guidance https://www.penndot.gov/ProjectAndPrograms/ResearchandTesting/Autonomous%20_Vehicles/Documents/PennDOT%20HAV%20Testing%20Guidance.pdf	July 2018
PennDOT AV Incident Response Plan	Under Development
Federal Communications Commission (FCC) First Report and Order https://public-inspection.federalregister.gov/2021-08802.pdf	May 2021
Office of Administration Information Technology (IT) Policies https://www.oa.pa.gov/Policies/Pages/itp.aspx	May 2021
PTC Maintenance & Protection of Traffic Standards https://www.paturnpike.com/business-hub/vendor-resources/engineering-standards	December 2019
PennDOT ADS Demonstration Data Management Plan	May 2021
PennDOT ADS Demonstration Data Privacy Plan	Under Development
PennDOT ADS Demonstration Deployment Plan	Under Development
PennDOT ADS Demonstration Project Evauation Plan	Under Development
PennDOT ADS Demonstration Project Management Plan	May 2021
PennDOT ADS Demonstration Systems Engineering Management Plan	October 2021
Stakeholder Meeting Minutes (Appendix C)	May 2021
CV Pooled Fund Study 5.9 GHz DSRC Vehicle-Based Road and Weather Condition Application Final Report	December 2017

SOURCE: PENNDOT

3 USER-ORIENTED OPERATIONAL DESCRIPTION

This chapter provides an overview of the user-oriented operational description. In order to develop the AV Work Zone System in a way that is useful to the end users, the use cases and user classes are defined. These users guide the identification and development of their needs, and in turn, the requirements of the project.

3.1 General Users

3.1.1 Profiles of User Classes

In the proposed system, a user is anyone who interacts with the AV Work Zone System, including operational users, system operators, operational support personnel, software maintainers and trainers. Each row in **Table 2** below provides a description of the user class, including any applicable responsibilities, education, background, skill level, activities and envisioned modes of interaction with the proposed system.

Table 2: AV Work Zone System User Classes

User Class	Description
Safety Driver	The Safety Driver operates the AV when the AV is not in autonomous mode and intervenes when the AV malfunctions in autonomous mode. The Safety Driver is trained by CMU on how to safely operate the vehicle and how to determine when the vehicle is malfunctioning in order to intervene. The Safety Driver will be responsible for driving the AV to the testing location, starting/stopping AV mode, and disengaging the AV when necessary.
Safety Associate	The Safety Associate operates equipment on board the AV and acts as a backup safety operator who can disengage autonomous mode to stop the AV. The Safety Associate is trained by CMU on how to safely operate the vehicle and how to determine when the vehicle is malfunctioning in order to intervene. The Safety Associate will be responsible for disengaging the AV when necessary, monitoring the AV performance, communicating with testing staff, and retrieving data from the AV.
Data Manager	The Data Manager manages, operates, and maintains the DMS. The Data Manager is responsible for creating user accounts and managing user roles, as well as checking the integrity of data being used by the system and monitoring the DMS status.
Simulation Operator	The Simulation Operator manages, operates, and maintains the Simulation System. The Simulation Operator is responsible for setting up a work zone configuration in the simulation and conducting the simulation (including both the AV simulation and the traffic simulation within the Simulation System).
Data User/Researcher	The Data User/Researcher queries data from the DMS to prepare reports and to conduct research. A Data User/Researcher may be a third-party user accessing the public datasets. The Data User/Researchers that are a part of the project team will be responsible for preparing reports and conducting research on behalf of the project team.

User Class	Description
Mapping Equipment Operator	The Mapping Equipment Operator operates the mapping equipment on the Mapping Van. The Mapping Equipment Operator is trained on the installation, calibration, and/or operation of the mapping equipment. The Mapping Van Equipment Operator will be responsible for starting/stopping the mapping equipment, monitoring the Mapping Van system performance, communicating with testing staff, retrieving data from the Mapping Van, and preprocessing data prior to insertion into the DMS.
Mapping Van Driver	The Mapping Van Driver drives the Mapping Van in the work zone. The Mapping Van Driver is trained by PSU on how to operate the vehicle. The Mapping Van Driver is responsible for driving the Mapping Van and communicating with the Mapping Equipment Operator.
Work Zone Operator	The Work Zone Operator sets up the work zone situations in which the AV will operate. The Work Zone Operator will set up traffic control devices and paint lines on the road as necessary for each work zone scenario. The Work Zone Operator will also be responsible for configuring the V2X devices for the work zone objects, work zone employee equipment, and roadside unit (RSU). The Work Zone Operator will also be responsible for setting up the work zones in accordance with the project plans.
Other Driver	The Other Driver drives other vehicles in a work zone during closed track testing and in the on-road live environment. The Other Drivers are responsible for the safe operation of their vehicle and abiding by the rules of the road.

SOURCE: PENNDOT

3.1.2 Other Involved Personnel

Other personnel listed in **Table 3** are personnel who will not directly interact with the system, but who have an influence on, and are influenced by, the system. Although these individuals may not have hands-on interaction with the system, they may significantly influence and be influenced by the new or modified system. These individuals will be involved in the project on an as-needed basis when a task is assigned or when an event occurs that requires the individual to respond to the system.

Table 3: Other Involved Personnel Classes

Class	Description
Research Assistant	Assists the researchers working on the project with analyzing data
Test Track Lead	Manages and schedules the testing at the work zone setup location
Maintenance Staff	Repairs components of the system if equipment breaks
Software Support Team	Programs software and provides support for the system software
Work Zone Employee	Is in the vicinity of the work zone
Safety Manager	Manages site safety at each of the work zone setup locations
First Responder	Responds to an incident involving the AV. They include police/ambulance/fire personnel.
Fleet Division Manager	Determines which PennDOT vehicles will be de-commissioned and used on the project as work zone vehicles with enhanced coatings
Project Team Member	Witnesses the testing, reviews data, and measures performance

SOURCE: PENNDOT

3.1.3 Stakeholder User Classes

A user class is distinguished by the ways in which the users interact with the system. Each user class is made up of one or more stakeholder groups that show common responsibilities, skill levels, work activities, and modes of interaction with the system. A given group of stakeholders can be involved in one or more user classes. Different user classes may have distinct operational scenarios for their interactions with the system.

The stakeholder that acts as the user class may vary based on the work zone scenario being tested and the phase of the project that is being conducted. For instance, the Pennsylvania Turnpike Commission (PTC) may be responsible for playing the role of the Work Zone Setup Operator when the work zone scenario is set up on the Turnpike, while a PennDOT District may be responsible for setting up the work zone while on a state route or interstate.

User classes impacted by the AV Work Zone System are identified in **Table 4**.

Table 4: Stakeholders and User Classes

Target Stakeholders	User Classes								
	Safety Driver	Safety Associate	Data Manager	Simulation Operator	Data User/Researcher	Mapping Equipment Operator	Mapping Van Driver	Work Zone Setup Operator	Other Driver
CMU	X	X		X	X				
Deloitte Consulting LLP (Deloitte)			X						
PSU				X	X	X	X		X
PennDOT Central Office					X				X
PennDOT District					X			X	X
PennDOT County								X	X
PPG					X			X	
PTC								X	
USDOT					X				
V2X Vendor								X	
Contractor								X	

SOURCE: PENNDOT

The descriptions of each stakeholder can be found in **Section 6.1.1**.

3.2 Use Cases

Use cases capture the high-level typical interactions between a user and a system with the goal to address a discrete goal of the user.

The use cases identified for the system are described in **Table 5**. Additionally, the table identifies how the success of the use case is defined. Due to the research-oriented nature of the project, the parameters of the system operations may need to be adjusted during testing to obtain the correct outcome of the use case and project. The context diagrams for each use case can be found in **Chapter 8**.

Table 5: Use Cases

Use Case ID	Use Case	Description	Success Measurement
UC1	Work Zone Mapping	The Mapping Van Driver drives the Mapping Van through a work zone scenario that was set up by the Work Zone Operators, and the Mapping Equipment is operated by the Mapping Equipment Operator. The sensor data is processed by the Map Processing Equipment in both real-time and post-mapping and sent to the DMS to be used by other users and subsystems. The Data Manager will ensure the integrity of the data ingested by the DMS.	The Work Zone Mapping use case will be successfully demonstrated if a threshold for the granularity of the work zone mapping, i.e. the level of detail and interval of mapping, is established. The format which is generated by the Mapping Van must also be in a format that is usable by the AV and Simulation Systems.
UC2	Simulation	The Simulation Operator retrieves mapping data from the DMS to set up a digital map. The Simulation Operator then sets up a work zone configuration in the simulation and conducts the simulation. The simulated ADS performance data is then sent to the DMS to be used by other users and subsystems. The Data Manager will ensure the integrity of the data used by the DMS.	The Simulation use case will be successfully demonstrated if the Simulation System software can: successfully be integrated with DMS data to import real-world cases; accurately represent and/or recreate the field conditions that are encountered by the AV; and predict behaviors outside those that were tested (e.g. "anticipate" situations outside the test plans, such as traffic congestion).
UC3	Work Zone Navigation	The AV retrieves via V2X communications the processed map data generated by the Mapping Van and then stored in the DMS. The AV navigates through a work zone scenario set up by the Work Zone Operators. The Safety Driver sits in the vehicle and intervenes if the AV malfunctions. The AV records ADS performance data and map data generated when passing through the	The Work Zone Navigation use case will be successfully demonstrated if a threshold can be established for the number and types of work zone objects that should be coated in enhanced coating to improve AV performance, the type and frequency of V2X data that should be transmitted to improve AV

Use Case ID	Use Case	Description	Success Measurement
		work zone. This date is uploaded to the DMS for use by other users and subsystems. The Data Manager will ensure the integrity of the data used by the DMS. In variations of this use case, updated map data is not passed to the AV and the AV must navigate using only map data generated in real-time from its onboard sensors. This use case may occur either during the day or at night and may occur either with or without enhanced coatings.	performance, and the type and granularity of mapping data that should be transmitted to the AV, as well as determining whether current data standards are sufficient for navigating AVs in work zones.
UC4	DMS Data Retrieval	The Mapping Van, Simulation System, and AV send data to the DMS for storage and processing. The DMS processes the data into a format that the Data Users/Researchers can use. Data Users/Researchers query data from the DMS.	The DMS Data Retrieval use case will be considered successfully demonstrated if the users are able to retrieve data from the DMS in the formats required for analyzing the project and subsystem performance, and if the DMS system clearly identifies levels of data agreement between AV, Mapping Van, Simulation System, RSU, and V2X Work Zone Objects.

Source: PennDOT

4 OPERATIONAL NEEDS

This section describes the situation that motivates development of a new system and provides justification for the features of the new system.

4.1 User Needs

User needs were developed through working groups with stakeholders. These user needs are expected to be supported through the deployment of a DMS and integration of an AV, Mapping Van, V2X Work Zone Objects, Simulation System and RSU. Since the AV, Mapping Van, and Simulation System are already owned by universities, and RSUs/OBUs are available as commercial-off-the-shelf equipment at the time of deployment, it is expected that only minor modifications should be needed to integrate them into the AV Work Zone System. The technology readiness level for the devices to be integrated that has been proposed to satisfy these user needs are discussed in **Appendix A**.

All user needs that have been developed for the project are considered essential. Through the stakeholder engagement, no user needs were identified that would be desirable, but not essential.

Table 6: AV Work Zone System User Needs

Identification	Title	Description	Rationale
Safety Driver Needs			
ADS-UN001-V01	Engage AV Operations	The Safety Driver needs to be able to engage AV operations when operating the vehicle.	To allow the vehicle to operate in AV mode.
ADS-UN002-V01	Manual AV Operation	The Safety Driver needs to be able to take manual control of the AV once deemed necessary.	To allow the driver to position the AV in the work zone to conduct the testing, or recover AV to safe operation if the need arises during autonomous operational testing.
ADS-UN003-V01	AV Control Notification	The Safety Driver needs the AV to provide safety warnings when a potentially safety-compromising situation is detected by onboard systems.	To allow the Safety Driver to know when the AV needs someone to take over manual operation of the vehicle.
ADS-UN004-V01	Driver Disengagement Monitoring	The Safety Driver needs the AV to monitor the vehicle systems and the traffic in the vicinity of the vehicle in order to determine if there are situations that require intervention by the driver or on-board safety system.	To allow the Safety Driver to know when the AV needs someone to take over manual operation of the vehicle.
ADS-UN005-V01	AV Operations	The Safety Driver needs the AV to be able to independently perform lateral and longitudinal control actions in order to operate the vehicle without direct driver intervention .	To allow for automated operations.
ADS-UN006-V01	AV Disengagement	The Safety Driver needs the AV to be able to perform actions that transition the vehicle from driver operation to autonomous operation and back to driver operation when the automated portion of the drive is completed.	To allow for safe disengagement of the ADS.
ADS-UN007-V01	AV Map Import	The Safety Driver needs the AV to be able to retrieve map data from the DMS through V2X and non-V2X communications, and update the ADS's internal map	To allow the AV to update the digital map that the ADS uses to navigate the roadway.

Identification	Title	Description	Rationale
ADS-UN008-V01	AV Mapping Data Generation	The Safety Driver needs the AV to be able to generate mapping data when traveling through the work zone.	In order to identify anomalies between the map data given to the AV and the map data generated in real-time.
ADS-UN009-V01	AV Data	The Safety Driver needs the AV to be able to generate data required for performance measurement (as indicated in the **Section 4.2**), as well as retain sensor and camera data.	To evaluate the success of the project and develop reports.
ADS-UN010-V01	V2X Work Zone Object Locations	The Safety Driver needs the AV to be able to detect V2X Work Zone Object locations via V2X and integrate them into its internal map.	To allow the ADS to better understand the work zone layout.
ADS-UN011-V01	Law Following – Open Traffic Environment	The Safety Driver needs the AV to be able to detect other objects and vehicles on the roadway, provide an automated reaction to detections that considers the appropriate right-of-way, and be capable of performing everyday traffic maneuvers.	To navigate the roadway, safely interact with other vehicles in mixed traffic, and avoid any potential incidents.
ADS-UN012-V01	Law Following – Regulatory	The Safety Driver needs the AV to have knowledge of and the ability to follow local, state, and federal driving laws, including the ability to detect and understand regulatory signs, pavement markings and traffic signals.	To operate in compliance with traffic laws.
ADS-UN013-V01	Law Following – Temporary Traffic Control	The Safety Driver needs the AV to be able to detect and respond to detours, work zone workers, and other temporary changes in traffic patterns.	To operate in compliance with traffic laws, even when conditions have deviated from the everyday.
ADS-UN014-V01	AV Time Synchronization	The Safety Driver needs the AV to be synchronized with a common time source.	To be synchronized with roadside devices and the data in the DMS from all sources.
ADS-UN015-V01	AV Positioning	The Safety Driver needs the AV to have available position information.	To be used as an input for in-vehicle applications, and to populate messages that require vehicle location and motion information.
Safety Associate Needs			

Identification	Title	Description	Rationale
ADS-UN016-V01	AV Audio Communications	The Safety Associate needs to be able to communicate with other staff at the testing site.	To notify other employees that the testing is beginning/ending or if there are issues on-board the AV, and to receive information from roadside personnel, for example about the safety and preparedness of the site for testing.
ADS-UN017-V01	Associate Disengagement Monitoring	The Safety Associate needs the AV to monitor the vehicle systems and the traffic in the vicinity of the vehicle in order to determine if there are situations that require intervention by the driver or on-board safety system.	To allow the Safety Associate to know when the AV needs someone to take over manual operation of the vehicle.
ADS-UN018-V01	AV System Status	The Safety Associate needs to be able to monitor the status of the AV software and hardware in near real-time. When fault levels are exceeded, the Safety Driver is able to determine when the AV has experienced faults, determine the degree of the fault, and determine the cause of the fault. The Safety Associate and other users needs to have the ability to review status, performance, and fault data at a deep level in post-processing.	To monitor whether the AV mode is engaged and to verify that the system is fully operational and be able to identify periods where the system was not operational. In real-time, the Safety Associate needs to be able to do a quick check to ensure that the subsystems are operational, however, in post processing, the Safety Associate and other users need to be able to dive into the data to find any data errors that may have occurred.
ADS-UN019-V01	Store ADS Results	The Safety Associate needs to be able to send the ADS results data to the DMS.	To allow the Data Users/Researchers to use the data that was generated by the test.
ADS-UN020-V01	AV Sensor Calibration	The Safety Associate needs to be able to calibrate the AV sensors.	To allow the AV to accurately perceive its surroundings.
ADS-UN021-V01	AV PII Removal	The Safety Associate needs to be able to configure the removal of PII from the data before it is passed to the DMS.	To prevent the data users from accessing data containing information with sensitive information.
ADS-UN022-V01	AV Data Processing	The Safety Associate needs to be able to process vehicle data sourced by themselves to a level allowing comparisons between data sources. This supports the reporting needs of the Data Manager and Data User/Researcher,	To support map updates, simulation modeling, performance measurement, and research.

Identification	Title	Description	Rationale
		and also provides the source data and metrics for government reports.	
Data Manager Needs			
ADS-UN023-V01	Data Storage	The Data Manager needs to be able to store map data, vehicle data and other data generated by the project. Data storage may include processes for rapid storage and retrieval of data, including processes that occur during AV or mapping operations, or long-term processes such as archiving data or large-scale data distributions to data users.	To support map updates, simulation modeling, performance measurement, and research.
ADS-UN024-V01	Format Data	The Data Manager needs to be able to manage data processing with regard to data labeling and archive functions, including data aggregation, data tagging (processed, edited, raw, transformed, etc.), data storage timing and longevity, data quality analysis, data formatting and metadata assignments.	To improve the usability and usefulness of data.
ADS-UN025-V01	View Data	The Data Manager needs to be able to view raw and processed data that is stored in the DMS in near-real time.	To verify data integrity.
ADS-UN026-V01	Edit Data	The Data Manager needs to be able to edit and remove data in the DMS.	To correct errors and remove data sets that were added erroneously.
ADS-UN027-V01	DMS System Status	The Data Manager needs to be able to monitor the status of the DMS software and hardware in near real-time. When fault levels are exceeded, the Data Manager is able to determine when the DMS System has experienced faults, determine the degree of the fault, and determine the cause of the fault. The Data Manager and other users need to have the ability to review status,	To verify that the system is fully operational and be able to identify periods where the system was not operational. In real-time, the Data Manager needs to be able to do a quick check to ensure that the subsystems are operational, however, in post processing, the Data Manager and other users need to be able to dive into the data to find any data errors that may have occurred.

Identification	Title	Description	Rationale
		performance, and fault data at a deep level in post-processing.	
ADS-UN028-V01	DMS User Management	The Data Manager needs to be able to create and manage user accounts for the DMS.	To enable Data Users/Researchers to use the DMS, or limit as necessary users from levels of access requests that prevent access of data by others, or access to protected data.
ADS-UN029-V01	DMS Roles	The Data Manager needs to be able to manage user access to DMS data based on user role.	To allow different users to have access to different data. Not all data is suitable for public access and some users may have additional privileges for modifying data.
ADS-UN030-V01	Data Handling	The Data Manager needs to be able to configure data handling requirements for DMS data.	To prevent data meant for simulation from impacting deployment operations.
ADS-UN031-V01	DMS Data Ingestion	The Data Manager needs the DMS to be able to aggregate data from the AV, Mapping Van, RSU, V2X Work Zone Objects, and Simulation System.	To allow users and subsystems within the AV Work Zone System to have access to the data generated by the project.
ADS-UN032-V01	WZDx Data Format	The Data Manager needs the DMS needs to be able to provide data in a format that is usable by the Work Zone Data Exchange (WZDx) Program.	To allow WZDx users to have access to the data.
ADS-UN033-V01	DMS Data Interface	The Data Manager needs the DMS to provide an interface to securely upload data.	To retain privacy and prevent data tampering.
ADS-UN034-V01	DMS Secure Access	The Data Manager needs the DMS to provide an interface to securely access the data.	To retain privacy and prevent data tampering.
ADS-UN035-V01	DMS Map Data	The Data Manager needs the DMS to provide updated mapping data to the AV.	To allow the AV to receive the digital map.
Simulation Operator Needs			
ADS-UN036-V01	Simulation Operations	The Simulation Operator needs to be able to simulate ADS operations in the Simulation System.	To enable the ADS simulation.

Identification	Title	Description	Rationale
ADS-UN037-V01	Simulation Data Import	The Simulation Operator needs to be able to retrieve map data from the DMS and import it into the Simulation System.	To allow the Simulation System to use map data that was generated in the field.
ADS-UN038-V01	Simulation Configuration	The Simulation Operator needs to be able to configure simulation parameters, including traffic generation, in the Simulation System.	To create a more realistic scenario in which the ADS can operate.
ADS-UN039-V01	Run Simulation	The Simulation Operator needs to be able to start, stop, and restart the simulation.	To enable the Simulation System to conduct the simulation.
ADS-UN040-V01	Simulation Progress	The Simulation Operator needs to be able to view the simulation progress.	To view the percent complete and any errors that may require the operator to stop the simulation.
ADS-UN041-V01	View Simulation Results	The Simulation Operator needs to be able to view the simulation results data.	To allow the Simulation Operator to verify that the simulation was completed successfully before data is sent to the DMS.
ADS-UN042-V01	Store Simulation Results	The Simulation Operator needs to be able to send the simulation results data to the DMS.	To allow Data Users/Researchers and other systems to have access to the data.
ADS-UN043-V01	Simulation System Status	The Simulation Operator needs to be able to monitor the status of the Simulation System software and hardware in near real-time. When fault levels are exceeded, the Simulation Operator is able to determine when the Simulation System has experienced faults, determine the degree of the fault, and determine the cause of the fault. The Simulation Operator and other users needs to have the ability to review status, performance, and fault data at a deep level in post-processing.	To verify that the system is fully operational and be able to identify periods where the system wasn't operational. In real-time, the Simulation Operator needs to be able to do a quick check to ensure that the subsystems are operational, however, in post processing, the Simulation Operator and other users need to be able to dive into the data to find any data errors that may have occurred.
ADS-UN044-V01	Simulation Performance Data	The Simulation Operator needs the Simulation System to be able to generate data required for performance measurement (as indicated in the **Section 4.2**).	To evaluate the success of the project and develop reports.
Data User/Researcher Needs			

Identification	Title	Description	Rationale
ADS-UN045-V01	Access System Data	The Data User/Researcher needs to be able to access all appropriate data generated by the project with an appropriate data latency.	To ensure that users have access to the data in a timely manner.
ADS-UN046-V01	Data User Role	The Data User/Researcher needs to be able to view data in the DMS that's appropriate for their role internal or external to the project team (i.e. third-party user).	To prevent users from having access to data that is not appropriate for their role.
ADS-UN047-V01	Data Export	The Data User/Researcher needs to be able to export data out of the DMS.	To allow the user to pull data from the database so they can use the data on their own device.
ADS-UN048-V01	Data Query	The Data User/Researcher needs to be able to query data in the DMS.	To allow the user to specify the data that they require.
ADS-UN049-V01	Data Feeds	The Data User/Researcher needs to be able to request and receive information without establishing formal relationships with data providers.	To allow users to subscribe to appropriate data feeds from the database without having an account.
ADS-UN050-V01	System Statuses	The Data User/Researcher needs to be able to access real-time, near real-time, and archival data on all system component statuses.	To allow the user to identify system components that aren't functioning properly.
Mapping Equipment Operator Needs			
ADS-UN051-V01	Conduct Mapping	The Mapping Equipment Operator needs to be able to start and stop the mapping function.	To enable the mapping functions.
ADS-UN052-V01	Mapping Van Operator Audio Communications	The Mapping Equipment Operator needs to be able to communicate with other staff at the testing site.	To notify other employees that the testing is beginning/ending or if there are issues on-board the AV, and to receive information from roadside personnel about the safety and readiness of sites for mapping activities.
ADS-UN053-V01	Mapping Van System Status	The Mapping Equipment Operator needs to be able to monitor the status of the Mapping Van software and hardware. When fault levels are exceeded, the Mapping Equipment Operator is able to determine when the Simulation System	To verify that the system is fully operational, to identify periods and/or situations where the mapping process is not operational, and to identify testing situations that prevent future faults.

Identification	Title	Description	Rationale
		has experienced faults, determine the degree of the fault, and determine the likely cause of the fault to mitigate, if necessary, future faults.	
ADS-UN054-V01	Mapping Van Login	The Mapping Equipment Operator needs to be able to log into the Mapping Van equipment.	To enable the user to access the system.
ADS-UN055-V01	Mapping Equipment Data Testing	The Mapping Equipment Operator needs to be able to test the equipment's ability to transfer data to the DMS.	To allow the user to verify that the transfer process is functioning property before starting a time-consuming data upload to the DMS.
ADS-UN056-V01	Mapping Van Sensor Calibration	The Mapping Equipment Operator needs to be able to calibrate appropriate sensors on the Mapping Van.	To allow the Mapping Van to accurately perceive its surroundings by correcting any sensors that have routine calibration drift.
ADS-UN057-V01	Mapping Van PII Removal	The Mapping Equipment Operator needs to be able to configure the removal of PII from the data before it is passed to the DMS.	To prevent the data users from accessing data containing information with sensitive information.
ADS-UN058-V01	Mapping Van Data Processing	The Mapping Equipment Operator needs to be able to process vehicle data sourced by themselves to a level allowing comparisons between data sources. This supports the reporting needs of the Data Manager and Data User/Researcher, and also provides the source data and metrics for government reports.	To support map updates, simulation modeling, performance measurement, and research.
ADS-UN059-V01	Mapping Van Data Format	The Mapping Equipment Operator needs the Mapping Van to be able to convert the data into a format that can be aggregated by the DMS and usable by the AV and Simulation systems.	To allow the map data to be usable by other subsystems.
ADS-UN060-V01	Real-time Mapping	The Mapping Equipment Operator needs the Mapping Van to be able to define lane markers and road obstacles in near real-time.	To allow for timely use of the data being generated by the Mapping Van.
ADS-UN061-V01	Mapping Van Connectivity	The Mapping Equipment Operator needs the Mapping Van to be able to communicate the map data to the DMS.	To enable communications between the subsystems.

Identification	Title	Description	Rationale
ADS-UN062-V01	Work Zone Mapping	The Mapping Equipment Operator needs the Mapping Van to be able to map the work zone objects, traffic control devices, lane lines, road conditions, and V2X communication points and signal availability boundaries.	To enable the Mapping Van to map the work zone.
ADS-UN063-V01	Mapping Van Time Synchronization	The Mapping Equipment Operator needs the Mapping Van to be synchronized with a common time source.	To be synchronized with roadside devices and the data in the DMS from all sources.
Mapping Van Driver Needs			
ADS-UN064-V01	Drive Mapping Van	The Mapping Van Driver needs to be able to drive the Mapping Van through the work zone.	To enable the Mapping Van to navigate the work zone.
ADS-UN065-V01	Mapping Van Driver Audio Communications	The Mapping Van Driver needs to be able to communicate with other staff at the testing site.	In order to notify other employees that the testing is beginning/ending or if there are issues on-board the AV, and to receive information from roadside personnel about the safety and readiness of sites for mapping activities.
Work Zone Operator Needs			
ADS-UN066-V01	Work Zone V2X Configuration	The Work Zone Operator needs to be able to configure and set up the RSU and V2X Work Zone Objects.	To enable the RSU and V2X Work Zone Objects.
ADS-UN067-V01	Work Zone Configuration	The Work Zone Operator needs to be able to set up the work zone in accordance with the Pennsylvania Typical Application (PATA) and Pennsylvania Turnpike Standards (PTS) figures applicable to the work zone scenario being tested.	To allow the Work Zone Operator to set up the work zones using the property equipment per the standards.
ADS-UN068-V01	Work Zone Equipment Monitoring	The Work Zone Operator needs to be able to monitor the status and performance of the V2X Work Zone Objects and RSU software and hardware in near real-time. When fault levels	To verify that the system is fully operational and be able to identify periods where the system wasn't operational. In real-time, the Work Zone Operator needs to be able to do

Identification	Title	Description	Rationale
		are exceeded, the Work Zone Operator is able to determine when the Vehicle System has experienced faults, determine the degree of the fault, and determine the cause of the fault. The Work Zone Operator and other users needs to have the ability to review status, performance, and fault data at a deep level in post-processing.	a quick check to ensure that the subsystems are operational, however, in post processing, the Work Zone Operator and other users need to be able to dive into the data to find any data errors that may have occurred.
ADS-UN069-V01	Work Zone Equipment Service Restoration	The Work Zone Operator needs to be able to detect, isolate and correct V2X Work Zone Objects and RSU service problems. Detection should be able to be performed in near real-time. Isolation and correction may be able to be performed in post-processing.	To restore service in a timely manner.
ADS-UN070-V01	RSU Time Synchronization	The Work Zone Operator needs the RSU to be synchronized with a common time source.	To be synchronized with in-vehicle devices and the data in the DMS from all soures.
ADS-UN071-V01	RSU Position Correction	The Work Zone Operator needs the RSU to have access to position correction information.	To send position correction information to vehicles so that vehicles can correct their position.
ADS-UN072-V01	RSU SPaT and MAP	The Work Zone Operator needs the RSU to be able to disseminate SPaT and MAP data to AV to facilitate improved movement through intersections and work zones.	To enable in-vehicle applications.
ADS-UN073-V01	V2X Work Zone Object Time Synchronization	The Work Zone Operator needs the V2X Work Zone Object to be synchronized with a common time source.	To be synchronized with in-vehicle devices and the data in the DMS from all soures.
ADS-UN074-V01	V2X Work Zone Object Position Correction	The Work Zone Operator needs the V2X Work Zone Object to have access to position location.	To be used as an input for in-vehicle applications, and to populate messages that require vehicle location and motion information.

