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Safe Integration of Automated Vehicles into Work Zones | PKG 00247169

TESTING PLAN
for the
Safe Integration of Automated Vehicles into Work Zones Project

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DEPARTMENT OF TRANSPORTATION

Notice

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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 safe integration of automated vehicles into work zones. This document defines the strategic plan for testing the core functionalities of the automated driving system and verifying system requirements are met. Testing will occur in four stages, starting with experimentation for initial system configuration and calibration, simulation testing, closed-track testing, and live on-road testing. After all stages of testing are complete, the project team will analyze the testing results and associated operational and performance data to evaluate the impacts of improved connectivity, visibility, and mapping between automated vehicles and work zone objects on the ability for automated vehicles to navigate safely through work zones.

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Chapter 1: Introduction

1.1 Project Overview

The project team will test the viability of Autonomous Driving Systems (ADS) to operate safely in various Pennsylvania Typical Application (PATA) and Pennsylvania Turnpike Commission (PTC) Maintenance and Protection of Traffic Standard (PTS) roadway work zone scenarios. The primary objective of testing is to evaluate the effectiveness of improved connectivity between the ADS and work zone objects, innovative coatings for enhanced sensor visibility and computer perception, and improved dissemination/standardization of high-definition (HD) mapping data to enable Autonomous Vehicles (AV) to navigate safely through work zones. Four stages of testing are planned, beginning with initial experimentation and system configuration, then simulation testing, closed-track testing, and lastly, limited live on-road testing.

Experimentation will involve several initial steps to establish baseline system configurations and models prior to conducting simulations. The intent of the simulation phase is to assess ADS performance and infrastructure interaction in a virtual environment. Simulation data will be used to calibrate Carnegie Mellon University's AV (CMU-AV) and ensure safe and correct driving behaviors prior to the start of physical, real-world testing. The closed-track test aims to demonstrate autonomous driving behaviors of the CMU-AV in various work zone scenarios and capture data using the on-board equipment such as cameras, sensors, computers, etc., for analysis. The live on-road test will be conducted in the same manner as that of the closed-course test, but in a limited on-road environment. The tests will provide the test team with simulated and real-world data that will be used to evaluate the impacts of enhanced connectivity, innovative coatings, computer perception, and HD mapping on the ability of AVs to safely navigate through work zone scenarios under a variety of conditions.

1.2 Purpose

The purpose of this test plan is to document the strategic plan for testing the core functionalities of the ADS project system during simulation, closed-track, and live on-road work zone deployment scenarios.

1.3 Scope

The scope of this testing plan is limited to information necessary to plan the testing that will occur during experimentation, simulation, closed-track, and live on-road testing stages of the ADS project. This testing plan includes the following sections:

- **Risks and Contingencies** - defines risks in testing that may be outside the control of the test team or may need to be considered before testing begins. These risks and their associated contingency strategies are outlined in this test plan to provide the team with potential threats to their safety and threats that may lead to unfulfilled or incomplete testing.

- **Test Items** – identifies core ADS functions to be tested and identifies assumptions
- **Testing Design and Approach** – describes the project team's overall approach to testing and test design. More specifically, this section defines the test phases, schedule, team roles and responsibilities, required test tools and instruments, test criteria, performance measures, pass fail items, and test deliverables.
- **Test Scenarios** – defines required test scenarios at a high-level. This section identifies specific functions of ADS subsystems that will be tested within modular and consolidated step-by-step test procedures.
- **ADS Demonstration Test Procedures** – provides step by step instructions and checklists for the test team to execute and document the results of testing. The cases and procedures provided in this section build upon the test scenarios identified in the previous section and will serve to facilitate and guide the testing process in a systematic manner.
- **Data Management System Verification Procedures** – provides step-by-step procedures to verify functionality of the Data Management System (DMS) developed specifically for the project.
- **Requirements Traceability Matrix** – maps system requirements to the test procedures to ensure traceability. Requirements ultimately map back to system use cases, needs, and project goals/objectives.
- **List of Acronyms and Key Terms/Definitions** – provides a list of acronyms and defines key terms used in the document.

1.4 Referenced Documents

- Federal Highway Administration (FHWA), Systems Engineering for Intelligent Transportation Systems, https://ops.fhwa.dot.gov/publications/seitsguide/section3.htm
- INCOSE, Systems Engineering Body of Knowledge, https://www.sebokwiki.org/wiki/System_Verification
- PennDOT, Deployment Plan for the Safe Integration of Automated Vehicles into Work Zones Project
- PennDOT, Project Evaluation Plan for the Safe Integration of Automated Vehicles into Work Zones Project
- PennDOT, Publication 213 Temporary Traffic Control Guidelines
- PennDOT, Risk Management Plan for the Safe Integration of Automated Vehicles into Work Zones Project
- PennDOT, System Requirements for the Safe Integration of Automated Vehicles into Work Zones Project

Chapter 2: Risks and Contingencies

There are factors in testing that are outside the control of the test teams but may impact the testing process. Risks are events with the potential to occur and result in negative consequences. The following list outlines the potential risks and contingencies for the project:

- Unpredictable/unusual weather and traffic conditions could affect testing procedures and may result in schedule delays if tests need to be extended and/or rescheduled.
- Cyber hacks could cause operational safety issues and equipment failures. Security measures should prevent cyber threats.
- Procurement of devices may be difficult due to vendor lead times. The current global chip shortages may have a direct effect on the devices used for this project, such as additional GPS units. This risk may be alleviated with potential loaner units.
- Legislation related to the evolving technologies affiliated with this project may create roadblocks or delays in testing and deployment.
- Assimilation and dissemination of map data from and with other mapping sources may not sync, thereby inhibit communications. This would compromise the effort of standardization of the map data.
- Operational risks related to the vehicle and environment could be present during testing. Proper training of operators and certified personnel will help mitigate potential mishaps during testing.
- Changes to the work zone layout will occur throughout testing. Staying consistent with work zone scenarios and maps will mitigate improper behaviors of the CMU-AV and re-calibration.
- The CMU-AV may encounter unexpected elements in the test resulting in erratic behaviors. The trained operator must intervene using relevant safety guidelines and training. Due to this risk, no other vehicles should operate within the CMU-AV navigational test zone. All objects considered in the test zone are stationary.
- Components necessary for data collection could become unaligned, unattached, etc. CMU-AV and work zone inspection can be used to ascertain an “all systems go” state prior to the test.
- A vehicle collision could halt testing and cause significant delays in completion. CMU has a backup AV as a replacement. In the case that map generation is inaccurate, the CMU-AV has the capability for collision avoidance via on-board sensors and safety driver intervention.
- Human injury could occur if the CMU-AV were to behave unexpectedly or if safety protocols are not properly followed. To help avoid human injury, testing needs to ensure active work zone identifiers, proper safety attire, hazard warnings or avoidances, proper lighting, safety training, etc.

- The Safety Driver needs to be able to engage CMU-AV operations, warned of required actions, and take manual control of the vehicle. It is possible the CMU-AV may not warn the Safety Driver or Safety Associate that intervention is necessary. The Safety Driver and Associate need to remain attentive during testing and be able to intervene immediately if an unsafe situation were to become imminent.
- DMS failures or communications downtime could occur. If there are instances the DMS is not operational in testing, it may cause gaps in data and necessitate repeat test runs. The DMS needs to be able to store, process, format, view, and disseminate the data. If the DMS fails to meet any of these needs it must be able to alert the Data Manager to address the issues prior to the resumption of testing.
- Simulation failures will necessitate retesting of any failed simulation component or configuration. It is necessary that the simulation program must be de-bugged and glitch free prior to simulation testing.
- Communication latencies could cause the CMU-AV to have command input lag, resulting in delayed actions. Safety could be impacted if the level of technological readiness and dependability of devices is not adequate.
- Updated map data may not pass to the CMU-AV and the CMU-AV must navigate using only data generated in real-time from its on-board sensors. The CMU-AV must be able to operate without map data during the day or night and with or without enhanced coatings, or the safety driver will need to intervene.

The list provided above is not all-inclusive, nor suggested as a minimum set of risks. In the event any anomaly occurs during the execution of testing, the team must document what occurs within the comments section of the test procedures provided in **Chapter 6** and **Appendix A** of this plan, and as indicated in the **Risk Management Plan**.

Chapter 3: Test Items

3.1 ADS Core Functionalities to be Tested

The main objective of ADS testing is to evaluate the impact of improved connectivity, HD mapping, and computer perception on the ability of the ADS vehicle to safely navigate through roadway work zone scenarios. Core functionalities of the ADS that will be tested are as follows:

- **Connectivity** –The CMU-AV operates based on a combination of pre-loaded information and real-time sensor inputs required to navigate the work zone. Hardware and software on-board the CMU-AV connect with Roadside Units (RSU) within or near the work zone to exchange information and data. Data exchange involves bi-directional connectivity with the cloud-based DMS to store and disseminate data, HD maps, CMU-AV performance data, and CMU-AV behavioral data.
- **HD Mapping** – Using Penn State University's (PSU) mapping van (MAPVAN), work zone scenario data is captured by on-board sensors and processed to provide spatial parameters of the roadway work zone layout. The ADS receives the HD map generated and uses it to visualize the work zone, set routes, and navigate through the work zone safely. The DMS is used to store and disseminate the mapping data.
- **Computer Perception** – With the use of on-board sensors and enhanced coatings provided by PPG, the CMU-AV is expected to achieve a higher level of work zone object identification. The CMU-AV processes sensor inputs and uses them to make safe driving decisions based on real-time sensor data.
- **Work Zone Navigation** – The CMU-AV uses HD map data as well as computer perception via on-board sensors and Connected and Autonomous Driving Research and Engineering (CADRE) software stack to process data and make driving decisions to safely navigate through PATA and PTS work zone scenarios as defined by the project. The CADRE stack is used in conjunction with CARLA system for simulated CMU-AV navigation testing, and SUMO will be used in conjunction with CARLA to investigate how the CMU-AV navigating through the work zone may impact simulated traffic.

Each of these core functions of the ADS will be tested in experimental, simulation, closed-track, and live on-road test stages. Each stage of testing is described in detail in **Chapter 4.**

3.2 Assumptions

This section identifies assumptions pertaining to the subsystems included within the ADS project system. The ADS project system includes multiple existing subsystems, as well as a new DMS developed specifically for the project. Existing subsystems and the new DMS are in different stages of the systems lifecycle, and therefore, require different levels of testing as described below. **Figure 1** indicates where existing and new ADS project subsystems are within the Systems V diagram lifecycle in relation to this testing plan.

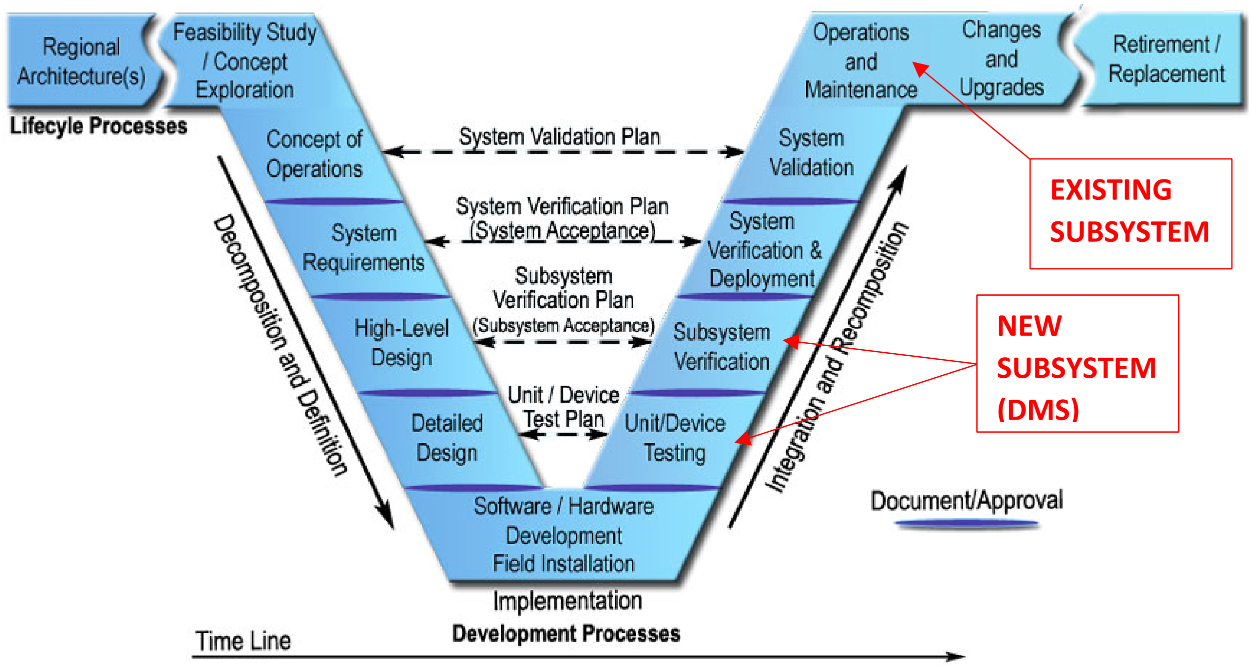

Figure 1 - Systems V Diagram: Existing vs. New ADS Project Subsystems

Source: FHWA, Systems Engineering for Intelligent Transportation Systems[1]

Subsystem Verification Testing focuses on the new DMS and provides procedures for verifying DMS functionality in all use cases required for the project. Subsystem verification testing for the DMS will occur prior to the start of ADS demonstration testing. Test procedures specific to verifying DMS functionality in the required project use cases are provided in **Appendix A** of this plan. Assumptions related to the new DMS deployed as part of the project are provided below:

- **Data Management System** – a new system developed by Deloitte Consulting, LLP as part of the project. The DMS is assumed to be fully installed, configured, and integrated prior to testing. DMS requirements related to data capture, logging, storage, and retrieval will be verified by the project team prior to the commencement of demonstration testing. DMS functionality will also be tested during demonstration testing as part of core functional tests (ex. confirming DMS receipt and storage of data captured during a mapping run, or AV navigation test).

ADS Demonstration Testing includes all existing and new subsystems and focuses on collecting data for project evaluation and demonstrating the core functionalities of the ADS system as a

[1] *https://ops.fhwa.dot.gov/publications/seitsguide/section3.htm*

whole. ADS demonstration testing procedures are provided in **Chapter 6** of this plan. As shown in **Figure 1**, existing ADS subsystems are in the Operations and Maintenance phase of the systems lifecycle and are assumed to comply with the system requirements defined in the project's **System Requirements** document. The owners/operators of their respective existing ADS subsystems will verify and document compliance with the system requirements related to their subsystems prior to the beginning of ADS demonstration testing. For ease of reference, **Appendix B** identifies all system requirements established for the project. Assumptions for existing subsystems are provided below:

- **CMU-AV** – an existing system owned and operated by CMU. It is assumed on-vehicle sensors, computing hardware and storage, communications, actuation equipment, and the CADRE system is fully operational and functions as designed.
- **PSU MAPVAN** – an existing system owned and operated by Penn State University (PSU). It is assumed that the map van's on-vehicle sensors (Light Detection and Ranging (LiDAR), radar, camera, encoders, global position system (GPS), inertial navigation system (INS), steering automatic shutdown relay (ASD)), onboard unit (OBU), computational system, two hard disk drives, on-board software systems), embedded trigger processes for GPS/PPS synchronization, and back-office processing computers are fully operational and function as designed.
- **Roadway Environment (RWE) Systems** – includes RSU, Edge High Performance Computer (HPC), RSU, V2X work zone objects (e.g., connected work zone objects such as construction vehicles, barriers, cones, etc.), and digital worker vests. These items are assumed to be configured and fully operational as standalone systems. Communications among other subsystems and the RWE will be confirmed as part of connectivity verification procedures performed prior to simulation, closed-track, and live on-road demonstration testing.
- **CARLA simulator software** – CMU and PSU are using the CARLA Simulator software, which requires many kinds of software and binaries integrations to run. It is assumed CARLA is an existing system, integrated, and fully functional prior to the start of simulation testing for this project.
- **CADRE simulator software** – The CADRE software will be used by CMU for analysis and measuring performance of AV simulations. It is assumed this system is existing, integrated, and fully functional prior to the start of simulation testing for this project.
- **Simulation of Urban MObility (SUMO) simulator software** – PSU is currently undergoing a separate effort to evaluate and implement the SUMO traffic simulation software. It is assumed that the SUMO software is an existing system, integrated, and fully functional prior to the start of simulation testing for this project. Traffic network models are assumed to be validated prior to simulation testing.
- **Enhanced coatings (in simulation)** – it is anticipated that PPG Industries, Inc. enhanced coatings will not be feasible to test within simulations. This is due to the lack of simulation models for how AV sensors react to the enhanced coatings in real-world environmental conditions.

Chapter 4: Testing Design and Approach

4.1 Approach

This section describes the project team's overarching approach to testing and test design. The project team will utilize standard methods for testing and verification, including inspection, demonstration, test, and analysis techniques as described in **Table 1** below, adapted from the INCOSE Systems Engineering Body of Knowledge[2].

Table 1 - Verification Methods

Method	Description
Inspection	Verification through a visual, auditory, olfactory, or tactile comparison.
Demonstration	Verification that exercises the system software or hardware as it is designed to be used, without external influence, to verify the results are specified by the requirement.
Test	Verification using controlled and predefined inputs and other external elements (e.g. data, triggers, etc.) that influence or induce the system to produce the output specified by the requirement.
Analyze	Verification through indirect and logical conclusion using mathematical analysis, models, calculations, testing equipment and derived outputs based on validated data sets.

Source: PennDOT

4.2 Test Stages

This section describes the stages of testing that will be performed during the deployment phase of the project. Testing will involve the following four (4) stages:

- Experimentation
- Simulation Testing
- Closed-Track Testing
- Live On-Road Testing

The stages of testing are defined below.

[2] https://www.sebokwiki.org/wiki/System_Verification

4.2.1 Experimentation

The experimentation stage will occur prior to simulation testing to address several challenges that the project team has identified. Experimentation may also be required throughout later stages in testing to address issues that may arise and to make system improvements as needed. As indicated in the **System Requirements** document developed as part of the project, the project team anticipates exploring the following items through experimentation:

- **Base Map Generation** — the project will conduct experiments to establish a baseline map for the project, evaluating fusion of data from Global Navigation Satellite System (GNSS), INS, and Continuously Operating Reference Station (CORS) subsystems. As part of base map generation experimentation, the project team will experiment with point cloud density and granularity of data points required for accurate mapping, defining start and end points of work zones, as well as the number of mapping van runs required to validate mapping data.
- **PPG Coating Detection and Classification** — the project team will need to evaluate and model how the CMU-AV will detect and classify PPG coatings, what features need to be analyzed, measured and how the CMU-AV will respond (e.g., tactical maneuvers) to detected PPG events.
- **Work Zone Object Detection and Classification** — given an HD map, the CMU-AV system will need to focus on centerline data and obstacle definitions.
- **Object and Event Detection and Response (OEDR) Process Flow Improvements** – The project may explore and experiment with concepts that allow for processing centerline data and obstacle definitions as the data flows in directly.
- **Map Generation Process Flow Improvements** — given MAPVAN data, the project may explore algorithms to reduce the time it takes to generate an HD map.
- **Message Formats and Transmittal Medium** — there will be some loss of mapping data that occurs as raw data is processed, and an HD map is generated. The resulting map may be too large to conform to SAE J2735 message set standard, which encodes data for Dedicated Short-Range Communications (DSRC) and Cellular Vehicle to Everything (C-V2X) transmissions. The project team will need to explore ways to conform to SAE J2735 encoding while preserving the integrity of a HD map (e.g., high-resolution, high-accuracy).
- **Privacy Preservation Tool** — the project prioritizes data privacy and may explore a tool the United States Department of Transportation (USDOT) developed designed to identify and remove secure data through techniques such as masking, obfuscating, and others.

Specific requirements pertaining to experimentation are provided in the **System Requirements** document. The owners/operators of the respective ADS subsystems related to the items identified above will experiment with their systems to optimize configurations and performance to the extent possible prior to simulation testing. All experimentation activities and results shall be documented for project team review and approval before simulation commences.

4.2.2 Simulation Testing

Simulation system modeling and testing will be performed by both CMU and PSU. CMU will conduct all microsimulations, and PSU will conduct all macrosimulations. An overview of micro and macrosimulation concepts is provided in **Table 2** below. The **Systems Requirements** document describes simulation concepts in detail.

Table 2 – Simulation Testing Overview

Simulation Type	Description	Responsible Party
Microsimulation	Involves simulated CMU-AV operations in a virtual world. The simulated CMU-AV (ego vehicle) is provided with a map and navigates a predefined path. The ego vehicle's CADRE simulator is connected to the CARLA simulator, which issues driving commands to the ego vehicle. CARLA outputs simulated sensor reading to the CADRE simulator to initiate CADRE to operate the vehicle in the virtual world.	CMU
Macrosimulation	Involves simulated CMU-AV interactions with traffic as it navigates through a work zone. SUMO is used to generate a simplified representation of CMU-AV behavior as simulated by the CARLA simulator. Traffic simulations will be used to perform before and after assessments on how the CMU-AV navigating work zone impacts traffic flow.	PSU

Source: PennDOT

Simulation data will be used to calibrate the test vehicle and address any issues prior to closed-track testing. Additionally, simulation offers a means to compare simulation data with real-life data and identify potential challenges in closed-track or live on-road testing. Prior to advancing to closed-track testing, successful micro and macro simulations must be completed for each PATA and PTS work zone scenario as designed in the project **Deployment Plan**, and results must be reviewed and approved by the project team.

4.2.3 Closed-Track Testing

Closed-track testing involves real-world physical tests at the PSU Larson Transportation Institute (LTI) test track. Closed-track testing serves to test the core functionalities of the ADS (and its subsystems) in a highly controlled environment, prior to testing in a limited live on-road environment. Closed-track testing will demonstrate the CMU-AV's ability to navigate through 17

PATA and two (2) PTS work zone scenarios as designed in the project **Deployment Plan** under multiple conditional permutations. Permutations will apply to both closed-track testing and live on-road testing, and are shown in **Table 3** and **Figure 2** below.

Table 3 – Testing Permutations

Permutation ID	HD Map	Connectivity	PPG Enhanced Coatings	Daytime/ Nighttime
Base Case 1	No	No	No	Daytime
Base Case 2	No	No	No	Nighttime
Permutation 1	No	No	Yes	Daytime
Permutation 2	No	No	Yes	Nighttime
Permutation 3	No	Yes	No	Daytime
Permutation 4	No	Yes	No	Nighttime
Permutation 5	No	Yes	Yes	Daytime
Permutation 6	No	Yes	Yes	Nighttime
Permutation 7	Yes	No	No	Daytime
Permutation 8	Yes	No	No	Nighttime
Permutation 9	Yes	No	Yes	Daytime
Permutation 10	Yes	No	Yes	Nighttime
Permutation 11	Yes	Yes	No	Daytime
Permutation 12	Yes	Yes	No	Nighttime
Permutation 13	Yes	Yes	Yes	Daytime
Permutation 14	Yes	Yes	Yes	Nighttime

Source: PennDOT

Figure 2 below provides a visual representation of the real-world testing permutations.

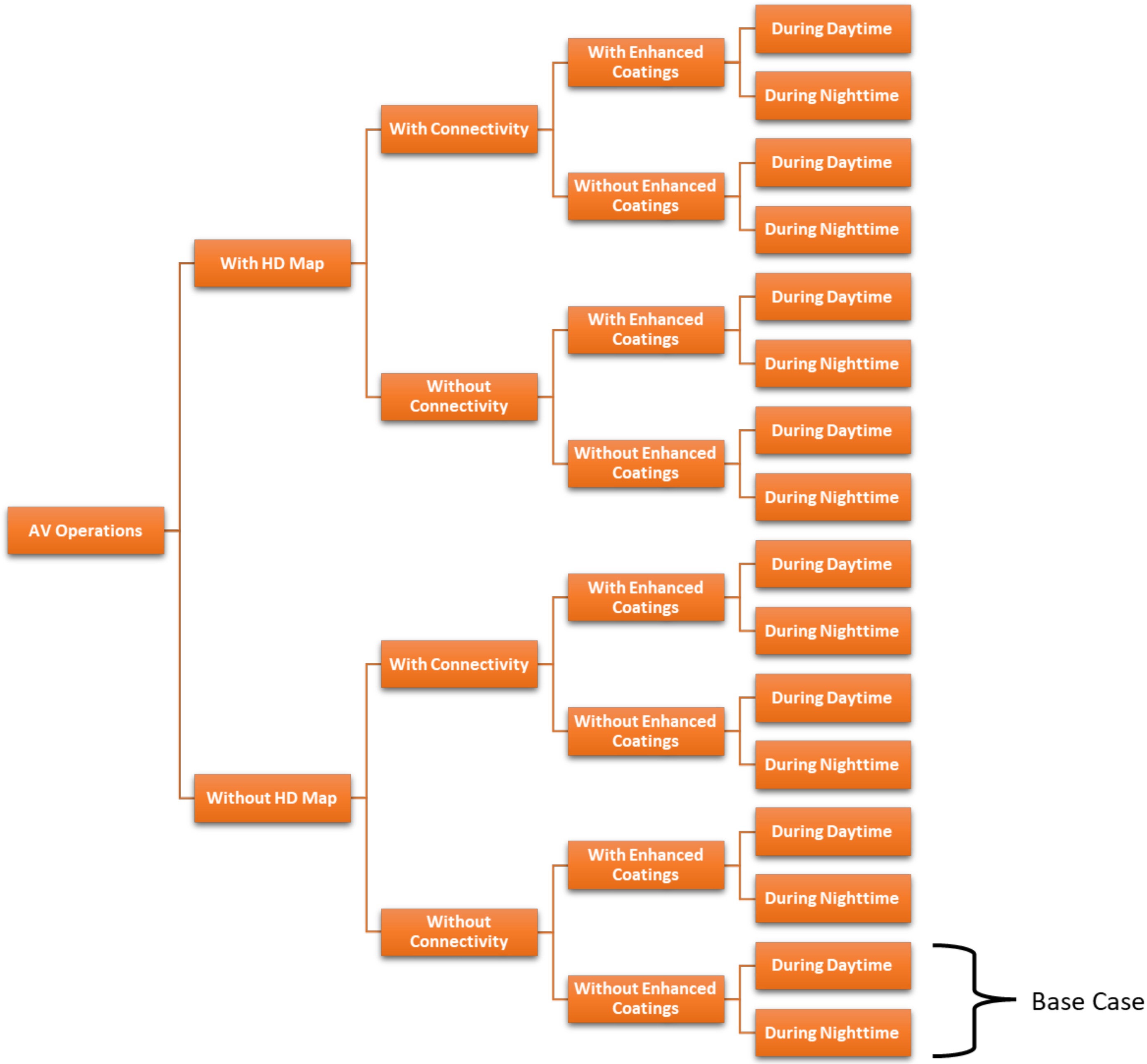

Figure 2 - Testing Permutations

Source: PennDOT

The testing permutations shown above provide a mechanism for comparing how improved connectivity, HD mapping, and enhanced coatings impact the CMU-AV's ability to navigate safely through work zone scenarios. Base Case 1 and Base Case 2 data will establish operational and performance data for the CMU-AV as a standalone system, which will be analyzed against Permutations 1 through 14 to evaluate and qualify the safety benefits of improved connectivity, HD mapping, and enhanced coatings for AV navigation.

Test runs will be completed for each approved PATA and PTS work zone scenario under each testing permutation identified above. Prior to advancing to live on-road testing, successful test runs must be completed for each PATA and PTS work zone scenario applicable to live on-road testing under each permutation, and results must be reviewed and approved by the project team.

4.2.4 Live On-Road Testing

Live on-road testing serves to test the core functionalities of the ADS (and its subsystems) in a limited and controlled open-road network. Closed-track testing will demonstrate the CMU-AV's ability to navigate through three (3) PATA and two (2) PTS work zone scenarios as designed in the project **Deployment Plan** under all conditional permutations shown in **Table 3** and **Figure 2** above.

Test runs will be completed for each approved PATA and PTS work zone scenario under each testing permutation identified above. Before the deployment phase of the project can conclude, successful test runs must be completed for each PATA and PTS work zone scenario under each permutation, and results must be reviewed and approved by the project team. Following acceptance of live on-road testing, the project team will progress to the evaluation phase of the project.

4.3 Schedule

All testing will occur during the deployment phase of the project. The deployment phase of the project is scheduled to commence in the second quarter of 2022 for a duration of two (2) years. During this time, experimentation, simulation, closed-track testing, and live on-road testing will occur.

Experimentation is anticipated to conclude prior to simulation, closed-track testing, and live on-road testing. However, experimentation may continue throughout subsequent testing stages of the project on an ad-hoc basis to address issues or make system improvements. If data impacting system improvements are made after simulation, closed-track, and/or live on-road testing has begun, previously completed simulations, closed-track testing, and live on-road testing would need to be reconducted to maintain the integrity of data to be used for comparison during evaluation.

As the project progresses, the project team will develop a detailed testing schedule to identify specific dates and milestones for testing activities. The detailed testing schedule will address the following items:

- Staff assignments and scheduling
- Simulation testing scheduling
- Closed-track testing scheduling
- Live on-road testing scheduling

- Travel arrangements and lodging
- Scheduling with contractors for work zone setup
- Staging and stockpiling of equipment needed for testing

Additional detail regarding scheduling is provided in the project **Deployment Plan**.

4.4 Test Equipment

Equipment required for demonstration testing is summarized in **Table 4** below.

Table 4 – Test Equipment

Test Equipment	Description
CMU-AV	SAE International (SAE) level 4 highly automated driving system. Capable of driving autonomously with minimal operator interaction.
PSU MAPVAN	Van used to collect HD map data via on-board sensors and computers by navigating through roadway networks. Data is offloaded to a hard disk drive and processed by PSU's back-office research lab computer (PSU-RMC).
CARLA Simulator	Used for issuing driving commands for the ego vehicle and returns (i.e., outputs) simulated sensor readings which are transmitted to the CADRE simulator.
CADRE Simulator	Used for operating the ego vehicle in a limited virtual world. Connected to the CARLA simulator to accept simulated sensor readings (CARLA outputs) which engage the CADRE subsystems to operate the ego vehicle in simulated roadway environments.
SUMO Simulator	Used to generate a simplified representation of the ego vehicle behavior as simulated by the CARLA tool, to test how the ego vehicle interacts with simulated traffic in a virtual connected roadway environment.
CMU Research Management Center (CMU-RMC)	Back-office computer system used for conducting vehicle simulation and other activities carried out for the project.
PSU Research Management Center (PSU-RMC)	Back-office computer system used for processing the data collected during mapping of the work zone and conducting traffic simulation.
RSU*	DSRC and C-V2X communication radios. Used for the aggregation, processing, and response to data received from the roadside, which will be offloaded to the Edge High Performance Computer.
HPC*	Roadside hardware used for processing, aggregating and logging data broadcasting among connected devices along the

Test Equipment	Description
	roadway network (e.g. AV, RSU, V2X work zone objects, Digital Work Vests, etc.). Aggregates and logs data from the CMU-AV. It serves as the facilitator of information exchange between the RSU and cloud environment (i.e., DMS).
V2X Work Zone Objects*	Represents connected work zone objects including construction vehicles, barriers, cones, and other safety equipment. Monitored within the work zone to enhance work zone safety.
Digital Worker Vests (Mounted GPS)*	Represents the personnel at the work zone that perform maintenance and construction field activities including vehicle operators, field supervisory personnel, field crews, and work zone safety personnel. The digital worker vests will monitor personnel within the work zone to enhance work zone safety.
Continuous Operating Reference Station (CORS)	Used in conjunction with Global Navigation Satellite System (GNSS) and Inertial Navigation System (INS) for correction of positional data generated by the MAPVAN. Also used to disseminate Real Time Kinematic (RTK) positional correctional signals to the CMU-AV to enhance location accuracy. PSU's CORS will be used for closed-track testing. A subscription service will be used for live on-road testing environments.
Data Management System	Cloud-based system for the ADS project and will be used for data archiving, data versioning, managing application programming interfaces (API) and securing data exchanges to, from, and at rest within storage container(s). Collects data from connected devices used during testing.
Ancillary Field Equipment	Includes walkie-talkies for communication among test teams, measuring tapes, temporary marking paint and chalk, tents/canopies, etc.
Roadside Support and Construction Equipment	Includes channelizers, truck mounted attenuator, portable message signs, barrels, cones, barriers, signs, temporary traffic signals, personal protective equipment, and arrow board equipment. Also includes construction vehicles and machinery such as trucks, lifts, pavement marking equipment, and other equipment necessary to set up the work zone scenarios.
Special Test Tools and Instruments	Includes special test tools and instruments needed for testing such as packet sniffers, radio frequency readers, sensor calibration devices, etc.

Source: PennDOT

**Collectively referred to as Roadway Environment (RWE)*

Additional context regarding the tools and instruments identified above is provided in the **System Requirements** document and the **Deployment Plan**.

4.5 Test Team Roles and Responsibilities

Roles and responsibilities of the test team are defined in **Table 5**.

Table 5 – Testing Roles and Responsibilities

Tester	Roles	Responsible Party
Safety Driver	• Drives the CMU-AV when not in autonomous mode • Brings the CMU-AV to the test start position • Activates autonomous mode when signaled by the Safety Associate of test commencement • Intervenes during CMU-AV malfunction • Resumes manual control of the CMU-AV when the test run is complete and enters staging area for data off-load	CMU
Safety Associate	• Operates equipment on-board the CMU-AV • Monitors the software and hardware status in near real-time • Calibrates the CMU-AV sensors • Signals test commencement • Disengages autonomous mode remotely to stop the CMU-AV in the event complications arise • Sends CMU-AV test data to the DMS	CMU
Data Manager	• Manages map data generated by the MAPVAN • Manages data generated by the CMU-AV test in the DMS • Manages test results and documentation uploaded to the DMS • Ensures the data is processed and formatted correctly and is ready for use and dissemination	Deloitte, CMU, PSU

Tester	Roles	Responsible Party
Simulation Operator	• Initially imports map data from the DMS and loads it into the Simulation System • Configures the work zone within the Simulation System map • Generates traffic within the Simulation System • Once the Simulation System is ready the operator starts and stops the simulation test • Stops or resets the test upon navigational failure • Once the test has been simulated, the resulting data is reviewed and sent to the DMS	CMU, PSU
Data User/ Researcher	• Queries data from the DMS to prepare reports and to conduct research	CMU, PSU, PennDOT Central Office, PennDOT District, PPG, USDOT
Mapping Equipment Operator	• Initially logs into the MAPVAN equipment • Starts the mapping equipment and calibrates before the test • Notifies the testing team when ready to begin and signals the MAPVAN Driver to start navigating the work zone • Upon exiting the work zone, the Mapping Equipment Operator stops the mapping equipment • Mapping of the work zone is repeated as necessary • Once the MAPVAN Driver has stopped within the staging area, the Mapping Equipment Operator removes the MAPVAN's hard drive and connects to the Map Processing Equipment • Processes MAPVAN data and uploads MAPVAN data and HD maps to the DMS	PSU

Tester	Roles	Responsible Party
MAPVAN Driver	• Brings the MAPVAN to the START location of the test zone • Upon go-ahead signal, the driver navigates through the work zone • Repeats navigation as necessary • Once mapping data has been taken the MAPVAN Driver ends at the staging area	PSU
Work Zone Operator	• Sets up work zone for the specific scenario. Refer to the Temporary Traffic Control Guidelines Publication 213 and **Deployment Plan** for each test scenario layout • Applies coatings to the designated work zone objects • Places the RWE equipment in the designated positions • Configures, calibrates, and activates RWE equipment • Paints roadway lines and markings • Disassembles and rearranges the work zone as required	PennDOT District, PennDOT County, PPG, Pennsylvania Turnpike Commission (PTC), V2X Vendor, Contractor* *In the event a contractor is used during the live test they will be responsible for acting as the role of the Work Zone Operator.
Other Driver	• Drives another vehicle in a work zone during closed-track testing and live testing • Drive the paint truck • Drive equipment vehicles	PSU, PennDOT Central, PennDOT District, PennDOT County
Field Testing Management and Support Staff	• Coordinates and supports testing activities among test teams present on-site • Monitors test team safety • Ensures proper test procedures are followed and completed • Gathers completed field testing documentation from all test teams performing testing activities • Uploads field testing documentation to the DMS	PennDOT, HNTB, PSU, CMU, Baker, Drive

Source: PennDOT

4.6 Test Criteria

This section defines test criteria for the project including the level of autonomy anticipated, pass/fail items, and testing in various weather conditions.