SOURCE: PENNDOT

4.2 Related Performance Measures

The goals and objectives are further integrated into a process-based evaluation plan as part of the *Project Evaluation Plan* development. The final set of performance measures will capture the ability of the system to effectively address the goals and objectives of the program, and can be calculated from data that can be collected from the system or from external sources.

5 SYSTEM OVERVIEW

This section provides a high-level overview of the proposed system, capturing the operational features that are to be provided without specifying design details. The level of information should be sufficient to fully explain how the proposed system is envisioned to operate in fulfilling user needs and project requirements. The ConOps does not aim to create design specifications, but it contains some examples of typical design strategies for the purpose of clarifying operational details of the proposed system. Design constraints are included in the description of the proposed system, as required, in order to avoid possible misunderstandings.

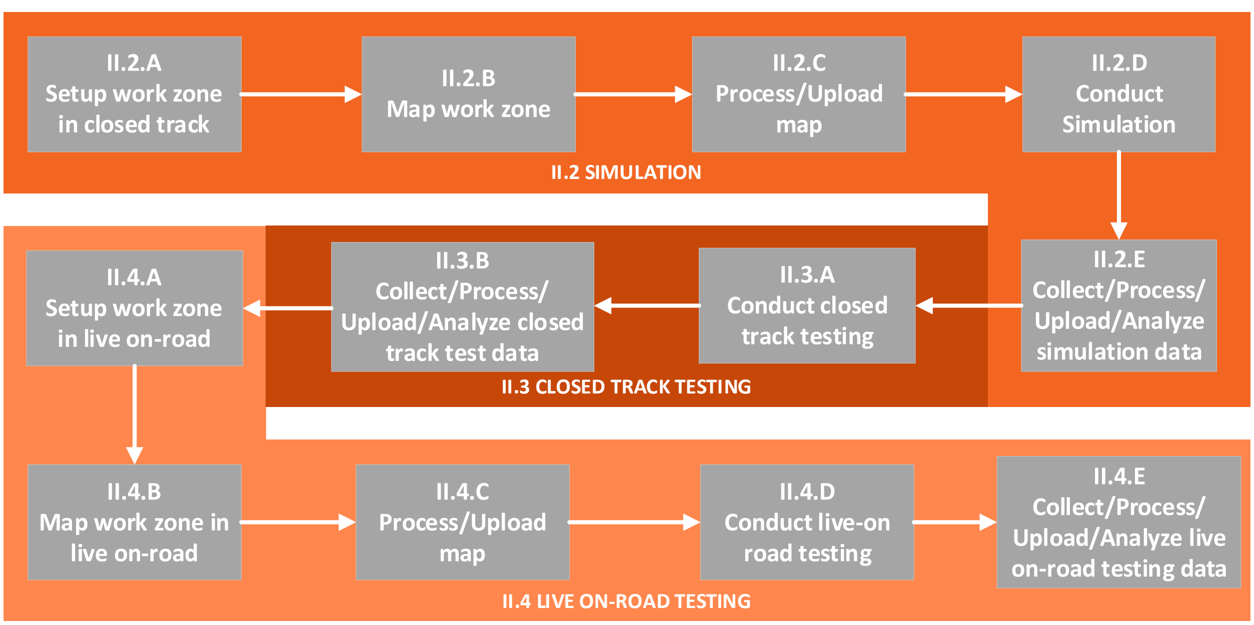
5.1 Description of the Proposed System

During the deployment phase of this project, an AV will be deployed and tested within different work zone scenarios in various environments including simulation, closed-track testing, and an on-road live testing environment as shown in **Figure 2**. These testing phases correspond to the project work breakdown structure identified in **Figure 1**.

Figure 2 shows the linear nature of the deployment methodology, but at every step, the team will review the data and make an assessment about moving forward to the next step or stepping back to a prior step to address any issues that arose. For instance, after closed track testing is complete, the simulations will be re-reviewed to check to see how well the simulation represented the real world, and the simulation may need to be tweaked or recalibrated to be more accurate. The exact process of transitioning between testing methodologies and the decision gates will be detailed in the *Deployment Plan*.

In addition, a DMS will be utilized for ingesting, processing and sharing the data from the deployment and testing.

Figure 2: Deployment Methodology



SOURCE: PENNDOT

PennDOT developed *Publication 213* with *Pennsylvania Typical Applications (PATA)* drawings for work zones to provide detailed guidelines for most common work zone situations. These are minimum desirable applications for normal situations, and additional protection may be needed when special complexities or potential hazards prevail. PTC also has similar Pennsylvania Turnpike Standards (PTS) which depict the standard work zone setups applicable to PTC roadways. The PTS standards will be used for any set ups that are configured on PTC roadways.

The team's goal is to deploy and test the AVs in the most common types of work zones. A total of 17 work zone scenarios are shown in **Table 7**. Within each work zone scenario, there will be multiple subsets, as shown in **Figure 3**, resulting in eight subsets, including the base case.

Figure 3: Work Zone Scenario Permutation Tree

SOURCE: PENNDOT

Each scenario subset will be tested in the simulation, closed course and live environment, with several exceptions. The intention is to field test the scenarios in good weather conditions in order to have a consistent baseline for testing, and use simulations to study agreement with good-weather data and then extend the software analysis, where possible, to more degraded situations. If field testing is successful and time, budget, and testing opportunities permit, field testing may occur during degraded weather events to understand the impacts of poor weather on the system performance. The limitations of which subsets can be tested in simulation, closed course and live-on road testing are discussed in **Section 6.2.7**.

Prior to conducting testing, a *Deployment Plan* will be developed to define the details of testing, define the testing team members' roles and responsibilities and mitigate testing risks. The plan may be updated as testing progresses and lessons learned from testing are developed.

Table 7: Work Zone Setup Scenarios for Demonstration

No.	Scenario Description		PennDOT Standard[3]	Simulation	Closed Course Testing	Live On-Road Testing
	Number of Lanes	**Scenario**				
Scenario 1	**Conventional Highways – Short-Term**					
Scenario 1.1	Any	Work on or Beyond the Shoulder – Single-Lane Approach – Shoulder Work with Minor Roadway Encroachment	PATA 102	X	X	
Scenario 1.2	Any	Road Closure with Detour – Standard Orange Detour Signs	PATA 116-A	X	X	
Scenario 1.3	3	Work on Single-Lane Approach – Self-Regulating Lane Shift into Opposing Lane	PATA 118	X	X	
Scenario 1.4	3	Work on Single-Lane Approach – Self-Regulating Lane Shift into Center Left-Turn Lane	PATA 121	X	X	
Scenario 1.5	3 or More	Work on Single-Lane Approach – Work in Center Left-Turn Lane	PATA 122	X	X	
Scenario 1.6	3 or More	Work on Multi-Lane Approach – Work in Left or Right Lane – Undivided Highway	PATA 123-A or 123-B	X	X	
Scenario 2	**Conventional Highways – Long-Term**					
Scenario 2.1	Any	Road Closure with Detour – Detour of a Numbered Traffic Route	PATA 214	X	X	X
Scenario 2.2	2	Work on a Single-Lane Approach – Self-Regulating Stop-Control	PATA 205	X	X	
Scenario 2.3	2	Temporary Roadway	Not Applicable	X	X	
Scenario 2.4	Temporary Signals	Complex Conditions – Trailer-Mounted Signals	PATA 706	X	X	

[3] Note: If PennDOT Publication 213 is updated before the project is deployed, the newest publication version will be used for the equivalent work zone scenario.

Scenario 3	**Conventional Highways – Mobile**					
Scenario 3.1	2 or More	Work on Single-Lane Approach – Moving Lane Closure	PATA 303	X	X	
Scenario 4	**Freeways and Expressways – Short-Term**					
Scenario 4.1	2 or More	Work on Two-Lane Approach – Work in Left or Right Lane	PATA 402-A or 402-B PTS 915-4	X	X	X
Scenario 4.2	Divided	Work Near Interchange Ramps – Work in Right Lane Near Right-Exit Ramp	PATA 404-A	X	X	
Scenario 4.3	Divided	Work Near Interchange Ramps – Work in Right Entrance Ramp with Stop or Yield Control	PATA 405-A or 406-A	X	X	
Scenario 5	**Freeways and Expressways – Mobile**					
Scenario 5.1	2 or More	Work on Two-Lane Approach – Work in Left or Right Lane	PATA 602-A or 602-B PTS 915-2	X	X	X
Scenario 5.2	Divided or One-Way	Work on Three-Lane Approach – Work in Left, Right, or Two (Right & Center or Left & Center) Lanes	PATA 603-A, 603-B, or 603-C	X	X	
Scenario 6	**Others**					
Scenario 6.1	2 or More	Freeways and Expressways – Long-Term Shoulder Use	Not Applicable	X	X	

Source: PennDOT

5.1.1 Project Phases

5.1.1.1 Simulation

The Simulation testing will include the following, as shown in **Figure 2**:

Task II.2.A – Set Up Work Zone in Closed Track – The testing process for any given scenario starts with the simulation of the AV operations in the work zone. Work zone simulation will be done by mapping the work zone setup at the closed track facility by PSU. The work zone setup will include setting up the traffic control devices and lane configuration as identified in each PATA drawing per the PennDOT Publication 213 for the given scenario.

In addition, RSUs, which provides connectivity with the traffic control devices, construction workers, and construction vehicles will be installed and tested. The approach will utilize a neutral position between DSRC and C-V2X and may employ one or both technologies, depending on availability of devices, ability to get FCC licenses, and direction of the technology. Qualcomm is one of part of the technical advisory committee and is committed to providing us with technical assistance in the connectivity ecosystem.

An alternative work zone setup will include the pavement markings and work zone objects coated with PPG's coating material, which will allow the AVs to "see" these objects better.

It is anticipated that the work zones will be less than half mile in length.

Task II.2.B – Map Work Zone – Once work zone is setup, PSU will use their Mapping Van to map the work zone. The PSU team will deploy its Mapping Van system to collect the geolocation information for lane designations, lane stripe information, camera images to assess visibility, RADAR information, and LIDAR information similar to what would be measured by an AV. The PSU team will map the work zones both with and without the coatings provided by PPG.

When mapping is being performed, the team will have the ability to run the Mapping Van through the work zone several times and combine the point clouds for a more detailed analysis of the work zone. The team will also have the ability to vary the speed of the Mapping Van, which will increase or decrease the interval of the collected data points. By altering the number of runs and the speed at which the Mapping Van travels through the work zone, the team will be able to identify a threshold at which the quality of the map is sufficient for the AV.

Task II.2.C – Process/Upload Map – From these collected data, the team can process the lane definitions to assist with AV guidance; however, the ADS itself would be responsible for classification of collision hazards, guidance policy decisions, etc. The intent of this project is to assess ADS performance and infrastructure interaction, not to design new ADS or redesign existing ADS systems to improve their performance.

Once processed, the PSU team will upload the applicable map information and other camera images, RADAR information, and LIDAR information to the DMS.

The project team will seek to use existing road-data formats, or as necessary modify a standard format, for the map information. Currently, each AV manufacturer and map developer uses their own proprietary method for managing work zone map information. The project would seek to develop a common method for communicating raw data – and with the assistance of the Community of Practice stakeholder SAE International (SAE) – lead to the development a specification or standard for the processed data after the project. The team will reach out to up to three (3) AV manufacturers and/or map developers to develop open data specification for harmonized map descriptions to include work zone information, which will be modeled on standards and specifications such as Open Street Maps, ASAM OpenDrive, the General Transit Feed Specification, RoadXML, etc. It is anticipated that open data specification for work zone mapping will encourage an incremental adoption of data elements from the broader specification documented in the work zone Activity Data Dictionary developed through the Federal Highway Administration's (FHWA) WZDx Initiative, which addresses the role of this data in use cases spanning the entire project delivery life-cycle. The team will also seek compatibility of this data with V2X delivery formats, for example the BSM and MAP definition for V2X radios.

Developing an industry standard for the map information is outside the scope of this project. However, the open data specification developed as part of this project may act as a template and thereby guide a standards development agency or USDOT to help industry and non-federal governments reach agreement on common data formats that lower the cost of data exchange. This project aims to produce a repeatable approach to accelerate harmonization of map data sources across the country, and a sustainable model for stakeholders to expand and maintain such open specifications over the long-term.

Task II.2.D – Conduct Simulation – CMU will use an already developed simulation software tool, which enables the simulation of connected and AVs in a virtual world. The simulation tool will use the map information provided by PSU to configure the work zones setup. Then, CMU will instantiate work zone workers and traffic in the area to study the AV behavior in the work zone. Simulation efforts at PSU will focus on traffic flow and corresponding safety impacts to surrounding vehicles.

Task II.2.E – Collect/Process/Upload/Evaluate – CMU will observe, collect, process and analyze the behavior of the AV in the simulation world. Collected data in the simulation environment would include the virtual camera and LIDAR data, safety data, operations data, and connectivity data (Basic Safety Message (BSM) Part I and Part II data) from the vehicles.

The collected data will be processed and uploaded in near real-time to the DMS using the process and format defined in the *Data Management Plan*. The *Data Management Plan* will be updated with the file formats as the project progresses and the formats are finalized before the testing.

BSM data may be stored in the format identified by the CV Pooled Fund Study project – 5.9 GHz DSRC Vehicle-Based Road and Weather Condition Application: Phase I. PennDOT is a member of the CV Pooled Fund Study and has access to the final report and format. Alternatively, BSM data may be stored in either eXtensible Markup Language (XML) or JavaScript Object Notation (JSON) format, both of which are relatively easy to parse.

The data will also be evaluated to debug and fine-tune algorithms such as path planning. Following the evaluation, the software tool will be used to calibrate the AV to adjust its behavior to ensure expected behaviors are obtained under multiple different combinations of traffic settings.

Test results from the simulation and evaluation will be documented in the *Test Results* document.

5.1.1.2 Closed-Track Testing

Following the simulation task, closed-track testing will be conducted at PSU's Larson Transportation Institute (LTI) for all scenarios.

Task II.3.A – Conduct Closed-Track Testing - The work zone setup used for mapping in the simulation phase will be reused for closed-track testing unless the setup has been modified or removed for any reason. Prior to the starting of the closed-track testing, PSU will ensure that the field work zone setup matches the test scenario PATA. In addition, the connectivity between the AV and the work zone objects will be tested.

CMU's AV will be pre-loaded with the map from the DMS prior to testing or loaded via 4G or V2X as the AV approaches the work zone. Once the map is uploaded, the AV will navigate the work zone collecting the camera images, sensor data, and connectivity data.

Task II.3.B – Collect/Process/Upload/Evaluate – The collected data will be processed and ingested into DMS using the process and format defined in the *Data Management Plan*.

The data will also be evaluated to monitor and control the AV behavior. Following the evaluation, the AV will be calibrated to adjust its behavior to ensure expected behaviors are obtained under multiple runs. Test results from the testing and evaluation will be documented in the *Test Results* document

5.1.1.3 Live On-Road Testing

Due to inherent risk associated with live on-road testing, only three of the 17 scenarios will be tested in this environment. The core team has selected one scenario in each of the long-term, short-term, and mobile work zone scenarios for live on-road testing. For each, the team will identify an existing or proposed work zone in which to conduct live on-road testing with live traffic. To minimize risk, the core team will select work zones with minimal traffic to conduct this testing.

Task II.4.A – Set Up Work Zone in Live On-Road Testing – Since the live on-road testing will be conducted in a real work zone, the work zone setup specifically for this testing is not required. Prior to testing, PennDOT will coordinate with the work zone construction team including the work zone contractor to ensure all involved parties are aware of the on-road testing. Also, connectivity equipment and coatings will be installed and tested in the work zone, using best practices determined from prior stages of testing.

Task II.4.B – Map Work Zone – PSU will map the live on-road work zone following the same process followed during the simulation and closed track testing phases.

Task II.4.C – Process/Upload Map – Once complete, PSU will process and upload the map to the DMS. The map would be able to be downloaded to the AV prior to the start of the testing or may be updated "on the fly" using a 4G or V2X map update, depending on best practices determined by on-track tests.

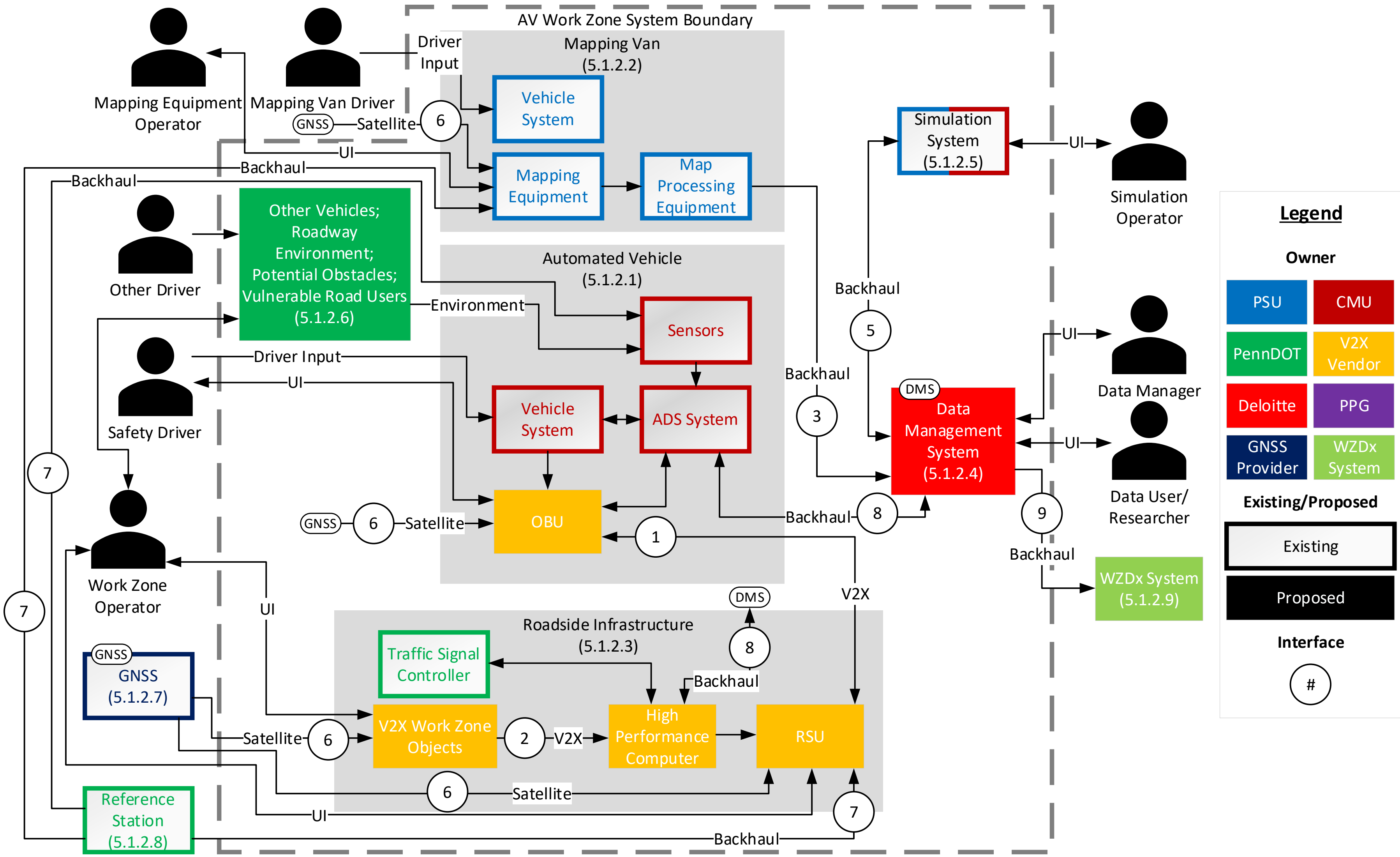
Task II.4.D – Conduct Live On-Road Testing – Once the map is downloaded, the AV will navigate the work zone collecting the camera images, sensor data, and connectivity data.

Task II.4.E – Collect/Process/Upload/Evaluate – CMU will collect, process and upload the data, then evaluate it in a manner similar to the closed track testing phase. Following the evaluation, the AV will be calibrated to adjust its behavior to ensure expected behaviors are obtained under multiple runs. Test results from the testing and evaluation will be documented in the *Test Results* document.

5.1.2 Subsystem Components

The AV Work Zone System can be described as a combination of subsystems that work together to make it safer for AVs to traverse work zones. The system will include an AV, Mapping Van, roadside infrastructure, V2X Work Zone Objects, a Simulation System, and DMS. The subsystems and interfaces are depicted at a high level in **Figure 4** and are described in the following sections. The required equipment and required modifications to existing subsystems are described in **Section 6.2**.

Figure 4: AV Work Zone System Context Diagram



Source: PennDOT

5.1.2.1 Automated Vehicle

CMU's AV will be used for the AV Work Zone System. The AV includes a touchscreen user interface that allows users to input a new destination or communicate route information. The AV also has access to information generated by the ADS through a computer system connected directly to the AV. Information that can be retrieved and used for the project includes the vehicle data, ecosystem data (RADAR, LIDAR, camera images), connectivity data, operations data and safety-related data in near real-time.

The AV requires two users to operate – a Safety Driver and Safety Associate. The Safety Driver will be responsible for driving the AV and monitoring for events that require disengagement, while the Safety Associate will be responsible for providing backup monitoring for disengagement.

The vehicle used is a Cadillac SRX with sensors embedded that allow the onboard ADS to control the vehicle, shown in **Figure 5**. Onboard the vehicle, the Onboard Unit (OBU) allows the AV to interact with CV infrastructure and other vehicles with CV technology. The OBU is DSRC-compatible and will therefore, for C-V2X testing, need to be altered to either be swappable with a C-V2X radio or be replaced with a dual-mode DSRC/C-V2X radio.

The AV is equipped with 4G-LTE communications and has the ability to receive data. The AV has on-board removable data storage which can be used to transfer data back to the DMS. Since the AV generates several gigabytes of data per second, it is not feasible to send all of the data back to the DMS via wireless communications, although it may be possible to send back small quantities of data that are required for real-time monitoring.

The sensor data and other data are processed in the AV's ADS compute hardware. Processing takes place in real-time and the processed and raw data are stored on the AV's data storage. Once the testing run is complete, the removable hard drive will be removed from the AV and connected to a computer at the testing site where the data can be uploaded to the DMS.

Figure 5: CMU Cadillac SRX AV

SOURCE: CMU

If the AV is severely damaged during operations, CMU has a backup AV that can be used as a replacement. The change management strategy defined in the *Project Management Plan* will be used to pivot the project from the original vehicle to the new vehicle. In order to create a fair comparison for the Final Evaluation Report, work zone scenarios may need to be re-run with the new vehicle.

5.1.2.2 Mapping Van

The Mapping Van, shown in **Figure 6**, is a retrofitted van with inertial and perception-based sensors for measuring the pose of the vehicle, as well as the surrounding environment, that was developed by PSU. From these data, the team can process the lane definitions to assist with AV guidance; however, the AV itself would be responsible for the classification of collision hazards, guidance policy decisions, etc.

The Mapping Van requires two users to operate – a Mapping Van Driver and Mapping Equipment Driver. The equipment within the vehicle will allow the Mapping Equipment Operator to monitor and operate the sensors and equipment while the Mapping Van Driver focuses on driving the van.

Figure 6: PSU Mapping Van

SOURCE: PSU

The Mapping Van houses three (3) HD FLIR Blackfly USB3 cameras mounted on a camera bar located above the windshield to measure the surrounding environment, and three (3) additional downward-facing cameras on a rear bar to image the road surface features.

The main sensor used to provide a global position estimate of the vehicle is a military-grade Novatel/Honeywell INS which integrates a Global Positioning System, Inertial Measurement Unit, and ring-laser gyroscope through an Extended Kalman Filter to provide a state estimate. A base station at the Larson Institute was calibrated to provide differential corrections (See **Section 5.1.2.8**). A lower-cost Inertial Measurement Unit produced by Analog Devices is attached to the same frame as the Honeywell.

Additionally, two US Digital HD25 optical wheel encoders are mounted on the rear tires to measure the orientation and angular velocity of each wheel.

A downward-facing SICK LMS511 LIDAR system, oriented in a “rake” style to measure the road perpendicular to the direction of travel, is mounted on the rear of the vehicle. This LIDAR generates a two-dimensional scan of the road, measuring both the range and bearing for a particular laser return. For point-cloud mapping, the vehicle is typically equipped with either a 16-scan line or 32-scan line LIDAR (Velodyne) similar to those used by AVs.

Unimeasure JX-PA string potentiometers are mounted to each front wheel to measure the road wheel angle.

Many real-word features can be mapped by the mapping vehicle including lane marker location, road geometry, road reflectivity, near-road geometry, road images, road conditions (potholes), and near-road barriers. The collected data is often used together with other map sources, such as features from traffic simulation and online data sets. The raw data are usually noisy and include outliers; thus, data are typically stored in a raw-data database. A data cleaning procedure is performed on the data to determine drop-outs, perform time alignment, outlier rejection, etc. The results are typically stored in a cleaned-data database. After that, the cleaned data is further processed to extract features such as lane markers, lane center line, road geometry, elevation changes in the road, etc. These aggregated data are in a shareable format – PSU typically uses datafields defined by RoadXML and ASAM OpenDRIVE – and stored in a road map database which can be queried for user applications such as localization, map-making for driving simulators, road assessment, fuel consumption, and road preview information for AVs.

The Map Processing Equipment represents the processing on the Mapping Van and the processing equipment off the Mapping Van, which may be a collection of computers or supercomputer clusters. The Map Processing Equipment that is functionally part of the Mapping Van, as shown in **Figure 4**, is primarily not physically on the Mapping Van. Limited pre-processing is available on the Mapping Van, which is enough to obtain lane markings to some degree of accuracy, however, offline post-processing allows for a higher degree of accuracy for the lane markings, as well as perform the data cleaning and gather previously mentioned data. To perform post-processing, the hard drives are removed from the Mapping Van after the mapping is completed and offloaded to the raw-data database, where the post-processing can occur. Due to the large quantity of data generated by the Mapping Van, it is not feasible to offload the raw data to the raw-data database wirelessly.

Currently, the data processing required to clean the data and extract features from the data is a labor-intensive process. The process of cleaning artifacts, errors, and synchronizing with the AV takes approximately 10 hours of post-processing for every hour of data collection time. PSU constantly works to automate and improve this process. This project may help to reduce this level of effort further by understanding what data AVs do and do not need to operate in work zones.

5.1.2.3 Roadside Infrastructure

Roadside infrastructure can be comprised of RSU, high performance computer (HPC) and traffic signal controllers.

5.1.2.3.1 Roadside Unit

RSU is made up of the RSU and any associated ITS field equipment that work as a system to enable vehicle-to-infrastructure (V2I) applications. An RSU is a wireless communications transceiver that is mounted along a road or pedestrian passageway. RSUs broadcast data to OBUs or exchange data with OBUs in its communications zone. The RSU and associated field equipment will be owned, operated, and maintained by the various project team members, depending on where the device is located.

The RSU also provides channel assignments and operating instructions to OBUs in its communications zone, when required. RSUs prepare and transmit messages to the vehicles and receive messages from the vehicles for the purpose of supporting the vehicle-to-infrastructure (V2I) applications.

The RSUs for this project will enable the AV to operate in the work zone by providing updated MAP; Signal Phasing and Timing (SPaT) from the interface with any signals on the project, including temporary signals; and position correction information. It is not anticipated that additional CV applications will be deployed on the roadside or onboard the vehicle as part of this project.

5.1.2.3.2 V2X Work Zone Objects

For this project, V2X Work Zone Objects collectively refer to all of the appropriate traffic control devices, construction workers and vehicles which are equipped with V2X technology within the work zone. Work zone objects that are not equipped with V2X connectivity are not included in this object definition. Note that the term V2X here refers both to vehicles transmitting to infrastructure (V2I) and other vehicles (V2V), and also infrastructure elements communicating to vehicle (I2V) and to the roadside infrastructure (I2I), namely the RSU. Each work zone object's V2X capability allows information flow directly from the object to either the vehicle or RSU, and example implementations would include smart construction worker vests, V2X equipped construction vehicles, or even smart traffic cones, barrels, barriers, and signs that transmit "here I am" data to approaching vehicles to avoid collisions. The communications equipment required to create the V2X Work Zone Objects is anticipated to include a communication radio (DSRC/C-V2X, Zigbee, LoRA, Wi-Fi, etc.), and a Global Navigation Satellite System (GNSS) receiver mounted on each device alongside power management systems. The V2X Work Zone Objects will have their positions communicated to a central point (the HPC), which will collect the information and forward the locations to the AV, and as well perform time-synchronized logging of information.

5.1.2.3.3 High Performance Computer

For this project, the edge HPC is responsible for two primary functions. First, it shall serve as a central connectivity hub. Using wired and wireless network interfaces, the HPC will enable transmissions to and from sources (RSU, MS Azure Cloud, PSU) having different communication profiles, including C-V2X, DSRC, GPS, 4/5G cellular, Zigbee, Wi-Fi, and Ethernet. Second, the HPC shall serve as a data broker, collecting, aggregating, logging, and sending data to and from configured network interfaces. The broker is responsible for facilitating information exchanges between the four types of (architectural) elements in this research project:

1. AV,
2. RSU field devices,
3. DMS support system in Azure cloud, and
4. the back-office processing Centers (PSU, CMU).

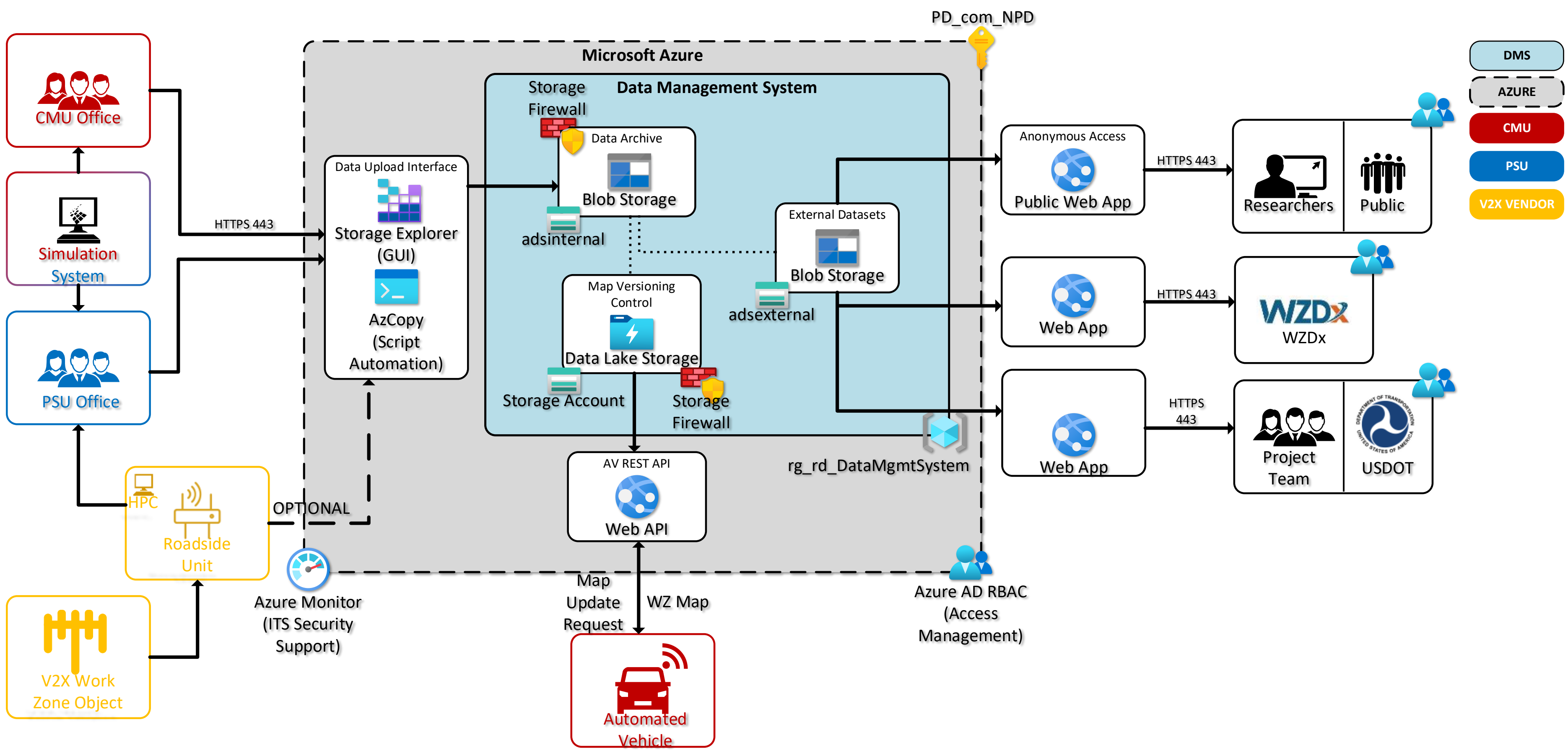
At the time of this writing, the project is evaluating BSM, TIM, and SPaT/MAP applications in support of data transmits for meeting use case objectives. If these (or other) CV apps are deemed necessary during research and testing, the HPC shall be capable of deploying off-the-shelf CV applications that read, write, create and transmit the necessary SAE formatted data messages that enable the desired functionality. Should connectivity to the DMS exist, which may be possible for the track testing portions of the project, the HPC may manage to pushi data updates (in a non-real-time manner) to the DMS, or pulling data from the DMS for distribution to the AV.

Additional information on connected vehicle applications can be found on the USDOT ITS Joint Program Office for connected vehicle deployments: https://www.its.dot.gov/pilots/cv_pilot_apps.htm.

5.1.2.4 Data Management System

The DMS will be a state-of-the-art, cloud data management tool built on the Azure platform. The DMS will have the ability to ingest, store, process, and provide access to data created by the ADS Demonstration project. The scalable Reference Architecture shown in **Figure 7** provides the high-level logical components and will serve as a guide for outlining the required building blocks for the ADS data management capabilities and allowing for future scale up.

Figure 7: DMS Reference Architecture



Source: PennDOT

See the final *Data Management Plan* for the most recent DMS architecture.

The DMS reference architecture shown in **Figure 7** consists of the components as explained below:

Upload: Data uploading is the process of importing, transferring, loading, and processing data for later use storage in a database. As shown in **Figure 7**, this involves uploading data from two sources.

The first source will contain the following data collected via the Mapping Van:

- Camera images
- Radar data
- LIDAR data
- PPS
- Steering Wheel Angle
- INS
- GPS
- MAP

The second source will contain the following data collected via the AV:

- AV Logs (Camera image)
- AV Logs (LIDAR data)
- AV Logs (Radar data)
- Simulated data
- Performance measures

For this Project, data upload will be performed on a weekly basis. As shown in **Figure 7**, the project teams will upload their data by using a graphical user interface (GUI) or a command-line utility for automation purposes. Azure Storage Explorer, the GUI, is a free tool of Microsoft that is available on Windows, Mac, and Linux. With this tool you can access and manage Azure Blob Storage as well as move data to and from Azure Data Lake Storage. AzCopy, Azure's command-line utility for copying data to or from Azure Blob Storage using simple commands that is designed for optimal performance.

Storage: The data generated is stored and managed through the Microsoft Azure cloud platform, which allows for the storage and traceability of structured and unstructured raw data. The data will be stored in blob storage. Azure Blob storage is Microsoft's object storage solution for the cloud. Blob storage is optimized for storing massive amounts of structured and unstructured data. The Azure Blob will be stored in in Azure Storage Account. The Azure Storage Account is what contains all Azure Storage data objects which includes blobs. The storage account provides a unique namespace for the Azure Storage data and is accessible from anywhere in the world over HTTP or HTTPS. The Metadata is generated as data is uploaded and stored in the data hierarchy structure.

Access: The DMS will leverage Azure Active Directory (Azure AD) for access management. Azure AD is Microsoft's cloud-based identity and access management service. Azure role-based access control (RBAC) will be used as the authorization system to implement what data each stakeholder group will have access to. Using Azure RBAC, each stakeholder group will be granted their respective access (e.g., read, read/write access). Each stakeholder group will have to authenticate using Azure Multi-Factor Authentication (MFA). Azure MFA is a layer of protection to the sign-in process. As each stakeholder group will attempt to access their respective data, they will provide additional identity verification (e.g., entering a code received by phone). Azure AD will help enable secure login. Azure Key Vault will be used to control access to any passwords, certificates or Application Programming Interface (API) keys that will be used within the DMS.

Security: To secure Azure resources, an Azure Virtual Network (VNet) will be implemented. The Azure VNet is essential for a private network in Azure. The VNet enables many types of Azure resources to securely communicate with each other, the internet, and on-premises networks. Other additional benefits of the Azure VNet include filtering network traffic, routing network traffic and integration with Azure services. All Azure resources deployed in a VNet are deployed into a subnet within a VNet. A VNet is a logical collection of subnets. All subnets must divide the VNet address range in a way so that no subnet overlaps the address range of another subnet. To filter network traffic to and from Azure resources in a VNet, Azure Network Security groups (NSGs) will be implemented. A network security group contains security rules that allow or deny inbound network traffic to, or outbound network traffic from Azure resources. For each rule, you can specify source and destination, port, and protocol. To protect the Azure VNet resources Azure Firewall will be deployed. Azure Firewall is a managed, cloud-based network security service that is a fully stateful firewall as a service with built-in high availability and unrestricted cloud scalability. Additional security services that will be implemented are TLS 1.2 encryption during data-at-transit, which aims to secure data actively being transferred from one location to another, as well as 256-bit AES encryption for data-at-rest, which aims to secure inactive data stored on any device or network.

The Data Operations layer discusses the day-to-day operations necessary to manage the data lifecycle activities. This includes capacity planning for scalability, monitoring and disaster recovery to ensure data is available, and user access management as well as services to support the data processors and users. The data operations expand to the support of data centers, cloud infrastructure, and any local network infrastructure that is necessary for data management.

Further information on the DMS and the data used by the system can be found in the *Data Management Plan*.

5.1.2.5 Simulation System

The Simulation System is made up of simulation systems owned by CMU and PSU. As shown in **Figure 8**, these systems will be integrated using a tool called CARLA. CARLA was developed by the Computer Vision Center and is an open-source, 3D open-source simulator that supports the development, training, and validation of ADSs. CARLA allows the flexible specification of sensor suites and environmental conditions, and user-defined elements including instances of other vehicles, pedestrians, and user-defined maps. In order to create the simulation environment, the ADS simulation system and traffic simulation systems will be integrated using APIs that pass data between the systems.

5.1.2.5.1 AV Simulation

For CMU's simulation of AV behaviors within a construction environment, their subsystem is known as CADRE TROCS and allows a simulated AV (i.e., the ego vehicle) to operate in a virtual environment. The Simulation System has previously been used to develop urban-driving motion-planning algorithms for the autonomous Cadillac SRX. CADRE TROCS allows the user to determine the path of the ego vehicle, change the map on the fly, and place obstacles within the simulation.

A graphical user interface for CADRE TROCS facilitates real-time monitoring and manipulation. It consists of six main functional components: real-world model plotter, XML-based scenario loading area, historical host vehicle measurement, a zoom/panning tool, simulator/planner stop/go toggle tool and an external trigger control panel. CADRE TROCS will be integrated with CARLA for enhanced visualization within the project. CARLA allows the user to visualize the environment in an enhanced 3D environment and allows the system to import real maps from Open Street Maps.

CADRE TROCS does have some limitations which will limit the types of work zone scenario variations that can be tested. The simulation always has good lane position accuracy, so the enhanced coating and time of day cannot be simulated without further enhancement of the software. CADRE TROCS also does not currently support CV communications. The software does, however, allow the user to change the map, allowing the Simulation Operator to simulate the effect of the map being updated via CV communications as the ego vehicle approaches the work zone.

5.1.2.5.2 Simulation of Traffic Response to AV Behavior in Work Zones

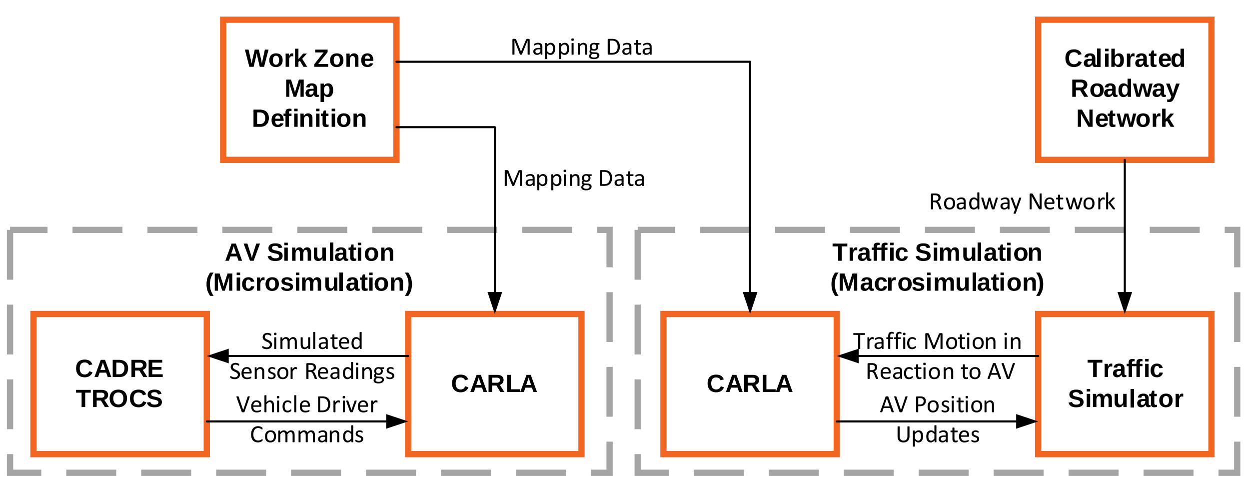
For PSU's integration of traffic simulations with motion simulations of vehicle chassis behavior, PSU typically uses AIMSUN or SUMO as their traffic simulation system, but can use VISSIM as well; for this project, SUMO is likely to be used due to its open-source availability and ongoing development within the CARLA environment. For motion simulations of the vehicle, PSU has used CARLA, LGVSL, MATLAB/Simulink, CarSim, and even gaming engines such as Unity or Blender. These software systems typically are used with Robot Operating System as middleware. The traffic simulation systems allow the user to import road networks and generate traffic on the roadway network using statistical traffic history.

SUMO is a traffic planning, simulation, and prediction tool that is used for analyzing roadway networks, and in this project will be used to study potential traffic impacts caused by AV behavior within workzones. The software tool is very flexible and can be used to analyze complex roadway environments with vehicles, multimodal transport, vulnerable road users (VRUs), pedestrians, ITS devices, and more. SUMO has the ability to program custom add-ins if the user would like to analyze the impact of a network change that has not been modeled yet or if the user has a new way of analyzing the network change.

5.1.2.5.3 Integration of the Simulations with Each Other

CARLA will receive the 2D vehicle locations from the traffic simulator, representing the vehicles in the roadway network, and turn them into 3D objects. The motion profiles of the traffic vehicles can then be stored and then later passed to the CADRE simulator via CARLA playback. Similarly, CADRE passes back the AV location to CARLA, which is then stored as a vehicle object that can be used by the traffic simulator. This iterative traffic / AV simulation approach will allow traffic to react to the AV operations, as well as allow the ADS to react to traffic in the network. As well, by monitoring how much AV behavior changes due to traffic updates, and vice versa, this process can quickly identify when AV or traffic behaviors are rapidly changing in feedback response to each other.

Figure 8: Simulation System Architecture



SOURCE: PENNDOT

5.1.2.6 Environment

Environment refer to the brick-and-mortar, non-connected objects that the AV may need to interact with in order to navigate through the work zone. These objects include other vehicles, the roadway environment, potential obstacles, and VRUs (if applicable). These objects do not transmit any data to other work zone users or systems and it will be the responsibility of the AV to detect any Environment conditions and objects that it encounters. In the Environment, there are both fixed and moveable objects. Fixed objects are objects that are not anticipated to move, like barriers, while moveable objects are objects that are anticipated to move, like work zone vehicles.

The roadway environment includes pavement, signs, pavement markings, non-V2X traffic signals, roadway geometry, horizontal and vertical sight distance obstructions (e.g. overhead structures, sharp curves), and other typical roadway features. The non-V2X work zone objects are all considered part of the roadway environment, including lane lines, signs, barrels, cones, flaggers, temporary signals, truck-mounted attenuators (TMAs), and other work zone traffic control devices. The non-V2X objects in the roadway environment are all considered “dumb” objects because they will not send any information to the subsystems.

It is anticipated that VRUs will be prohibited from the work zones during live testing in this project for safety reasons. Although the AV has the ability to appropriately react to VRUs, allowing VRUs in the work zones with the AV during a research project is an inherent safety risk. Temporary traffic control specifying an alternate route for VRUs should be provided during times of testing. Advance notice should be given to VRUs that an alternate route will be designated during those times. In the unplanned situation where VRUs enter the work zone during testing, the AV is expected to react appropriately to the users.

5.1.2.7 GNSS

GNSS refers to a constellation of satellites providing signals from space that transmit positioning and timing data to GNSS receivers. The receiver then uses this data to determine its location (longitude, latitude, elevation) to a degree of precision that can vary from a few centimeters to several meters. There are four global GNSS, with the most well known being the Global Positioning System, as well as several regional GNSS. Project subsystems may use one or several of the available GNSS.

5.1.2.8 Reference Station

Several Reference Stations will be used for the project to provide high-precision location data. As opposed to GNSS, CORS are able to provide sub-centimeter level accuracy with a good connection. There are currently over 1,350 CORS sites as part of the National CORS system with 20 being in Pennsylvania, as well as some privately owned CORS.

For this project, the RSU will use the CORS operated by PennDOT as part of the National CORS network, the Mapping Van will use the CORS that is owned by PSU and located at LTI, and the AV will utilize a CORS network to which CMU subscribes.

5.1.2.9 WZDx System

The WZDx System refers to any system that receives the WZDx information from the DMS WZDx page. User systems that may receive the WZDx include map services (e.g. Waze, Google, Apple, etc.) and vehicle OEMs.

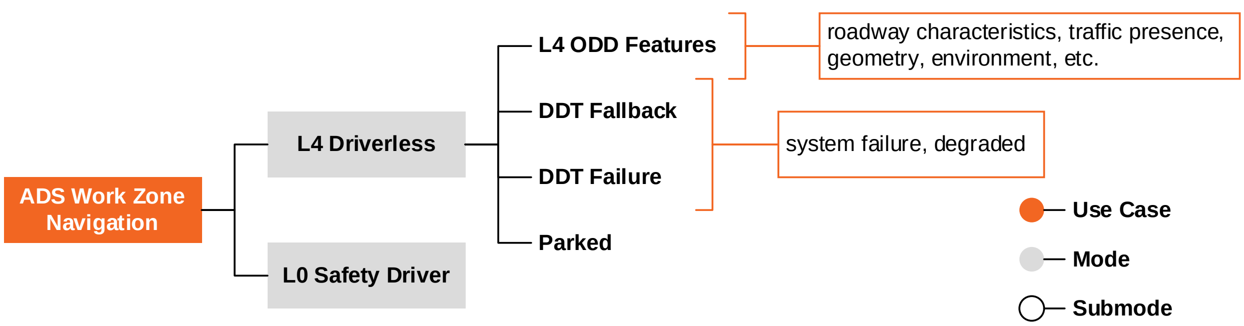
The information that will be received by the WZDx System will be JSON in the WZDx format established by USDOT’s WZDx Program. The WZDx information will be provided in the format that was established at the time of the development of the project and will not be updated as the project progresses. The information that is provided by the DMS will originate in PSU’s map processing system and will be sent along with the map information. The API link where the WZDx information will be provided may be available on the USDOT WZDx Program website.

5.2 Modes of Operation

Together, modes and states provide a way to *command and control* a system, subsystem, element or task safely, which will be used to measure use case performance during testing, having a number of different configurations.

A **mode** provides the project team with an abstract label for describing a user-selectable option that enables use case capabilities to operate with other processes/procedures. For instance, aligning with SAE J3016, vehicles in the ADS project will have two primary modes of operation: SAE level 0 driver assisted operation and SAE level 4, driverless automated mode. Submodes will also be used to provide further detail on operating conditions, such as L4 ODD object and event detection and response features, L4 dynamic driving task (DDT) failure, fallback (to safety driver), etc. **Figure 9** provides an illustration of how modes and submodes will be related and measured against use case capabilities.

Figure 9: ADS Work Zone Navigation Modes



SOURCE: PENNDOT

A system **state** of various types will be used to indicate the condition or logistical availability of a system, subsystem, element or task under test. For instance, the *system state* of the AV during testing will either be in service (i.e., available for use), in operation (actively in-use), in maintenance (triggered by an error or mechanical failure that needs fixing), or unavailable (i.e., not available for use, as a catch-all state). It will also have two *dynamic states*: in operation, indicating a vehicle is actively undergoing a test run; and minimal risk condition to indicate the vehicle performed a DDT fallback without transitioning control to the Safety Driver. In this case, the AV is expected to respond safely by turning on the hazard flashers, maneuvering the vehicle to the road shoulder, and parking itself.

These modes and states will be tested under a number of different **configurations** that reflect the input parameters the project team will fine-tune and use to measure performance against the metrics established in the project safety and evaluation plans. **Table 8** details the modes, submodes, states and configurations and how those relate to each of the four use cases established for the project.

Table 8: ADS System Modes and States

<table>
<tr><th>Use Case</th><th>Mode of Operation</th><th>States
(SYSTEM, DYNAMIC, OPERATIONAL)</th><th>Configuration
(Factors)</th></tr>
<tr><td>Work Zone Mapping</td><td>▪ Operated
▪ Mapping
▪ Parked
▪ Inoperable</td><td>SYSTEM
▪ In service
▪ In operation
▪ In maintenance
▪ Unavailable
DYNAMIC
▪ Data transferring</td><td>▪ Base case
▪ Factor
o PPG coating</td></tr>
<tr><td>Simulation</td><td>▪ L4 automated
o L4 drive behavior
o L4 traffic behavior
▪ Inoperable</td><td>OPERATIONAL
▪ Online
▪ Offline
SYSTEM
▪ In maintenance
▪ Unavailable</td><td>▪ ODD Base case
▪ Factor
o HD map
o PPG coating</td></tr>
<tr><td>Work Zone Navigation</td><td>• ADS Navigation
o L0 safety assisted
o L4 automated
▪ L4 ODD OEDR feature (many)
▪ DDT fallback
▪ DDT failure
o Parked
o Inoperable
• Roadside Environment
o Single, dual
o User, system
o Broadcasting
o Receiving
o Inoperable</td><td>SYSTEM
• ADS Navigation
o In service
o In operation
o In maintenance
o Unavailable
OPERATIONAL
• Roadside Environment
o Online
o Offline
DYNAMIC
• ADS Navigation
o Fallback ready
o Minimal risk condition
• Roadside Environment
o In maintenance
o Unavailable</td><td>• ADS Navigation
o ODD base case
o Factor
▪ Communication
▪ HD map
▪ PPG coating
• Roadside Environment
o RSU system architecture
o Factor
▪ Communication</td></tr>
</table>

<table>
<tr><th>Use Case</th><th>Mode of Operation</th><th>States
(SYSTEM, DYNAMIC, OPERATIONAL)</th><th>Configuration
(Factors)</th></tr>
<tr><td>DMS Data Retrieval</td><td>▪ Listening
▪ Sending
▪ Receiving
▪ Inoperable</td><td>OPERATIONAL
▪ Online
▪ Offline
SYSTEM
▪ In maintenance
▪ Unavailable</td><td>▪ Interface
▪ Factor
○ Communication</td></tr>
</table>

SOURCE: PENNDOT

During the second phase of the project, the operations and maintenance (O&M) team will monitor and report on the progress of test activities. O&M aims to ensure testing activities are on track and conditions that present risk, such as failures, degraded or maintenance conditions are monitored and resolved in a timely manner. **Table 9** provides the O&M operating condition classifications.

Table 9: AV Work Zone System ADS Demonstration System Modes of Operation

Mode	Description
Mode 1: Normal Operating Conditions	*A normal operating condition exists when the four use case capabilities listed in **Table 8** are online, in service, and operating as designed without system defects or failures of any kind. Examples include:* • AV is operating through the work zone as designed, abiding by traffic laws and traffic control devices. • The DMS ingests, stores, and processes data as designed. • The Mapping Van is sensing the environment and processing map information as designed. • The system is fully functioning as intended, generating outputs when necessary and not generating outputs when unnecessary.
Mode 2: Degraded/Failure Conditions	*A degraded condition exists when functionality for any of the four use case capabilities listed in **Table 8** are diminished or lost, the state reflects unavailable, fallback or minimal risk condition. In degraded conditions, an alternative (though less precise) means of accomplishing system functions may exist. Examples include:* • AV may have a non-working sensor but may be able to adhere to existing regulations associated with traffic control devices (e.g. traffic signals, signage, and lane markings) and the work zone traffic control. *A failure condition exists when the system is unable to perform any of the four use case capabilities listed in **Table 8**, the mode of operation is inoperable, and the state reflects offline or unavailable for any reason. Examples include:* • AV does not detect work zone objects or does detect, but does not initiative the tactical maneuvers established in the safety and evaluation plan to navigate safely within the work zone. • AV is unable to perform the DDT and does not fallback maneuver to the safety driver. • Equipment of mechanical failures that disable a subsystem (e.g., GPS provides incorrect location data for workers (i.e., instrumented vests)).
Mode 3: Maintenance Conditions	*A maintenance condition exists when any of the four use case capabilities listed in **Table 8** are inoperable or offline due to system maintenance state and the condition prevents test activities from progressing. Examples include:* • Routine, planned or unplanned maintenance is scheduled on infrastructure critical to the project. In this case, the physical system, subsystem, or element must be taken out of service to be repaired by an appropriately trained entity and returned to service in a timely manner. • An RSU needs to be calibrated. • The Mapping Van requires a system upgrade, enhancement, or patch.

SOURCE: PENNDOT

5.3 Interfaces

Interfaces provide the specifications of the relevant properties of a system or component that can be connected to other systems or components while instances of interaction are identified in order to specify the actual integration to other systems or components. The anticipated interfaces for the AV Work Zone System are specified in **Table 10**. The Interface IDs correspond to the interfaces shown in **Figure 4**.

Table 10: Expected Interfaces of Proposed System

Interface ID	Description
1	→ SPaT, MAP, and other CV data
2	→ V2X Work Zone Object location
3	→ Raw and processed sensor data and map data
4	→ Performance data
5	→ Performance data ← Map data
6	→ Time and location information
7	→ Position correction information
8	→ Performance data and ADS generated map ← Map data
9	→ WZDx data

Source: PennDOT

6 OPERATIONAL ENVIRONMENT

This section describes the physical environments that the system will operate in. The changes that are required in order to integrate the existing components are also described.

6.1 Operational Environment

6.1.1 Stakeholders

This section describes the stakeholders. These include all existing stakeholders who have an influence on the operation of the proposed AV Work Zone System. This will include all staff and agencies whose operation and duties may be affected by the envisioned system.

6.1.1.1 Carnegie Mellon University

Founded in 1900, CMU is a private research university based in Pittsburgh, Pennsylvania. CMU's College of Engineering is the academic unit that manages engineering research and education at CMU. The College of Engineering employs 207 faculty members and has over 700 doctoral students performing research activities. CMU is the birthplace of AVs and has been a pioneering leader in AV technologies since the 1980s. Within the College of Engineering, CMU has various labs working on technology specifically for the advancement of AV technology, like the Argo AI Center for AV Research. These centers focus on fundamental research that will produce advanced perception and next-generation decision-making algorithms that enable vehicles to perceive and navigate autonomously in diverse real-world urban conditions. CMU's Department of Electrical and Computer Engineering within the College of Engineering will be the stakeholder participating in this project.

6.1.1.2 Contractor

For the live on-road testing, it is anticipated that a real work zone with limited traffic will be used. The testing location may be either a work zone set up my PennDOT maintenance crews or a contractor. In the event that the work zone is operated by a contractor, the contractor will be responsible for acting as the role of the Work Zone Operator and will coordinate with PennDOT Central Office, PennDOT District and PennDOT County (maintenance crew). The contractor will be responsible for setting up the work zone in accordance with the traffic control plan for the project. Prior to choosing the work zone location, PennDOT Central Office will verify that the traffic control plan for the project accurately reflects the PATA figures.

6.1.1.3 Deloitte

Deloitte Consulting LLP, known as Deloitte, is the US division of a multinational professional services network with offices around the world. Deloitte's Cloud Engineering department is one of the global leaders of cloud infrastructure and engineering and managing cloud services. The Cloud Engineering department will be participating in this project as the developer of the DMS and DMS documentation, including the DMP, Data Privacy Plan, and DMS Incident Response Plan.

6.1.1.4 PennDOT County

There are 67 counties in the Commonwealth. Each county has their own maintenance team that is responsible for the maintenance of the state-owned roadway network in the county.

6.1.1.5 PennDOT Central Office

PennDOT Central Office is located in Harrisburg, PA. PennDOT Central Office is responsible for the central planning activities of PennDOT. For this project, Central Office will refer to Transportation Systems Management and Operations – Operations and Performance Section of the Highway Safety and Transportation Operations Division and the Office of Transformational Technology.

6.1.1.6 PennDOT Districts

There are 11 PennDOT districts in the Commonwealth. Each district has their own district office and staff. The districts are responsible for coordinating maintenance of their state-owned roadway network and coordination with local governments, residents, and contractors.