4.6.1 Level of Autonomy Anticipated

The CMU-AV is a level 4 autonomous driving vehicle. Level 4 is considered to be a highly automated vehicle which can handle highly complex urban driving situations with little to no user intervention.

4.6.2 Performance Measures

ADS project performance measures are defined and described in detail in the **Project Evaluation Plan**. Performance measures as they relate to each demonstration testing procedure are identified in the procedure tables provided in **Chapter 6** of this plan. All data required to evaluate the project will be collected by the project team during experimentation, simulation, closed-track, and live on-road test runs as described in the **Project Evaluation Plan**.

4.6.3 High-Level Pass Criteria

This section identifies high-level pass criteria for each test procedure included in this plan. The high-level pass criteria define, in general terms, what is required for a test procedure to pass. **Table 6** below identifies the test procedures and associated high-level pass criteria to aid the project team in determining whether a test procedure passes or fails overall, and in turn, whether any data captured during the test procedure is valid for purposes of evaluation. For a test to successfully pass, the system being tested must meet the high-level pass criteria identified below by exhibiting all of the associated expected results identified each step of the test procedure. Expected results for demonstration testing are indicated in the test procedures provided in **Chapter 6**. Steps specific to the DMS are provided in **Appendix A.**

Table 6 – High-Level Pass Criteria

Test Cases	Pass Criteria
Work Zone Scenario Setup	PATA or PTS work zone scenario is setup properly per the approved designs and all RWE devices are installed, configured, and ready for work zone connectivity testing.
Work Zone Connectivity	Data is transmitted, received, and processed successfully among all RWE devices, CORS, DMS, and CMU-AV.

Test Cases	Pass Criteria
HD Mapping	MAPVAN traverses the work zone setup and successfully collects raw data without errors in object detection/classification or receiving alerts from its internal health verification system. Validated raw data is processed into a validated HD map, which is successfully uploaded to the DMS.
Microsimulation	CARLA and CADRE simulation software run in sync with less than 10ms of latency. The HD map successfully loads from the DMS into the simulation system, and the ego vehicle is able to successfully navigate the work zone scenario without errors. Simulation data is processed and uploaded to the DMS successfully.
Macrosimulation	CARLA and SUMO simulation software run in sync with less than 10ms of latency. The HD map successfully loads from the DMS into the simulation system, and the ego vehicle is able to successfully navigate the work zone scenario linked to the SUMO roadway traffic network without errors. Simulation data is processed and uploaded to the DMS successfully.
Closed-track and Live On-Road Work Zone Navigation	CMU-AV navigates towards the work zone and autonomous mode is activated. CMU-AV receives notification that it is approaching the work zone*, receives the HD map*, and traverses the work zone safely without manual intervention. While traversing the work zone, CMU-AV detects V2X work zone objects*, transmits/receives BSM*, and collects/stores CMU-AV operational data on the OBU. Aggregated CMU-AV BSM and operational data is successfully uploaded to the DMS. *if applicable per testing permutation
Data Management System Verification	DMS successfully transmits and receives data from the HPC, PSU-RMC, and CMU-RMC. Users can successfully access the DMS and perform data storage and retrieval activities, as appropriate for their respective user group and DMS use case. DMS pass criteria differs among user groups and use cases. For a DMS test to pass, a user must be able to successfully complete each step in the DMS verification procedures provided in **Appendix A**.

Source: PennDOT

4.6.4 Testing in Various Weather Conditions

Generally, testing will occur in fair weather conditions. Testing under best case scenarios, such as fair weather, will allow the project team to develop a consistent baseline for comparison of testing data. Testing will be conducted in both daytime and nighttime light conditions.

Testing under adverse weather conditions (i.e. rain, fog, etc.) will be considered if initial testing is successful and sufficient time and budget is available for additional testing. Testing will not occur during any weather condition deemed unsafe or otherwise extreme.

4.7 Test Deliverables

As testing is performed, the project team will produce documentation to log each test procedure performed, results of each test, and any additional notes/observations. Test deliverables will consist of a summary report for each test performed for every work zone scenario and permutation, as well as completed test procedures tables provided in **Chapter 6** of this plan. At the conclusion of testing, test deliverables will be compiled and used to analyze results and develop a final evaluation report of the project during the post-deployment project phase.

Chapter 5: Test Scenarios

This section provides an overview of test scenarios for the core functionalities of the ADS system. The scenario details column indicates key functional items that will be tested as part of the test procedures detailed in **Chapter 6.**

Table 7 – Test Scenarios

High Level Requirement	Scenario Description	Scenario Details
CMU-AV Functional Verification (CMU-AV System)	CMU-AV is a level 4 automated vehicle capable of operating in a virtual world and limited real-world environment. Given an HD map, the CMU-AV (i.e., ego-vehicle) is expected to read the map correctly and perform the dynamic driving task (DDT), using the CADRE stack to navigate a work zone while following the rules of the road.	• Assumed fault analysis and verification has been conducted to ensure the CMU-AV is free from hardware bugs, random hardware failures, systemic software failures and failures in the interaction between the vehicle hardware and software • Demonstrate that the CMU-AV data logger captures operational data (i.e., fused data elements including sensor data, object detection and classification, location on road, speeds driven, performance data, etc.) and does not record all streaming sensory data • Demonstrate that the CMU-AV shall be capable of independent object detection and collision avoidance • Demonstrate the CMU-AV is capable of transmitting and receiving SAE J2735-defined basic safety message (BSM) over a DSRC and C-V2X wireless communications link • Demonstrate the safety driver can manage/terminate the operation of the vehicle • Demonstrate the CMU-AV can receive a high-definition map file from the roadway environment in {SAE encoded} format via DSRC/C-V2X

High Level Requirement	Scenario Description	Scenario Details
		• Demonstrate the CMU-AV can receive a high-definition map file via a private 4G or 5G network from roadside equipment in various formats, which could include XML, JSON, GEOJSON, GML, KML, KMZ, SHP, SHX, DBF, GPX, etc. • Demonstrate the CMU-AV can receive notifications of an approaching work zone prior to entering it
MAPVAN Functional Verification (PSU's MAPVAN System)	Verify, MAPVAN is mapping data acquisition to create a digital representation of the construction zone in a high-definition map.	• Demonstrate the MAPVAN can log all sensor data when driven manually • Verify the MAPVAN is able to collect and store OBU data • Verify the MAPVAN is able to collect and store sensor data • Verify the MAPVAN data can be uploaded to the DMS from the PSU-RMC • Verify data flow between internal database to external cloud server to CMU-AV
Vehicle Simulation System	The micro simulator tool for the connected and autonomous driving research and engineering (CADRE) stack is responsible for operating the CMU-AV in a limited virtual world. Given a map, the simulated CMU-AV (i.e., the ego vehicle) drives along those roads along a given path, with a limited number of objects able to be injected into the simulator for testing.	• Demonstrate CARLA is integrated and fully functional prior to the start of the test • Demonstrate CADRE is integrated and fully functional prior to the start of the test • Verify the HD map can be loaded correctly • Verify the ego vehicle can read the map correctly • Verify the ego vehicle can follow the rules of the road (i.e., stop at stop lights, react to traffic, etc.) • Verify the ego vehicle can drive along the given path navigating {X m/ft.} from the mapped construction zone boundary

High Level Requirement	Scenario Description	Scenario Details
Traffic Simulation System	For the project, SUMO will be used to generate a simplified representation of the CMU-AV behavior as simulated by the CARLA tool, testing how it interacts with traffic via simulation.	• Demonstrate CARLA is integrated and fully functional prior to the start of the test • Demonstrate SUMO is integrated and fully functional prior to the start of the test • Demonstrate the closed/open-track connection of roads in the virtual environment that make up the closed-track roadway network include {highway, arterial, etc.} at a {radial distance} from closed-track test site • Verify that source destination densities are calibrated such that the simulator is able to match real-world traffic flows at particular measurement locations, which should include intersections with traffic light timing calibrations to the real world as well
Research Centers	The PSU-RMC is responsible for processing the data collected during mapping of the work zone and conducting traffic simulation. The CMU-RSC is responsible for conducting vehicle simulation and other activities carried out for the project.	• Verify the PSU-RMC can establish a secure tunnel via virtual private network to send data to the DMS • Verify the CMU-RMC can establish a secure tunnel via virtual private network to send data to the DMS
Roadside Units	The RSU is serving as DSRC and C-V2X communication radios. The aggregation, processing and responding to data received from the roadside will be offloaded to a	• Verify the RSU shall receive BSM broadcasts from vehicles in its vicinity • Demonstrate the RSU shall broadcast SAE J2735 compliant MAP messages • Demonstrate RSU is capable of providing channel assignments and operating instructions to OBUs in its communications zone

High Level Requirement	Scenario Description	Scenario Details
	connected high-performance computing system.	• Verify the RSU shall broadcast SAE J2735 compliant messages using DSRC and C-V2X communication standards • Verify the RSU can offload messages • Demonstrate the RSU is capable of transmitting messages over DSRC to the CMU-AV within the roadway environment in {SAE encoded} format • Demonstrate the RSU is capable of transmitting messages over C-V2X to the CMU-AV within the roadway environment in {SAE encoded} format • Verify the RSU is capable of transmitting messages over a private {Zigbee, Wi-Fi} roadside network to the CMU-AV and capable of receiving a high-definition map file from {roadside equipment} in {XML, JSON, GEOJSON, GML, KML, KMZ, SHP, SHX, DBF, GPX, etc.} formats
Edge HPC	The Edge HPC aggregates and logs data from the CMU-AV. It serves as the facilitator of information exchange between the RSU and cloud environment (i.e., DMS).	• Demonstrate the HPC can transmit HD maps files in {XML, TXT, etc.} format received from the DMS to the CMU-ADS OBU via {Zigbee, LTE, WiFi} • Demonstrate the HPC can collect, aggregate, and log BSM messages received from the RSU and transmit to the DMS • Verify the HPC can aggregate position information from GPS equipped work zone devices and transmit securely {SSL, TLS, IPSec} over {Zigbee, LTE, WiFi} to the DMS for archival • Demonstrate the HPC shall provide administrative access to authenticated users from the local network and remotely through a virtual private network interface

High Level Requirement	Scenario Description	Scenario Details
V2X Work Zone Objects	V2X work zone objects represent connected work zone objects including construction vehicles, barriers, cones, and other safety equipment. Monitored within the work zone to enhance work zone safety.	• Verify the V2X work zone objects are instrumented with GPS communication devices • Verify the V2X work zone objects are capable of securely transmitting data over {Zigbee, LTE, Wi-Fi} • Verify the V2X work zone objects can provide location information from its GPS device to the {Base Station, HPC}
Digital Worker Vests	Digital vest represents the personnel at the work zone that perform maintenance and construction field activities including vehicle operators, field supervisory personnel, field crews, and work zone safety personnel. The digital worker vests will monitor personnel within the work zone to enhance work zone safety.	• Verify the digital worker vests are instrumented with GPS communication devices • Verify the digital worker vests are capable of securely transmitting data over {Zigbee, LTE, Wi-Fi} • Demonstrate the digital worker vests can provide location information from its GPS device to the {Base Station, HPC}
Data Management System	The DMS for this project performs as an archive data center. From the transportation perspective, the ITS archive data system serves to collect, archive, manage, and distribute data generated from ITS sources for administration purposes, for policy evaluation, safety, planning, performance	• Demonstrate secure data exchange among DMS and other ADS project system components (HPC, simulation system, PSU-RMC, CMU-RMC, etc.) • Demonstrate the membership-based access control list (ACL) • Demonstrate the project team's ability to access and use the DMS Web Application • Demonstrate the USDOT's ability to access and use the DMS Web Application

High Level Requirement	Scenario Description	Scenario Details
	monitoring, program assessment, operations, and supports research applications	• Demonstrate the public's ability to access and use the DMS Public Web Application

Source: PennDOT

Chapter 6: ADS Demonstration Test Procedures

This section includes step by step procedures to test the key functional items identified within the test scenarios identified in **Chapter 5**. The procedures are provided in a table format, providing a checklist and mechanism to document test results, as well as additional notes/observations, punchlist items, or system defects and significant deviations from designs.

The test procedures provided in this chapter are intended to be modular and can be applied to all PATA and PTS work zone scenario demonstrations. Any deviations or caveats to procedural applicability for specific scenarios or test permutations are identified within the following subsections where necessary. The procedures required for demonstration testing that will be performed throughout the deployment phase of the project are outlined below. Each procedure will be led by a test team consisting of a combination of the roles described in **Section 4.5**.

Work zone scenario setup and verification procedures provide the steps required for setting up PATA and PTS work zone scenarios and installing, configuring, and calibrating associated RWE devices in the field. The goal of the procedure is to verify the work zone scenarios are setup in accordance with approved work zone designs detailed in the ADS project **Deployment Plan**. Work zone scenario setup and verification procedures will be completed by PennDOT and its contractors, with support from field testing management and support staff.

Initial work zone connectivity verification procedures outline the steps required for verifying communications among connected devices present within the work zone scenario to ensure the work zone is ready for subsequent field testing activities. Initial work zone connectivity verification procedures will be completed by PennDOT and its contractors, with support from field testing management and support staff.

HD mapping procedures define the steps required for HD map data collection in closed-track and live on-road environments. HD mapping procedures will be completed by PSU with support from field testing management and support staff.

Microsimulation testing (vehicle navigation simulation) procedures list the steps required for running CMU-AV work zone navigation simulations using CARLA and CADRE software on the CMU-RMC. Microsimulation testing procedures will be completed by CMU.

Macrosimulation testing (traffic simulation modeling) procedures list the steps required for running CMU-AV work zone navigation simulations within a linked traffic network using CARLA and SUMO software on the PSU-RMC. Microsimulation testing procedures will be completed by CMU.

Closed-track and live on-road CMU-AV work zone navigation procedures describe the steps required to conduct CMU-AV work zone navigation demonstrations in closed-track and live on-road environments. Closed-track and live on-road CMU-AV work zone navigation procedures will be completed by CMU with support from field testing management and support staff.

*Please Note: Testing procedures outlined above will not necessarily be completed in the order listed. For example, work zone scenario setup and verification, initial work zone connectivity verification, and HD mapping will need to be performed again after simulation testing and before closed-track or live on-road testing if a work zone layout or testing location were to change. The project team will coordinate testing efforts to maximize the efficiency of work zone setups and subsequent mapping and testing that will occur. The exact process of transitioning between test procedures and the decision gates required are described in the **Deployment Plan**.*

6.1 Work Zone Scenario Setup and Verification Procedures

This procedure defines required steps for the set up and verification of PATA and PTS work zone scenarios prior to HD mapping, simulation testing, closed-track testing, and live on-road testing. This procedure will need to be repeated throughout the project deployment phase to accommodate changes in PATA and PTS work zone layouts, testing permutations, and testing stages.

Table 8 – Work Zone Scenario Setup and Verification

Test Name	**Work Zone Scenario Setup and Verification**
Test Stage and Permutation	
Date Performed	
Location	
Objectives	Prepare the work zone layout for HD mapping, simulation system setup, and CMU-AV navigation per the approved PATA and PTS work zone designs provided in the project **Deployment Plan**
Prerequisites	• Work zone PATA and PTS scenario design, review, and approval • Approval from PennDOT and proper staffing arrangements made prior to beginning closed-track and live on-road testing as per work zone testing application form requirements and AV testing regulations in the state of Pennsylvania (ref. SRD section 2.2 RG-014)

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	• Identify setup location on test track (includes start location for MAPVAN/CMU-AV and staging area) • Procure and deliver all equipment to test track and stage in secure storage, as needed • Agreements with contractors for work zone setup are executed • The closed-track and live on-road roadways are clear from debris, unwanted obstructions, etc. • All testing personnel are equipped with personal protective equipment
Equipment and Environment	• PSU Test Track and live on-road environments • Channeling devices • Road signs • Communications equipment (RSU, Edge HPC, etc.) • V2X work zone objects and worker vests • Other work zone vehicles (if applicable) • Personal protective equipment (PPE)
Method of Verification	Inspection
Notes/Additional Information	• If there is a need to deviate from the standard Pub. 213 PATA or PTS 900 series layout, any deviation must be noted in the approved designs. • It is possible for some scenarios to use a Shadow Vehicle (SV) in lieu of channeling devices. Verify proper use of channeling devices or SV in the approved designs. • Steps provided below shall be applied as necessary to correspond with required testing permutations identified in **Table 3.** The test team shall make a note in the comments section of this form to indicate step(s) that may not apply to the testing permutation being setup.

Procedures

Step	Description	Check	Comments
1	Mark MAPVAN and CMU-AV start location using channeling devices, paint marker, etc. per approved PATA or PTS work zone layout designs		

Step	Description	Check	Comments
2	Establish geofenced work zone from base set criteria and approved PATA or PTS work zone scenario designs		
3	Cover or remove existing pavement markings as necessary. Paint roadway lines/markings per approved PATA or PTS work zone layout designs		
4	Arrange the work zone objects and equipment on the test track in accordance with approved PATA or PTS work zone layout designs		
5	Install, configure, and calibrate RWE communications devices per approved PATA or PTS work zone layout designs		
6	Install V2X work zone objects and worker vests per approved PATA or PTS work zone layout designs		
7	Apply enhanced coatings per approved PATA or PTS work zone layout designs (as applicable for testing permutation)		
8	Store all unused equipment and work zone objects in the designated secure location		
9	Inspect work zone setup to verify it matches the approved PATA or PTS work zone layout design. Ensure the roadway is clear of debris and unwanted obstructions.		

Source: PennDOT

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6.2 Initial Work Zone Connectivity Verification Procedures

This procedure defines required steps to verify communications among ADS project system components after the PATA or PTS work zone scenario setup has been approved. Communications will be verified once daily for each PATA or PTS work zone scenario setup prior to performing HD mapping, closed-track testing, or live on-road testing procedures. Additionally, this procedure will need to be repeated throughout the project deployment phase to verify communications after changes in PATA and PTS work zone layouts and testing locations.