6.1.1.7 PPG Industries

PPG, headquartered in Pittsburgh, PA, is an American Fortune 500 company and global supplier of paints, coatings, and specialty materials. They are the largest coatings company in the world. In recent years, PPG has developed advanced coatings that can improve detection for cameras and LIDAR sensors. As part of this project, these coatings will be tested to see if they aid ADS operations.

6.1.1.8 Pennsylvania State University

PSU, founded in 1855, is a public state-related land-grant research university with campuses and facilities throughout Pennsylvania. The PSU College of Engineering employs over 400 research and teaching faculty. The Department of Civil and Environmental Engineering and Department of Mechanical Engineering will be the stakeholders from PSU involved in the project. The activities in this project are coordinated through the Thomas D. Larson Transportation Research Institute, often called the Larson Transportation Institute (LTI). This is a center housed within the College of Engineering whose purpose is to coordinate transportation projects and research.

6.1.1.9 Pennsylvania Turnpike Commission

The Pennsylvania Turnpike is a toll highway operated by PTC in Pennsylvania. The 360-mile controlled-access highway runs east-west across the state, connecting the Pittsburgh, Harrisburg, and Philadelphia areas as well as extensions connection other southwest and northeast regions of the Commonwealth.

6.1.1.10 Pennsylvania Turnpike Commission Maintenance & Construction

PTC has its own maintenance crews, which set up work zones on the Turnpike roadway for maintenance activities. Construction contractors set up work zones for all short and long term construction work zones. For this project, the Traffic Engineering and Operations department will be the stakeholder group that participates in the project.

6.1.1.11 United States Department of Transportation

USDOT is a Federal Cabinet department of the U.S. government concerned with transportation. USDOT employs almost 55,000 people across the country, in its operating administrations and bureaus, each with its own management and organizational structure. FHWA provides stewardship over the construction, maintenance and preservation of the Nation's highways, bridges and tunnels. FHWA also conducts research and provides technical assistance to state and local agencies to improve safety, mobility, and to encourage innovation. For this project, FHWA and their local Pennsylvania office will be the participant in the project.

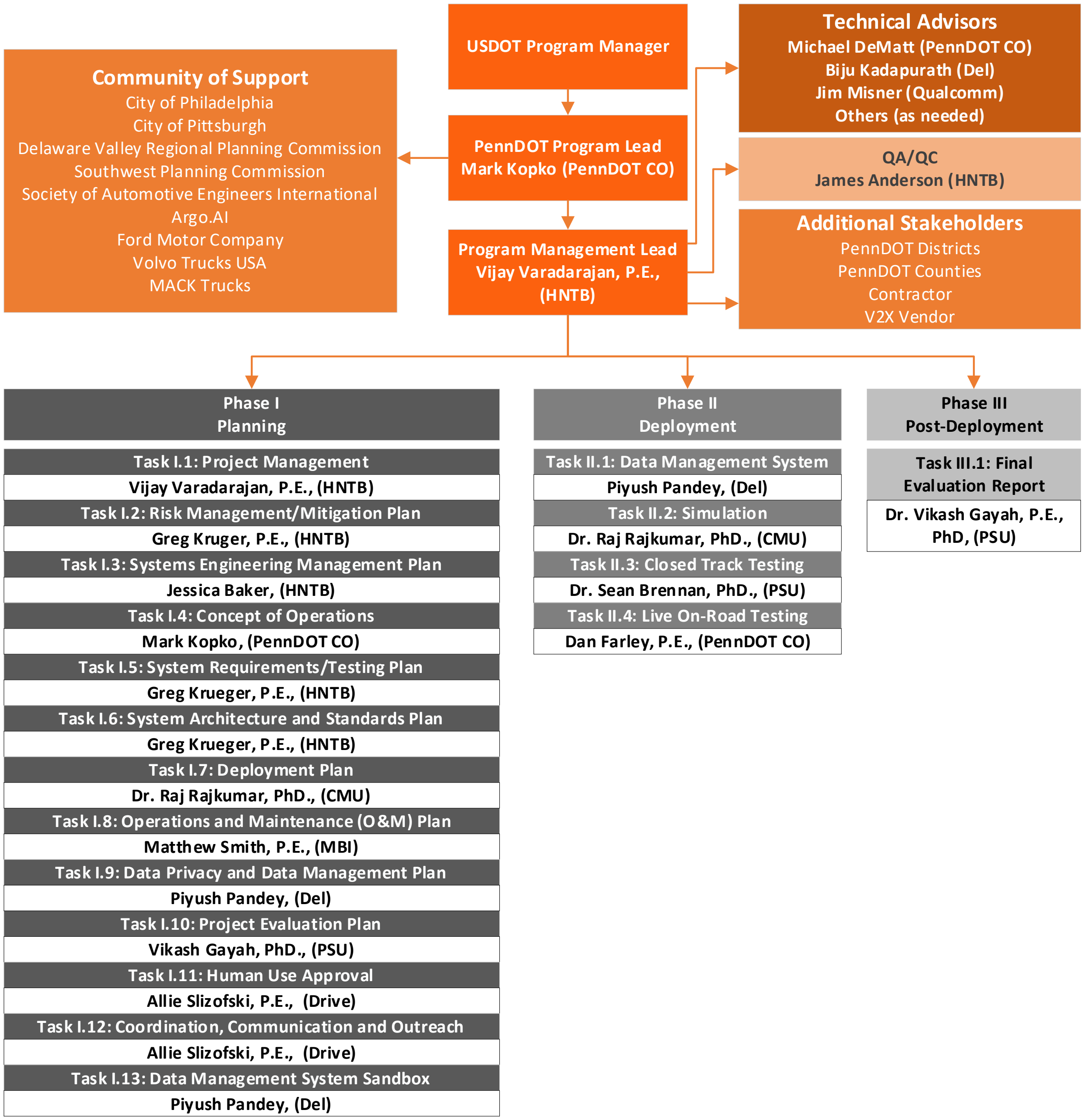
6.1.1.12 V2X Vendor

The V2X Vendor will be procured as part of deployment. The V2X Vendor acts as the work zone operator who will be responsible for setting up and configuring the V2X Work Zone Objects. It will be expected that the V2X Vendor will have a history of successful V2X deployments and have the ability to provide guidance and expertise on V2X device integration.

6.1.2 Organizational Structure

The organization chart for the ADS Demonstration Project can be found in **Figure 10**. It is not anticipated that there will be any changes to individuals' roles within their own organizations for this project. A detailed description of each role's responsibility for deliverable development can be found in the *Project Management Plan* and *Systems Engineering Management Plan*.

Figure 10: ADS Demonstration Organizational Chart



SOURCE: PENNDOT

6.1.2.1 Core Team

The core team will consist of key management staff from PennDOT, PSU, PTC, and CMU. HNTB Corporation (HNTB), a consulting firm, will also be part of the Core Team.

The core team is responsible for the essential business issues associated with the project which are critical to the delivery of the project outputs and the attainment of project outcomes. The core team members will meet weekly to monitor and control the scope, schedule, budget, quality, deliverables and risks of the project.

6.1.2.2 Planning Phase Leads

Each task within the Planning Phase will be led by an individual from the organization responsible for the task. Each task lead will be responsible for defining the work that needs to be completed in order to develop the deliverables and responsible for developing the deliverable for their respective tasks. Each task lead will be supported by their support team, who will develop the deliverables and assist the task leads with planning and estimating the resources required to complete the task.

6.1.2.3 Deployment Phase Leads

PennDOT has also assembled a group of representatives identified as deployment partners, who will be part of the project deployment team. The deployment partners include CMU, PSU, PPG, Deloitte and PennDOT.

Each task within the Deployment Phase will be led by a different organization, and each task will be led by an individual from that respective organization. Each task lead has experience leading teams with the skillsets required to carry out the tasks. The task lead will be responsible for scheduling all staff and resources required for the testing; overseeing the conducting of the testing, development, and setup of the work zones; monitoring staff performance; and making sure that the required data is stored in the DMS. Each task lead will be supported by their support team, who will set up the work zones, conduct the testing, record the data, and assist the project manager with planning and estimating the resources required to complete the task.

6.1.2.4 Post-Deployment Phase Lead

The Post-Deployment Phase consists of one task to create the Final Evaluation Report. This task will be led by PSU, who has defined a task lead to complete the work. The task lead will be responsible for defining the work that needs to be completed in order to develop the Final Evaluation Report and responsible for developing the report. The task lead will be supported by their support team, who will develop the report and assist the task lead with planning and estimating the resources required to complete the task.

6.1.2.5 Technical Advisors

The technical advisors will consist of technical experts from PennDOT, Turnpike, PPG, CMU, Deloitte and Qualcomm outside of the project team, who will provide technical advisory services to the project team. Qualcomm will provide expertise on connectivity ecosystems, PennDOT and Office of Administration (who serves as PennDOT’s IT Department) will provide support DMSs and Deloitte will provide support with their expertise oncommunication networks and Internet of Things. Technical advisors may also include others outside of the project team who are committed to providing technical advisory expertise on an as needed basis and at the quarterly meetings.

6.1.2.6 Community of Support

Community of support members have provided a letter of support indicating their support for this project. They will be part of the project audience and kept abreast of progress through outreach efforts. The community of support does not have an operational role in the project.

6.1.3 Roles and Responsibilities

The project will be supported by expanding the responsibilities of the various stakeholders of the project. The roles and responsibilities of each stakeholder for the project can be found in **Table 11**.

Table 11: Stakeholder Roles and Responsibilities

Stakeholder	Roles and Responsibilities
PennDOT Central Office	• Support DMS development, simulation testing, closed-track testing, and final evaluation report • Manage live on-road testing • Install and maintain V2X equipment
PennDOT Districts	• Set up work zones • Drive other vehicles in the closed-track testing
PennDOT Counties	• Set up work zones • Drive other vehicles in the closed-track testing
HNTB	• Support DMS development, simulation testing, closed-track testing, live on-road testing, and final evaluation report • Project management
PSU	• Support DMS development, simulation testing, and live on-road testing • Manage closed-track testing • Develop final evaluation report • Integrate, maintain and operate Mapping Van and Simulation Systems • Prepare and submit for closed-track testing IRB approval, if necessary • Drive other vehicles in the close track testing
CMU	• Support DMS development, closed track testing, live on-road testing, and final evaluation report • Manage simulation testing • Integrate, maintain and operate AV and Simulation Systems • Prepare and submit for live on-road testing IRB approval
Deloitte	• Develop, maintain and operate DMS
PPG	• Support DMS development, simulation testing, closed-track testing, live on-road testing, and final evaluation report • Provide coating and integrate into work zones
PTC	• Support DMS development, simulation testing, closed-track testing, live on-road testing, and final evaluation report
PTC Maintenance & Construction	• Set up work zones
Michael Baker International (MBI)	• Support DMS development, simulation testing, closed-track testing, live on-road testing, and final evaluation report • Develop O&M plan
Drive	• Support simulation testing, closed-track testing, live on-road testing, and final evaluation report • Coordinate IRB approval • Coordinate communication and outreach efforts
V2X Vendor	• Integrate and configure V2X equipment
Contractor	• Set up work zones

SOURCE: PENNDOT

6.1.3.1 Long-Term Roles and Responsibilities

In order to plan for the future of AVs in transportation, it is important to identify how the findings of this project may impact the existing and future workforce needs, as well as the changing roles and responsibilities of the workforce. Identifying these changes as early as possible will allow labor relations and unions to plan for changes in workforce development needs. **Table 12** identifies the potential impacts in the long-term roles and responsibilities of the workforce in the Commonwealth of Pennsylvania.

Table 12: Long-Term Roles and Responsibilities Changes

Role	Responsibilities Removed	Responsibilities Added
PennDOT Central Office	• None	• Additional coordination with Districts, contractors, and consultants for implementing new work zone traffic control measures • Approving new work zone traffic control devices in Bulletin 15 • Adding the new work zone traffic control devices in guidance publication documents • Creating and maintaining a permanent DMS for the V2X devices and WZDx data, likely integrated into the ATMS
PennDOT District Maintenance	• None	• Additional coordination with consultants, contractors, and county maintenance for implementing new work zone traffic control measures
PennDOT County Maintenance	• None	• Implementing and maintaining new work zone traffic control measures
PTC Maintenance	• None	• Additional coordination with consultants and contractors for implementing new work zone traffic control measures • Implementing and maintaining new work zone traffic control measures
Design Consultants	• None	• Adding new work zone traffic control measures to project plans and specifications
Contractors	• None	• Implementing and maintaining new work zone traffic control measures

SOURCE: PENNDOT

6.2 Physical Environment

This section describes the facilities within which equipment and personnel will be housed, additional furniture and equipment that will be required, new computing hardware and software that will be required, operational procedures and any additional support that will be needed.

6.2.1 Hardware and Software

6.2.1.1 Onboard Equipment

Communications devices along with other affiliated equipment located in the vehicle as part of the V2X operations are collectively known as the OBU. The OBU is envisioned to consist of a V2X radio and a processing unit, and potentially a GNSS receiver and display (the existing GNSS receiver that's part of the AV may be able to be utilized). Further, it includes any software installed on these devices to enable their functions and that of V2X applications. The OBU will not include any equipment related to the ADS or sensors.

To maintain a consistent point of reference, many in-vehicle sensors must remain in the same location on the vehicle, as measured in a body-fixed coordinate system. This data is used to populate safety (and other) messages that are broadcast by the vehicle. The OBU broadcasts and receives messages to/from RSUs and other (remote) OBUs. The processing unit performs various tasks with the data received from in-vehicle sensors, GNSS, and message data received via the OBU. Finally, the in-vehicle display provides alerts and/or warnings to the Safety Driver based on outputs from the processing unit.

The OBU for this project will be procured from a V2X Vendor. CMU will also be responsible for maintenance of the OBU. The OBU will be required to maintain a level of performance and standard of care identified in the requirements and procurement materials. The V2X Vendor will work with CMU and PSU to integrate the OBU into the AV and Mapping Van, to perform testing.

6.2.1.2 Roadside Equipment and V2X Work Zone Objects

The RSU can be comprised of any or all the following items: GNSS receiver, a DSRC/C-V2X radio capable of broadcasting in the 5.9 GHz wireless band, a message handler/processing computer unit, and power systems to support this equipment. It is important to note that the message handler/processor can take multiple forms – it could be incorporated into the Traffic Signal Controller or the RSU, or it could be its own dedicated component. Only a device that contains a message handler/processing unit is capable of interfacing with remote equipment via backhaul. GNSS data is used primarily for time-alignment of data, but may also be used to determine position information for the intersection. GNSS data, along with data received from traffic control equipment is populated into various messages – SPaT, MAP, etc. The RSU broadcasts and receives messages to/from vehicle OBUs. The processing unit performs various tasks with the data received from the GNSS, traffic control equipment, and message data received via the RSU. In addition to providing traffic control data for the processing unit, the traffic control equipment receives outputs from the processing unit that affect the operations of the signal(s) that it is controlling.

Furthermore, the Traffic Signal Controller must be capable of providing traffic signal data as an output – National Transportation Communications for ITS (NTCIP) 1202-compliant traffic signal controllers are capable of generating a uniform output that contains signal data used to support the project's applications.

V2X Work Zone Objects can be comprised of any or all the following items: GNSS receiver and a communication radio, as well as the work zone object hosting this equipment. The work zone objects could be many different physical items: cones, barrels, smart vests/hats worn by workers, parked or operational construction vehicles or machinery, or any other work zone channelizing device which defines the lane for the AV.

The RSU for this project will be procured from a V2X Vendor. The V2X Work Zone Objects for this project will be procured from a V2X Vendor or built in-house by PSU. PennDOT and PSU will also be responsible for maintenance of the RSU and V2X Work Zone Objects. The RSU and V2X Work Zone Objects will be required to maintain a level of performance and standard of care identified in the requirements and procurement materials. The V2X Vendor will work with PennDOT to integrate the RSU with the DMS, Traffic Signal Controller and TMC, as necessary, and perform testing.

6.2.1.3 Communications/Backhaul

A variety of communications media are used in the project. Communication between most devices is constrained either by communication standards or by the availability of infrastructure. The standardized means of communication between OBUs and between an OBU and an RSU is DSRC/C-V2X. DSRC (5.895-5.925 GHz)/C-V2X (5.850-5.895 GHz) use designated spectrum bands reserved for vehicular safety applications. They are two-way, short- to medium-range wireless communications characterized by low data transfer latency, high data transmission rates, and dependability in extreme weather conditions. Some equipment on the roadside may be connected by a local, wired connection such as Ethernet or other data transfer cables (with standardized external interfaces, such as CAN). Backhaul connections provide communication between the message handler/processor and management centers (such as the DMS or TMC) and are typically also Ethernet protocol systems. The physical layer for back-haul is typically implemented in the form of wired connections or fiber-optic cable. Backhaul fiber optic cable either already exists or will be expanded to include areas where V2I-compatible RSUs will be installed. Satellite communications are used for the reception of time and calculation of location data via GNSS satellites.

Connectivity will be provided by DSRC and/or C-V2X. It should be noted that, although DSRC and C-V2X were proposed as part of this project, the feasibility of doing both will depend on the ability to get FCC licenses for both devices and the FCC's plan for re-allocating the spectrum for wireless communications. At the time of the ConOps development, the FCC has halted approvals of all DSRC licenses and plans on vacating the lower 45 megahertz and transitioning the remaining DSRC spectrum to C-V2X in a phased approach over several years.

The project team will work with C-V2X vendors and use the latest versions of commercially available C-V2X hardware. The hardware that is available at the time of procurement may not be compatible with the C-V2X hardware that is available at the end of the project, due to the fact that the the technology may change as the technology matures and becomes the primary CV protocol. Although the hardware may not be compatible with later version, the project's emphasis is to find the right data that should be used rather than an evaluation of the hardware that is moving the data. The project's change management strategy identified in the *Project Management Plan* will be followed to handle the transition from DSRC to C-V2X.

> ***NOTE:*** *The project is aware of the FCC First Report and Order (R&O)[4] released May 3rd, 2021. The order states the following:*
>
> ***Bandwidth Reallocated:*** *the May 2021 R&O repurposed the 5.9 GHz band, reducing band allocation for V2X services from 75 megahertz to 30 megahertz.*
>
> ***Moving Away from DSRC:*** *the R&O also concludes that the public interest would be best served by adopting C-V2X as the sole Intelligent Transportation Systems (ITS) delivery system and phasing out the existing DSRC technology.*

[4] https://public-inspection.federalregister.gov/2021-08802.pdf

6.2.1.4 Automated Vehicle

The AV provided by CMU is described in **Section 5.1.2.1**. Minor modifications will be required to integrate the AV into the project. New OBU may need to be integrated into the vehicle in order to receive messages from V2X Work Zone Objects and RSU. The existing vehicle software may require updates to receive the map data and WZDx data in the format provided by the DMS. The data received from the DMS will then need to be integrated into the ADS's map that is used to allow the vehicle to navigate. The vehicle does not currently operate using either data format, but the new formats will allow the AV to understand its environment in the work zone area. The AV, including the basic vehicle, sensors and ADS components, will be maintained, updated and operated by CMU.

6.2.1.5 Mapping Vehicle

The Mapping Van provided by PSU is described in **Section 5.1.2.2**. In order to integrate the Mapping Van into the project, there will need to be several modifications to the vehicle. If sensors are not available via the coatings supplier, the Mapping Van will require the integration of infrared and hyperspectral cameras to detect objects and measure spectroscopy for specially-coated surfaces. The LIDAR sensors are currently in need of repair and will be replaced with the same or better model LIDAR that the AV is using for consistency, e.g. the Velodyne 16-scan or 32-scan LIDAR systems.

Software updates will be required in order to turn the sensor data received into the map format required by the AV. The Mapping Van and associated equipment currently has the ability to map standard roadway environments and turn the sensor data into map files similar to what the AV would ingest, but the formats need to be tested for work zone information, and to match the exact agreed upon format that will be used by the AV.

As well, to map the connectivity around the work zone, V2X equipment on the Mapping Van will be installed to ensure compatibility with the RSU and AV.

The Mapping Van, including the basic vehicle, sensors, and processing equipment, will be maintained, updated and operated by PSU.

6.2.1.6 Simulation Systems

The Simulation Systems provided by CMU and PSU are described in **Section 5.1.2.5**. In order to integrate the Simulation Systems into the project, there will need to be several modifications to the simulation programs.

CADRE TROCS currently has the ability to simulate most of the ADS functionality. The ability to receive vehicle positions from CARLA and turn the positions into vehicles that can be detected by the ego vehicle needs to be added to the program. CADRE TROCS will be hosted on a computer owned by CMU or PSU.

CARLA, the bridge between the simulation tools, must be customized to receive both the AV position and the other vehicle positions, convert the vehicles between 2D and 3D, and send the 2D and 3D points to the correct simulation system. In order to send the vehicle positions between the programs, socket connections will be required between the computers running CADRE TROCS, CARLA, and SUMO. CARLA will be hosted on a computer owned by CMU and/or PSU.

SUMO currently has the ability to simulate all vehicle traffic in the roadway network. The traffic simulation tools need to be programmed to receive the AV position. SUMO will be hosted on a computer owned by PSU.

Note that SUMO and CARLA ingest traffic network information via different file formats and import capabilities. The simulation tools need to be coordinated to receive the same map in the same format so that all vehicles in the network are operating on the same paths. All of the programs may be able to receive OpenStreetMap XML, but further testing will be required to ensure that they can be integrated using this format and produce identical traffic network definitions after import.

6.2.1.7 Data Management System

The DMS will be hosted on the Azure platform; therefore, additional hardware will not be needed for the project. The cloud hardware and software will be operated and maintained by Microsoft per the Azure service agreement. The software used to operate the DMS will be maintained by Deloitte. Deloitte will be responsible for keeping the DMS up-to-date and performing any required software maintenance.

6.2.2 DSRC/C-V2X Messages

Messages transmitted via DSRC/C-V2X are used to communicate data between vehicles, personal devices, and infrastructure. The DSRC Message Set Dictionary (SAE J2735) enumerates message types that must be used in the project, along with the data frames and data elements of which they are comprised.

6.2.2.1 WAVE Service Advertisement (WSA)

Available services and messages are advertised by way of sending periodic messages known as WAVE Service Advertisements (WSA). Each WSA may include a list of Provider Service Identifiers (PSIDs) for services that are available on the network, as well as information needed to receive and process the WSMs pertaining to each service being advertised. Each allocated PSID value is associated with a WAVE service.

6.2.2.2 Basic Safety Message (BSM)

The BSM conveys safety information about a given vehicle. Broadcast from a vehicle, the BSM data is organized into two parts. Part I data is comprised of required data elements including but not limited to vehicle size, position (latitude/longitude), speed, heading, acceleration, and brake system status. This data is used to support safety-critical applications that rely on frequent transmission of data. BSM Part II data is comprised of optional data elements that provide weather data (e.g. roadway surface condition, temperature, air pressure) and vehicle data (e.g. vehicle classification, wiper status, traction control status, exterior lights status). Some of the data items used to populate these messages can be obtained from the vehicle CAN bus. Data made available by the vehicle that is not standardized under SAE J1979 may require CAN bus libraries to be obtained from vehicle manufacturers if it is to be utilized to populate data elements in the BSM.

6.2.2.3 Map Data (MAP) Message

The MAP message contains the road geometry necessary for the AV to navigate the area. This would include, for example, the layout of all lanes, crosswalks, and definitions of entry and exit locations. The MAP message is used to position a vehicle with respect to roadway geometries that are identified in the message. The data for this message is in this project typically acquired though mapping van surveys, but manual measurements, and other sources may be available in general. For example, some agencies may already have geometry data on-hand that can be converted into a MAP message format.

For this project, there are two areas where the MAP message may be relevant – temporary signals and transmitting work zone layout information. There will be no work zones set up at intersections, but there is at least one scenario where a temporary traffic signal will be used. When the MAP message would be used for transmitting work zone information, the MAP message set may need to be expanded to provide additional information to the AV traveling through the work zone. Rather than the road geometry that is typically distributed in the MAP message, the entire work zone may be turned into a MAP message using the data generated by the Mapping Van and sent to the AV. Any additional information that may need to be added to the MAP message will be determined during the design phase of the project. Alternatives to a MAP message that may be used for transmitting the map created by the Mapping Van to the AV would be Open Road Specification and WZDx with modifications.

6.2.2.4 Signal Phasing and Timing (SPaT) Message

The SPaT message is used to communicate information regarding the signal state of a given intersection. It contains the signal indication for every phase of the intersection, phase timing information, crosswalk status, and a movement number, which allows the data to be paired to the physical layout of the intersection described in the MAP message. This data can be used to support intersection-related safety applications. The data that is used to populate this message can be found in NTCIP 1202-compliant traffic signal controller outputs. For this project, SPaT may be used to transmit temporary signal SPaT to the AV.

6.2.2.5 Traveler Information Message (TIM)

TIMs contain advisory information used by vehicle operators. TIMs are sent from the roadside to vehicles, which must subscribe to receive the TIM. The TIM protocol provides the location and situation (e.g. vehicle speed) parameters that must be met for the TIM to be delivered to the vehicle operator. For instance, a TIM that advises a vehicle operator of a speed limit in a designated area would only be displayed to the vehicle operator when approaching the area and if the vehicle operator is traveling above the speed limit within the area. Work Zone Operators must develop the TIM message – the Work Zone Operator may use a program that allows them to input TIM message parameters and generates the TIM message based on those parameters to be broadcast from the roadside. Due to the fact that TIMs vary significantly and have few standards, they may be used to notify the AV of the V2X Work Zone Object locations.

6.2.3 Facilities

The testing will take place at various site locations which contain facilities for staff, storage, and testing purposes. This section will describe the facilities in which the system will directly interact with the system components and users. The resources required to support the facilities can be found in **Section 7.1**.

6.2.3.1 Laboratory Facility

PSU's lab facilities may be used for simulation and research during the project. The labs will be equipped with computers and servers equipped with software required for performing simulation and research activities. The software required to support the project is discussed in **Section 7.4**.

CMU's lab facility may be used for simulation during the project. If the simulation software can be integrated so that CMU may use a remote location, CMU will likely host their computers and servers at their own lab. If the simulation software requires a lower latency to function properly and in a timely manner, CMU's computers will be hosted in the PSU lab facilities.

6.2.3.2 Storage Facilities

The Mapping Van, AV, and traffic control devices will need to be stored at night and during times where testing is not occurring. The storage facilities should have space for the vehicles, traffic control devices, maintenance equipment, and site equipment. The storage facilities must be secured with locks for protection. Storage facilities will be available at LTI, PSU's campus garage, and near construction sites.

6.2.3.3 Test Track Facility

PSU's LTI test track located in Bellefonte, PA, just outside State College, will be used for setting up work zones to be used in both simulation and closed track testing. LTI features a one-mile oval loop with an in-field area that may be used for staging, fueling stations, and offices which may be utilized by the testers.

Figure 11: LTI Overview

SOURCE: PSU

LTI has a perched hillside area that can be used by the test team for overseeing the testing from a safe distance. Although the site is shared by other users, the other users will primarily be operating on the durability course on the opposite side of the oval, out of the way of the testing associated with this project. Work zones may be set up for long-term usage on the track for this project; line stripping may be changed as needed.

LTI does not have the required equipment to set up the work zone and perform line striping setup/removal. PennDOT will be responsible for providing all equipment and services required to set up the work zones.

6.2.3.4 Construction Site Facilities

The construction sites used for testing live on-road environments will have facilities for testing staff. The required items needed for testing are construction trailers, portable toilets (if not in the construction trailers), computers, office furniture, a printer, climate control, utility connections, and secure storage. Additionally, the sites must have a 120V AC pluggable charging station for the Mapping Van. The construction sites need to have an outdoor viewing area near the testing staff to view the testing from a safe distance, which will be identified when live on-road testing sites are selected.

PennDOT and the Contractor will be responsible for providing the facilities at the construction sites. The items that will the responsibility of the Contractor to provide will be identified during the development of the *Deployment Plan*. In order to for the contractor to perform their role, the project items will need to be included in the construction project's plans, specifications,and estimate prior to bidding. Prior to live on-road testing, prospective construction projects will be identified by PennDOT Central Office and Districts. PennDOT Central Office will coordinate with the PennDOT District offices to generate the required construction project documents. Work zone scenarios that are short-term will be identified three to six months before live on-road testing, while long-term work zone scenarios will first be identified during the development of the *Deployment Plan* because they have a longer contracting process.

6.2.4 Physical Security

All project equipment must be physically protected to reduce the chance of theft or unauthorized access. Roadside infrastructure will be located inside locking traffic signal cabinets and RSUs will be mounted high on poles. Project vehicles and traffic control devices will be stored in locking garages and storage containers. PSU labs will be locked and require card keys, codes, or hard keys to facilitate access.

6.2.5 System/Data Security

System and data security is expected to include the network security and the protection of Personally Identifiable Information (PII), which are described in the sections below.