Table 9 – Initial Work Zone Connectivity Verification

Test Name	Initial Work Zone Connectivity Verification
Test Stage and Permutation	
Date Performed	
Location	
Functions Tested	Data dissemination (map, GPS positioning, BSMs, CORS, etc.)
Test Objectives	Verify all data is being received, processed, and transmitted properly among connected work zone devices, RSU, Edge HPC, the DMS, and the CMU-AV.
Equipment and Environment	• Test Track and live on-road environments • CMU-AV • Edge HPC • DMS • V2X work zone objects • Digital worker vests (GPS) • RSU • CORS

Performance Measures Evaluated	• Connection Drop • Data Standards Incompatibility
Prerequisites	• Work zone scenario setup and verification procedures have been completed and have been reviewed and approved • Base map data (generated during experimentation) has been transferred to DMS • The closed-track and live on-road roadways are clear from debris, unwanted obstructions, etc. • All testing personnel are equipped with personal protective equipment
Notes / Additional Information	• The HPC facilitates data transfer to/from the DMS to RSU and the transfer of CORS positional correction data to RSU • GNSS passes positional data to RSU directly • SAE J2735 Basic Safety Messages (BSM) will be transmitted and received by the CMU-AV via DSRC and C-V2X wireless communications • HD maps will be received by the CMU-AV by DSRC and C-V2X in SAE format • HD maps will be received by the CMU-AV over a private Zigbee or Wi-Fi roadside network in XML, JSON, GEO, JSON, GML, KML, KMZ, SHP, SHX, DBF, GPX, etc. format • Communications verification must be completed for DSRC, C-V2X, Zigbee, and Wi-Fi communications types separately

Test Procedures

Step #	Procedure	Expected Result	Pass/Fail	Comments
1	The work zone operator powers-up all RSU, V2X work zone objects, and digital worker vests present in the work zone scenario	Each RSU, V2X work zone object, and digital worker vest will be powered and will have an active radio signal broadcasting		
2	The safety driver activates the CMU-AV and, in turn, the OBU	The CMU-AV will be running and the OBU will have an active signal reception		

Step #	Procedure	Expected Result	Pass/Fail	Comments
3	The work zone operator powers on the CORS reference station server	The CORS reference station is activated		
4	Broadcast location and RTK data to the RSU from the CORS system	CORS data will be ingested by the RSU and transmitted to the CMU-AV		
5	The safety associate verifies location and RTK data is received by the CMU-AV OBU	CMU-AV OBU receives RTK positional correction data		
6	The work zone operator verifies access to the HPC over secured VPN on work zone Wi-Fi network. The work zone operator pings all RSU, V2X work zone objects, and digital worker vests from the HPC	HPC is accessible over the work zone Wi-Fi network. All RSU, V2X work zone objects, and digital worker vests respond to pings from the HPC		
7	The work zone operator verifies connectivity to DMS. The data manager transmits base map (generated during experimentation) to the HPC	Base map is received by the HPC		
8	The safety associate verifies base map data is received by the CMU-AV over the roadway Wi-Fi network	The OBU receives the base map over Wi-Fi		

Step #	Procedure	Expected Result	Pass/Fail	Comments
9	The safety associate verifies base map data is received by the CMU-AV from the RSU	The OBU receives the base map from the RSU		
10	The work zone operator verifies the RSU, V2X work zone objects, and digital worker vests are broadcasting their geographical position	RSU, V2X work zone objects, and digital worker vests transmits positional data to the OBU. The OBU receives RSU, V2X work zone objects, and digital worker vests locations		
11	The safety associate verifies CMU-AV OBU can transmit Basic Safety Messages (BSM)	BSM are transmitted from OBU and are received by the RSU		
12	The work zone operator verifies RSU transmits BSM received from the CMU-AV to the HPC	HPC receives BSM from the RSU		
13	The safety associate verifies RSU can transmit Signal Phase and Timing (SPaT)/MAP messages*	SPaT/MAP messages are transmitted from RSU and are received by the OBU		
14	The safety associate verifies CMU-AV OBU time synchronization with RSU	The RSU and OBU do not have significant time delays; messages are passed between RSU and OBU in near real-time		

Source: PennDOT

** Only applies to PATA work zone scenarios that include traffic signals*

6.3 HD Mapping Procedures

This procedure defines required steps to generate HD maps after the PATA or PTS work zone scenario has been setup and initial work zone connectivity has been verified, and prior to simulation testing, closed-track testing, and live on-road testing procedures. This procedure will need to be repeated throughout the project deployment phase to create new HD maps after changes in PATA or PTS work zone layouts.

Table 10 - HD Mapping Procedures

Test #/Name	HD Mapping
Test Stage and Permutation	
Date Performed	
Location	
Functions Tested	• HD map data collection and storage • HD map generation • HD map transmittal to DMS • HD map dissemination to the simulation system and HPC
Test Objectives	Ensure the PSU MAPVAN can collect data and generate an HD map by traveling through work zone scenarios: • Evaluate the impact of providing HD mapping of work zone objects (i.e., cones, barrels, workers, vehicles) • Improve the map information dissemination process from the mapping providers and/or infrastructure owners/operators to the AVs through standardization of digital mapping information for work zones

Equipment and Environment	• Test-track and live on-road environments • Work zone equipment and objects as defined by approved PATA and PTS work zone scenario designs • PSU MAPVAN • PSU-RMC back-office processing computer • CORS • DMS
Performance Measures Evaluated	• Binary Mapping Error • Binary Presence Error • Accuracy
Prerequisites	• Work zone scenario setup and verification test procedures have been completed, passed, and have been approved • Initial work zone connectivity verification test procedures have been completed, passed, and have been approved • Sensor calibration preprocess has been completed by PSU • Initial MAPVAN health verification process has been completed • The closed-track and live on-road roadways are clear from debris, unwanted obstructions, etc. • All testing personnel are equipped with personal protective equipment

Notes / Additional Information	• The PSU MAPVAN navigates along the ideal path through the given work zone scenario and collects/logs data. PSU MAPVAN data is processed, and an HD map is generated and sent to the DMS. The HD map is stored and accessible from the DMS • For every hour of data collection, it takes 10 hours of processing time, therefore the HD map will be available to consuming systems (DMS, CMU-AV, simulation systems) the day after mapping takes place • HD map runs will be completed before and after AV traversal of the work zone to obtain before and after datasets for comparison • For each PATA and PTS work zone setup, the MAPVAN will make a minimum of three (3) consecutive HD mapping runs to allow for map data validation through comparison of mapping data captured during each run • See UC1-S2 in ConOps for degraded operating conditions • See UC1-S3 in ConOps for failure operating conditions

Test Procedures

Step #	**Procedure**	**Expected Result**	**Pass/Fail**	**Comments**
1	The MAPVAN driver brings the MAPVAN to the start position	The MAPVAN is readied for mapping run		
2	The mapping equipment operator commences mapping run by signaling the MAPVAN driver and field testing management/support staff and initiating MAPVAN data collection	MAPVAN data collection begins and the MAPVAN driver begins to traverse the work zone		

Step #	Procedure	Expected Result	Pass/Fail	Comments
3	The MAPVAN driver navigates the PATA or PTS work zone scenario. The mapping equipment operator monitors the health verification process throughout the mapping run to flag any issues that occur during mapping	A full navigation of the PATA or PTS work zone scenario is conducted successfully without any issues alerted by the health verification process		
4	The mapping equipment operator monitors MAPVAN progress through the work zone. Immediately upon completion of navigation through the work zone, the mapping equipment operator stops data collection function	MAPVAN data collection stops		
5	The MAPVAN driver resets to the starting position, or navigates to the next PATA or PTS work zone setup	The MAPVAN is setup to perform additional map data collection runs		
6	Repeat steps 3-6 as necessary for additional PATA or PTS work zone scenarios that are ready to map	N/A		

Step #	Procedure	Expected Result	Pass/Fail	Comments
7	After sufficient data collection, the Mapping Equipment Operator signals the MAPVAN Driver to head to the staging area upon final work zone exit	The MAPVAN heads to the staging area		
8	The MAPVAN Driver parks the MAPVAN within the staging area and notifies field testing management/support staff that mapping runs are complete	The MAPVAN Driver parks for data off-load		
9	The mapping equipment operator shuts down all equipment and removes the MAPVAN data hard drive	The hard drive with the mapping data is disconnected from the MAPVAN		
10	The mapping equipment operator takes the MAPVAN data hard drive to the PSU-RMC processing computer	N/A		

Step #	Procedure	Expected Result	Pass/Fail	Comments
11	The mapping equipment operator connects the MAPVAN hard drive to the PSU-RMC processing computer and validates the sets of raw map data collected for each PATA or PTS work zone scenario by comparing the datasets collected through multiple mapping runs	The raw map data collected from multiple mapping runs of the PATA or PTS work zone is free from errors and deviations of raw data captured in each run (i.e., failure to detect a sign, cone, etc.)		
12	The mapping equipment operator processes the raw map data	The PSU-RMC processes the raw MAPVAN sensor data into an HD map. For every hour of data collection, processing takes approximately 10 hours		
13	The mapping equipment operator verifies successful generation of an HD map from the PSU-RMC. The mapping equipment operator validates map by comparing the HD map generated from the raw data captured in multiple runs.	An HD map was generated successfully and HD map is valid		

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Step #	Procedure	Expected Result	Pass/Fail	Comments
14	Within 24 hours of HD map generation, the mapping equipment operator sends the HD map file to the DMS via the established virtual private network. The mapping equipment operator coordinates with the data manager to verify the HD map file has been received and is stored on the DMS	HD map file is successfully transmitted to the DMS and is available for dissemination to the simulation systems and HPC		

Source: PennDOT

6.4 Microsimulation Testing Procedures (Vehicle Simulation)

This procedure defines required steps to perform CMU-AV navigation simulations after all PATA and PTS work zone scenarios have been setup and HD maps for all PATA and PTS work zone scenarios have been created. Microsimulation will occur prior to macrosimulation, closed-track testing, and live on-road testing procedures. All PATA work zone scenarios being tested at the Penn State test track must be simulated and approved/cleared by the project team for closed-track testing. Likewise, all PTS work zone scenarios being tested in the limited on-road environment must be simulated and approved/cleared by the project team for live on-road testing.

Table 11 - Microsimulation Testing Procedures (Vehicle Simulation)

Test #/Name	Vehicle Simulation Testing
Test Stage and Permutation	
Date Performed	
Location	
Functions Tested	• CMU-AV navigation through simulated PATA and PTS work zone scenarios • Simulation data collection, retrieval and processed for work zone mapping and traffic simulation

Test Objectives	• Simulation System software can be integrated with DMS data to import real-world cases:
	  ○ Accurately represent field conditions encountered by the CMU-AV
	  ○ Predict behaviors outside those that were tested
	• Assess ADS performance and infrastructure interaction in a virtual environment
	  ○ Perform Simulation System Virtual CMU-AV Navigation:
	    ▪ Ensure simulated CMU-AV (ego vehicle) can navigate through mapped simulated work zone scenario
	    ▪ Demonstrate ego vehicle can detect and respond to obstacles – moving and static
	      • Ego vehicle can navigate given work zone path with simulated traffic and environments– "X m/ft" from work zone boundaries
	• Ensure ADS performance data can be sent to DMS

Equipment and Environment	• Virtual environment • CMU-RMC • Vehicle Simulation Systems (CADRE and CARLA) • DMS

Performance Measures Evaluated	• Data latency • Data Standards Incompatibility • Excessive hard braking • Hard swerving • Lateral distance • Longitudinal distance • Velocity • Time to collision • Time to lane crossing/departures • Detection range • Detection accuracy • Classification accuracy
Prerequisites	• CARLA and CADRE integration and interfaces have been verified • Work zone scenario setup and verification test procedures have been completed, passed, and have been approved • Initial work zone connectivity verification test procedures have been completed, passed, and have been approved • HD mapping procedures have been completed, passed, and have been approved • Map accuracy has been validated through repeated mapping runs and analysis of HD maps generated • Map data transferred to DMS
Notes / Additional Information	• This procedure will be repeated for each PATA and PTS work zone scenario map generated and stored on the DMS as well as under daytime and nighttime testing permutations • Simulation is exempt from testing permutations related to connectivity and enhanced coatings • See UC2-S2 in ConOps for degraded operating conditions • See UC2-S3 in ConOps for failure operating conditions • Simulated CMU-AV and ego vehicle are terms used interchangeably

Test Procedures				
Step #	**Procedure**	**Expected Result**	**Pass/Fail**	**Comments**
1	Simulation operator loads the CARLA simulation software and CADRE vehicle simulator. Simulation operator analyzes CARLA and CADRE time stamps to determine system latency for synchronization	CARLA and CADRE load properly and are in sync with less than 10ms latency		
2	Simulation operator engages digital twin of work zone and loads PATA or PTS work zone map from the DMS	HD map successfully loads in the simulation system Digital HD-map accurately represents field conditions expected within PATA or PTS work zone scenarios scenario		
3	Simulation operator starts specified PATA or PTS work zone scenario simulation	Vehicle navigation simulation begins		
4	Simulation operator engages ego vehicle	Ego vehicle follows operator commands. Simulation Operator can start, stop and restart simulation		
5	Simulation operator inputs designated route for ego vehicle	Ego vehicle has successfully received designated route information		

Step #	Procedure	Expected Result	Pass/Fail	Comments
6	Simulation operator monitors system status in real-time	Simulation Operator verifies systems are fully operational and/or can identify periods in which the system was not operational		
7	Ego vehicle navigates through specified PATA or PTS work zone scenario	CARLA begins to feed simulated sensor data to CADRE. CADRE issues driving commands to the ego vehicle. Ego vehicle navigates the designated PATA or PTS work zone scenario with work zone assets properly according to PATA or PTS Navigation Checklists (See ***Section 6.7***).		
8	Simulation Operator monitors progress of simulation.	Simulation Operator can view completion percentage and any errors that may impact simulation.		
9	Ego vehicle completes navigation through desired PATA or PTS work zone simulation	Simulation operator verifies simulation complete by reviewing simulation result data		
10	Simulation operator ends simulation testing	Simulation stops		
11	Simulation operator collects simulation data	Virtual camera and LIDAR data, safety data, operations data, and performance data are collected and processed		

Step #	Procedure	Expected Result	Pass/Fail	Comments
12	Simulation operator uploads simulation data to the DMS	All vehicle simulation data are transferred to DMS. Data are stored and available for analysis		

Source: PennDOT

6.5 Macrosimulation Testing Procedures (Traffic Simulation)

This procedure defines required steps to conduct traffic impact simulation testing for all PATA and PTS work zone scenarios prior to closed-track testing, and live on-road testing procedures. All PATA work zone scenarios being tested at the Penn State test track must be simulated and approved/cleared by the project team for closed-track testing. Likewise, all PTS work zone scenarios being tested in the limited on-road environment must be simulated and approved/cleared by the project team for live on-road testing.

Table 12 – Macrosimulation Testing Procedures (Traffic Simulation)

Test #/Name	Traffic Simulation Testing
Test Stage and Permutation	
Date Performed	
Location	
Functions Tested	• CMU-AV navigation through simulated PATA and PTS work zone scenarios in a connected roadway network • Simulation data collection, retrieval and processed for work zone mapping and traffic simulation

Test Objectives	• Simulation System software can be integrated with DMS data to import real-world cases:
	    ○ Accurately represent field conditions encountered by the CMU-AV
	    ○ Predict behaviors outside those that were tested
	• Assess ADS performance and infrastructure interaction in a virtual environment
	• Evaluate traffic flow impacts on a connected roadway network of an AV navigating through PATA and PTS work zone scenarios
	    ○ Perform Simulation System Virtual CMU-AV Navigation:
	        ▪ Ensure simulated CMU-AV (ego vehicle) can navigate through mapped simulated work zone scenario
	        ▪ Demonstrate ego vehicle can detect and respond to obstacles – moving and static
	            • Ego vehicle can navigate given work zone path with simulated traffic and environments– “X m/ft” from work zone boundaries
	• Ensure ADS performance data can be sent to DMS

Equipment and Environment	• Virtual environment • PSU-RMC • Vehicle and Traffic Simulation Systems (CARLA, SUMO) • DMS

Performance Measures Evaluated	• Data latency • Data Standards Incompatibility • Excessive hard braking • Hard swerving • Lateral distance • Longitudinal distance • Velocity • Time to collision • Time to lane crossing/departures • Detection range • Detection accuracy • Classification accuracy
Prerequisites	• CARLA and SUMO integration and interfaces have been verified • Work zone scenario setup and verification test procedures have been completed, passed, and have been approved • Initial work zone connectivity verification test procedures have been completed, passed, and have been approved • HD mapping procedures have been completed, passed, and have been approved • Map data transferred to DMS

Notes / Additional Information	• This procedure will be repeated for each PATA and PTS work zone scenario map generated and stored on the DMS as well as under daytime and nighttime testing permutations • Simulation is exempt from testing permutations related to connectivity and enhanced coatings • There will be a need for a roadway network related to the closed-track test and the on-road test. The Simulation Operator will select the corresponding roadway network appropriate to the simulation being conducted. • SUMO traffic flow rates in-out of the CARLA simulation boundaries will need to be defined • SUMO traffic network is assumed to be validated prior to traffic simulation testing • See UC2-S2 in ConOps for degraded operating conditions • See UC2-S3 in ConOps for failure operating conditions • Simulated CMU-AV and ego vehicle are terms used interchangeably

Test Procedures

Step #	**Procedure**	**Expected Result**	**Pass/Fail**	**Comments**
1	Simulation operator loads the CARLA simulation software and SUMO traffic simulator. Simulation operator analyzes CARLA and SUMO time stamps to determine system latency for synchronization	CARLA and SUMO load properly and are in sync with less than 10ms latency		
2	Simulation operator engages digital twin of work zone and loads PATA or PTS work zone map from the DMS	HD map successfully loads in the simulation system. HD-map accurately represents field conditions expected within PATA or PTS work zone scenarios scenario. Roadway network with simulated traffic is linked to the HD map		

Step #	Procedure	Expected Result	Pass/Fail	Comments
3	Simulation operator starts specified PATA or PTS work zone scenario simulation	Vehicle and traffic simulation systems begin functioning within the defined traffic and vehicle simulation parameters		
4	Simulation operator engages ego vehicle	Ego vehicle follows operator commands and is set to begin navigation of the roadway network. Simulation operator can start, stop, and restart simulation		
5	Simulation operator inputs designated route for ego vehicle	Ego vehicle has successfully received designated route information		
6	Simulation operator monitors system status in real-time	Simulation operator verifies systems are fully operational and/or can identify periods in which the system was not operational		
7	Ego vehicle navigates through specified PATA or PTS work zone scenario	Ego vehicle navigates the designated roadway network with simulated traffic and work zone assets properly according to PATA or PTS Navigation Checklists (See ***Section 6.7***).		
8	Simulation operator monitors progress of simulation	Simulation operator can view completion percentage and any errors that may impact simulation		

Step #	Procedure	Expected Result	Pass/Fail	Comments
9	Ego vehicle completes navigation through desired PATA or PTS work zone and roadway network	Simulation operator verifies simulation complete by reviewing simulation result data		
10	Simulation operator ends simulation testing	Simulation test ends		
11	Simulation operator collects simulation data	Virtual camera and LIDAR data, safety data, operations data, and performance data are collected and processed		
12	Simulation operator uploads simulation data to the DMS	All vehicle simulation data and traffic simulation data are transferred to DMS. Data is stored and available for analysis		

Source: PennDOT

6.6 Closed-Track and Live On-Road CMU-AV Work Zone Navigation Procedures

This procedure defines required steps to conduct closed-track and live on-road testing for all PATA and PTS work zone scenarios and testing permutations. All scenarios being tested at the Penn State test track shall have been previously simulated in a traffic simulator, drive simulator, and vehicle actuation simulator (i.e., CADRE) and approved/cleared by the project team for closed-track testing. All scenarios being tested on the open-road shall have been previously tested at the Penn State closed-track and approved/cleared by the project team for open-road testing.

Table 13 – Closed-Track and Live On-Road CMU-AV Work Zone Navigation Procedures

Test #/Name	Closed-Track & Live On-Road CMU-AV Work Zone Navigation
Test Stage and Permutation	
Date Performed	
Location	
Functions Tested	• CMU-AV navigation through Closed-Track/Live On-Road PATA and PTS work zones • Closed-Track/Live On-Road data collection and retrieval • DMS data retrieval, transmission, and storage

Test Objectives	• Verify that a CMU-AV can accurately traverse a work zone environment in each PATA and PTS work zone scenario and testing permutation
	• Verify that a CMU-AV can collect the camera images, sensor data, and connectivity data during work zone traversal
	• Verify aggregated CMU-AV operational/performance data is sent under the following scenarios:
	    o From the OBU to the RSU, then to the HPC to the DMS
	    o From CMU-RPC to the DMS

Equipment and Environment	• Closed-track and live on-road environments • CMU-AV • Test-track and live on-road environments • Work zone equipment and objects as defined by approved PATA and PTS work zone scenario designs • CORS • DMS
Performance Measures Evaluated	• Binary vs continuum errors • Data latency • Data drop • Connection drop • Data Standards Incompatibility • Manual interventions • Excessive hard braking • Hard swerving • Lateral distance • Longitudinal distance • Velocity • Detection range (closed-track only) • Detection accuracy (closed-track only) • Classification accuracy (closed-track only) • Binary mapping error (real-time) • Binary presence error (real-time) • Accuracy (real-time)

Prerequisites	• Work zone scenario setup and verification test procedures have been completed, passed, and have been approved • Initial work zone connectivity verification test procedures have been completed, passed, and have been approved • HD mapping procedures have been completed, passed, and have been approved • Simulation procedures have been completed, passed, and have been approved • Map data transferred to DMS • The closed-track and live on-road roadways are clear from debris, unwanted obstructions, etc. • All testing personnel are equipped with personal protective equipment • CMU-AV OBU, integrated visual display, and sensor functional verification has been performed (once daily) prior to test runs
Notes / Additional Information	This procedure will be repeated for all PATA and PTS work zone scenarios and all testing permutations. For each PATA and PTS work zone scenario and testing permutation, the procedure must also be performed with induced CMU-AV Fail-Safe (FS) and Fail-Operational (FO) modes to test how the CMU-AV handles fallback response. SAE J2735 Basic Safety Messages (BSM) will be transmitted and received by the CMU-AV via DSRC and C-V2X wireless communications. HD maps will be received by the CMU-AV by DSRC and C-V2X in SAE format. HD maps will be received by the CMU-AV over a private Zigbee or WiFi roadside network in XML, JSON, GEOJSON, GML, KML, KMZ, SHP, SHX, DBF, GPX, etc. format. C-V2X communications will be used for the majority of test runs for the project. DSRC will be used on a limited basis for select test runs, to be determined by the project team during deployment.

Test Procedures				
Step #	**Procedure**	**Expected Result**	**Pass/Fail**	**Comments**
1	The safety driver and safety associate enter the vehicle. The safety driver drives the CMU-AV in manual mode to the start position defined in the approved PATA or PTS work zone design	CMU-AV responds to manual controls and stops at the start position		
2	The safety associate signals to the safety driver and field testing management/support staff that autonomous navigation can commence	The safety driver confirms autonomous navigation will begin		
3	The safety driver activates autonomous mode and allows the CMU-AV to approach the work zone	The CMU-AV receives notification that it is approaching a work zone from RSU		
4	The safety associate verifies receipt of the HD Map prior to arriving at work zone*	The CMU-AV receives the HD map*		

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Step #	Procedure	Expected Result	Pass/Fail	Comments
5	The safety driver allows the CMU-AV to navigate through the work zone. The safety associate verifies that the CMU-AV detects and responds to work zone objects properly and documents results on the appropriate PATA or PTS work zone navigation checklist (See ***Section 6.7****)*	CMU-AV navigates through work zone properly according to PATA or PTS Navigation Checklists (See ***Section 6.7***).		
6	The safety associate monitors the integrated visual display and verifies receipt of SAE J2735 BSM while the CMU-AV is navigating through the work zone*	CMU-AV detects work zone objects and generates audible and visual warnings of obstructions within the work zone*		
7	The safety driver allows the CMU-AV to clear the work zone	CMU-AV clears the work zone safely and successfully		
8	The safety driver disengages CMU-AV autonomous mode and resumes manual control of the vehicle. The safety driver navigates to the designated vehicle staging area and parks	CMU-AV seizes autonomous operations, and the safety driver can take complete control the vehicle		

Step #	Procedure	Expected Result	Pass/Fail	Comments
9	The safety associate verifies the CMU-AV data logger captured operational data from the test run and is stored on the OBU	CMU-AV data logger captured operational data from the test run and is stored on the OBU		
10	The safety associate coordinates with the data manager to verify CMU-AV BSM and aggregated operational data has been received by the DMS via RSU and the HPC*	CMU-AV BSM and aggregated operational data has been received by the DMS via RSU and the HPC. Data can be queried by the data user/researcher		
11	The safety associate offloads CMU-AV operational data stored on the OBU to the HPC for manual transmission to the DMS. The safety associate coordinates with the data manager to verify CMU-AV operational data has been received by the DMS via the HPC**	CMU-AV operational data stored on the OBU successfully uploads the HPC. HPC successfully transmits data to the DMS. Data can be queried by the data user/researcher		

Source: PennDOT

**Indicates steps that do not apply to testing permutations without connectivity*
***Indicates steps that do not apply to testing permutations with connectivity*

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6.7 PATA and PTS Work Zone Navigation Checklists

The checklists provided below will be used by test teams to document detection of work zone objects and required maneuvers of the ego vehicle in simulation and CMU-AV in closed-track and live on-road environments as it navigates through each PATA and PTS work zone scenario. The appropriate checklist shall be attached to the Microsimulation Testing Procedures (Vehicle Simulation), Macrosimulation Testing Procedures (Traffic Simulation), and Closed-Track and Live On-Road CMU-AV Work Zone Navigation Procedures table at the completion of each test run.

Please Note: The checklists provided below are limited to behavioral verification of the ego vehicle and CMU-AV as it navigates through the specified work zone scenarios. As part of the project evaluation, calibration targets will be established and used to compare CMU-AV data (including sensor data and communications data) to MAPVAN data to evaluate the performance of the CMU-AV.

Table 14 – PATA 102 Work Zone Navigation Checklist

PATA 102									
Navigation Step	“Road Work” signage detected	CMU-AV shifts left from work zone encroachment	CMU-AV shifts right to return to normal roadway conditions						
Pass/Fail									

PATA 102									
Notes									

Source: PennDOT

Table 15 – PATA 116-A Work Zone Navigation Checklist

PATA 116-A									
Navigation Step	"Detour" signage detected	CMU-AV turns right at intersection	"Detour" signage detected	CMU-AV turns left at intersection	"Detour" signage detected	CMU-AV turns left at intersection	"Detour" signage detected	CMU-AV turns right at intersection	
Pass/Fail									
Notes									

Source: PennDOT

Table 16 – PATA 121 Work Zone Navigation Checklist

PATA 121									
Navigation Step	"Road Work" signage detected	"W1-4L" signage detected	CMU-AV shifts to the Left Lane avoiding work zone encroachment	"W1-4L" signage detected	CMU-AV shifts to the Right Lane return to normal traffic conditions				
Pass/Fail									
Notes									

Source: PennDOT

Table 17 – PATA 123-A and 123-B Work Zone Navigation Checklist

PATA 123-A and 123-B									
Navigation Step	"Road Work" signage detected	"One Lane Road" signage detected	"W20-7" signage detected	CMU-AV shifts Left over two Lanes	CMU-AV shifts Right over two Lanes				
Pass/Fail									
Notes									

Source: PennDOT

Table 18 – PATA 214 Work Zone Navigation Checklist

PATA 214									
Navigation Step	"Road Work" signage detected	"Right Lane Closed" signage detected	"Left Lane Closed" signage detected	"W4-2L" signage detected	"W1-4R" signage detected	CMU-AV shifts Left into new traffic Lane	"W6-3" signage detected	"W4-2R" signage detected	CMU-AV shifts Right into new traffic Lane
Pass/Fail									
Notes									

Source: PennDOT

Table 19 – PATA 205 Work Zone Navigation Checklist

PATA 205									
Navigation Step	“Road Work” signage detected	“W14-3” signage detected	“One Lane Road” signage detected	“W3-1” signage detected	CMU-AV stops at “Stop” signage	CMU-AV shifts to the Left Lane avoiding work zone encroachment	CMU-AV shifts to the Right Lane returning to normal traffic conditions		
Pass/Fail									
Notes									

Source: PennDOT

Table 20 – PATA 706 Work Zone Navigation Checklist

PATA 706									
Navigation Step	“Road Work” signage detected	“One Lane Road” signage detected	“W3-3” signage detected	“R10-6AL” signage detected	CMU-AV stops at “Stop” signage	CMU-AV shifts to the Left Lane avoiding work zone encroachment	CMU-AV shifts to the Right Lane returning to normal traffic conditions		
Pass/Fail									
Notes									

Source: PennDOT

Table 21 – PATA 303 Work Zone Navigation Checklist

PATA 303									
Navigation Step	"Road Work" signage detected	"W Series" signage detected on the back of Shadow Vehicle	CMU-AV shifts to the Left Lane overtaking the Shadow Vehicle	CMU-AV shifts to the Right Lane passing the Shadow Vehicle					
Pass/Fail									
Notes									

Source: PennDOT

Table 22 – PATA 402-A, PTS 915-4, and 402-B Work Zone Navigation Checklist

PATA 402-A, PTS 915-4, and 402-B									
Navigation Step	"Road Work" signage detected	"Right Lane Closed" signage detected	"W4-2R" signage detected	CMU-AV shifts to the Left Lane avoiding work zone encroachment	CMU-AV shifts to the Right Lane returning to normal traffic conditions				
Pass/Fail									
Notes									

Source: PennDOT

Table 23 – PATA 404-A Work Zone Navigation Checklist

PATA 404-A									
Navigation Step	"Road Work" signage detected	"Right Lane Closed" signage detected	"W4-2R" signage detected	CMU-AV shifts to the Left Lane avoiding work zone encroachment	"Exit" signage detected	CMU-AV shifts to the Right Exit Lane			
Pass/Fail									
Notes									

Source: PennDOT

Table 24 – PATA 405-A and 406-A Work Zone Navigation Checklist

PATA 405-A and 406-A									
Navigation Step	"Road Work" signage detected	"Right Lane Closed" signage detected	"W4-2R" signage detected	CMU-AV shifts to the Left Lane avoiding work zone encroachment	CMU-AV shifts to the Right Lane returning to normal traffic conditions				
Pass/Fail									
Notes									

Source: PennDOT

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Table 25 – PATA 602-A, PTS 915-2, and 602-B Work Zone Navigation Checklist

PATA 602-A, PTS 915-2, and 602-B										
Navigation Step	"Road Work" signage detected	"W Series" signage detected on the back of Shadow Vehicle	CMU-AV shifts to the Left Lane overtaking the Shadow Vehicle	CMU-AV shifts to the Right Lane passing the Shadow Vehicle						
Pass/Fail										
Notes										

Source: PennDOT

Table 26 – PATA 603-A, 603-B, and 603-C Work Zone Navigation Checklist

PATA 603-A, 603-B, and 603-C									
Navigation Step	"Road Work" signage detected	"W Series" signage detected on the back of Shadow Vehicle	CMU-AV shifts to the Left Lane overtaking the Shadow Vehicle	CMU-AV shifts to the Right Lane passing the Shadow Vehicle					
Pass/Fail									
Notes									

Source: PennDOT

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Appendix A: Data Management System Verification Test Procedures

6.8 CMU-AV Use Cases

Table 27 – CMU_AV – Download Work Zone Map Via API Testing & Verification

Test Name	Download work zone map via API		
Requirement ID	CMURMC-SR-001		
Date Performed			
Location			
Objectives	As an AV, I want to connect via API to download a Work Zone (WZ) map in XML format		
Prerequisites	• Connectivity between DMS & CMU AV		
Equipment and Environment	• DMS • CMU AV		
Method of Verification	• Demonstration		
Notes/Additional Information			
Procedures			
Step	**Description**	**Pass / Fail**	**Notes**
1	Connect the external hard drive to the laboratory computer.		

Step	Description	Pass / Fail	Notes
2	On your device click **Microsoft Azure Storage Explorer** to launch the application.		
3	On the left side under the subscription **(PD_com_NPD)** click the drop-down on the storage account that contains the blob you would like to view.		
4	Click the drop-down on **Blob Containers**.		
5	Click the **Blob Container** that contains the blob you would like to download.		
6	On the container ribbon on top click **Download**.		
7	Enter a name and a location where you want the blob downloaded to and click **Save**.		

Source: PennDOT

6.9 MAPVAN Use Cases

Table 28 – PSU_VAN – Download Work Zone Map Via API Testing & Verification

Test Name	Download work zone map via API		
Requirement ID	PSURMC-SR-001		
Date Performed			
Location			
Objectives	As a mapping van, I want to connect via API to download a Work Zone (WZ) map in XML format		
Prerequisites	• Connectivity between DMS and PSU Mapping Van		
Equipment and Environment	• DMS • PSU Mapping Van		
Method of Verification	• Demonstration		
Notes/Additional Information			
Procedures			
Step	**Description**	**Pass / Fail**	**Notes**
1	Connect the external hard drive to the laboratory computer.		
2	On your device click **Microsoft Azure Storage Explorer** to launch the application.		

Step	Description	Pass / Fail	Notes
3	On the left side under the subscription **(PD_com_NPD)** click the drop-down on the storage account that contains the blob you would like to view.		
4	Click the drop-down on **Blob Containers**.		
5	Click the **Blob Container** that contains the blob you would like to download.		
6	On the container ribbon on top click **Download**.		
7	Enter a name and a location where you want the blob downloaded to and click **Save**.		

Source: PennDOT

6.10 HPC Use Cases

Table 29 – HPC – Transmit HD Map Files Testing & Verification

Test Name	Transmit HD map files		
Requirement ID	UC03-DATA-006		
Date Performed			
Location			
Objectives	As an HPC, I want to transmit HD map files from the DMS to the OBU		
Prerequisites	• Connectivity between DMS, HPC and RSU		
Equipment and Environment	• DMS • HPC • RSU		
Method of Verification	• Demonstration		
Notes/Additional Information			
Procedures			
Step	**Description**	**Pass / Fail**	**Notes**
1	Using a SAS token, obtain the client ID and secret to retrieve the SAS token to retrieve files from a Data Lake container.		

Source: PennDOT

Table 30 – HPC – Collect Data Testing & Verification

Test Name	Collect Data		
Requirement ID	UC03-DATA-001		
Date Performed			
Location			
Objectives	As an HPC, I want to collect data from the RSU to the DMS		
Prerequisites	• Connectivity between DMS, HPC and RSU		
Equipment and Environment	• DMS • HPC • RSU		
Method of Verification	• Demonstration		
Notes/Additional Information			
Procedures			
Step	**Description**	**Pass / Fail**	**Notes**
1	Using a SAS token, obtain the client ID and secret to retrieve the SAS token to send files to a Data Lake container.		

Source: PennDOT

Table 31 – HPC – Aggregate Data Testing & Verification

Test Name	Aggregate Data		
Requirement ID	UC03-DATA-002		
Date Performed			
Location			
Objectives	As an HPC, I want to aggregate data from the RSU to the DMS		
Prerequisites	• Connectivity between DMS, HPC and RSU		
Equipment and Environment	• DMS • HPC • RSU		
Method of Verification	• Demonstration		
Notes/Additional Information			
Procedures			
Step	**Description**	**Pass / Fail**	**Notes**
1	Using a SAS token, obtain the client ID and secret to retrieve the SAS token to send files to a Data Lake container.		

Source: PennDOT

Table 32 – HPC – Log Data Testing & Verification

Test Name	Log Data		
Requirement ID	UC03-DATA-003		
Date Performed			
Location			
Objectives	As an HPC, I want to log data from the RSU to the DMS		
Prerequisites	• Connectivity between DMS, HPC and RSU		
Equipment and Environment	• DMS • HPC • RSU		
Method of Verification	• Demonstration		
Notes/Additional Information			
Procedures			
Step	**Description**	**Pass / Fail**	**Notes**
1	Using a SAS token, obtain the client ID and secret to retrieve the SAS token to send files to a Data Lake container.		

Source: PennDOT

Table 33 – HPC – Send Data Testing & Verification

Test Name	Send Data		
Requirement ID	HPC-IF-001.C HPC-FN-003		
Date Performed			
Location			
Objectives	As an HPC, I want to send data from the RSU to the DMS		
Prerequisites	• Connectivity between DMS, HPC and RSU		
Equipment and Environment	• DMS • HPC • RSU		
Method of Verification	• Demonstration		
Notes/Additional Information			
Procedures			
Step	**Description**	**Pass / Fail**	**Notes**
1	Using a SAS token, obtain the client ID and secret to retrieve the SAS token to send files to a Data Lake container.		