6.2.5.1 Network Security

A network is vulnerable to malicious attacks if not properly protected. Access to the Commonwealth Network, CMU's network, PSU's network, and the DMS servers (collectively referred to as the project networks) have the potential to compromise the operations of all components of the project, and security measures need to be in place to reduce the likelihood of an attack that may disrupt the system. The most common methods by which individuals with malicious intent may be expected to access the project networks include, but are not limited to:

- Through the internet
- Breaking into an equipment cabinet and connecting directly to the network with a personal device
- Severing physical fiber-optic wire and creating a new connection to a personal device
- Accessing the network via wireless communications media (e.g., V2X)

These vulnerabilities can be addressed through a combination of security measures which will include the use of firewalls to prevent unauthorized access through a local network or the internet; physical security in the form of locks, and fiber connectivity alarms; and proper implementation of wireless security protocols. More specific measures may include implementing strong passwords, encryption of data sent across the network, logging and monitoring network traffic, and disabling unused ports and removing unnecessary devices from the network. Proper use of these security measures will minimize the opportunity for individuals with malicious intent to gain access to components connected the project networks.

The project intends to utilize standard industry practice as a foundation for securing the networks, as well as the IT Policies that have been put in place by the Commonwealth Office of Administration. Specifics regarding network security will be developed in the *Data Management Plan* and *Data Privacy Plan* for this project.

6.2.5.2 Protecting PII

The protection of PII is crucial for capturing the trust of system users who wish to maintain their privacy. The primary source of PII in the project is cameras and sensors from the AV and Mapping Van. Both vehicle's camera and sensor sources may have pictures of the people around the closed track and live work zones. These images must be scrubbed of PII before they can be released to the public.

A data strategy (detailed in the *Data Management Plan*) will be implemented to specify how PII will be removed in order to reduce the amount of data scrubbing required, the participants filmed in the closed areas must sign a waiver. Raw data should be treated to preserve anonymity while supporting safety and mobility applications. This could be as simple as removing any identifying features, increasing or decreasing the frequency with which data from a particular area is stored, or aggregating the data spatially and temporally (e.g. averaging across several images) to obfuscate individual users. If it is found that processing of this nature is required to preserve PII, it is expected to be performed within the DMS.

In addition to technical solutions for removing PII, process protections will be in place to protect PII that is stored in the DMS and other locations. Process protections will include an inventory will be taken for locations of where PII data lies, categorization of PII data, and access controls and authentication.

6.2.6 Traffic Control Equipment

6.2.6.1 Traffic Control Devices

The traffic control devices required for the project include barrels, cones, barriers, traffic control signs, sign flashing lights, temporary traffic signals, flagger equipment and arrow boards trailers. At LTI, the traffic control devices will be provided and setup by PennDOT Districts and Counties. In the live environment, the contractor will be responsible for providing the traffic control for the work zone setup. Any additional traffic control equipment that is needed will be procured by PennDOT Central Office. The barrels, cones, barriers, signs, and flagger equipment will be treated with the enhanced coating in some variations of the work zone scenarios.

In lieu of a concrete barrier, a water-filled plastic barrier may be used at LTI in order to make the work zone scenarios easier to set up. If a water-filled plastic barrier is used, its color will be consistent with work zones yet not difficult for the computer perception subsystem to sense. A plain black or plain white plastic barrier may be difficult for the ADS to perceive, so a combination of orange and white plastic barriers is likely to be used.

Traffic control devices of varying conditions will be used in the work zone, ranging from new equipment to equipment that is deteriorated past its usable condition. In existing work zones, traffic control devices may be in a wide range of conditions and, due to budget constraints, many of the devices are of poor quality, past their end of life and however remain in use. Using devices that are of a wide range of quality will allow the team to create conditions that are similar to what an AV would experience in a real work zone.

6.2.6.2 Line Striping

Line striping equipment will be used to deploy paint and bead line striping and line striping containing the enhanced coating in the work zones. Pavement marking removal equipment will be required to restripe the work zone between scenarios. At LTI, District 9-0 may provide the line-striping services for the facility. If District 9-0 is unavailable, another District may be used. If no other districts are available, a vendor would be used to provide line striping. In the live environment, a contractor would be responsible for providing the line-striping services.

Alternatively to the line striping equipment, temporary line striping tape may be used to create the pavement markings.

6.2.6.3 Decommissioned Work Zone Vehicles

For this project, decommissioned work zone vehicles will be provided by PennDOT Districts and Counties to act as shadow vehicles. A shadow vehicle is used in upstream of the work area to protect workers on low-speed roadways. TMAs are required for the shadow vehicle when the work zone is along a freeway or expressway.

In typical work zones in PA, the shadow vehicle can be any vehicle on a conventional roadway as long as it is equipped with a flashing, oscillating, or revolving yellow light which is visible from any direction (360° visibility) and is not being used as a work vehicle. The shadow vehicles will be treated with the enhanced coating in some variations of the work zone scenarios.

6.2.6.4 Automated Truck-Mounted Attenuator

In addition to the static traffic control devices, an Autonomous TMA (ATMA) will be procured for the project to deploy in work zones that require a TMA, particularly the mobile work zone scenario. The ATMA will enable a "leader/follower" operation which will allow the ATMA to follow a human-driven maintenance vehicle. In addition to testing the AV's interaction with TMAs, the ATMA will allow the project team to understand how the automated systems might interact with each other. The ATMA and maintenance vehicle will communicate via V2V communications. The ATMA will be procured and operated by PennDOT Central Office.

6.2.6.5 Other Vehicles

Other vehicles in the work zones will be operated by the owner of the vehicle. The other vehicles will be provided by PSU, PennDOT Central Office, PennDOT Districts, PennDOT counties, and the public. The general public will only be operating vehicles in the live on-road environment. The other vehicles will be made up of a variety of makes and models.

6.2.7 Work Zone Setups and Locations

6.2.7.1 Simulation Testing

The simulation testing will take place at a laboratory on PSU's campus. The exact building will be determined as part of the *Deployment Plan*. Work zone scenarios to be tested in the simulation testing can be found in **Table 7**.

The Simulation System can be programmed to have perfect lane-level accuracy and to always read the lane lines and objects correctly. Therefore, there are some work zone scenario variations that cannot be tested during simulation testing, at least not without noise models for real-world sensors. Specifically, the enhanced coating may not be able to be simulated until after test track trials collect sufficient data to model the coating performance.

The Simulation System also cannot simulate CV communications to update the vehicle map data, at least not without modification. To re-create this effect, the route and map data can be changed dynamically to simulate the vehicle's map data updating when approaching the work zone.

6.2.7.2 Closed-Course Testing

The closed-course testing will take place at LTI's test track. Work zone scenarios to be tested in the closed course testing can be found in **Table 7**.

Several of the work zone scenarios that will be tested will require workarounds to "fake" the setup. For instance, PATA 116-A and 214 are detoured routes, so a fake detour will be created at the track. Several PATAs, like 122 and 205 require three lanes, so options will be explored to temporarily simulate three lanes. Several PATAs require divided highways or on-/off-ramps, which can be simulated with barrier and the track entrances. The options to create these simulated track environments will be explored during the *Deployment Plan* development.

The track allows for speeds of approximately 50 mph on the straight sections and large curve, and approximately 35-40 mph on the smaller curve. The track speeds should allow for sufficient testing of the work zone scenarios.

6.2.7.3 Live On-Road Testing

The live on-road work zones are anticipated to use either active PennDOT or PTC work zones or work zones that are set up with the sole purpose of testing the AV. Work zone scenarios to be tested in the live environment can be found in **Table 7**. The locations of the work zones will be determined during the development of the *Deployment Plan*. The work zone locations will require nearby staging and storage facilities to set up the AV, V2X Work Zone Objects, RSU, and other appropriate equipment for work zone set up.

Since the live environments can be chosen based the work zone scenarios being tested, it is anticipated that all variations of the work zone scenario can be tested in the field.

6.3 Operational Policies and Constraints

Operational policies are pre-determined decisions regarding the operations of each component or sub-component of the system, typically in the form of general decisions or understandings that guide development and decision-making activities. Operational policies inform decisions made in the design of the system. Constraints are impediments outside of policy that restrict the system from achieving its goal with respect to objectives.

Operational policies and constraints listed in **Table 13** have been identified as constraints on the design and implementation of the proposed system.

Table 13: Operational Policies and Constraints of Proposed System

Category	Operational Policies and Constraints
Policy	Pennsylvania has passed a law that allows automated truck-mounted attenuators to be used on public roadways (PA Code, Title 75, Chapter 85, Subchapter B, § 8502).
Policy	Pennsylvania code allows AVs on public roadways given that a safety driver is present (PA Code, Title 75, Chapter 85, Subchapter B, § 8502 and Pennsylvania AV Testing Guidance).
Policy	The municipalities own all traffic signals in the Commonwealth of Pennsylvania. If a work zone is constructed at a signalized intersection, the municipality must be consulted before installing any RSU in the traffic signal controller cabinet.
Policy	Stakeholders managing data have IT and data security policies that must be accommodated when designing, planning, delivering, operating, and controlling the DMS and its data inputs.
Policy	PennDOT has an *AV Incident Response Plan*, which would be used in the event of an incident involving the AV.
Constraint	C-V2X/DSRC interfaces should follow the National ITS Architecture standards for subsystems and interfaces that aren't intentially being modified for research purposes.
Constraint	C-V2X/DSRC devices must be licensed by the FCC.
Constraint	The system architecture that is deployed should meet applicable ITS standards.
Constraint	Testing must be conducted in a manner that does not impact the safety of other road users.
Constraint	There are limited locations that already have CV infrastructure in place for on-road testing.
Constraint	Design constraints and considerations will limit the locations where C-V2X/DSRC RSU may be installed.
Constraint	The effective distance of C-V2X/DSRC coverage will limit where the RSUs may be placed.
Constraint	Work zone setups will come from PennDOT Publication 213.
Constraint	ADS will utilize CMU's already-built AV with limited modifications.

Category	Operational Policies and Constraints
Constraint	The Operational Design Domain of the AV during the course of the project will be the same as the existing Operational Design Domain of the AV.
Constraint	The Mapping Van will utilize PSU's already-built Mapping Van with limited modifications.
Constraint	LTI does not have every roadway element that needs to be tested (i.e. highway on-ramps/off-ramps and roads to create detours).
Constraint	The Simulation System has perfect lane level accuracy.
Constraint	The Mapping Van generates large quantities of data (10+ Gb/s) and cannot process all the data in real time. The data must by physically off loaded by removing the hard drive and processed offline before sending to the DMS.
Constraint	The AV generates large amounts of data and cannot send all of the data back via 4G. The data must be physically off loaded by removing the hard drive and transferred to the DMS.
Constraint	Testing will require day and night testing, therefore staffing resources and track scheduling may be constrained.

Source: PennDOT

7 SUPPORT ENVIRONMENT

This section describes the support concepts and support environment for the proposed system, including the support agency or agencies, facilities, equipment, support software, repair or replacement criteria, maintenance levels and cycles, and storage, distribution, and supply methods. The support environment includes the users, resources, and processes that don't directly interface with the system, but enables the system and operational environment to function.

7.1 Facilities

This section describes the support resources required for the facilities utilized by the project.

7.1.1 Laboratory Facility

The PSU lab will be supported by the PSU Office of Physical Plant which maintains the facility. PSU will be responsible for cleaning and other day-to-day maintenance activities. PSU will be responsible for maintaining the computers and making sure that the computers have access to the internet and the correct software to run the Simulation System. PSU will verify that the simulation team has access to the lab and log-on access to the computers in the lab.

The CMU lab will be supported by the CMU Facilities department which maintains the facility. CMU will be responsible for cleaning and other day-to-day maintenance activities. CMU will be responsible for maintaining the computers and making sure that the computers have access to the internet and the correct software to run the Simulation System. CMU will verify that the simulation team has access to the lab and log-on access to the computers in the lab.

7.1.2 Test Track Facility

LTI is supported by the PSU Facilities department which maintains the facility. The maintenance crew has the ability to perform minor track repair, lawnmowing, gravel brushing/removal, snowplowing and other day-to-day maintenance activities. PSU will facilitate access to LTI for the closed-course testing team.

7.1.3 Construction Site Facilities

The construction site facilities will need to be supported by the contractor of the project. The contractor will be responsible for performing maintenance on the construction trailer, cleaning the facility restrooms, snowplowing access to the facilities, and making sure that the staging and stockpile area is clear for the testing team. The contractor will verify that the team has access to their secured trailer. Supplies and materials that are not able to be provided by the Contractor will be provided by PennDOT.System Architecture Constraints

The architecture of the system will be constrained by the communications, processing power, and standards.

The limitations of the wireless backhaul bandwidth will limit the amount of data that can be transmitted wirelessly. The Mapping Van and AV can generate several GB of data per second, so it will not be feasible to transfer all of the raw data wirelessly. The Mapping Van and AV will have removable hard drives, which will allow data to be transferred to the DMS via the physical backhaul. Some data, such as lane designations and roadside obstacle coordinates, may be able to be transferred wirelessly in real-time to improve the efficiency and allow testing to occur faster. For instance, the lane locations may be able to be streamed off the Mapping Van wirelessly in near real-time, but the raw sensor data will require a physical transfer of the data.

The Mapping Van processing power is limited by the amount of vehicle electrical power that processing consumes. The lane markings can be processed to a certain degree of precision in near real-time. However, further offline processing will allow for a much greater level of precision.

The architecture of the project will follow the Architecture Reference for Cooperative and Intelligent Transportation V9.0 service packages as closely as possible and use standards where applicable. While entire service packages may not be applicable to the project, pieces of service packages may apply. The following service packages are anticipated to be incorporated into the project to some degree:

- DM01 - ITS Data Warehouse
- DM02 - Performance Monitoring
- TM02 - Vehicle-Based Traffic Surveillance
- TM04 - CV Traffic Signal System
- MC07 - Work Zone Safety Monitoring
- SU01 - CV System Monitoring and Management
- SU03 - Data Distribution
- SU04 - Map Management
- SU05 - Location and Time
- SU08 - Security and Credentials Management
- SU09 - Device Certification and Enrollment
- VS01 - AV Safety Systems
- VS16 - AV Operations

Although a Security and Credentials Management System is not anticipated to be used in the project due to the fact that it is out of scope, there may still be an exchange of pre-programmed certificates in order to improve the security of the project. This may or may not be required depending on the V2X Vendor that is chosen for the project.

7.2 Utilities

Utilities will be required to support the equipment and staff at the facilities on the project. The PSU laboratory and LTI will require electric, gas, water, communications, and sewer. Additionally, LTI will require that the on-site gasoline fueling stations be maintained and supplied with gasoline. PSU will be responsible for providing the utilities at the PSU laboratory and LTI.

The construction sites will require electricity and communications capabilities. It is not typical for construction trailers to have water, sewer and gas hooked up, but water bottles and portable restrooms will be supplied. The contractor will be responsible for providing the utility connections at the construction site.

7.3 Equipment

The Mapping Van and V2X devices will require additional equipment to support the subsystems.

The Mapping Van and RSU may require that PennDOT install a new CORS site near State College, PA. PennDOT previously had a CORS site in the area, but it was deactivated several years ago. The new CORS site would improve the accuracy of the Mapping Van and RSU location.

Both the AV and Mapping Van may require updated V2X hardware if standards replacing the deprecated DSRC standards are released and commercial off-the-shelf equipment becomes available.

The V2X devices will require testing equipment to support system testing. Testing equipment will include sniffers, data loggers, testing laptops, and other standard testing equipment. The V2X Vendor will be responsible for providing the equipment.

7.4 Software

CMU is responsible for developing the software for the ADS to operate the AV. Any updates to the ADS software will performed by CMU. CMU is responsible for verifying that the AV software is functioning property and operational.

CMU is responsible for developing the CADRE TROCS software and integrating with the CARLA software. Any software updates to the ADS simulation software will be performed by CMU. CMU is responsible for verifying that the ADS simulation software is functioning property and operational.

PSU is responsible for keeping the traffic simulation software up-to-date and procuring any necessary add-ons required for the simulation. PSU will develop custom modules as needed to create the traffic simulation. PSU is responsible for verifying that the traffic simulation software is functioning property and operational.

PSU is responsible for keeping the Mapping Van software up-to-date. Any software updates to the Mapping Van software will be performed by PSU. PSU is responsible for verifying that the Mapping Van software is functioning property and operational.

PSU will be responsible for obtaining any software required for the final project evaluation. PSU will be responsible for keeping the software up-to-date. PSU plans on using MATLAB, Python, and C++ development tools to perform the final evaluation and for data processing steps. As well, Penn State may temporarily host data on an internal, firewalled PostgreSQL database to facilitate rapid processing and data transfer to the DMS.

Deloitte will be responsible for keeping DMS up-to-date and install any software updates. The Azure platform on which the DMS runs may occasionally be updated and the DMS may require updates in order to remain fully operational. Deloitte will backup data weekly. System status will be monitored by Deloitte to verify that the system is operational.

The V2X Vendor is responsible for keeping RSU software up to date. The V2X Vendor will also be responsible for maintaining any central system software required for the RSUs. The system status will be monitored by the on-site testing team and will notify the V2X Vendor if there are any issues.

PSU and CMU need to have code/data repositories for software development tracking. PSU will use GitHub repositories for version tracking for the Mapping Van. For both the ADS and simulation software, CMU will use internal Linux repositories for version control.

7.5 Personnel

The anticipated number of direct and support staff required for the project can be found in **Table 14**.

Table 14: Personnel Staffing

Description	Anticipated Number Required
System User Staff	
Safety Drivers	• CMU: 1
Safety Associates	• CMU: 1
Simulation Operators	• CMU: 2 • PSU: 2

Description	Anticipated Number Required
Mapping Van Drivers	• PSU: 1
Mapping Equipment Operators	• PSU: 1
Data Manager	• Deloitte: 1
Researchers	• PSU: 2
Work Zone Setup Operators	• PennDOT: 4
Support Staff	
Vehicle Maintenance	• CMU: 1 • PSU: 1
Administrative Staff	• CMU: 1 • PennDOT: 1 • PSU: 1
Software Programming	• Deloitte: 2 • CMU: 2 • PSU: 2
Safety Managers	• PSU: 1 • PennDOT: 1
Site Managers	• CMU: 1 • PennDOT: 1 • PSU: 1

Source: PennDOT

The personnel resources will be organized and scheduled by the stakeholder responsible for providing the staff. Except for researchers, personnel are anticipated to be existing staff, rather than hired specifically for this project.

The hours and number of staff will vary by testing location needs and could be up to 24 hours per day depending on testing rigor. If long durations of testing are required, more staff will be required in order to schedule reasonable shift times.

Any required training will be provided by the stakeholder responsible for providing the staff. The appropriate Staff will be trained on how to use the software, how to operate the AV, how to operate the Mapping Van and equipment, how to use the DMS, and their duties and responsibilities.

7.6 Operating Procedures

The operating procedures to be followed during testing will be developed by CMU as part of the *Deployment Plan*. The testing managers – PSU, CMU, and PennDOT – will be responsible for carrying out the operating procedures during testing.

In order to ensure the safety of the Safety Drivers, the *AV Incident Response Plan* developed by PennDOT will be used to educate emergency responders if an incident were to occur during testing. The AV Incident Response Plan gives instructions to emergency responder on how to properly respond to an incident involving an AV, including how to stop an AV.

Data-handling procedures will be developed by CMU as part of the *Deployment Plan*. Data handling procedures are an important part of ADS simulation and deployment to ensure that simulation data is not mixed with deployment data. If simulation and real-world data is mixed, the ADS may use simulation training data to respond to real-world locations and respond improperly. Policies can be established to avoid such situations; for example, it is common to use Nemo coordinates within the ocean to center simulated roads; thus, there is no possibility that these simulations could be confused for actual road data.

User account setup procedures and DMS management procedures will follow the Office of Administration IT's recommended procedures from the IT Policies[5].

[5] https://www.oa.pa.gov/Policies/Pages/itp.aspx

8 OPERATIONAL SCENARIOS

This section presents scenarios that capture how the system serves the needs of users when the system is operating under various modes of operation. To the extent possible, these use cases only describe external events that pertain to how the AV Work Zone System is expected to benefit system users, and will minimize specifying details regarding the internal workings of the system – scenarios are developed in this fashion to allow for flexibility in the development of requirements and design of the AV Work Zone System (with the exception of constraints provided in **Section 6.3**). The scenarios are grouped into use cases, which correspond to each proposed use case described in **Chapter 3**. Scenarios for each use case describe various modes of operations that are expected: normal operating conditions and degraded and/or failure conditions, as necessary. Each use case is accompanied by a process diagram that represents the exchange of information between processes performed by the devices.

Note: These operational scenarios are not intended to cover each work zone scenario identified in **Table 7**. Each work zone scenario will be tested under various conditions (including connectivity, enhanced coating, daytime/nighttime, and more). All of these work zone scenarios and permutations can be derived from the four primary use cases from the user-oriented perspective. Therefore, there will not be an operational scenario for each work zone scenario or variation.

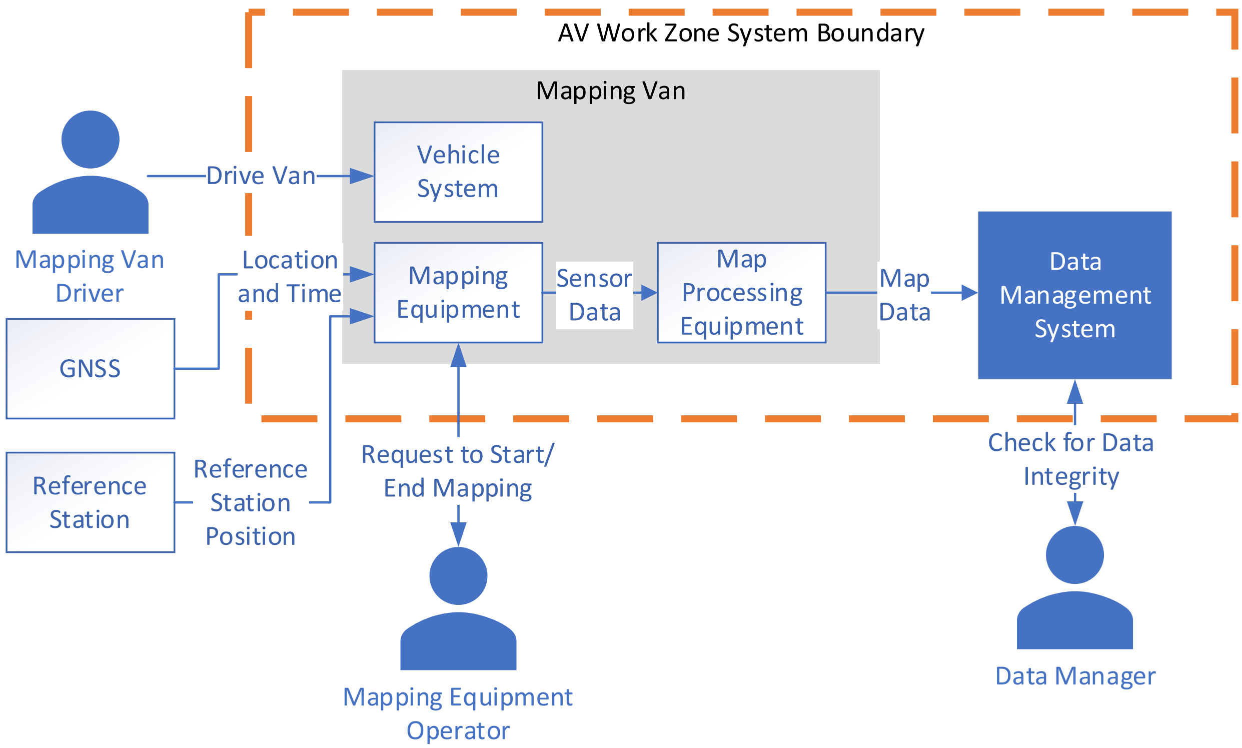
8.1 Use Case 1: Work Zone Mapping

This use case contains scenarios associated with work zone mapping. **Figure 12** provides a context diagram for all scenarios associated with this use case. Scenarios for this use case are listed below and are described in detail in tables following the context diagram.

Use Case 1 scenarios:

- Table 15: UC1-S1 – Normal Operating Conditions
- Table 16: UC1-S2 – Degraded Operating Conditions – Faults Detected
- Table 17: UC1-S3 – Failure Operating Conditions – Sensor Failure

Figure 12: Work Zone Mapping Context Diagram



SOURCE: PENNDOT

Table 15: UC1-S1 – Normal Operating Conditions

<table>
<tr><th>Use Case</th><th colspan="4">Work Zone Mapping</th></tr>
<tr><td>Scenario ID and Title</td><td colspan="4">UC1-S1: Normal Operating Conditions</td></tr>
<tr><td>Scenario Objective</td><td colspan="4">• Map the work zone environment and send the data to the DMS</td></tr>
<tr><td>Operational Event(s)</td><td colspan="4">• Mapping Van Driver navigates the Mapping Van through the work zone multiple times
• Mapping Equipment Operator operates the mapping equipment
• Map data is offloaded, processed and sent to the DMS</td></tr>
<tr><td rowspan="7">Actor(s)</td><td>Actor</td><td colspan="3">Role</td></tr>
<tr><td>Mapping Van</td><td colspan="3">Collects sensor data, performs simple processing</td></tr>
<tr><td>Map Processing Equipment</td><td colspan="3">Processes sensor data offline beyond simple calculations.</td></tr>
<tr><td>Mapping Van Driver</td><td colspan="3">Navigates Mapping Van through the work zone</td></tr>
<tr><td>Mapping Equipment Operator</td><td colspan="3">Communicates with testing staff, verifies that Mapping Van is transmitting data, starts/stops the mapping equipment, and monitors the mapping systems</td></tr>
<tr><td>DMS</td><td colspan="3">Receives data</td></tr>
<tr><td>Data Manager</td><td colspan="3">Reviews data integrity of the data</td></tr>
<tr><td>Pre-conditions</td><td colspan="4">• Mapping Van Driver and Mapping Equipment Operator enter the Mapping Van</td></tr>
<tr><td rowspan="8">Key Actions and Flow of Events</td><td>Actor</td><td>Step</td><td>Key Action</td><td>Comments</td></tr>
<tr><td>Work Zone Operators</td><td>1</td><td>Set up and configure the work zone</td><td></td></tr>
<tr><td>Mapping Van Driver</td><td>2</td><td>Navigates Mapping Van to the starting point of the work zone scenario testing</td><td></td></tr>
<tr><td>Mapping Equipment Operator</td><td>3</td><td>Logs into the Mapping Van equipment, ensures static calibration.</td><td></td></tr>
<tr><td>Mapping Equipment Operator</td><td>4</td><td>Starts mapping equipment, dynamically calibrates the Mapping Van sensors, and verifies that the mapping equipment is transmitting data</td><td></td></tr>
<tr><td>Mapping Equipment Operator</td><td>5</td><td>Notifies the testing team that testing will begin</td><td>Using cellphone or walkie talkie</td></tr>
<tr><td>Mapping Van Driver</td><td>6</td><td>Navigates Mapping Van through the work zone (multiple times)</td><td></td></tr>
<tr><td>Mapping Van</td><td>7</td><td>Processes and stores sensor data</td><td></td></tr>
</table>

Use Case	Work Zone Mapping			
Scenario ID and Title	UC1-S1: Normal Operating Conditions			
	Mapping Equipment Operator	8	Stops mapping equipment	
	Mapping Equipment Operator	9	Notifies testing team that the Mapping Van has completed mapping the work zone	
	Mapping Van Driver	10	Navigates Mapping Van to the staging area and stops the Mapping Van	
	Mapping Equipment Operator	11	Remove the Mapping Van's hard drive and connects to Map Processing Equipment	
	Map Processing Equipment	12	Processes map sensor data	
	Map Processing Equipment	13	Sends raw and processed map and sensor data to the DMS via the upload interface	
	Data Manager	14	Checks the integrity of the data	
Post Conditions	• The DMS has received the map and sensor data			
Policies and Business Rules	• None			
User Needs Traceability	• ADS-UN023-V01 – Data Storage • ADS-UN025-V01 – View Data • ADS-UN031-V01 – DMS Data Ingestion • ADS-UN033-V01 – DMS Data Interface • ADS-UN034-V01 – DMS Secure Access • ADS-UN051-V01 – Conduct Mapping • ADS-UN052-V01 – Mapping Van Operator Audio Communications • ADS-UN054-V01 – Mapping Van Login • ADS-UN055-V01 – Mapping Equipment Data Testing • ADS-UN056-V01 – Mapping Van Sensor Calibration • ADS-UN057-V01 – Mapping Van PII Removal • ADS-UN058-V01 – Mapping Van Data Processing • ADS-UN059-V01 – Mapping Van Data Format • ADS-UN060-V01 – Real-time Mapping • ADS-UN061-V01 – Mapping Van Connectivity • ADS-UN062-V01 – Work Zone Mapping • ADS-UN063-V01 – Mapping Van Time Synchronization • ADS-UN064-V01 – Drive Mapping Van • ADS-UN065-V01 – Mapping Van Driver Audio Communications • ADS-UN066-V01 – Work Zone V2X Configuration • ADS-UN067-V01 – Work Zone Configuration			
Inputs Summary	Human Input: Manual navigation and equipment operation			

Use Case	Work Zone Mapping
Scenario ID and Title	UC1-S1: Normal Operating Conditions
Output Summary	Map and sensor data in the DMS