Source: PennDOT

6.11 Project Team Use Cases

Table 34 – Project Team – View a Blob Testing & Verification

Test Name	View a blob		
Requirement ID	DMS-FN-003 DMS-SR-001		
Date Performed			
Location			
Objectives	As a project team member, I want to view a blob in a blob container via Storage Explorer		
Prerequisites	• Authentication via Storage Explorer		
Equipment and Environment	• Azure Storage Explorer		
Method of Verification	• Demonstration		
Notes/Additional Information			
Procedures			
Step	**Description**	**Pass / Fail**	**Notes**
1	On your device click **Microsoft Azure Storage Explorer** to launch the application.		
2	On the left side under the subscription **(PD_com_NPD)** click the drop-down on the storage account that contains the blob you would like to view.		

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Step	Description	Pass / Fail	Notes
3	Click the drop-down on **Blob Containers**.		
4	Click the **Blob Container** that contains the blob you would like to view.		

Source: PennDOT

Table 35 – Project Team – Upload a Blob Testing & Verification

Test Name	Upload a blob		
Requirement ID	DMS-FN-003 DMS-SR-001		
Date Performed			
Location			
Objectives	As a project team member, I want to upload a blob to a blob container via Storage Explorer		
Prerequisites	• Authentication via Storage Explorer		
Equipment and Environment	• Azure Storage Explorer		
Method of Verification	• Demonstration		
Notes/Additional Information			
Procedures			
Step	**Description**	**Pass / Fail**	**Notes**
1	On your device click **Microsoft Azure Storage Explorer** to launch the application.		
2	On the left side under the subscription **(PD_com_NPD)** click the drop-down on the storage account where you want to upload a blob.		
3	Click the drop-down on **Blob Containers.**		

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Step	Description	Pass / Fail	Notes
4	Click the **Blob Container** where you would like to upload the blob.		
5	On the container ribbon on top click **Upload**.		
6	Click **Upload Files…**		
7	Select the file you would like to upload under **Selected files:**		
8	Keep **Blob Type:** as **Block Blob**		
9	Click **Upload**		
10	Confirm you see the file you selected to upload in the blob container.		

Source: PennDOT

Table 36 – Project Team – Create a Blob Container Testing & Verification

Test Name	Create a blob container		
Requirement ID	DMS-FN-003 DMS-SR-001		
Date Performed			
Location			
Objectives	As a project team member, I want to view a blob in a container via Storage Explorer		
Prerequisites	• Authentication via Storage Explorer		
Equipment and Environment	• Azure Storage Explorer		
Method of Verification	• Demonstration		
Notes/Additional Information			
Procedures			
Step	**Description**	**Pass / Fail**	**Notes**
1	On your device click **Microsoft Azure Storage Explorer** to launch the application.		
2	On the left side under the subscription **(PD_com_NPD)** click the drop-down on the storage account that contains the blob you would like to view.		
3	Right-click on **Blob Containers** and select **Create Blob Container.**		

Step	Description	Pass / Fail	Notes
4	Enter the name you would like to call your blob container.		
5	Confirm you see the blob container you just created under the **Blob Containers** section for the selected storage account.		

Source: PennDOT

Table 37 – Project Team – Delete a Blob Testing & Verification

Test Name	Delete a blob		
Requirement ID	DMS-FN-003 DMS-SR-001		
Date Performed			
Location			
Objectives	As a project team member, I want to list a file via Storage Explorer		
Prerequisites	• Authentication via Storage Explorer		
Equipment and Environment	• Azure Storage Explorer		
Method of Verification	• Demonstration		
Notes/Additional Information			
Procedures			
Step	**Description**	**Pass / Fail**	**Notes**
1	On your device click **Microsoft Azure Storage Explorer** to launch the application.		
2	On the left side under the subscription **(PD_com_NPD)** click the drop-down on the storage account that contains the blob you would like to view.		
3	Click the drop-down on **Blob Containers**		

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Step	Description	Pass / Fail	Notes
4	Click the **Blob Container** that contains the blob you would like to delete.		
5	Click the **Blob** you would like to delete.		
6	On the container ribbon on top click **Delete**.		
7	In the popup window click **Yes** to confirm you want to permanently delete this blob.		

Source: PennDOT

6.12 USDOT DMS Access Use Cases

Table 38 – USDOT – Read a File Testing & Verification

Test Name	View a blob		
Requirement ID	DMS-FN-002 UC04-FN-002 UC04-FN-003		
Date Performed			
Location			
Objectives	As a USDOT member, I want to view a blob in a blob container via Storage Explorer		
Prerequisites	• Authentication via Storage Explorer		
Equipment and Environment	• Azure Storage Explorer		
Method of Verification	• Demonstration		
Notes/Additional Information			
Procedures			
Step	**Description**	**Pass / Fail**	**Notes**
1	On your device click **Microsoft Azure Storage Explorer** to launch the application.		

Step	Description	Pass / Fail	Notes
2	On the left side under the subscription **(PD_com_NPD)** click the drop-down on the storage account that contains the blob you would like to view.		
3	Click the drop-down on **Blob Containers**.		
4	Click the **Blob Container** that contains the blob you would like to view.		

Source: PennDOT

Table 39 – USDOT – Create a File Testing & Verification

Test Name	Create a blob container		
Requirement ID	DMS-FN-002 UC04-FN-002 UC04-FN-003		
Date Performed			
Location			
Objectives	As a USDOT member, I want to create a blob in a container via Storage Explorer		
Prerequisites	• Authentication via Storage Explorer		
Equipment and Environment	• Azure Storage Explorer		
Method of Verification	• Demonstration		
Notes/Additional Information			
Procedures			
Step	**Description**	**Pass / Fail**	**Notes**
1	On your device click **Microsoft Azure Storage Explorer** to launch the application.		
2	On the left side under the subscription **(PD_com_NPD)** click the drop-down on the storage account that contains the blob you would like to view.		

Step	Description	Pass / Fail	Notes
3	Right-click on **Blob Containers** and select **Create Blob Container.**		
4	Enter the name you would like to call your blob container.		
5	Confirm you see the blob container you just created under the **Blob Containers** section for the selected storage account.		

Source: PennDOT

6.13 Public DMS Access Use Cases

Table 40 – Public – Read a File Testing & Verification

Test Name	Read a file		
Requirement ID	DMS-FN-005		
Date Performed			
Location			
Objectives	As a public user, I want to read a file via DMS Public Web App		
Prerequisites	• Access to DMS Public Web Application		
Equipment and Environment	• DMS Public Web Application		
Method of Verification	• Demonstration		
Notes/Additional Information			
Procedures			
Step	**Description**	**Pass / Fail**	**Notes**
1	Navigate to your preferred browser and in the address bar enter https://xyz.com.		
2	Navigate and click the container that contains the file you would like to read.		
3	Click on the file you would like to read.		

Step	Description	Pass / Fail	Notes
4	Confirm the file opens and you can view its content.		

Source: PennDOT

Table 41 – Public – Create a File Testing & Verification

Test Name	Create a file		
Requirement ID	DMS-FN-005		
Date Performed			
Location			
Objectives	As a public user, I want to create a file via DMS Public Web App		
Prerequisites	• Access to DMS Public Web Application		
Equipment and Environment	• DMS Public Web Application		
Method of Verification	• Demonstration		
Notes/Additional Information			
Procedures			
Step	**Description**	**Pass / Fail**	**Notes**
1	Navigate to your preferred browser and in the address bar enter https://xyz.com.		
2	Navigate and click the container that you would like the file to be created in.		
3	Click the plus (+) sign at the top of the page to create the file.		
4	Enter the file name and click save.		

Source: PennDOT

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Table 42 – Public – Write a File Testing & Verification

Test Name	Write a file		
Requirement ID	DMS-FN-005		
Date Performed			
Location			
Objectives	As a public user, I want to write a file via DMS Public Web App		
Prerequisites	• Access to DMS Public Web Application		
Equipment and Environment	• DMS Public Web Application		
Method of Verification	• Demonstration		
Notes/Additional Information			
Procedures			
Step	**Description**	**Pass / Fail**	**Notes**
1	Navigate to your preferred browser and in the address bar enter https://xyz.com.		
2	Navigate and click the container that contains the file you would like to edit.		
3	Click on the file you would like to edit.		
4	Confirm the file opens and you can edit its content.		

Source: PennDOT

Table 43 – Public – List a File Testing & Verification

Test Name	List a file		
Requirement ID	DMS-FN-005		
Date Performed			
Location			
Objectives	As a public user, I want to list a file via DMS Public Web App		
Prerequisites	• Access to DMS Public Web Application		
Equipment and Environment	• DMS Public Web Application		
Method of Verification	• Demonstration		
Notes/Additional Information			
Procedures			
Step	**Description**	**Pass / Fail**	**Notes**
1	Navigate to your preferred browser and in the address bar enter https://xyz.com.		
2	Navigate and click the container that contains the file you would like to view.		
3	Confirm you can view the file in the container.		

Source: PennDOT

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Table 44 – Public – Read a Container Testing & Verification

Test Name	Read a container		
Requirement ID	DMS-FN-005		
Date Performed			
Location			
Objectives	As a public user, I want to read a container via DMS Public Web App		
Prerequisites	• Access to DMS Public Web Application		
Equipment and Environment	• DMS Public Web Application		
Method of Verification	• Demonstration		
Notes/Additional Information			
Procedures			
Step	**Description**	**Pass / Fail**	**Notes**
1	Navigate to your preferred browser and in the address bar enter https://xyz.com.		
2	Navigate and click the container you would like to read.		
3	Confirm the container opens and you can view the files.		

Source: PennDOT

Table 45 – Public – Create a Container Testing & Verification

Test Name	Create a container		
Requirement ID	DMS-FN-005		
Date Performed			
Location			
Objectives	As a public user, I want to write a container via DMS Public Web App		
Prerequisites	• Access to DMS Public Web Application		
Equipment and Environment	• DMS Public Web Application		
Method of Verification	• Demonstration		
Notes/Additional Information			
Procedures			
Step	**Description**	**Pass / Fail**	**Notes**
1	Navigate to your preferred browser and in the address bar enter https://xyz.com.		
2	Click the plus (+) sign at the top of the page to create the container.		
3	Enter the container name and click save.		

Source: PennDOT

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Table 46 – Public – Write a Container Testing & Verification

Test Name	Write a container		
Requirement ID	DMS-FN-005		
Date Performed			
Location			
Objectives	As a public user, I want to write a container via DMS Public Web App		
Prerequisites	• Access to DMS Public Web Application		
Equipment and Environment	• DMS Public Web Application		
Method of Verification	• Demonstration		
Notes/Additional Information			
Procedures			
Step	**Description**	**Pass / Fail**	**Notes**
1	Navigate to your preferred browser and in the address bar enter https://xyz.com.		
2	Navigate and click the container that you would like to edit.		
3	Click the ellipsis (…) next to the container name at the top of the page and edit the container name.		

Step	Description	Pass / Fail	Notes
4	Click save and confirm changes have been applied.		

Source: PennDOT

Table 47 – Public – List a Container Testing & Verification

Test Name	List a container		
Requirement ID	DMS-FN-005		
Date Performed			
Location			
Objectives	As a public user, I want to list a container via DMS Public Web App		
Prerequisites	• Access to DMS Public Web Application		
Equipment and Environment	• DMS Public Web Application		
Method of Verification	• Demonstration		
Notes/Additional Information			
Procedures			
Step	**Description**	**Pass / Fail**	**Notes**
1	Navigate to your preferred browser and in the address bar enter https://xyz.com.		
2	Navigate and click the container you would like to view.		
3	Confirm you can view the container contents.		

Source: PennDOT

Appendix B: Requirements Traceability Matrix

REQ ID	REQ TYPE	*TITLE*	DESCRIPTION	IMPORTANCE	VERIFICATION METHOD
GEN-IM-001	Information/Document Mgt	*General Project and Research Activities*	Frequent and detailed documentation during the project's development process, particularly key challenges, proposed methods to address challenges, system design considerations, concepts for experimentation, environment conditions and variables, analysis and trade offs, and all project inputs and outputs relevant to test outcomes is required and a top priority throughout the project. As managers, engineers and researchers identify, evaluate, and advance the concepts and activities in this program, capturing measurable and verifiable information will be important.	Should	Inspection
GEN-NF-001	Non-Functional	*General Project and Research Activities*	Ideal conditions may be exhibited during testing; however, the project shall demonstrate real-world conditions to the extent possible, including ADS behavior in traffic conditions simulated for a given roadway network on- and off-peak hours.	Shall	Demonstration
GEN-RG-001	Policy and Regulation	*General Project and Research Activities*	SAE J3016_202104 Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems shall be used.	Shall	Inspection
GEN-RG-002	Policy and Regulation	*General Project and Research Activities*	SAE SS_V2X_001 Security Specification through the Systems Engineering Process for SAE V2X Standards shall be considered.	Shall	Inspection
GEN-RG-003	Policy and Regulation	*General Project and Research Activities*	SAE J3161 C-V2X Deployment Profiles V2X Communications Message Set Dictionary shall be used to assure applications using cellular communications are interoperable. Applications, including collision avoidance, emergency vehicle warnings, and signage, require this standard to be effective. Provides reference system architecture based on CV2X technology, using 3GPP Release 14 & Release 15 PC5.	Shall	Test
GEN-RG-003.A	Policy and Regulation	*General Project and Research Activities*	SAE J3161/1 On-Board System Requirements for LTE V2X V2V Safety Communications shall be used. NOTICE: As of this SRD publication, the 90-day IP Ballot for J3161/1 is in-process and scheduled to end late February. The standard is anticipated to publish in March or April of 2022.	Shall	Test
GEN-RG-003.B			SAE J3161/1A Vehicle-Level Validation Test Procedures for LTE-V2X V2V Safety Communications must be used to verify OBU radio	Shall	Test

REQ ID	REQ TYPE	*TITLE*	DESCRIPTION	IMPORTANCE	VERIFICATION METHOD
			parameters conform to LTE-V2X vehicle-level requirements specified in SAE J3161/1 Standard WIP.		
GEN-RG-004			SAE J2735_201603 Dedicated Short Short-Range Communications (DSRC) Message Set Dictionary shall be used to assure applications using DSRC are interoperable.	Shall	Test
GEN-RG-005	Policy and Regulation	*General Project and Research Activities*	SAE J2945/1_202004 Onboard Minimum Performance Requirements for V2V Safety Communications shall be used for minimum performance requirements and interface standard features required to establish interoperability between onboard units for V2V safety systems.	Shall	Test
GEN-RG-006	Policy and Regulation	*General Project and Research Activities*	SAE J2945/2_201810 DSRC Performance Requirements for V2V Safety Awareness shall be used to specify interface requirements for V2V Safety applications.	Shall	Test
GEN-RG-007	Policy and Regulation	*General Project and Research Activities*	SAE J2945/3_202003 Requirements for Road Weather Applications shall be used to specify interface requirements between vehicles and infrastructure for any weather applications the project may choose to introduce as part of the ODD.	Shall	Test
GEN-RG-008	Policy and Regulation	*General Project and Research Activities*	IEEE 1609.2-2016 Standard for Wireless Access in Vehicular Environments (WAVE) Security Services for Applications and Management Messages may be used to defines secure message formats and processing within DSRC/WAVE.	May	Test
GEN-RG-009	Policy and Regulation	*General Project and Research Activities*	IEEE 1609.3-2016 Standard for WAVE Networking Services standard may be used to define network and transport layer services, including addressing and routing, in support of secure WAVE data exchange. The standard also defines WAVE short messages, providing an efficient WAVE-specific alternative to Internet Protocol version 6 that can be directly supported by applications, and the Management Information Base for the WAVE protocol stack.	May	Test
GEN-RG-010	Policy and Regulation	*General Project and Research Activities*	IEEE 1609.4-2016 Standard for WAVE Multi-Channel Operations standard shall be used to provide enhancements of the IEEE 802.11	Shall	Test

REQ ID	REQ TYPE	*TITLE*	DESCRIPTION	IMPORTANCE	VERIFICATION METHOD
			Media Access Control to support WAVE operations and describes various standard message formats for DSRC applications.		
GEN-RG-011	Policy and Regulation	*General Project and Research Activities*	IEEE 1609.12-2016 Standard for WAVE Identifier Allocations standard shall be used to specify allocations of WAVE identifiers defined in the IEEE 1609TM series of standards.	Shall	Test
GEN-RG-012	Policy and Regulation	*General Project and Research Activities*	NMEA 0183 v4.1 shall be used to combine standards associated with GNSS Data with those for GNSS serial interface. The GNSS Data standards include upper-layer standards required to obtain location and time information from a satellite-positioning-system-based geolocation receiver. The GNSS serial interface standards include lower-layer standards that support communications between connected ITS equipment and geolocation equipment such as a GPS receiver.	Shall	Test
GEN-RG-013	Policy and Regulation	*General Project and Research Activities*	NTCIP 1202 v02, v03 Object Definitions for Actuated Signal Controllers (ASC) standard shall be supported in order to define how an object allows ITS operators to monitor, configure, and control traffic signal controllers.	Shall	Test
GEN-RG-014	Policy and Regulation	*General Project and Research Activities*	The ATC family of standards shall be supported: · ATC 5201 ATC Standard · ATC 5401 Application Programming Interface (API) Standard · ATC 5301 ATC Cabinet Standard	Shall	Test
GEN-RG-015	Policy and Regulation	*General Project and Research Activities*	A Notice of Testing application shall be submitted through the PennDOT website www.penndot.gov/av [1]prior to testing.	Shall	Inspection
GEN-RG-015.A	Policy and Regulation	*General Project and Research Activities*	The Safety and Risk Mitigation Plan shall be submitted with Notice of Testing.	Shall	Inspection
GEN-RG-015.B	Policy and Regulation	*General Project and Research Activities*	Testing activities shall meet PennDOT's operational requirements for automated vehicle testing as per the AUTOMATED VEHICLE TESTING GUIDANCE (July 23, 2018).	Shall	Inspection
GEN-SR-001	Security	*General Project and Research Activities*	Project assets (hardware, software, communication and data) must be protected from intentional or unintentional access from unauthorized personnel. Security measures such as keeping assets in a locked space, requiring credentials to access digital systems, etc. are good practices to ensure project integrity. Security	Shall	Demonstration

REQ ID	REQ TYPE	*TITLE*	DESCRIPTION	IMPORTANCE	VERIFICATION METHOD
			requirements specific to systems, processes, and data are detailed in their respective section.		
USR-SFTY-001	Safety	*Stakeholders, Drivers, Operators*	A Safety Driver must have a valid driver's license.	Shall	Demonstration
USR-SFTY-002	Safety	*Stakeholders, Drivers, Operators*	A Safety Driver must have enhanced AV operations training and experience.	Shall	Demonstration
USR-SFTY-003	Safety	*Stakeholders, Drivers, Operators*	Safe operating vehicle condition		Demonstration
USR-SFTY-004	Safety	*Stakeholders, Drivers, Operators*	A Safety Driver must be able to intervene in system interruption conditions.	Shall	Demonstration
USR-SFTY-005	Safety	*Stakeholders, Drivers, Operators*	A Safety Driver must be able to safely maneuver the vehicle under all system modes of operation as defined in ConOps section 5.2.	Shall	Demonstration
USR-SFTY-006	Safety	*Stakeholders, Drivers, Operators*	A Safety Associate must have enhanced training of AV operations.	Shall	Demonstration
USR-SFTY-007	Safety	*Stakeholders, Drivers, Operators*	A Safety Associate must have knowledge of AV backend operations.	Shall	Demonstration
USR-SFTY-008	Safety	*Stakeholders, Drivers, Operators*	A Data Manager must have training in data management practices and analysis of CAV data.	Shall	Demonstration
USR-SFTY-009	Safety	*Stakeholders, Drivers, Operators*	A Data Manager possess knowledge of data collection, integrity and flow.		Demonstration
USR-SFTY-010	Safety	*Stakeholders, Drivers, Operators*	A Data Manager must be able to monitor data and respond to any malfunctions.	Shall	Demonstration
USR-SFTY-011	Safety	*Stakeholders, Drivers, Operators*	A Simulation Operator shall conduct both AV and Traffic Simulation	Shall	Demonstration
USR-SFTY-012	Safety	*Stakeholders, Drivers, Operators*	A Simulation Operator shall have knowledge and experience in scenario development for testing AVs through simulation.	Shall	Demonstration

REQ ID	REQ TYPE	*TITLE*	DESCRIPTION	IMPORTANCE	VERIFICATION METHOD
USR-SFTY-013	Safety	*Stakeholders, Drivers, Operators*	A Data User/Researcher should have experience accessing data from a cloud-based DMS.	Should	Demonstration
USR-SFTY-014	Safety	*Stakeholders, Drivers, Operators*	A Data User/Researcher must be able to interpret test data and generate a report.	Shall	Demonstration
USR-SFTY-015	Safety	*Stakeholders, Drivers, Operators*	A Mapping Equipment Operator must be trained on the installation, calibration, and/or operation of the mapping equipment.	Shall	Demonstration
USR-SFTY-016	Safety	*Stakeholders, Drivers, Operators*	A Mapping Equipment Operator shall have enhanced Mapping Van operations training and experience.	Shall	Demonstration
USR-SFTY-017	Safety	*Stakeholders, Drivers, Operators*	A Mapping Equipment Operator shall communicate with a mapping van driver for safe operations.	Shall	Demonstration
USR-SFTY-018	Safety	*Stakeholders, Drivers, Operators*	A Mapping Van Driver must have a valid driver's license	Shall	Demonstration
USR-SFTY-019	Safety	*Stakeholders, Drivers, Operators*	A Mapping Van Driver must have enhanced Mapping Van operations training and experience.	Shall	Demonstration
USR-SFTY-020	Safety	*Stakeholders, Drivers, Operators*	A Mapping Van Driver must maintain safe operating vehicle conditions for data collection.	Shall	Demonstration
USR-SFTY-021	Safety	*Stakeholders, Drivers, Operators*	A Work Zone Operator shall maintain safe conditions within the work zone.	Shall	Demonstration
USR-SFTY-022	Safety	*Stakeholders, Drivers, Operators*	A Work Zone Operator shall wear a safety vest.	Shall	Demonstration
USR-SFTY-023	Safety	*Stakeholders, Drivers, Operators*	A Work Zone Operator shall wear a safety hard hat and boots.	Shall	Demonstration
USR-SFTY-024	Safety	*Stakeholders, Drivers, Operators*	A Work Zone Operator shall maintain a safe environment for before, during and after testing each work zone scenario, which will have static and dynamic work zone devices.	Shall	Demonstration
USR-SFTY-024	Safety	*Stakeholders, Drivers, Operators*	CMU must maintain the automated vehicle in safe operable condition.	Shall	Demonstration
USR-SFTY-024	Safety	*Stakeholders, Drivers, Operators*	Penn State must maintain the mapping van in safe operable condition.	Shall	Demonstration

REQ ID	REQ TYPE	*TITLE*	DESCRIPTION	IMPORTANCE	VERIFICATION METHOD
USR-SFTY-024	Safety	*Stakeholders, Drivers, Operators*	PennDOT must maintain all field devices and support systems in operable condition.	Shall	Demonstration
ADS-CN-001	Constraints	*CMU ADS System*	The CMU ADS is an existing L4 automated vehicle. It is assumed the AV meets industry safety standards (e.g., ISO 26262 functional safety standard for passenger vehicles).		Inspection
ADS-CN-002	Constraints	*CMU ADS System*	As an existing system, it is assumed fault analysis and verification has been conducted to ensure the CMU ADS is free from hardware bugs, random hardware failures, systemic software failures and failures in the interaction between the vehicle hardware and software.		Inspection
ADS-CN-003	Constraints	*CMU ADS System*	Due to the highly complex computing load, the CMU ADS data logger captures operational data only and does not record all streaming sensory data.		Test
ADS-SFTY-001	Safety	*CMU ADS System*	The CMU ADS shall be capable of independent object detection and collision avoidance.	Shall	Test
ADS-SFTY-002	Safety	*CMU ADS System*	The CMU ADS shall be capable of mitigating operational failures using standard techniques for fail-operational such as safe navigation out of a travel lane, transitioning control back to the safety driver, safely stopping in a lane, etc.	Shall	Test
ADS-SFTY-003	Safety	*CMU ADS System*	The CMU ADS shall be capable of instituting fail-safe techniques to enable ADS function at reduced capacity (e.g., if LiDAR fails, weight of camera data increased sufficient to fail-operational).	Shall	Test
ADS-SFTY-004	Safety	*CMU ADS System*	The CMU ADS shall be capable of mitigating failures when data affects safe driving within its operational design domain and minimal risk condition triggered.	Shall	Test
ADS-FN-001	Functional	*CMU ADS System*	The CMU ADS must be capable of performing the entire DDT while navigating a work zone without any driver supervision, as per SAE Level 4 ADS feature definition.	Shall	Test
ADS-FN-002	Functional	*CMU ADS System*	The CMU ADS shall be capable of transmitting and receiving SAE J2735-defined basic safety message (BSM) over a DSRC and C-V2X wireless communications link as defined in the Institute of	Shall	Test

REQ ID	REQ TYPE	*TITLE*	DESCRIPTION	IMPORTANCE	VERIFICATION METHOD
			Electrical and Electronics Engineers (IEEE) 1609 suite and IEEE 802.11 standards [2] to [6].		
ADS-FN-003	Functional	*CMU ADS System*	The CMU ADS shall provide a mechanism that allows the safety driver to initiate and monitor the automatic operation and control of the vehicle in motion.	Shall	Test
ADS-FN-004	Functional	*CMU ADS System*	The CMU ADS shall provide a mechanism that allows the safety driver to manage and terminate the automatic control and operation of the vehicle.	Shall	Test
ADS-FN-005	Functional	*CMU ADS System*	The CMU ADS shall detect, analyze, classify, and monitor objects greater than {QxRxS} within {sensor range} proximity to the vehicle.	Shall	Test
ADS-FN-006	Functional	*CMU ADS System*	The CMU ADS shall provide audible and visual (optionally haptic) warnings to the driver of potential dangers based on analysis of sensor input during all modes of operation.	Shall	Test
ADS-FN-007	Functional	*CMU ADS System*	The CMU ADS shall monitor its subsystems and inform the safety driver of errors, power or communication failures with any of its subsystem elements.	Shall	Test
ADS-FN-008	Functional	*CMU ADS System*	The CMU ADS shall not respond to incoming TCP-IP requests.	Shall Not	Demonstration
ADS-FN-009	Functional	*CMU ADS System*	Req Type	May	Test
ADS-FN-010	Functional	*CMU ADS System*	Transmitting over DSRC, the CMU ADS must be capable of receiving a high-definition map file from the roadway environment in SAE encoded format.	Shall	Test
ADS-FN-011	Functional	*CMU ADS System*	Transmitting over C-V2X, the CMU ADS must be capable of receiving a high-definition map file from the roadway environment in SAE encoded format.	Shall	Test
ADS-FN-012	Functional	*CMU ADS System*	Transmitting over a private 4G or5G roadside network, the CMU ADS must be capable of receiving a high-definition map file from roadside equipment in various formats, which could include XML, JSON, GEOJSON, GML, KML, KMZ, SHP, SHX, DBF, GPX, etc.	Shall	Test
ADS-FN-013	Functional	*CMU ADS System*	The CMU-RMS must document the method for the CMU ADS to ingest, process, read, and use HD map file(s).	Shall	Inspection

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REQ ID	REQ TYPE	*TITLE*	DESCRIPTION	IMPORTANCE	VERIFICATION METHOD
ADS-FN-014	Functional	*CMU ADS System*	The CMU-RMS shall document the processing steps required for the CMU-AV to use the HD map it receives. Processing is expected to include: — Verify the sender — Verify the message or file received (e.g., checksum, codesign, etc.) — Validate CADRE stack can successfully read the HD map — Fuse/link HD map with/to internal GPS/PPS — Position the vehicle in reference to the HD map (RWM:absolute, perception:relative?) — Verify the CMU-AV can use the map to navigate along path — Validate the CMU-AV knows when it is approaching (a) geofenced work zone, (b) work zone objects	Shall	Test
ADS-FN-015	Functional	*CMU ADS System*	CMU ADS must receive notification it is approaching a work zone with sufficient time to perform drive maneuvers. For instance, there is a lane closure at peak hours, the CMU ADS must have sufficient time to engage the blinker, brake, and merge into the next lane safely among other drivers. Specific scenarios will be documented and measured by the project.	Shall	Test
MAPVAN-FN-001	Functional	*PSU MAPVAN System*	A baseline HD map will need to be established for the project and defined in terms of scale, data accuracy, resolution, and density.		Test
MAPVAN-FN-002	Functional	*PSU MAPVAN System*	A baseline HD map shall be used for the closed-track roadway network.	Shall	Test
MAPVAN-FN-003	Functional	*PSU MAPVAN System*	A baseline HD map shall be used for the open-road roadway network.	Shall	Test
MAPVAN-FN-004	Functional	*PSU MAPVAN System*	The PSU mapping van shall collect and store LiDAR scan data, high-precision GPS data, readings from its inertial navigation system, RGB camera data from a work zone mapping task.	Shall	Test
MAPVAN-FN-005	Functional	*PSU MAPVAN System*	The mapping function shall preserve time synchronization between all data collected during a mapping task while splitting and fusing separated camera data and the hash records linked to images collected during the map task.	Shall	Test

REQ ID	REQ TYPE	*TITLE*	DESCRIPTION	IMPORTANCE	VERIFICATION METHOD
MAPVAN-FN-006	Functional	*PSU MAPVAN System*	MAPVAN data and encoded data resulting from the mapping task shall be offloaded onto disk and physically transmitted to the PSU research management center (i.e., a designated, authorized laboratory for conducting project testing) for creating a digital representation of the construction zone in a HD map.	Shall	Demonstration
MAPVAN-FN-007	Functional	*PSU MAPVAN System*	MAPVAN camera data may be used for redundancy verification of data collected by the ego vehicle.	May	Analysis
MAPVAN-FN-008	Functional	*PSU MAPVAN System*	The mapping task may explore methods for identifying, processing and defining obstacles and centerline data during data capture.	May	Analysis
SIMDRIVE-CN-001	Constraints	*Drive Simulation System*	CMU and PSU shall use the CARLA Simulator software, which requires many kinds of software and binaries integrations to run. As an existing system, it is assumed the system has already been integrated and fully functional prior to the start of this project.	Shall	Demonstration
SIMDRIVE-CN-002	Constraints	*Drive Simulation System*	The CADRE software shall be used by CMU for analysis and measuring performance of AV simulations. It is assumed this system is existing, integrated, and fully functional prior to the start of this project.	Shall	Demonstration
SIMDRIVE-CN-003	Constraints	*Drive Simulation System*	Simulation requires real-time data and shall receive HD map files from the DMS, which is not a real-time data system.	Shall	Test
SIMDRIVE-FN-001	Functional	*Drive Simulation System*	A basic configuration for the CADRE stack shall be established using the generated HD map provided by the DMS.	Shall	Test
SIMDRIVE-FN-001.A	Functional	*Drive Simulation System*	The system shall verify the HD map can be loaded correctly.	Shall	Test
SIMDRIVE-FN-001.B	Functional	*Drive Simulation System*	The system shall verify the ego vehicle can read the map correctly.	Shall	Test
SIMDRIVE-FN-001.C	Functional	*Drive Simulation System*	The system shall verify the ego vehicle can follow the rules of the road (i.e., stop at stop lights, react to traffic, etc.).	Shall	Test
SIMDRIVE-FN-002	Functional	*Drive Simulation System*	The system shall verify the ego vehicle can drive along the given path navigating {X m/ft.} from the mapped construction zone boundary.	Shall	Test

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REQ ID	REQ TYPE	*TITLE*	DESCRIPTION	IMPORTANCE	VERIFICATION METHOD
SIMTRAFFIC-CN-001	Constraints	*Traffic Simulation System*	PSU is currently undergoing a separate effort to evaluate and implement the SUMO traffic simulation software. It may be advantageous to leverage this tool for the project in order to integrate with CARLA and simulate traffic flows.	May	Analysis
SIMTRAFFIC-FN-001	Functional	*Traffic Simulation System*	PSU shall conduct traffic simulation to understand how a construction zone and the CMU ADS navigating that work zone would affect traffic flow, both before and after.	Shall	Test
SIMTRAFFIC-NF-001	Non-Functional	*Traffic Simulation System*	The closed-track connection of roads in the virtual environment that make up the closed-track roadway network shall include {highway, arterial, etc.} at a {radial distance} from closed-track test site.	Shall	Demonstration
SIMTRAFFIC-NF-002	Non-Functional	*Traffic Simulation System*	The open-road connection of roads in the virtual environment that make up the closed-track roadway network shall include {highway, arterial, etc.} at a {radial distance} from closed-track test site.	Shall	Demonstration
SIMTRAFFIC-NF-003	Non-Functional	*Traffic Simulation System*	Source destination densities shall be calibrated such that the simulator is able to match real-world traffic flows at particular measurement locations, which should include intersections with traffic light timing calibrations to the real world as well.	Shall	Demonstration
PSURMC-SR-001	Security	*Research Management Centers*	The PSU-RMC shall establish a secure tunnel via virtual private network to send data to the DMS.	Shall	Demonstration
CMURMC-SR-001	Security	*Research Management Centers*	The CMU-RMC shall establish a secure tunnel via virtual private network to send data to the DMS.	Shall	Demonstration
RSU-DR-001	Data	*Smart Infrastructure: Roadside Units*	An RSU shall receive basic safety messages (BSM) broadcast from vehicles in its vicinity.	Shall	Test
RSU-DR-002	Data	*Smart Infrastructure: Roadside Units*	An RSU shall broadcast SAE J2735 compliant MAP messages.	Shall	Test
RSU-FN-001	Functional	*Smart Infrastructure: Roadside Units*	An RSU shall be capable of providing channel assignments and operating instructions to OBUs in its communications zone.	Shall	Test
RSU-FN-002	Functional	*Smart Infrastructure: Roadside Units*	An RSU shall broadcast SAE J2735 compliant messages using DSRC and C-V2X communication standards.	Shall	Test

REQ ID	REQ TYPE	*TITLE*	DESCRIPTION	IMPORTANCE	VERIFICATION METHOD
RSU-FN-003	Functional	*Smart Infrastructure: Roadside Units*	The RSU shall off load messages received to the HPC for transmission to the DMS.	Shall	Test
RSU-FN-004	Functional	*Smart Infrastructure: Roadside Units*	The RSU shall be capable of transmitting messages over DSRC to the CMU ADS within the roadway environment in {SAE encoded} format.	Shall	Test
RSU-FN-005	Functional	*Smart Infrastructure: Roadside Units*	The RSU shall be capable of transmitting messages over C-V2X to the CMU ADS within the roadway environment in {SAE encoded} format.	Shall	Test
RSU-FN-006	Functional	*Smart Infrastructure: Roadside Units*	The RSU may be capable of transmitting messages over a private 4G or 5G roadside network to the CMU ADS and capable of receiving a high-definition map file from the HPC in the format determined from the experimentation phase in building a baseline HD map. Formats may include XML, JSON, GEOJSON, GML, KML, KMZ, SHP, SHX, DBF, GPX, etc..	May	Test
HPC-DR-002	Data	*Smart Infrastructure: High Performing Computer*	The HPC shall be capable of transmitting HD maps files from the DMS to the CMU-ADS OBU.	Shall	Test
HPC-NF-001	Non-Functional	*Smart Infrastructure: High Performing Computer*	The HPC shall function as a central connectivity hub and shall enable transmissions to and from various sources (RSE, MS Azure Cloud, Penn State, PennDOT TMC network) having multiple communication profiles, including LTE C-V2X, DSRC, GPS, 4/5G cellular, Zigbee, Wi-Fi, and Ethernet. Interface requirements HPC-IF-001.A through HPC-IF-001.G provides the requirement definition for enabling this connectivity.	Shall	Test
HPC-IF-001.A	Interface	*Smart Infrastructure: High Performing Computer*	The HPC shall be equipped with a dedicated wired network interface (Ethernet or Fiber Optics) joined to internal domain managing the RSE and capable of transmitting data to and from a configurable Center source over the PennDOT fiber network.	Shall	Test
HPC-IF-001.B	Interface	*Smart Infrastructure: High Performing Computer*	The HPC should be equipped with a dedicated wireless network interface capable of facilitating data exchanges to and from a configurable source, over PennDOT's internal Wi-Fi network and the guest Wi-Fi network as appropriate for testing an array of communication scenarios.	Should	Test