Source: PennDOT

Table 16: UC1-S2 – Degraded Operating Conditions – Faults Detected

Use Case	Work Zone Mapping			
Scenario ID and Title	UC1-S2: Degraded Operating Conditions – Faults Detected			
Scenario Objective	• Mapping Van detects faults in the sensor data and Mapping Equipment Operator responds appropriately			
Operational Event(s)	• Mapping Van detects faults in the data during live data feeds • Mapping Equipment Operator determines the severity of the faults			
Actor(s)	**Actor**	**Role**		
	Mapping Van	Processes sensor data		
	Map Processing Equipment	Processes sensor data		
	Mapping Van Driver	Navigates Mapping Van through the work zone		
	Mapping Equipment Operator	Communicates with testing staff, verifies that Mapping Van is transmitting data, starts/stops the mapping equipment, and monitors the mapping systems		
	DMS	Receives data		
Pre-conditions	• Work zone has been set up and configured by Work Zone Operators • Mapping Van Driver and Mapping Equipment Operator begin navigating the Mapping Van through the work zone			
Key Actions and Flow of Events	**Actor**	**Step**	**Key Action**	**Comments**
	Mapping Van Driver	1	Navigates Mapping Van through the work zone	
	Mapping Van	2	Processes and stores sensor data	
	Mapping Van	3	Detects faults in sensor data and notifies Mapping Equipment Operator	
	Mapping Equipment Operator	4a	Determines the faults are minor and allows the Mapping Van to continue along the route	
	General	5a	See UC1-S1 steps 7-14	
	Mapping Equipment Operator	4b	Determines the faults are major and notifies the Mapping Van Driver to stop the mapping	
	Mapping Equipment Operator	6b	Stops mapping equipment	
	Mapping Equipment Operator	7b	Notifies testing team that the Mapping Van has stopped mapping the work zone	

Use Case	Work Zone Mapping			
Scenario ID and Title	UC1-S2: Degraded Operating Conditions – Faults Detected			
	Mapping Van Driver	8b	Navigates Mapping Van to the staging area and stops the Mapping Van	
	Mapping Equipment Operator	9b	Remove the Mapping Van's hard drive and connects to Map Processing Equipment	
	Map Processing Equipment	10b	Processes map sensor data	
	Map Processing Equipment	11b	Sends raw and processed map and sensor data to the DMS	
Post Conditions	• The DMS has received the map and sensor data with meta tags about the data quality			
Policies and Business Rules	• None			
User Needs Traceability	• ADS-UN023-V01 – Data Storage • ADS-UN025-V01 – View Data • ADS-UN031-V01 – DMS Data Ingestion • ADS-UN051-V01 – Conduct Mapping • ADS-UN052-V01 – Mapping Van Operator Audio Communications • ADS-UN053-V01 – Mapping Van System Status • ADS-UN054-V01 – Mapping Van Login • ADS-UN055-V01 – Mapping Equipment Data Testing • ADS-UN056-V01 – Mapping Van Sensor Calibration • ADS-UN059-V01 – Mapping Van Data Format • ADS-UN060-V01 – Real-time Mapping • ADS-UN061-V01 – Mapping Van Connectivity • ADS-UN062-V01 – Work Zone Mapping • ADS-UN064-V01 – Drive Mapping Van • ADS-UN065-V01 – Mapping Van Driver Audio Communications			
Inputs Summary	Human Input: Manual navigation and equipment operation			
Output Summary	Map and sensor data in the DMS with meta tags about the data quality			

SOURCE: PENNDOT

Table 17: UC1-S3 – Failure Operating Conditions – Sensor Failure

<table>
<tr><th>Use Case</th><th colspan="4">Work Zone Mapping</th></tr>
<tr><td>Scenario ID and Title</td><td colspan="4">UC1-S3: Failure Operating Conditions – Sensor Failure</td></tr>
<tr><td>Scenario Objective</td><td colspan="4">• Mapping Van detects faults in the sensor data</td></tr>
<tr><td>Operational Event(s)</td><td colspan="4">• Mapping Van detects large-scale equipment failure
• Mapping Van equipment is repaired</td></tr>
<tr><td rowspan="4">Actor(s)</td><td>Actor</td><td colspan="3">Role</td></tr>
<tr><td>Mapping Van</td><td colspan="3">Processes sensor data</td></tr>
<tr><td>Mapping Van Driver</td><td colspan="3">Navigates Mapping Van through the work zone</td></tr>
<tr><td>Mapping Equipment Operator</td><td colspan="3">Communicates with testing staff, verifies that Mapping Van is transmitting data, starts/stops the mapping equipment, and monitors the mapping systems</td></tr>
<tr><td>Pre-conditions</td><td colspan="4">• Work zone has been set up and configured by Work Zone Operators
• Mapping Van Driver and Mapping Equipment Operator begin navigating the Mapping Van through the work zone</td></tr>
<tr><td rowspan="6">Key Actions and Flow of Events</td><td>Actor</td><td>Step</td><td>Key Action</td><td>Comments</td></tr>
<tr><td>Mapping Van Driver</td><td>1</td><td>Navigates Mapping Van through the work zone</td><td></td></tr>
<tr><td>Mapping Van</td><td>2</td><td>Detects that a sensor has failed and notifies Mapping Equipment Operator</td><td></td></tr>
<tr><td>Mapping Equipment Operator</td><td>3</td><td>Stops mapping equipment</td><td></td></tr>
<tr><td>Mapping Equipment Operator</td><td>4</td><td>Notifies testing team that the mapping will be stopped due to equipment failure</td><td></td></tr>
<tr><td>Mapping Van Driver</td><td>5</td><td>Navigates Mapping Van to the staging area and stops the Mapping Van</td><td></td></tr>
<tr><td>Post Conditions</td><td colspan="4">• The Mapping Van sensors are repaired, and the Mapping Van is returned to service</td></tr>
<tr><td>Policies and Business Rules</td><td colspan="4">• None</td></tr>
<tr><td>User Needs Traceability</td><td colspan="4">• ADS-UN051-V01 – Conduct Mapping
• ADS-UN052-V01 – Mapping Van Operator Audio Communications
• ADS-UN053-V01 – Mapping Van System Status
• ADS-UN065-V01 – Mapping Van Driver Audio Communications</td></tr>
<tr><td>Inputs Summary</td><td colspan="4">Human Input: Manual navigation and equipment operation</td></tr>
<tr><td>Output Summary</td><td colspan="4">Record of equipment failure event</td></tr>
</table>

SOURCE: PENNDOT

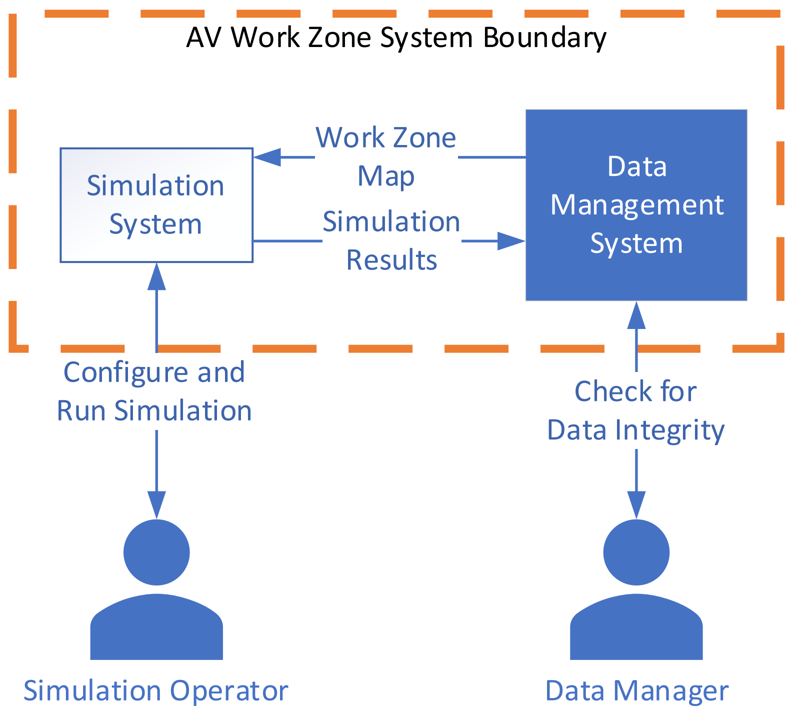
8.2 Use Case 2: Simulation

This use case contains scenarios associated with the ADS simulation. **Figure 13** provides a context diagram for all scenarios associated with this use case. Scenarios for this use case are listed below and are described in detail in tables following the context diagram.

Use Case 2 scenarios:

- Table 18: UC2-S1 – Normal Operating Conditions
- Table 19: UC2-S2 – Degraded Operating Conditions – Faults Detected
- Table 20: UC2-S3 – Failure Operating Conditions – Software Failure

Figure 13: Simulation Context Diagram



SOURCE: PENNDOT

Table 18: UC2-S1 – Normal Operating Conditions

<table>
<tr><th>Use Case</th><th colspan="4">Simulation</th></tr>
<tr><td>Scenario ID and Title</td><td colspan="4">UC2-S1: Normal Operating Conditions</td></tr>
<tr><td>Scenario Objective</td><td colspan="4">• Conduct simulation and record simulation results</td></tr>
<tr><td>Operational Event(s)</td><td colspan="4">• Map data is imported from DMS
• Simulation Operator sets up and runs the simulation
• Results are sent to the DMS</td></tr>
<tr><td rowspan="5">Actor(s)</td><td>Actor</td><td colspan="3">Role</td></tr>
<tr><td>Simulation Operator</td><td colspan="3">Operates the Simulation System</td></tr>
<tr><td>Simulation System</td><td colspan="3">Conducts the simulation</td></tr>
<tr><td>DMS</td><td colspan="3">Receives data</td></tr>
<tr><td>Data Manager</td><td colspan="3">Reviews data integrity of the data</td></tr>
<tr><td>Pre-conditions</td><td colspan="4">• Map data has been generated by the Mapping Van and stored in the DMS</td></tr>
<tr><td rowspan="9">Key Actions and Flow of Events</td><td>Actor</td><td>Step</td><td>Key Action</td><td>Comments</td></tr>
<tr><td>Simulation Operator</td><td>1</td><td>Imports map data from DMS and loads into Simulation System</td><td></td></tr>
<tr><td>Simulation Operator</td><td>2</td><td>Configures work zone within the Simulation System map</td><td></td></tr>
<tr><td>Simulation Operator</td><td>3</td><td>Generates traffic within the Simulation System</td><td></td></tr>
<tr><td>Simulation Operator</td><td>4</td><td>Starts simulation</td><td></td></tr>
<tr><td>Simulation System</td><td>5</td><td>Conducts the simulation and provides live updates to the Simulation Operator of the simulated ADS operations</td><td></td></tr>
<tr><td>Simulation Operator</td><td>6</td><td>After simulation is complete, reviews the results data</td><td></td></tr>
<tr><td>Simulation Operator</td><td>7</td><td>Sends results to DMS</td><td></td></tr>
<tr><td>Data Manager</td><td>8</td><td>Reviews integrity of the data</td><td></td></tr>
<tr><td>Post Conditions</td><td colspan="4">• The DMS has received the simulation results data</td></tr>
<tr><td>Policies and Business Rules</td><td colspan="4">• None</td></tr>
<tr><td>User Needs Traceability</td><td colspan="4">• ADS-UN023-V01 – Data Storage
• ADS-UN025-V01 – View Data
• ADS-UN036-V01 – Simulation Operations
• ADS-UN037-V01 – Simulation Data Import
• ADS-UN038-V01 – Simulation Configuration
• ADS-UN039-V01 – Run Simulation
• ADS-UN040-V01 – Simulation Progress
• ADS-UN041-V01 – View Simulation Results</td></tr>
</table>

Use Case	Simulation
Scenario ID and Title	UC2-S1: Normal Operating Conditions
	• ADS-UN042-V01 – Store Simulation Results • ADS-UN044-V01 – Simulation Performance Data
Inputs Summary	System Initialization Input: Map data and simulation parameters Human Input: Simulation controls
Output Summary	Simulation results data

SOURCE: PENNDOT

Table 19: UC2-S2 – Degraded Operating Conditions – Faults Detected

<table>
<tr><th>Use Case</th><th colspan="4">Simulation</th></tr>
<tr><td>Scenario ID and Title</td><td colspan="4">UC2-S2: Degraded Operating Conditions – Faults Detected</td></tr>
<tr><td>Scenario Objective</td><td colspan="4">• Demonstrate the reaction of the Simulation Operator to elevated fault levels in the system</td></tr>
<tr><td>Operational Event(s)</td><td colspan="4">• Faults are detected as the simulation is conducted
• Simulation Operator responds to the faults detected during the simulation</td></tr>
<tr><td rowspan="5">Actor(s)</td><td>Actor</td><td colspan="3">Role</td></tr>
<tr><td>Simulation Operator</td><td colspan="3">Operates the Simulation System</td></tr>
<tr><td>Simulation System</td><td colspan="3">Conducts the simulation</td></tr>
<tr><td>DMS</td><td colspan="3">Receives data</td></tr>
<tr><td>Data Manager</td><td colspan="3">Reviews data integrity of the data</td></tr>
<tr><td>Pre-conditions</td><td colspan="4">• Map data has been generated by the Mapping Van and imported into the Simulation System
• Simulation has been started by the Simulation Operator</td></tr>
<tr><td rowspan="13">Key Actions and Flow of Events</td><td>Actor</td><td>Step</td><td>Key Action</td><td>Comments</td></tr>
<tr><td>Simulation System</td><td>1</td><td>Simulation has already been started</td><td></td></tr>
<tr><td>Simulation System</td><td>2</td><td>Conducts the simulation and provides live updates to the Simulation Operator of the simulated ADS operations</td><td></td></tr>
<tr><td>Simulation System</td><td>3</td><td>Detects elevated fault levels and notifies the simulation operator</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td>Simulation Operator</td><td>4a</td><td>Determines that the faults are minor and allows the simulation to continue</td><td></td></tr>
<tr><td>General</td><td>5a</td><td>See UC2-S1 steps 6-8</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td>Simulation Operator</td><td>4b</td><td>Determines that the faults are major and stops the simulation</td><td></td></tr>
<tr><td>Simulation Operator</td><td>5b</td><td>After simulation is complete, reviews the results data</td><td></td></tr>
<tr><td>Simulation Operator</td><td>6b</td><td>Sends results to DMS</td><td></td></tr>
<tr><td>Data Manager</td><td>7b</td><td>Reviews integrity of the data</td><td></td></tr>
<tr><td colspan="4" style="display:none"></td></tr>
<tr><td>Post Conditions</td><td colspan="4">• The DMS has received the simulation results data with meta tags about the data quality</td></tr>
<tr><td>Policies and Business Rules</td><td colspan="4">• None</td></tr>
<tr><td>User Needs Traceability</td><td colspan="4">• ADS-UN023-V01 – Data Storage
• ADS-UN025-V01 – View Data</td></tr>
</table>

Use Case	Simulation
Scenario ID and Title	UC2-S2: Degraded Operating Conditions – Faults Detected
	• ADS-UN036-V01 – Simulation Operations • ADS-UN039-V01 – Run Simulation • ADS-UN040-V01 – Simulation Progress • ADS-UN041-V01 – View Simulation Results • ADS-UN042-V01 – Store Simulation Results • ADS-UN043-V01 – Simulation System Status • ADS-UN044-V01 – Simulation Performance Data
Inputs Summary	System Initialization Input: Map data and simulation parameters Human Input: Simulation controls
Output Summary	Simulation results data with meta tags about the data quality

Source: PennDOT

Table 20: UC2-S3 – Failure Operating Conditions – Software Failure

<table>
<tr><th>Use Case</th><th colspan="4">Simulation</th></tr>
<tr><td>Scenario ID and Title</td><td colspan="4">UC2-S3: Failure Operating Conditions – Software Failure</td></tr>
<tr><td>Scenario Objective</td><td colspan="4">• Demonstrate the reaction of the Simulation Operator to software failures</td></tr>
<tr><td>Operational Event(s)</td><td colspan="4">• Simulation System software runs into errors and fails to conduct the simulation
• Simulation Operator determines the cause of the failure and the software support team repairs the software</td></tr>
<tr><td rowspan="4">Actor(s)</td><td>Actor</td><td colspan="3">Role</td></tr>
<tr><td>Simulation Operator</td><td colspan="3">Operates the Simulation System</td></tr>
<tr><td>Simulation System</td><td colspan="3">Attempts to conduct the simulation</td></tr>
<tr><td>Software Support Team</td><td colspan="3">Receives data</td></tr>
<tr><td>Pre-conditions</td><td colspan="4">• Map data has been generated by the Mapping Van and imported into the Simulation System</td></tr>
<tr><td rowspan="9">Key Actions and Flow of Events</td><td>Actor</td><td>Step</td><td>Key Action</td><td>Comments</td></tr>
<tr><td>Simulation Operator</td><td>1</td><td>Starts the simulation</td><td></td></tr>
<tr><td>Simulation System</td><td>2</td><td>Conducts the simulation and provides live updates to the Simulation Operator</td><td></td></tr>
<tr><td>Simulation System</td><td>3</td><td>Detects errors in the program and stops the simulation</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td>Simulation Operator</td><td>4a</td><td>Determines that the errors are minor and restarts the simulation</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td>Simulation Operator</td><td>4b</td><td>Determines that the errors are major and contacts the Software Support Team</td><td></td></tr>
<tr><td>Software Support Team</td><td>5b</td><td>Repairs the Simulation System</td><td></td></tr>
<tr><td>Post Conditions</td><td colspan="4">• The Simulation System software is repaired, and the Simulation System is returned to service</td></tr>
<tr><td>Policies and Business Rules</td><td colspan="4">• None</td></tr>
<tr><td>User Needs Traceability</td><td colspan="4">• ADS-UN036-V01 – Simulation Operations
• ADS-UN039-V01 – Run Simulation
• ADS-UN040-V01 – Simulation Progress
• ADS-UN043-V01 – Simulation System Status</td></tr>
<tr><td>Inputs Summary</td><td colspan="4">System Initialization Input: Map data and simulation parameters
Human Input: Simulation controls</td></tr>
</table>

Use Case	Simulation
Scenario ID and Title	UC2-S3: Failure Operating Conditions – Software Failure
Output Summary	Record of software failure event

Source: PennDOT

8.3 Use Case 3: Work Zone Navigation

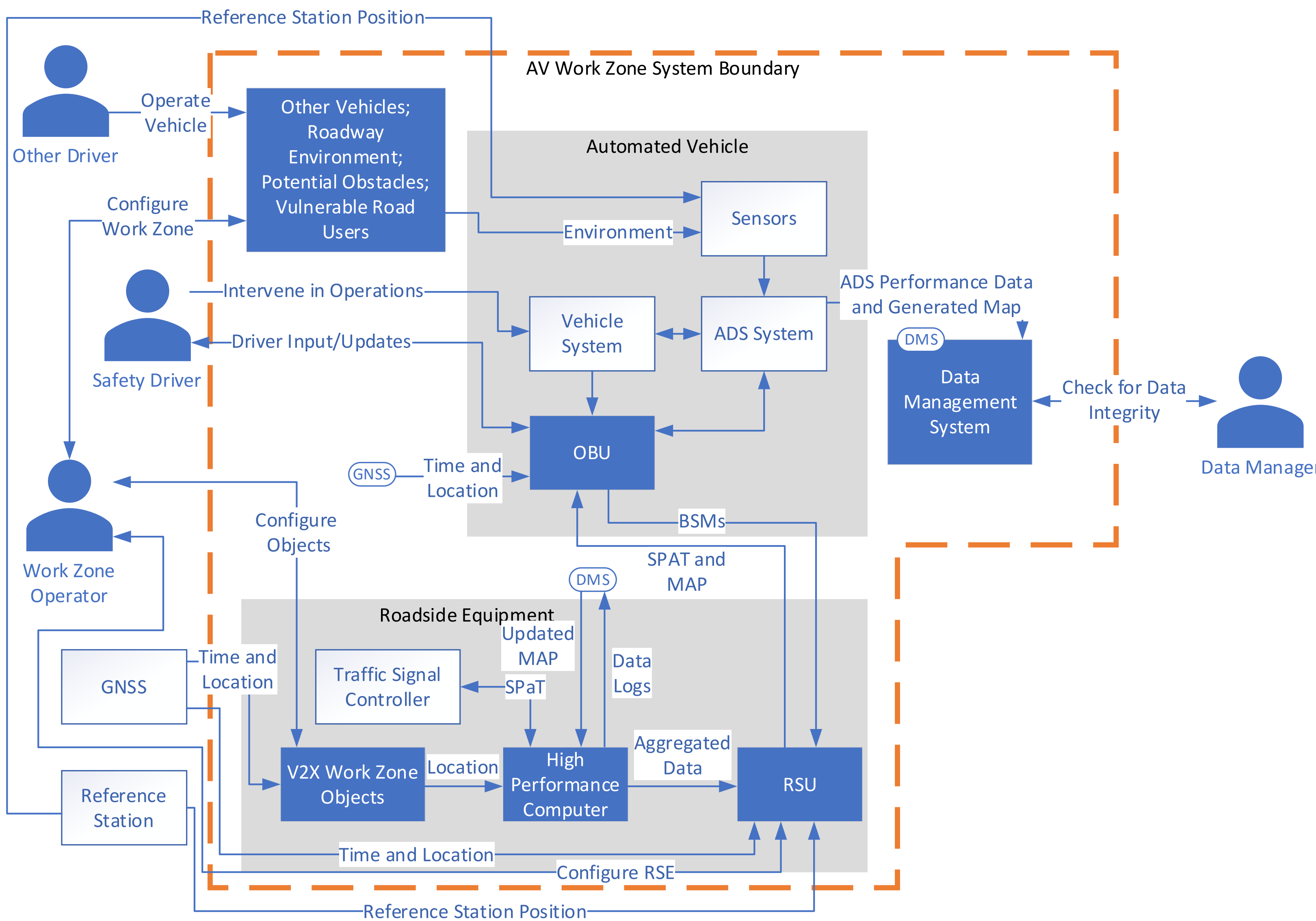
This use case contains scenarios associated with ADS work zone navigation. **Figure 14** and **Figure 15** provide context diagrams for all scenarios associated with this use case. Scenarios for this use case are listed below and are described in detail in tables following the context diagram.

Figure 14 shows the setup including all of the optional variations, including work zone objects and employee vests with V2X communications and the inclusion of RSU. For clarity, **Figure 15** has been included to show this use case without the use of RSU to communicate the map data to the AV, which would be the case of variant work zone scenarios that do not communicate the updated map data for work zones not at intersections.

Use Case 3 scenarios:

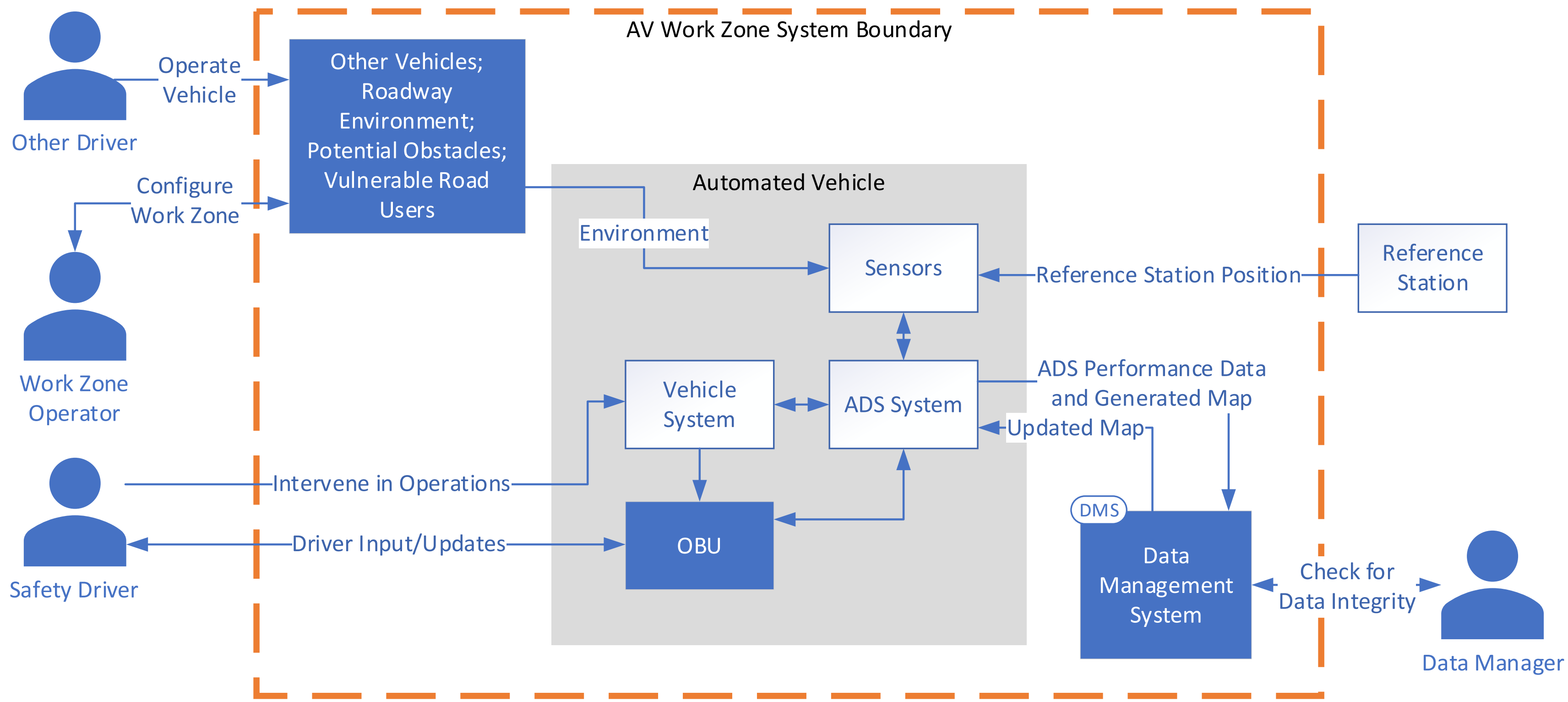
- Table 21: UC3-S1 – Normal Operating Conditions – Basic Work Zone
- Table 22: UC3-S2 – Normal Operating Conditions – Regulatory and Warning Signs and Pavement Markings
- Table 23: UC3-S3 – Normal Operating Conditions – HD Map Update
- Table 24: UC3-S4 – Normal Operating Conditions – V2X Work Zone Object
- Table 25: UC3-S5 – Normal Operating Conditions – Temporary Signal Navigation
- Table 26: UC3-S6 – Normal Operating Conditions – Object Detection
- Table 27: UC3-S7 – Normal Operating Conditions – Avoiding an Incident
- Table 28: UC3-S8 – Degraded Operating Conditions – Uncertainty in Course of Action
- Table 29: UC3-S9 – Degraded Operating Conditions – Equipment Failure
- Table 30: UC3-S10 – Failure Operating Conditions – Object Misdetection

Figure 14: Work Zone Navigation Context Diagram (Variation 1)



SOURCE: PENNDOT

Figure 15: Work Zone Navigation Context Diagram (Variation 2)



SOURCE: PENNDOT

Table 21: UC3-S1 – Normal Operating Conditions – Basic Work Zone

Use Case	Work Zone Navigation			
Scenario ID and Title	UC3-S1: Normal Operating Conditions – Basic Work Zone			
Scenario Objective	• Demonstrate the AV's ability to navigate through a basic work zone			
Operational Event(s)	• AV encounters a work zone and navigates through the work zone • The performance data is recorded for evaluation			
Actor(s)	Actor	Role		
	AV	Navigates through the work zone		
	Safety Driver	Navigates AV to and from the testing area and ensures the AV is operating in a safe manner		
	Safety Associate	Communicates with other testing staff and ensures the AV is operating in a safe manner		
	DMS	Sends and receives project data		
	Data Manager	Reviews data integrity of the data		
Pre-conditions	• Safety Drivers enter the AV • Work zone has been set up and configured by Work Zone Operators			
Key Actions and Flow of Events	Actor	Step	Key Action	Comments
	Safety Driver	1	Calibrates the AV sensors	
	Safety Driver	2	Navigates AV to the starting point of the work zone scenario testing	
	Safety Associate	3	Notifies the testing team that testing will begin	Using cellphone or walkie talkie
	Safety Driver	4	Engages autonomous operations	
	AV	5	Navigates through the work zone	
	Safety Driver	6	Disengages autonomous mode	
	Safety Associate	7	Notifies testing team that the AV has completed navigating the work zone	
	Safety Driver	8	Navigates AV to the staging area and stops the AV	
	AV	9	Sends raw and processed map, sensor, and performance data to the DMS via the upload interface	
	Data Manager	10	Checks the integrity of the data	
Post Conditions	• The DMS has received the map and sensor data			
Policies and Business Rules	• Pennsylvania AV Testing Guidance • PA Code Title 75, § 8502 – Highly Automated Vehicles • PA Code Title 75, § 3326 – Duty of Driver in Construction and Maintenance Areas or on Highway Safety Corridors			

Use Case	Work Zone Navigation
Scenario ID and Title	UC3-S1: Normal Operating Conditions – Basic Work Zone
User Needs Traceability	• ADS-UN001-V01 – Engage AV Operations • ADS-UN002-V01 – Manual AV Operation • ADS-UN005-V01 – AV Operations • ADS-UN008-V01 – AV Mapping Data Generation • ADS-UN009-V01 – AV Data • ADS-UN011-V01 – Law Following – Open Traffic Environment • ADS-UN013-V01 – Law Following – Temporary Traffic Control • ADS-UN016-V01 – AV Audio Communications • ADS-UN019-V01 – Store ADS Results • ADS-UN020-V01 – AV Sensor Calibration • ADS-UN021-V01 – AV PII Removal • ADS-UN022-V01 – AV Data Processing • ADS-UN023-V01 – Data Storage • ADS-UN025-V01 – View Data • ADS-UN033-V01 – DMS Data Interface • ADS-UN034-V01 – Secure Access • ADS-UN035-V01 – DMS Map Data
Inputs Summary	System Initialization Input: AV operating parameters Human Input: AV navigation controls
Output Summary	AV performance and sensor data

SOURCE: PENNDOT

Table 22: UC3-S2 – Normal Operating Conditions – Regulatory and Warning Signs and Pavement Markings

Use Case	Work Zone Navigation			
Scenario ID and Title	UC3-S2: Normal Operating Conditions – Regulatory and Warning Signs and Pavement Markings			
Scenario Objective	• Demonstrate the AV's ability to detect and properly interpret traffic control devices specified in the Manual on Uniform Traffic Control Devices (MUTCD)			
Operational Event(s)	• AV detects and safely responds to roadway signage, including regulatory and warning signs, pavement markings, and temporary traffic control devices			
Actor(s)	Actor	Role		
	AV	Navigates through the work zone		
Pre-conditions	• Work zone has been set up and configured by Work Zone Operators • AV is already in autonomous mode and is approaching the work zone			
Key Actions and Flow of Events	Actor	Step	Key Action	Comments
	AV	1a	Detects a regulatory sign	
	AV	2a	Comprehends sign information	
	AV	3a	Uses information to understand what it must or should do (or not do)	The AV may take a more conservative approach than an expert human driver.
	AV	1b	Detects a warning sign	
	AV	2b	Comprehends sign information	
	AV	3b	Uses information to understand conditions that might call for a reduction of speed or an action in the interest of safety and efficient traffic operations	The AV may take a more conservative approach than an expert human driver.
	AV	1c	Detects a pavement marking	
	AV	2c	Comprehends pavement marking information	
	AV	3c	Uses information to understand pavement and curb boundaries, boundary types, regulation, guidance, and warnings	
	AV	1d	Detects a temporary traffic control device	

Use Case	Work Zone Navigation			
Scenario ID and Title	UC3-S2: Normal Operating Conditions – Regulatory and Warning Signs and Pavement Markings			
	AV	2d	Comprehends temporary traffic control device information	
	AV	3d	Uses information to understand what it must or should do (or not do)	The AV may take a more conservative approach than an expert human driver. Human assistance may also be required under some conditions.
Post Conditions	• The AV continues its route and proceeds safely through the work zone in a lawful manner			
Policies and Business Rules	• PA Code Title 75, § 3111 – Obedience to Traffic-Control Devices • https://mutcd.fhwa.dot.gov/kno_2009r1r2.htm • MUTCD Part 2 – Signs – https://mutcd.fhwa.dot.gov/htm/2009r1r2/part2/part2_toc.htm • MUTCD Part 3 – Markings – https://mutcd.fhwa.dot.gov/htm/2009r1r2/part2/part2_toc.htm • MUTCD Part 6 – Temporary Traffic Control – https://mutcd.fhwa.dot.gov/htm/2009r1r2/part6/part6_toc.htm			
User Needs Traceability	• ADS-UN010-V01 – V2X Work Zone Object Locations • ADS-UN011-V01 – Law Following – Open Traffic Environment • ADS-UN012-V01 – Law Following – Regulatory • ADS-UN013-V01 – Law Following – Temporary Traffic Control			
Inputs Summary	System Initialization Input: Map data and AV operating parameters Human Input: None			
Output Summary	Record of objects detected and decisions made			

SOURCE: PENNDOT

Table 23: UC3-S3 – Normal Operating Conditions – HD Map Update

<table>
<tr><th>Use Case</th><th colspan="4">Work Zone Navigation</th></tr>
<tr><td>Scenario ID and Title</td><td colspan="4">UC3-S3: Normal Operating Conditions – HD Map Update</td></tr>
<tr><td>Scenario Objective</td><td colspan="4">• Demonstrate the AV's ability to navigate through a work zone using an updated HD map via Wide-Area Wireless and V2X</td></tr>
<tr><td>Operational Event(s)</td><td colspan="4">• AV receives updated map via Wide-Area Wireless and V2X and navigates through the work zone</td></tr>
<tr><td rowspan="3">Actor(s)</td><td>Actor</td><td colspan="3">Role</td></tr>
<tr><td>AV</td><td colspan="3">Navigates through the work zone</td></tr>
<tr><td>DMS</td><td colspan="3">Sends and receives project data</td></tr>
<tr><td>Pre-conditions</td><td colspan="4">• Work zone has been set up and configured by Work Zone Operators
• Mapping Van has mapped the work zone and data has been stored in the DMS
• AV is already in autonomous mode and is approaching the work zone</td></tr>
<tr><td rowspan="14">Key Actions and Flow of Events</td><td>Actor</td><td>Step</td><td>Key Action</td><td>Comments</td></tr>
<tr><td>AV</td><td>1</td><td>Approaches the work zone</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td>AV</td><td>2a</td><td>Requests updated map from the DMS via Wide-Area Wireless</td><td></td></tr>
<tr><td>DMS</td><td>3a</td><td>Sends updated map to the AV</td><td></td></tr>
<tr><td>AV</td><td>4a</td><td>Receives updated map</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td>RSU</td><td>2b</td><td>Broadcasts updated map</td><td></td></tr>
<tr><td>AV</td><td>3b</td><td>Receives updated map</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td>AV</td><td>5</td><td>Updates internal map</td><td></td></tr>
<tr><td>AV</td><td>6</td><td>Updates route</td><td></td></tr>
<tr><td>AV</td><td>7</td><td>Continues its route and navigates safely through the work zone</td><td></td></tr>
<tr><td>Post Conditions</td><td colspan="4">• The AV continues its route and proceeds safely through the work zone</td></tr>
<tr><td>Policies and Business Rules</td><td colspan="4">• None</td></tr>
<tr><td>User Needs Traceability</td><td colspan="4">• ADS-UN007-V01 – AV Map Import</td></tr>
<tr><td>Inputs Summary</td><td colspan="4">System Initialization Input: Map data and AV operating parameters
Human Input: None</td></tr>
<tr><td>Output Summary</td><td colspan="4">Record of decisions made</td></tr>
</table>

SOURCE: PENNDOT

Table 24: UC3-S4 – Normal Operating Conditions – V2X Work Zone Object

<table>
<tr><th>Use Case</th><th colspan="4">Work Zone Navigation</th></tr>
<tr><td>Scenario ID and Title</td><td colspan="4">UC3-S4: Normal Operating Conditions – V2X Work Zone Object</td></tr>
<tr><td>Scenario Objective</td><td colspan="4">• Demonstrate the AV’s ability to navigate through a work zone using an updated HD map via V2X</td></tr>
<tr><td>Operational Event(s)</td><td colspan="4">• AV receives updated map via V2X and navigates through the work zone</td></tr>
<tr><td rowspan="3">Actor(s)</td><td>Actor</td><td colspan="3">Role</td></tr>
<tr><td>AV</td><td colspan="3">Navigates through the work zone</td></tr>
<tr><td>V2X Work Zone Object</td><td colspan="3">Broadcasts device location</td></tr>
<tr><td>Pre-conditions</td><td colspan="4">• Work zone has been set up and configured by Work Zone Operators
• Mapping Van has mapped the work zone and data has been stored in the DMS
• AV is already in autonomous mode and is approaching the work zone</td></tr>
<tr><td rowspan="7">Key Actions and Flow of Events</td><td>Actor</td><td>Step</td><td>Key Action</td><td>Comments</td></tr>
<tr><td>AV</td><td>1</td><td>Approaches the work zone</td><td></td></tr>
<tr><td>V2X Work Zone Object</td><td>2</td><td>Broadcasts device location</td><td></td></tr>
<tr><td>AV</td><td>3</td><td>Receives V2X Work Zone Object device location</td><td></td></tr>
<tr><td>AV</td><td>4</td><td>Updates internal map</td><td></td></tr>
<tr><td>AV</td><td>5</td><td>Updates route</td><td></td></tr>
<tr><td>AV</td><td>6</td><td>Continues its route and navigates safely through the work zone</td><td></td></tr>
<tr><td>Post Conditions</td><td colspan="4">• The AV continues its route and proceeds safely through the work zone</td></tr>
<tr><td>Policies and Business Rules</td><td colspan="4">• None</td></tr>
<tr><td>User Needs Traceability</td><td colspan="4">• ADS-UN010-V01 – V2X Work Zone Object Locations
• ADS-UN073-V01 – V2X Work Zone Object Time Synchronization
• ADS-UN074-V01 – V2X Work Zone Object Position Correction</td></tr>
<tr><td>Inputs Summary</td><td colspan="4">System Initialization Input: Map data and AV operating parameters
Human Input: None</td></tr>
<tr><td>Output Summary</td><td colspan="4">Record of decisions made, V2X data received by the AV</td></tr>
</table>

SOURCE: PENNDOT

Table 25: UC3-S5 – Normal Operating Conditions – Temporary Signal Navigation

<table>
<tr><th>Use Case</th><th colspan="4">Work Zone Navigation</th></tr>
<tr><td>Scenario ID and Title</td><td colspan="4">UC3-S5: Normal Operating Conditions – Temporary Signal Navigation</td></tr>
<tr><td>Scenario Objective</td><td colspan="4">• Demonstrate the AV's ability to navigate through a work zone that utilizes a temporary traffic signal</td></tr>
<tr><td>Operational Event(s)</td><td colspan="4">• AV approaches a temporary signal and navigates through safely</td></tr>
<tr><td rowspan="3">Actor(s)</td><td>Actor</td><td colspan="3">Role</td></tr>
<tr><td>AV</td><td colspan="3">Navigates through the work zone</td></tr>
<tr><td>RSU</td><td colspan="3">Broadcasts SPaT and MAP</td></tr>
<tr><td>Pre-conditions</td><td colspan="4">• Work zone has been set up and configured by Work Zone Operators
• AV is already in autonomous mode and is approaching the work zone</td></tr>
<tr><td rowspan="7">Key Actions and Flow of Events</td><td>Actor</td><td>Step</td><td>Key Action</td><td>Comments</td></tr>
<tr><td>AV</td><td>1</td><td>Approaches the work zone</td><td></td></tr>
<tr><td>RSU</td><td>2</td><td>Broadcasts SPaT and MAP of the temporary signal location</td><td></td></tr>
<tr><td>AV</td><td>3</td><td>Detects that the AV is on a signalized approach</td><td></td></tr>
<tr><td>AV</td><td>4</td><td>Detects the signal state of the AV's approach</td><td></td></tr>
<tr><td>AV</td><td>5</td><td>Responds appropriately</td><td>Stopping if red, continuing through if green, and determining whether to continue at current speed or stop if yellow</td></tr>
<tr><td>AV</td><td>6</td><td>Safely proceeds through the intersection and continues on its route</td><td></td></tr>
<tr><td>Post Conditions</td><td colspan="4">• The AV continues its route and proceeds safely through the work zone</td></tr>
<tr><td>Policies and Business Rules</td><td colspan="4">• PA Code Title 75, § 3112 – Traffic-Control Signals</td></tr>
<tr><td>User Needs Traceability</td><td colspan="4">• ADS-UN013-V01 – Law Following – Temporary Traffic Control
• ADS-UN014-V01 – AV Time Synchronization
• ADS-UN015-V01 – AV Positioning
• ADS-UN070-V01 – RSU Time Synchronization
• ADS-UN071-V01 – RSU Position Correction
• ADS-UN072-V01 – RSU SPaT and MAP</td></tr>
<tr><td>Inputs Summary</td><td colspan="4">System Initialization Input: Right-of-way rules and hierarchy to be programmed into AV in compliance with US laws, regulations, and normal travel behavior
Human Input: None</td></tr>
<tr><td>Output Summary</td><td colspan="4">Record of decisions made</td></tr>
</table>

SOURCE: PENNDOT

Table 26: UC3-S6 – Normal Operating Conditions – Object Detection

Use Case	Work Zone Navigation			
Scenario ID and Title	UC3-S6: Normal Operating Conditions – Object Detection			
Scenario Objective	• Demonstrate the AV's ability to detect an object in the roadway and pass			
Operational Event(s)	• AV approaches an object, determines whether it can be driven over or needs to be passed, and proceeds when safe			
Actor(s)	Actor	Role		
	AV	Detect object in the roadway, safely go around the object		
Pre-conditions	• Work zone has been set up and configured by Work Zone Operators • AV is already in autonomous mode and is approaching the work zone			
Key Actions and Flow of Events	Actor	Step	Key Action	Comments
	AV	1	Approaches an object in its path	
	AV	2	Detects the object	
	AV	3a	Determines that object is obstructing the AV's path, but it can be passed without leaving the AV's current lane of travel	Could be a stopped vehicle or construction equipment partially on the curb, or a small object such as a cone or animal
	AV	4a	Maneuvers within its lane of travel around the object	
	AV	5a	Continues along route	
	AV	3b	Determines that the object is obstructing the AV's path, and that it can be passed but only by encroaching into another lane of traffic	Could be a stopped vehicle, construction equipment, large animal, or a cone or flashing arrow signifying the lane is closed
	AV	4b	Detects that it can safely pass the object without affecting traffic in the other lane	
	AV	5b	Passes the object using the other lane of traffic	
	AV	6b	Continues along route	
Post Conditions	• The AV continues its route and proceeds safely through the work zone			
Policies and Business Rules	• PA Code Title 75, § 3303 – Overtaking Vehicle on the Left			
User Needs Traceability	• ADS-UN011-V01 – Law Following – Open Traffic Environment			

Use Case	Work Zone Navigation
Scenario ID and Title	UC3-S6: Normal Operating Conditions – Object Detection
Inputs Summary	System Initialization Input: Program how to identify objects and whether they need to be passed and whether they can be driven over, as well as the laws on passing and how to determine it is safe Human Input: May require driver to disengage AV and intervene in operations.
Output Summary	Record of decisions made

Source: PennDOT

Table 27: UC3-S7 – Normal Operating Conditions – Avoiding an Incident

<table>
<tr><th>Use Case</th><th colspan="4">Work Zone Navigation</th></tr>
<tr><td>Scenario ID and Title</td><td colspan="4">UC3-S7: Normal Operating Conditions – Avoiding an Incident</td></tr>
<tr><td>Scenario Objective</td><td colspan="4">• Demonstrate the AV’s ability to detect intersection type, traffic conditions, assess right-of-way, and complete a movement through an intersection</td></tr>
<tr><td>Operational Event(s)</td><td colspan="4">• AV approaches an intersection and navigates through safely</td></tr>
<tr><td rowspan="6">Actor(s)</td><td>Actor</td><td colspan="3">Role</td></tr>
<tr><td>AV</td><td colspan="3">Detect an imminent crash situation and brake if necessary</td></tr>
<tr><td>First Responder</td><td colspan="3">Responds to incident</td></tr>
<tr><td>Safety Driver</td><td colspan="3">Investigates cause of crash and near-miss events</td></tr>
<tr><td>Safety Associate</td><td colspan="3">Communicates with other testing staff</td></tr>
<tr><td>Testing Manager</td><td colspan="3">Notifies public safety officials, responds to scene, and restores service if a crash occurs</td></tr>
<tr><td>Pre-conditions</td><td colspan="4">• Work zone has been set up and configured by Work Zone Operators
• AV is already in autonomous mode and is approaching the work zone</td></tr>
<tr><td rowspan="10">Key Actions and Flow of Events</td><td>Actor</td><td>Step</td><td>Key Action</td><td>Comments</td></tr>
<tr><td>AV</td><td>1a</td><td>Detects that it has lost control on the roadway</td><td></td></tr>
<tr><td>AV</td><td>1b</td><td>Detects that its path and the path of another vehicle will result in a side impact crash</td><td></td></tr>
<tr><td>AV</td><td>1c</td><td>Detects that its path and the path of another vehicle will result in a head-on crash</td><td></td></tr>
<tr><td>AV</td><td>1d</td><td>Detects that its path and the path of another vehicle will result in a rear-end crash</td><td></td></tr>
<tr><td>AV</td><td>1e</td><td>Detects that its path will result in a road departure</td><td></td></tr>
<tr><td>AV</td><td>1f</td><td>Detects that its path and the path of a pedestrian will result in a crash</td><td></td></tr>
<tr><td>AV</td><td>1g</td><td>Detects that its path and the path of a bicyclist will result in crash</td><td></td></tr>
<tr><td>AV</td><td>2</td><td>Immediately decreases speed and/or stops. Swerving may also be necessary to avoid obstacles in some circumstances.</td><td>In an attempt to avoid or minimize the impact of a potential crash</td></tr>
<tr><td>AV</td><td>3</td><td>Notifies Safety Driver that they should take control of the vehicle</td><td>The Safety Driver will proactively intervene and not wait for the</td></tr>
</table>

Use Case	Work Zone Navigation			
Scenario ID and Title	UC3-S7: Normal Operating Conditions – Avoiding an Incident			
				vehicle's notification
	AV	4a	Avoids the crash situation	
	AV	5a	Reports the near-incident situation	The Safety Driver takeover will be recorded
	AV	6a	Continues on its route	
	Safety Driver	7a	Assesses what led to the near-crash situation	AV may be out of service during investigation
	AV	4b	Gets into a crash	
	AV	5b	Immediately comes to a stop	
	Safety Associate	6b	Notifies AV testing team that a crash has occurred	
	Testing Manager	7b	Dispatches first responders and other pertinent personnel to the crash scene	
	Testing Manager	8b	Makes plans to restore service	AV may be out of service during crash investigation and repairs
Post Conditions	• AV is taken out of service, either because it is physically disabled and needs to be repaired or in order to update its software to avoid other crashes and near-misses in the future			
Policies and Business Rules	• PA Code Title 75, § 3747 – Written Report of Accident by Driver or Owner • *AV Incident Response Plan*			
User Needs Traceability	• ADS-UN002-V01 – Manual AV Operation • ADS-UN003-V01 – AV Control Notification • ADS-UN004-V01 – Driver Disengagement Monitoring • ADS-UN005-V01 – AV Operations • ADS-UN006-V01 – AV Disengagement • ADS-UN009-V01 – AV Data • ADS-UN016-V01 – AV Audio Communications • ADS-UN017-V01 – Associate Disengagement Monitoring			
Inputs Summary	System Initialization Input: Fall back and other response protocol to be programmed into AV Human Input: None			
Output Summary	Record of crashes, near-misses, and decisions made			

SOURCE: PENNDOT

Table 28: UC3-S8 – Degraded Operating Conditions – Uncertainty in Course of Action

Use Case	**Work Zone Navigation**			
Scenario ID and Title	UC3-S8: Degraded Operating Conditions – Uncertainty in Course of Action			
Scenario Objective	• Demonstrate the AV's ability to exercise caution when there is uncertainty in the detection or interpretation of a traffic control device. May occur when work zone traffic control objects have been moved and there are significant differences between the vehicle's updated internal map and the presented work zone traffic control.			
Operational Event(s)	• The AV encounters a situation it does not understand and alerts the Safety Driver to determine whether the situation is unusual and something the AV has not been programmed to understand or whether there is a maintenance issue with the AV. • The Vehicle Support Staff can then work to fix the AV or program in additional scenarios to avoid the same situation in the future.			
Actor(s)	Actor	Role		
	AV	Safely navigate roadways and understand when it is not fully able to operate normally, alert the Safety Driver and move to fall back state in the event of abnormal conditions		
	Safety Driver	Respond to messages from AV and understand issues AV is having		
Pre-conditions	• Work zone has been set up and configured by Work Zone Operators • AV is already in autonomous mode and is approaching the work zone			
Key Actions and Flow of Events	Actor	Step	Key Action	Comments
	AV	1	Detects traffic control device	Such as a human controlling traffic, a traffic signal, or a regulatory sign
	AV	2	Is not certain of its interpretation of this traffic control device	
	AV	3	Decreases speed	In an attempt to properly interpret traffic control device
	AV	4	Notifies Safety Driver that it has encountered an issue	
	AV	5a	Resumes certain interpretation of traffic control devices	
	AV	6a	Continues along route at nominal speed	
	AV	5b	Continues to not be certain of its interpretation of traffic control devices	

Use Case	Work Zone Navigation			
Scenario ID and Title	UC3-S8: Degraded Operating Conditions – Uncertainty in Course of Action			
	AV	6b	Comes to a complete stop	
	Safety Driver	7b	Manually navigate around the object	
	AV	8b	Continues along route	
Post Conditions	• AV safely avoided an incident by returning to its fall back condition until issues could be resolved. Issues are now resolved and the AV can return to normal operations.			
Policies and Business Rules	• None			
User Needs Traceability	• ADS-UN002-V01 – Manual AV Operation • ADS-UN003-V01 – AV Control Notification • ADS-UN004-V01 – Driver Disengagement Monitoring • ADS-UN005-V01 – AV Operations • ADS-UN006-V01 – AV Disengagement • ADS-UN013-V01 – Law Following – Temporary Traffic Control • ADS-UN017-V01 – Associate Disengagement Monitoring • ADS-UN018-V01 – AV System Status			
Inputs Summary	System Initialization Input: Fall back response must be programmed into AV at time of configuration Human Input: Operations staff must intervene and work to determine the cause of the error in order to resolve and allow the AV to return to autonomous operations			
Output Summary	Record of incident and AV's response			

Source: PennDOT

Table 29: UC3-S9 – Degraded Operating Conditions – Equipment Failure

Use Case	Work Zone Navigation			
Scenario ID and Title	UC3-S9: Degraded Operating Conditions – Equipment Failure			
Scenario Objective	• Demonstrate the AV's ability to react to a testing scenario given equipment has failed but is still able to complete the work zone.			
Operational Event(s)	• A V2X Work Zone Object stops transmitting its location • The AV encounters the obstacle and reacts to the situation • The Work Zone Operator fixes the V2X Work Zone Object.			
Actor(s)	**Actor**	**Role**		
	AV	Safely navigate roadways and understand when it is not fully able to operate normally, alert the Safety Driver and move to fall back state in the event of abnormal conditions		
	Safety Driver	Respond to messages from AV and understand issues AV is having		
	Work Zone Operator	Monitors status of V2X Work Zone Object and repairs equipment		
	V2X Work Zone Object	Fails to transmit its location		
Pre-conditions	• Work zone has been set up and configured by Work Zone Operators • AV is already in autonomous mode and is approaching the work zone			
Key Actions and Flow of Events	**Actor**	**Step**	**Key Action**	**Comments**
	V2X Work Zone Object	1	Fails to transmit its location due to internal error	
	AV	2	Detects traffic control device	
	AV	3a	Is certain of its interpretation of traffic control devices	
	AV	4a	Continues along route	
	AV	3b	Is uncertain of its interpretation of traffic control devices	
	AV	4b	Comes to a complete stop	
	Safety Driver	5b	Manually navigate around the object	
	AV	6b	Continues along route	
	Work Zone Operator	7	Reviews status of the V2X Work Zone Objects and determines a device is not working	
	Work Zone Operator	8	Repairs and reconfigures device and returns to service	

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Use Case	Work Zone Navigation
Scenario ID and Title	UC3-S9: Degraded Operating Conditions – Equipment Failure
Post Conditions	• AV safely avoided an incident by returning to its fall back condition until issues could be resolved. Issues are now resolved, and the AV can return to normal operations.
Policies and Business Rules	• None
User Needs Traceability	• ADS-UN002-V01 – Manual AV Operation • ADS-UN003-V01 – AV Control Notification • ADS-UN004-V01 – Driver Disengagement Monitoring • ADS-UN005-V01 – AV Operations • ADS-UN006-V01 – AV Disengagement • ADS-UN013-V01 – Law Following – Temporary Traffic Control • ADS-UN017-V01 – Associate Disengagement Monitoring • ADS-UN018-V01 – AV System Status • ADS-UN066-V01 – Work Zone V2X Configuration • ADS-UN068-V01 – Work Zone Equipment Monitoring • ADS-UN069-V01 – Work Zone Equipment Service Restoration
Inputs Summary	System Initialization Input: Fall back response must be programmed into AV at time of configuration Human Input: Operations staff must intervene and work to determine the cause of the error in order to resolve and allow the AV to return to autonomous operations
Output Summary	Record of incident and AV's response

SOURCE: PENNDOT

Table 30: UC3-S10 – Failure Operating Conditions – Object Misdetection

Use Case	**Work Zone Navigation**			
Scenario ID and Title	UC3-S10: Failure Operating Conditions – Object Misdetection			
Scenario Objective	• Demonstrate consequence of not detecting objects in the roadway environment, and to report an incident once it occurs			
Operational Event(s)	• The AV drives into an object that it does not detect			
Actor(s)	Actor	Role		
	AV	Detect and properly respond to an object in the roadway		
	Safety Driver	Attempt to intervene before object is struck		
Pre-conditions	• Work zone has been set up and configured by Work Zone Operators • AV is already in autonomous mode and is approaching the work zone			
Key Actions and Flow of Events	Actor	Step	Key Action	Comments
	AV	1	Approaches an object in its path	Could be a vehicle or an object
	AV	2	Does not detects the object	
	AV	3	Strikes the object	
	General	4	See UC3-S8 steps 3b-7b	
Post Conditions	• AV has crashed into an object and Safety Driver must notify the Testing Manager to form a plan on how to proceed			
Policies and Business Rules	• PA Code Title 75, § 3747 – Written Report of Accident by Driver or Owner • *PennDOT AV Incident Response Plan*			
User Needs Traceability	• ADS-UN011-V01 – Law Following – Open Traffic Environment			
Inputs Summary	System Initialization Input: Same as Normal Operating Scenario, but in this case the input was not sufficient Human Input: Assist the AV in recovering from the incident			
Output Summary	Record of incident and decisions made			

SOURCE: PENNDOT

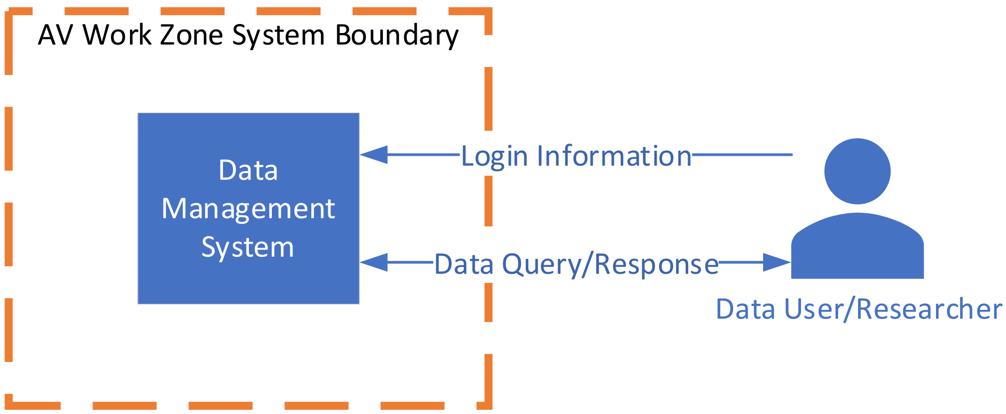
8.4 Use Case 4: DMS Data Retrieval

This use case contains scenarios associated with DMS data retrieval. **Figure 16** provides a context diagram for all scenarios associated with this use case. Scenarios for this use case are listed below and are described in detail in tables following the context diagram.

Use Case 4 scenarios:

- Table 31: UC4-S1 – Normal Operating Conditions
- Table 32: UC4-S2 – Normal Operating Conditions – WZDx Data Feed
- Table 33: UC4-S3 – Normal Operating Conditions – Access Denied

Figure 16: DMS Data Retrieval Context Diagram



SOURCE: PENNDOT

Table 31: UC4-S1 – Normal Operating Conditions

<table>
<tr><th>Use Case</th><th colspan="4">DMS Data Retrieval</th></tr>
<tr><td>Scenario ID and Title</td><td colspan="4">UC4-S1: Normal Operating Conditions</td></tr>
<tr><td>Scenario Objective</td><td colspan="4">• Demonstrate the DMS’s ability to return data to the user</td></tr>
<tr><td>Operational Event(s)</td><td colspan="4">• Data User/Researcher requests data from the DMS
• DMS returns data to the user</td></tr>
<tr><td rowspan="3">Actor(s)</td><td>Actor</td><td colspan="3">Role</td></tr>
<tr><td>Data User/Researcher</td><td colspan="3">Requests data from the DMS</td></tr>
<tr><td>DMS</td><td colspan="3">Processes request and provides data to the user</td></tr>
<tr><td>Pre-conditions</td><td colspan="4">• Data has been stored in the DMS
• Data User/Research has an authorized account for the DMS</td></tr>
<tr><td rowspan="5">Key Actions and Flow of Events</td><td>Actor</td><td>Step</td><td>Key Action</td><td>Comments</td></tr>
<tr><td>Data User/Researcher</td><td>1</td><td>Logs into DMS</td><td></td></tr>
<tr><td>Data User/Researcher</td><td>2</td><td>Enters data query</td><td></td></tr>
<tr><td>DMS</td><td>3</td><td>Validates and processes query and returns data</td><td></td></tr>
<tr><td>Data User/Researcher</td><td>4</td><td>Exports data</td><td></td></tr>
<tr><td>Post Conditions</td><td colspan="4">• User retains data to be used in offline processing</td></tr>
<tr><td>Policies and Business Rules</td><td colspan="4">• Office of Administration IT Policies</td></tr>
<tr><td>User Needs Traceability</td><td colspan="4">• ADS-UN045-V01 – Access System Data
• ADS-UN047-V01 – Data Export
• ADS-UN048-V01 – Data Query</td></tr>
<tr><td>Inputs Summary</td><td colspan="4">System Initialization Input: DMS data collected from project subsystems
Human Inputs: Data query request</td></tr>
<tr><td>Output Summary</td><td colspan="4">Queried data</td></tr>
</table>

SOURCE: PENNDOT

Table 32: UC4-S2 – Normal Operating Conditions – WZDx Data Feed

<table>
<tr><th>Use Case</th><th colspan="4">DMS Data Retrieval</th></tr>
<tr><td>Scenario ID and Title</td><td colspan="4">UC4-S2: Normal Operating Conditions</td></tr>
<tr><td>Scenario Objective</td><td colspan="4">• Demonstrate the DMS’s ability to publish data feeds and convert data into WZDx format</td></tr>
<tr><td>Operational Event(s)</td><td colspan="4">• Data User/Researcher subscribes to WZDx data feed</td></tr>
<tr><td rowspan="3">Actor(s)</td><td>Actor</td><td colspan="3">Role</td></tr>
<tr><td>Data User/Researcher</td><td colspan="3">Requests data from the DMS</td></tr>
<tr><td>DMS</td><td colspan="3">Processes request and provides data feed to user</td></tr>
<tr><td>Pre-conditions</td><td colspan="4">• Data has been stored in the DMS
• User has logged into the DMS</td></tr>
<tr><td rowspan="4">Key Actions and Flow of Events</td><td>Actor</td><td>Step</td><td>Key Action</td><td>Comments</td></tr>
<tr><td>Data User/Researcher</td><td>1</td><td>Requests subscription to WZDx data feed</td><td></td></tr>
<tr><td>DMS</td><td>2</td><td>Validates and processes request</td><td></td></tr>
<tr><td>DMS</td><td>3</td><td>Provides WZDx data feed</td><td></td></tr>
<tr><td>Post Conditions</td><td colspan="4">• User receives WZDx data</td></tr>
<tr><td>Policies and Business Rules</td><td colspan="4">• Office of Administration IT Policies</td></tr>
<tr><td>User Needs Traceability</td><td colspan="4">• ADS-UN032-V01 – WZDx Data Format
• ADS-UN049-V01 – Data Feeds</td></tr>
<tr><td>Inputs Summary</td><td colspan="4">System Initialization Input: DMS data collected from project subsystems
Human Inputs: Data query request</td></tr>
<tr><td>Output Summary</td><td colspan="4">Queried data</td></tr>
</table>

Source: PennDOT

Table 33: UC4-S3 – Normal Operating Conditions – Access Denied

Use Case	DMS Data Retrieval			
Scenario ID and Title	UC4-S3: Normal Operating Conditions – Access Denied			
Scenario Objective	• Demonstrate the DMS's ability to deny data based on the user's role			
Operational Event(s)	• Data User/Researcher requests data from the DMS • DMS denies access to data outside user's role			
Actor(s)	Actor	Role		
	Data User/Researcher	Requests data from the DMS		
	DMS	Processes request and denies data to the user		
Pre-conditions	• Data has been stored in the DMS • Data User/Research has an authorized account for the DMS			
Key Actions and Flow of Events	Actor	Step	Key Action	Comments
	Data User/Researcher	1	Logs into DMS	
	Data User/Researcher	2	Enters data query for data privileges only to higher level users	
	DMS	3	Validates and processes query	
	DMS	4	Returns error denying access to the data	May give user the option to request access to the data
Post Conditions	• User may enter a new query or request access to the data			
Policies and Business Rules	• Office of Administration IT Policies			
User Needs Traceability	• ADS-UN045-V01 – Access System Data • ADS-UN046-V01 – Data User Role • ADS-UN048-V01 – Data Query			
Inputs Summary	System Initialization Input: DMS data collected from project subsystems Human Inputs: Data query request			
Output Summary	Record of attempted access			

SOURCE: PENNDOT

8.5 User Needs to Scenarios Summary

Table 34 provides the traceability between the user needs and the scenarios presented previously in this section.

Table 34: User Needs to Scenarios Summary

User Need Identification	User Need Title	Applicable Scenarios		
Safety Driver Needs				
ADS-UN001-V01	Engage AV Operations	UC3-S1		
ADS-UN002-V01	Manual AV Operation	UC3-S1	UC3-S7	UC3-S8
		UC3-S9		
ADS-UN003-V01	AV Control Notification	UC3-S7	UC3-S8	UC3-S9
ADS-UN004-V01	Driver Disengagement Monitoring	UC3-S7	UC3-S8	UC3-S9
ADS-UN005-V01	AV Operations	UC3-S1	UC3-S7	UC3-S8
		UC3-S9		
ADS-UN006-V01	AV Disengagement	UC3-S7	UC3-S8	UC3-S9
ADS-UN007-V01	AV Map Import	UC3-S3		
ADS-UN008-V01	AV Mapping Data Generation	UC3-S1		
ADS-UN009-V01	AV Data	UC3-S1	UC3-S7	
ADS-UN010-V01	V2X Work Zone Object Locations	UC3-S4		
ADS-UN011-V01	Law Following – Open Traffic Environment	UC3-S1	UC3-S2	UC3-S6
		UC3-S10		
ADS-UN012-V01	Law Following – Regulatory	UC3-S2		
ADS-UN013-V01	Law Following – Temporary Traffic Control	UC3-S1	UC3-S2	UC3-S5
		UC3-S8	UC3-S9	
ADS-UN014-V01	AV Time Synchronization	UC3-S5		
ADS-UN015-V01	AV Positioning	UC3-S5		
Safety Associate Needs				
ADS-UN016-V01	AV Audio Communications	UC3-S1	UC3-S7	
ADS-UN017-V01	Associate Disengagement Monitoring	UC3-S7	UC3-S8	UC3-S9
ADS-UN018-V01	AV System Status	UC3-S8	UC3-S9	
ADS-UN019-V01	Store ADS Results	UC3-S1		
ADS-UN020-V01	AV Sensor Calibration	UC3-S1		
ADS-UN021-V01	AV PII Removal	UC3-S1		
ADS-UN022-V01	AV Data Processing	UC3-S1		
Data Manager Needs				
ADS-UN023-V01	Data Storage	UC1-S1	UC1-S2	UC2-S1
		UC2-S2	UC3-1	
ADS-UN024-V01	Format Data		N/A	
ADS-UN025-V01	View Data	UC1-S1	UC1-S2	UC2-S1
		UC2-S2	UC3-S1	
ADS-UN026-V01	Edit Data		N/A	
ADS-UN027-V01	DMS System Status		N/A	
ADS-UN028-V01	DMS User Management		N/A	
ADS-UN029-V01	DMS Roles		N/A	
ADS-UN030-V01	Data Handling		N/A	

User Need Identification	User Need Title	Applicable Scenarios		
ADS-UN031-V01	DMS Data Ingestion	UC1-S1	UC1-S2	
ADS-UN032-V01	WZDx Data Format	UC4-S2		
ADS-UN033-V01	DMS Data Interface	UC1-S1	UC3-S1	
ADS-UN034-V01	DMS Secure Access	UC1-S1	UC3-S1	
ADS-UN035-V01	DMS Map Data	UC3-S1		
Simulation Operator Needs				
ADS-UN036-V01	Simulation Operations	UC2-S1	UC2-S2	UC2-S3
ADS-UN037-V01	Simulation Data Import	UC2-S1		
ADS-UN038-V01	Simulation Configuration	UC2-S1		
ADS-UN039-V01	Run Simulation	UC2-S1	UC2-S2	UC2-S3
ADS-UN040-V01	Simulation Progress	UC2-S1	UC2-S2	UC2-S3
ADS-UN041-V01	View Simulation Results	UC2-S1	UC2-S2	
ADS-UN042-V01	Store Simulation Results	UC2-S1	UC2-S2	
ADS-UN043-V01	Simulation System Status	UC2-S2	UC2-S3	
ADS-UN044-V01	Simulation Performance Data	UC2-S1	UC2-S2	
Data User/Researcher Needs				
ADS-UN045-V01	Access System Data	UC4-S1	UC4-S3	
ADS-UN046-V01	Data User Role	UC4-S3		
ADS-UN047-V01	Data Export	UC4-S1		
ADS-UN048-V01	Data Query	UC4-S1	UC4-S3	
ADS-UN049-V01	Data Feeds	UC4-S2		
ADS-UN050-V01	System Statuses		N/A	
Mapping Equipment Operator Needs				
ADS-UN051-V01	Conduct Mapping	UC1-S1	UC1-S2	UC1-S3
ADS-UN052-V01	Mapping Van Operator Audio Communications	UC1-S1	UC1-S2	UC1-S3
ADS-UN053-V01	Mapping Van System Status	UC1-S2	UC1-S3	
ADS-UN054-V01	Mapping Van Login	UC1-S1	UC1-S2	
ADS-UN055-V01	Mapping Equipment Data Testing	UC1-S1	UC1-S2	
ADS-UN056-V01	Mapping Van Sensor Calibration	UC1-S1	UC1-S2	
ADS-UN057-V01	Mapping Van PII Removal	UC1-S1		
ADS-UN058-V01	Mapping Van Data Processing	UC1-S1		
ADS-UN059-V01	Mapping Van Data Format	UC1-S1	UC1-S2	
ADS-UN060-V01	Real-time Mapping	UC1-S1	UC1-S2	
ADS-UN061-V01	Mapping Van Connectivity	UC1-S1	UC1-S2	
ADS-UN062-V01	Work Zone Mapping	UC1-S1	UC1-S2	
ADS-UN063-V01	Mapping Van Time Synchronization	UC1-S1		
Mapping Van Driver Needs				
ADS-UN064-V01	Drive Mapping Van	UC1-S1	UC1-S2	
ADS-UN065-V01	Mapping Van Driver Audio Communications	UC1-S1	UC1-S2	UC1-S3
Work Zone Operator Needs				
ADS-UN066-V01	Work Zone V2X Configuration	UC1-S1	UC3-S9	
ADS-UN067-V01	Work Zone Configuration	UC1-S1		

User Need Identification	User Need Title	Applicable Scenarios
ADS-UN068-V01	Work Zone Equipment Monitoring	UC3-S9
ADS-UN069-V01	Work Zone Equipment Service Restoration	UC3-S9
ADS-UN070-V01	RSU Time Synchronization	UC3-S5
ADS-UN071-V01	RSU Position Correction	UC3-S5
ADS-UN072-V01	RSU SPaT and MAP	UC3-S5
ADS-UN073-V01	V2X Work Zone Object Time Synchronization	UC3-S4
ADS-UN074-V01	V2X Work Zone Object Position Correction	UC3-S4

Source: PennDOT

APPENDIX A: ACRONYMS AND ABBREVIATIONS

Table 35: Acronyms and Abbreviations

Acronym/Abbreviation	Definition
ADS	Automated Driving System
AIAA	American Institute of Aeronautics and Astronautics
ANSI	American National Standards Institute
API	Application Programming Interface
ATMA	Autonomous Truck-Mounted Attenuator
ATMS	Advanced Traffic Management System
AV	Automated Vehicle
BSM	Basic Safety Message
CAN	Controller Area Network
CMU	Carnegie Mellon University
ConOps	Concept of Operations
CORS	Continuously Operating Reference Station
CV	Connected Vehicle
C-V2X	Cellular Vehicle-to-Everything
DDT	Dynamic Driving Task
Deloitte	Deloitte Consulting LLP
DGPS	Differential Global Positioning System
DMS	Data Management System
Drive	Drive Engineering Corporation
DSRC	Dedicated Short-Range Communications
FCC	Federal Communications Commission
FHWA	Federal Highway Administration
GNSS	Global Navigation Satellite System
HD	High Definition
INS	Inertial Navigation System
IT	Information Technology
ITS	Intelligent Transportation Systems
JSON	JavaScript Object Notation
LIDAR	Light Detection and Ranging
LTI	Larson Transportation Institute
MAP	Map Message
MBI	Michael Baker International
MUTCD	Manual on Uniform Traffic Control Devices
NTCIP	National Transportation Communications for ITS
OBU	Onboard Unit
O&M	Operations and Maintenance
PATA	Pennsylvania Typical Application
PennDOT	Pennsylvania Department of Transportation
PII	Personally Identifiable Information
PPG	PPG Industries, Incorporated
PSID	Public Service Identifier
PSU	Pennsylvania State University

Acronym/Abbreviation	Definition
PTC	Pennsylvania Turnpike Commission
RADAR	Radio Detection and Ranging
RF	Radio Frequency
RSU	Roadside Unit
SAE	SAE International
SPaT	Signal Phasing and Timing
TMA	Truck-Mounted Attenuator
TMC	Traffic Management Center
USDOT	United States Department of Transportation
V2I	Vehicle-to-Infrastructure
V2X	Vehicle-to-Everything
VRU	Vulnerable Road Users
WSA	WAVE Service Announcement
WZDx	Work Zone Data Exchange
XML	eXtensible Markup Language

Source: PennDOT

APPENDIX B: TECHNOLOGY READINESS ASSESSMENT

The section below discusses our project requirements in terms of components and infrastructure for the safe integration of ADS vehicles in work zones and our degree of readiness:

Table 36: Technology Readiness Assessment

Component	Discussion	Degree of Readiness
AV with Sensors	CMU's AV with sensors proposed for this project is operational and available. Integration with CARLA, C-V2X, WZDx and detection of work zone objects must be carried out.	High
Mapping Vehicle with Sensors	PSU's HD mapping vehicle with sensors proposed for this project is operational and available.	High
Connectivity Equipment	Our project proposes the use of connectivity equipment with in-built DSRC and C-V2X chipset since our team take a neutral position between DSRC and C-V2X for connectivity, and may employ both technologies, pending their final resolution of which technology will become the dominant standard. There are already few manufacturers who manufacturers these devices currently. Our team anticipates this connectivity equipment will be widely available in the market prior to the deployment of our project in 2022.	High
Coating Technology	All technologies proposed by PPG for coating of work zone objects are a minimum Technology Readiness Level of 4, meaning they have been demonstrated to operate at a lab scale. Some lab work may be necessary to customize the coating to work in the specific end use. For example, PPG has tested LIDAR enhanced coatings on cars to prove the effect, but PPG may need to do some lab work to customize the formula so that it can be applied to a flexible, plastic traffic barrel. PPG confirmed that the coating technology will be available prior to the end of year 2020, in time for Deployment phase.	High
Traffic Control Devices	Only standard traffic control devices are proposed for our project, which are readily available for procurement.	High
Closed Track for Testing	PSU's closed track facility is already operational and will be readily available for use.	High
ADS Simulation Tool	CMU's ADS simulation tool is already operational and will be readily available for use.	High
Cloud-based DMS	Our team proposes to use an already existing cloud-based DMS. Some level of development will be required to enable the DMS for the project, which will be completed as part of this project prior to the deployment phase.	High

SOURCE: PENNDOT

APPENDIX C: STAKEHOLDER MEETING MINUTES

PENNDOT ADS PROJECT

CMU CONOPS STAKEHOLDER MEETING MINUTES

Meeting Location: Online (Microsoft Teams)

Meeting Time/Date: 3:00 pm – 5:00 pm; 4/26/2021

Attendees:

PennDOT – Mark Kopko, Gunnar Rhone

CMU – Raj Rajkumar, Iljoo Baek, Mengwen (Alex) He, Weijing Shi, Shounak Sural

HNTB – Vijay Varadarajan, Sneha Chityala

AGENDA

S.No	Items	Time	Lead
1.	Introduction	3:00 pm – 3:05 pm	Gunnar Rhone
2.	Status/Schedule	3:05 pm – 3:10 pm	Gunnar Rhone
3.	Concept of Operations • System Architecture ○ Raj stated that the AV currently only has DSRC connectivity. Since the project uses C-V2X, a new OBE will need to be procured. ○ Need to find the message format used between V2X Work Zone Artifacts to OBE ○ Need to find out if the V2X Vests are required per the scope ○ Need to schedule a meeting between PSU/CMU for simulation system to figure out how the systems will be integrated ○ Raj stated that the AV doesn't currently support MAP, but CMU will look into incorporating it. ○ Raj stated that the vendor matters for the V2X devices – the RSE/OBE should be the same vendor ○ Raj suggested that PennDOT prohibit VRU's from the work zones – can use dummies if we're going to include them	3:10 pm – 4:50 pm	Gunnar Rhone

S.No	Items	Time	Lead
	◦ The system being used for the simulation is CADRE TROCS / CARLA. The systems are not currently integrated, but will attempt to be integrated for the project. CARLA is more for visualization while most of the processing is done by CADRE. ◦ The ADS will have wireless connectivity, not the OBE. • Users ◦ CMU will not be driving other vehicles in the work zone scenarios • Roles and Responsibilities • User Needs ◦ Data will not be collected by wireless backhaul, will be collected by hard drive. The AV produces too much data per second to bring the data back wirelessly. ◦ Need to discuss data format with Deloitte/PSU ◦ The AV needs to be able to work in day and night – Additionally, the testing team will need access to LTI day and night and for a few days before the demo ◦ Need to procure both the vendor and someone who can maintain the RSE. This can be done in one procurement, but it may be two different companies providing two different services. ◦ Vijay to send Raj the list of USDOT names ◦ Need to discuss the granularity of the simulation with PSU • Test Scenarios ◦ Raj stated that the WZDx specification will need to be extended to work with the AV ◦ Need to ask PPG if the enhanced coating is for camera, LiDAR or both ◦ PPG mentioned they have 2 coatings, how should we implement those? Need to discuss with PPG. ◦ Raj suggested that the testing team do a baseline test with no objects coating, 2nd test with some objects coated, 3rd with all objects coated ◦ Raj stated that 6-12 runs per scenario would make the testing statistically significant ◦ Need to have a baseline without connectivity/coating (Need to discuss if this would it be AV or human control) ◦ The testing team needs to plan ahead with setting up at night for the close track and live environment and getting the resources and people together for that • Locations ◦ Raj mentioned that the AV will need a secure location – locked garage ◦ Raj stated that the locations will need snow removal and need to test without rain ◦ Raj stated that it would be nice to test in a fake construction zone that we set up on the live road.		

S.No	Items	Time	Lead
	Operating in a live work zone would increase safety risks and the sensors may get coated in dust, impacting performance. • Required Resources		
4.	Next Steps	4:45 pm – 4:50 pm	Gunnar Rhone
5.	CMU presented their CADRE-CARLA software that will be modified and used for the project	4:50 pm – 5:20 pm	Raj Rajkumar
6.	Wrap-up	5:20 pm	Gunnar Rhone

Action Items:

Responsible Party	Due Date	Action Item
Gunnar Rhone	5/14/2021	Schedule meeting between CMU and PSU to discuss simulation system integration
Gunnar Rhone	5/14/2021	Schedule meeting between CMU, PSU, and Deloitte to figure out how and where the messages will be formatted, and the systems will be integrated
Vijay Varadarajan	5/7/2021	Send Raj a list of the USDOT contacts
Gunnar Rhone	5/21/2021	Ask PPG if the enhanced coating is for camera, LiDAR or both, and how the coatings will be integrated into the work zones (put in PPG ConOps meeting)

PENNDOT ADS PROJECT

CONOPS STAKEHOLDER MEETING - PSU

Meeting Location: Online (Microsoft Teams)

Meeting Time/Date: 3:00 pm – 5:00 pm; 5/3/2021

Attendees:

PennDOT – Mark Kopko, Gunnar Rhone

PSU – Sean Brennan, Eric Donnell, Vikash Gayah

HNTB – Vijay Varadarajan

AGENDA

S.No	Items	Time	Lead
1.	Introduction	3:00 pm – 3:05 pm	Gunnar Rhone
2.	Status/Schedule	3:05 pm – 3:10 pm	Gunnar Rhone
3.	Concept of Operations • System Architecture ○ Need to discuss with CMU how we're defining where the work zone is located (roadway segment/lat long/etc.). ○ The mapping van can generate 10 Gb/s from cameras. ○ Can blur images to protect PII or get consent to release certain PII ○ PSU can use VISSIM or AIMSUN for simulation ▪ May need to buy some add-ons ○ Need to define what the user is looking for in the UI ○ Need to define UI between work zone setup and operator ○ Need to connect V2X WZA to DMS ○ Need to talk to CMU to figure out if the systems will be integrated into one system or interface with each other.	3:10 pm – 4:50 pm	Gunnar Rhone

S.No	Items	Time	Lead
	○ The mapping van can send back near-real time lane level information over 4G/4G LTE, but the accuracy would be better if the data was fully processed. Need to discuss what CMU needs in real-time ○ The hard drive on the mapping van is removable so the data can be retrieved. ○ There is no 5G in the area yet, but PSU is currently working on getting 5G for LTI ○ The format that the mapping van currently exports is OpenStreetMaps XML and RoadXML. Need to find out what the minimum fidelity that CMU needs ○ Human factors that may be tested are how far in advance of the work zone do we need to be giving the vehicle notice of the work zone and the human driver taking over control in the middle of the work zone • Users ○ PSU doesn't have equipment for setting up the work zones. Using D-2's equipment and staff to set up the work zones would be the preferred route. ○ PSU may be operating PSU vehicles in the work zone. Whoever owns the vehicle should be the one driving it. If PennDOT vehicles are being used, then PennDOT should be the one driving those vehicles. ○ PSU would like to see other CAVs being used in the project. Need to talk to CMU about integrating more CAVs for validating the work zone and catching/correcting incorrect work zone information. • Roles and Responsibilities • User Needs ○ Various operators need to be able to identify when systems exceed allowable fault levels ○ Need to define the latency required for data processing and how often the data is updated ○ Does CMU need forecasted operations data? Would need to be done in the DMS since it likely wouldn't be able to be done on-vehicle. (This isn't in the scope of the project) ○ Data User/Researcher needs to know the system status/health status of the systems and know how often faults are happening (CAN data failures, uptime/downtime, communication link failures, etc.) ○ Need to define what "ADS operations" are ○ Need to define data handling ▪ Data that is meant for pure simulation, pure deployment, hybrid, etc. needs to be		

S.No	Items	Time	Lead
	handled differently and has different handling requirements ▪ Mapping van needs to define lane markers in real time. Need to discuss level of accuracy needed with CMU; if CMU needs a high degree of accuracy, the map may not be able to process in real time ▪ Mapping van needs to pick up communication point strength too ▪ The mapping van driver doesn't do the mapping – they just drive ▪ The Mapping Van Driver, as currently identified, should be a Mapping Equipment Operator. This person also needs to be able to log into the van and reset roadside equipment to verify dataflow (testing only) • Test Scenarios ○ PSU can have a dedicated part of LTI to set up work zones so we can test nearly all year ○ Need to figure out how do we mimic road closure/detour ▪ We can fake a highway exit and merge back onto the highway ○ 3 lane and divided highway may be difficult to test ○ We can achieve speeds up to 50 mph on the straightaway/large curve, probably 35-40 on the smaller curve ○ Choose a couple scenarios and run data fault tests where we try to mess up the AV on purpose ▪ Ask CMU for fault cases that we might want to look at • Locations ○ We can test the simulation in a PSU lab or in the transportation building. ○ PSU has garage at main campus – can fit 2 vehicles ○ Garage space at test track that can store several vehicles – preferred location of AV ○ Faculty lots are currently used when debugging the mapping van. Vehicles with PSU plates can park at any location on PSU campus ○ Do CMU lidar sensors work in cold weather or do they fog? Need to ask CMU to see if we will be able to test in very cold weather and snow ○ PSU has snow removal equipment at LTI ○ There's a perched hillside area that can be used for a viewing area ○ LTI has walkie talkies, but cellphones are the preferred communication tool ○ There's some on-site safety equipment (first aid, fire extinguisher, etc.)		

S.No	Items	Time	Lead
	◦ Eric needs to check with the test track manager to see if we can use the office building. Needs to know the number of people and duration. ◦ LTI doesn't have a DSRC FCC permit ◦ The live environments will need to have 120V AC pluggable charging. ◦ We need to ask CMU which LiDAR sensors they're using for testing the AV. PSU would like to match those LiDAR sensors in the Mapping Van. ◦ PSU needs to obtain IR/hyper-spectral cameras since we mentioned din the proposal that these would be measured. • Required Resources ◦ PSU has 6 RSUs and 12 OBUs (all DSRC) that could be used for the project, however, they're fairly old, so we would be better off procuring new RSUs/OBUs ◦ PSU needs to have code/data repositories (project tracking system)		
4.	Next Steps	4:50 pm – 4:55 pm	Gunnar Rhone
5.	Wrap-up	4:55 pm – 5:00 pm	Gunnar Rhone

Action Items:

Responsible Party	Due Date	Action Item
Gunnar Rhone	5/14/2021	Identify the number of staff needed at the track that may need the office and duration
Eric Donnell	5/21/2021	Discuss office availability with test track manager
Gunnar Rhone	5/14/2021	Schedule meeting between CMU and PSU to discuss simulation system integration (or invite both to weekly meeting if they both agree to it)
Sean Brennen, Vikash Gayah, Eric Donnell	5/7/2021	Review slides for additional comments

PENNDOT ADS PROJECT

CONOPS STAKEHOLDER MEETING – PENNDOT/PTC

Meeting Location: Online (Microsoft Teams)

Meeting Time/Date: 3:00 pm – 5:00 pm; 5/17/2021

Attendees:

PennDOT CO – Mark Kopko, Dan Farley, Brian Crossley, Gunnar Rhone

PennDOT Districts – Brian Smith (1-0), Dennis Prestash (2-0), Raymond Kauffman (2-0), Donald Maicki (2-0), George Maines (2-0), Eric Brown (2-0), Alan Keller (3-0), Bob Kretschmer (4-0), Derrick Herrmann (5-0), Andrew Samy (5-0), Emmanuel Anastasiadis (6-0), Aswin Panel (6-0), Janet Vogel (6-0), Jason Bewley (8-0), Ernest Cascino (9-0), Jeffrey Thompson (11-0), Stephanie Zolnak (11-0)

PTC – Todd Leiss, Tom Macchione

HNTB – Vijay Varadarajan

AGENDA

S.No	Items	Time	Lead
1.	Introduction	3:00 pm – 3:05 pm	Gunnar Rhone
2.	Status/Schedule	3:05 pm – 3:10 pm	Gunnar Rhone
3.	Concept of Operations • System Architecture ○ Need to talk to IT about integrating RSE into the PennDOT network ○ Vendor should be responsible for all V2X device configuration • Users ○ D-2 may be able to provide equipment and services for LTI, but need to coordinate with county maintenance organization ○ D-9 paints Centre County lines ○ Gunnar to send D-2 the required equipment list	3:10 pm – 4:50 pm	Gunnar Rhone

S.No	Items	Time	Lead
	◦ Other counties may be able to help set-up live on-road testing, but need to identify the scope of the traffic control required for testing ◦ Off hours testing is preferred so it doesn't compromise safety of the work zone ◦ Need to look into adding experimental items in the work zones. The contractor "owns" the roadway when it's under construction. ◦ Counties are better equipped/suited for short term work zones than long term ◦ Many counties have long term bridge shutdowns with detours that the project team could work with • Roles and Responsibilities • User Needs ◦ Need to be able to measure hard breaking ◦ Access to camera footage may be beneficial for districts ◦ In the live environment, there should be notifications to the public that testing is taking place • Test Scenarios ◦ The project team can begin identifying short term work zones 3-6 months in advance of testing. Long term will require coordination with the contractor far ahead of time due to the nature of the experimental coatings and AV operations • Locations ◦ Will need to follow-up on the equipment required with districts after we know where the AV testing will be deployed in the live environment. Some districts may have the required equipment while others may not. • Required Resources ◦ Need to talk to Mike Martin about fleet vehicles ◦ Talk to equipment managers to see if we could get them to hold on to the devices for this project		
4.	Next Steps	4:50 pm – 4:55 pm	Gunnar Rhone
5.	Wrap-up	4:55 pm – 5:00 pm	Gunnar Rhone

Action Items:

Responsible Party	Due Date	Action Item
Gunnar Rhone	5/28/2021	Send D-2 the work zone traffic control equipment that will be required
Gunnar Rhone	6/25/2021	Discuss required fleet equipment with Mike Martin