REQ ID	REQ TYPE	*TITLE*	DESCRIPTION	IMPORTANCE	VERIFICATION METHOD
HPC-IF-001.C	Interface	*Smart Infrastructure: High Performing Computer*	The HPC should be capable of facilitating data exchanges to and from a configurable 4G or 5G, over-the-air network device to facilitate data exchanges to and from the cloud-based, DMS system using cellular.	Should	Test
HPC-IF-001.D	Interface	*Smart Infrastructure: High Performing Computer*	The HPC shall be capable of facilitating data exchanges to and from an LTE C-V2X configured RSU.	Shall	Test
HPC-IF-001.E	Interface	*Smart Infrastructure: High Performing Computer*	The HPC shall be capable of facilitating data exchanges to and from a DSRC configured RSU.	Shall	Test
HPC-IF-001.F	Interface	*Smart Infrastructure: High Performing Computer*	The HPC should be capable of facilitating data exchanges to and from a configurable GPS device.	Should	Test
HPC-IF-001.G	Interface	*Smart Infrastructure: High Performing Computer*	The HPC should be capable of facilitating data exchanges to and from a configurable Zigbee mesh network.	Should	Test
HPC-FN-003	Functional	*Smart Infrastructure: High Performing Computer*	The HPC shall collect, aggregate, store and send SAE formatted messages, as defined in the SAE V2X Communication Message Set Dictionary, from the RSU to the DMS.	Shall	Test
HPC-DR-004	Data	*Smart Infrastructure: High Performing Computer*	The HPC shall aggregate precise location and time information from GPS equipped V2X work zone objects and transmit securely SSL, TLS, or IPSec to the DMS for archival.	Shall	Test
HPC-SR-001	Security	*Smart Infrastructure: High Performing Computer*	All communications to and from the edge HPC must be authorized, authenticated, and the payload secured.	Shall	Test
HPC-FN-001	Functional	*Smart Infrastructure: High Performing Computer*	The HPC shall provide administrative access to authenticated users from the local network and remotely through a virtual private network interface.	Shall	Test
WZO-FN-001	Functional	*V2X Work Zone Objects*	V2X work zone objects shall be instrumented with global positioning system (GPS) communication devices.	Shall	Demonstration

REQ ID	REQ TYPE	*TITLE*	DESCRIPTION	IMPORTANCE	VERIFICATION METHOD
WZO-FN-002	Functional	*V2X Work Zone Objects*	V2X work zone objects shall be capable of securely transmitting data over the air via 4G, 5G, or Wi-Fi radio.	Shall	Test
WZO-FN-003	Functional	*V2X Work Zone Objects*	V2X work zone objects should be capable of being configured as end devices (no routing) within PennDOT's ZigBee mesh network.	Should	Test
WZO-FN-004	Functional	*V2X Work Zone Objects*	V2X work zone objects may use PennDOT's reference station to receive position correction.	May	Test
WZO-DR-001	Data	*V2X Work Zone Objects*	V2X work zone objects shall provide precise position and time information from its GPS device.	Shall	Test
DWV-FN-001	Functional	*Digital Worker Vests*	Digital worker vests shall be instrumented with global positioning system (GPS) communication devices.	Shall	Demonstration
DWV-FN-002	Functional	*Digital Worker Vests*	Digital worker vests shall be capable of securely transmitting data over the air via 4G, 5G, or Wi-Fi radio	Shall	Test
DWV-FN-003	Functional	*Digital Worker Vests*	Digital worker vests should be capable of being configured as end devices (no routing) within PennDOT's ZigBee mesh network.	Should	Test
DWV-FN-004	Functional	*Digital Worker Vests*	Digital worker vests may use PennDOT's reference station to receive position correction.	May	Test
DWV-DR-001	Data	*Digital Worker Vests*	Digital worker vests shall provide precise position and time information from its GPS device.	Shall	Test
DMS-FN-001	Functional	*Data Management System*	Data received by the DMS must be formatted and tagged with attributes that define the data source, conditions under which it was collected, what data transformations were applied (if any), and appropriate meta data (i.e., timestamp, etc.) necessary to interpret and understand the data in context.	Shall	Test
DMS-FN-002	Functional	*Data Management System*	For the Project Team, the DMS shall provide a web-based graphical user interface to access, view, and interact with all data stored in the DMS (interact meaning, query, export, compute and visualize data for analysis) for the full duration of the project, including the five (5) year period beyond project completion; per USDOT contractual requirements for the ADS project.	Shall	Test

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REQ ID	REQ TYPE	*TITLE*	DESCRIPTION	IMPORTANCE	VERIFICATION METHOD
DMS-FN-003	Functional	*Data Management System*	For the Project Team, the DMS shall provision a secure mechanism for large data files to be transferred securely into the DMS using Azure Storage Explorer and AZcopy.	Shall	Test
DMS-FN-004	Functional	*Data Management System*	For the USDOT, the DMS shall provide a secure API for accessing and exporting project data and computed data.	Shall	Test
DMS-FN-005	Functional	*Data Management System*	For anonymous researchers and the general public, the DMS shall provide a WebApp to access data that is predefined and flagged as publicly accessible.	Shall	Test
DMS-SR-001	Security	*Data Management System*	A membership-based access control list (ACL) will be maintained by the DMS using Azure AD to allow the project team, USDOT, and authorized project researchers to access data.		Test
DMS-SR-002	Security	*Data Management System*	Azure cloud environment shall implement and configure a firewall protective measure to ensure the DMS system is secured.	Shall	Test
DMS-NF-001	Non-Functional	*Data Management System*	Access violations shall be investigated and reported to the project within one (1) day of discovery.	Shall	Test
DMS-NF-002	Non-Functional	*Data Management System*	The DMS shall minimize the cost of ownership where possible. For instance, researchers may extract data and conduct analysis on the client-side.	Shall	Test
DMS-FN-006	Functional	*Data Management System*	The DMS shall maintain separate containers for each system (CMU ADS, MAPVAN, HPC) to store data.	Shall	Test
DMS-FN-007	Functional	*Data Management System*	The DMS shall optimize storage for fast access for data that is accessed frequently.	Shall	Test
DMS-FN-008	Functional	*Data Management System*	The DMS shall optimize archive storage access for raw sensor data.	Shall	Test
DMS-FN-009	Functional	*Data Management System*	The DMS shall optimize archive storage costs for data sets that have not been accessed within 180 days or more.	Shall	Test
UC01-CN-001	Constraints	*UC01: Map Generation*	Processing and transforming sensor data into exportable formats currently takes approximately 10 hours per hour of data collection. As a result, the HD map will be made available to consuming		Analysis

REQ ID	REQ TYPE	*TITLE*	DESCRIPTION	IMPORTANCE	VERIFICATION METHOD
			systems (i.e., the DMS and CMU ADS drive simulator) the day after the mapping took place.		
UC01-CN-002	Constraints	*UC01: Map Generation*	Due to high energy needs and power limitations in an automobile, the function of generating maps must be offloaded as a back-office task at the PSU-RMC.	Shall	Demonstration
UC01-CN-003	Constraints	*UC01: Map Generation*	The MAPVAN uses a combination of global navigation satellite system (GNSS) and inertial navigation system (INS) to compliment GNSS in heavily dense areas to enhance accuracy of an autonomous driving when GNSS is unreliable. Satellite bias, atmospheric effects, and clock desynchronization and other factors can produce errors. The PennDOT continuous operating reference station (CORS) offers position correction and may also be used. Map generation will need to establish a base map which will require experimentation.	May	Analysis
UC01-PF-001	Performance	*UC01: Map Generation*	Through experimentation, the project may consider identifying areas where processes can be revised and/or improved to reduce the time it takes to generate a HD map.	May	Analysis
UC01-FN-001	Functional	*UC01: Map Generation*	A geofence work zone shall be established from a base set of criteria, which must be documented.	Shall	Inspection
UC01-FN-002	Functional	*UC01: Map Generation*	Geofenced zone boundaries shall use edge objects/artifacts with a configurable buffer cushion from detected objects.	Shall	Demonstration
UC01-FN-003	Functional	*UC01: Map Generation*	The zone mapped must be accurate to 5 (cm), accounting for inaccuracies, standard and anomalous deviations in processing (time, space).	Shall	Inspection
UC01-FN-004	Functional	*UC01: Map Generation*	The processed HD map file must be generated and made available in the format(s) determined during experimentation (see section 6.1).	Shall	Inspection
UC01-PF-002	Performance	*UC01: Map Generation*	HD map file(s) must be sent to the DMS over an established virtual private network within 24 hours of the work zone being mapped.	Shall	Inspection
UC01-CN-004	Constraints	*UC01: Map Storage*	Processing and transforming sensor data into exportable formats should be completed within a 24-hour turn around period. Generally, for every hour of MAPVAN data collection, it takes an approximate hour of data transfer and 10 hours of processing by the PSU-RMC.	Should	Demonstration

REQ ID	REQ TYPE	*TITLE*	DESCRIPTION	IMPORTANCE	VERIFICATION METHOD
UC01-CN-005	Constraints	*UC01: Map Storage*	Due to power limitations, the function of generating maps must be offloaded as a back-office task to the PSU-RMC. However, the project is exploring potential ways to improve the approach to map generation.	Shall	Demonstration
UC01-NF-001	Non-Functional	*UC01: Map Storage*	One raw data set must be made available in the DMS for USDOT. Raw data from all other map runs must be retained and made available upon request.	Shall	Inspection
UC01-FN-005	Functional	*UC01: Map Storage*	The DMS shall maintain a copy of all raw data as ingested.	Shall	Inspection
UC02-FN-001	Functional	*UC02: Road Network Linking*	The HD map shall be linked to the physical road network architecture.	Shall	Test
UC02-FN-002	Functional	*UC02: Road Network Linking*	Traffic data shall be calibrated to the network map, ensuring simulated traffic matches realistic traffic volumes and turning counts.	Shall	Test
UC02-CN-001	Constraints	*UC02: Traffic Simulator*	The PSU-RMC has traffic simulations for both highway and urban levels at community scale from a separate initiative which can be leveraged for this project.		Test
UC02-FN-003	Functional	*UC02: Traffic Simulator*	A roadway network shall be selected and flow rates of vehicles in-out of the CARLA simulation boundaries shall be defined.	Shall	Test
UC02-FN-004	Functional	*UC02: Traffic Simulator*	A co-simulation task shall create a process for time synchronization and data synchronization in order to generate smooth transitions in simulations.	Shall	Demonstration
UC02-IM-001	Information/Document Mgt	*UC02: Traffic Simulator*	The output from simulation runs shall be archived in the DMS.	Shall	Inspection
UC02-CN-002	Constraints	*UC02: Simulator ADS Work Zone Navigation*	Processing and transforming sensor data into exportable formats should be completed within a 24-hour turn around period. Generally, for every hour of MAPVAN data collection, it takes an approximate hour of data transfer and 10 hours of processing by the PSU-RMC.	Should	Test
UC02-CN-003	Constraints	*UC02: Simulator ADS Work Zone Navigation*	Due to power limitations in the van, the function of generating maps must be offloaded as a back-office task.	Shall	Test

REQ ID	REQ TYPE	*TITLE*	DESCRIPTION	IMPORTANCE	VERIFICATION METHOD
UC02-CN-004	Constraints	*UC02: Simulator ADS Work Zone Navigation*	The MAPVAN uses a combination of global navigation satellite system (GNSS) and inertial navigation system (INS) to compliment GNSS in heavily dense areas to enhance accuracy of an autonomous driving when GNSS is unreliable. Satellite bias, atmospheric effects, and clock desynchronization and other factors can produce errors. The PennDOT continuous operating reference station (CORS) offers position correction and may be used during simulation. Map generation will need to establish a base map which may require experimentation.	May	Test
UC03-SFTY-001	Safety	*UC03: Work Zone Navigation*	The project team shall attempt to identify, correct or address potential failures of in the “work zone navigation” pipeline before and during testing.	Shall	Test
UC03-SFTY-001.A	Safety	*UC03: Work Zone Navigation*	Identify potential failure modes for CMU ADS communications, sensing, perception, navigation and control, and HMI.		Test
UC03-SFTY-001.B	Safety	*UC03: Work Zone Navigation*	Identify potential causes and effects of those failure modes.		Test
UC03-SFTY-001.C	Safety	*UC03: Work Zone Navigation*	Prioritize failure modes based on risk.		Test
UC03-SFTY-001.D	Safety	*UC03: Work Zone Navigation*	Identify and demonstrate an appropriate corrective action or a mitigation strategy for each failure mode.		Test
UC03-NF-001	Non-Functional	*UC03: Work Zone Navigation*	A work zone shall be tested using a baseline configuration without communications, which includes the CMU ADS demonstrating detecting an intersection, traffic conditions, assessing right-of-way, and completing movement through an intersection without project enhancements (static work zone devices without coatings, HD maps, etc.).	Shall	Test
UC03-NF-002	Non-Functional	*UC03: Work Zone Navigation*	A work zone shall be tested measuring regulatory and warning signs and pavement markings.	Shall	Test
UC03-NF-003	Non-Functional	*UC03: Work Zone Navigation*	A work zone shall be tested given an HD map from the DMS to the CMU ADS	Shall	Test

REQ ID	REQ TYPE	*TITLE*	DESCRIPTION	IMPORTANCE	VERIFICATION METHOD
UC03-NF-004	Non-Functional	*UC03: Work Zone Navigation*	A work zone shall be tested using connected V2X work zone objects. This may be using GPS devices connected to ZigBee mesh network or other form of connectivity.	Shall	Test
UC03-NF-005	Non-Functional	*UC03: Work Zone Navigation*	A work zone shall be tested using temporary signal navigation.	Shall	Test
UC03-NF-006	Non-Functional	*UC03: Work Zone Navigation*	A work zone shall be tested measuring object detection while operating in normal mode.	Shall	Test
UC03-NF-007	Non-Functional	*UC03: Work Zone Navigation*	A work zone shall be tested with induced failure modes.	Shall	Test
UC03-NF-007.A	Non-Functional	*UC03: Work Zone Navigation*	A work zone shall be tested under degraded conditions with predefined course of action of uncertainty.	Shall	Test
UC03-NF-007.B	Non-Functional	*UC03: Work Zone Navigation*	A work zone shall be tested with equipment failure.	Shall	Test
UC03-NF-007.C	Non-Functional	*UC03: Work Zone Navigation*	A work zone may be tested with object misdetection.	May	Test
UC03-NF-008	Non-Functional	*UC03: Work Zone Navigation*	The project may review and update the scenarios considered for testing based on modeling and simulation test results.	May	Test
UC03-SR-001	Security	*UC03: Work Zone Navigation*	The DMS shall provision an SSL Transport Layer Security (TLS) 1.2 over HTTPS for the HPC within the roadway network to exchange data files and messages securely to and from the roadside and DMS.	Shall	Test
UC03-DATA-001	Constraints	*UC03: Work Zone Navigation*	The DMS should collect, store, and process CMU ADS BSM messages from the HPC on the roadway network.	Should	Test
UC03-DATA-002	Constraints	*UC03: Work Zone Navigation*	The DMS should collect, store, and process incoming aggregated data from the HPC on the roadway network.	Should	Test
UC03-DATA-003	Constraints	*UC03: Work Zone Navigation*	The DMS should collect, store, and process log data from the HPC on the roadway network.	Should	Test

REQ ID	REQ TYPE	*TITLE*	DESCRIPTION	IMPORTANCE	VERIFICATION METHOD
UC03-DATA-004	Constraints	*UC03: Work Zone Navigation*	The DMS should receive incoming data requests from the HPC on the roadway network.	Should	Test
UC03-DATA-005	Constraints	*UC03: Work Zone Navigation*	The DMS shall send map data to the CMU-RMC.	Shall	Test
UC03-DATA-006	Constraints	*UC03: Work Zone Navigation*	The DMS shall send map data to the HPC on the roadway network.	Shall	Test
UC04-DR-001	Data	*UC04: DMS Data Retrieval*	The DMS shall receive incoming data requests from the CMU-RMC.	Shall	Test
UC04-DR-002	Data	*UC04: DMS Data Retrieval*	The DMS shall receive incoming data requests from the HPC.	Shall	Test
UC04-DR-002	Data	*UC04: DMS Data Retrieval*	The DMS shall send map data to the CMU-RMC.	Shall	Test
UC04-DR-003	Data	*UC04: DMS Data Retrieval*	To evaluate the success of the project and develop reports.	Shall	Test
UC04-DR-004	Data	*UC04: DMS Data Retrieval*	The DMS shall collect, store, and process camera image data from the MAPVAN.	Shall	Test
UC04-DR-005	Data	*UC04: DMS Data Retrieval*	The DMS shall collect, store, and process LiDAR data from the MAPVAN.	Shall	Test
UC04-DR-006	Data	*UC04: DMS Data Retrieval*	The DMS shall collect, store, and process radar data from the MAPVAN.	Shall	Test
UC04-DR-007	Data	*UC04: DMS Data Retrieval*	The DMS shall collect, store, and process GPS/INS data from the MAPVAN.	Shall	Test
UC04-DR-008	Data	*UC04: DMS Data Retrieval*	The DMS shall collect, store, and process camera image data from the CMU ADS.	Shall	Test
UC04-DR-010	Data	*UC04: DMS Data Retrieval*	The DMS shall collect, store, and process GPS/PPS data from the CMU ADS.	Shall	Test
UC04-DR-011	Data	*UC04: DMS Data Retrieval*	The DMS shall collect, store, and process simulated data from the traffic simulation process.	Shall	Test

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REQ ID	REQ TYPE	*TITLE*	DESCRIPTION	IMPORTANCE	VERIFICATION METHOD
UC04-DR-012	Data	*UC04: DMS Data Retrieval*	The DMS shall collect, store, and process simulated data from the drive simulation process.	Shall	Test
UC04-DR-013	Data	*UC04: DMS Data Retrieval*	The DMS shall collect, store, and process processed map files from the PSU-RMC.	Shall	Test
UC04-FN-001	Functional	*UC04: DMS Data Retrieval*	API will be provided for the USDOT and other researchers to extract research data.		Test
UC04-FN-002	Functional	*UC04: DMS Data Retrieval*	A web-based user interface (web UI) shall be made available for data access.	Shall	Test
UC04-FN-003	Functional	*UC04: DMS Data Retrieval*	**The ADS project team shall be granted access to the web-based UI.**	Shall	Test
UC04-FN-004	Functional	*UC04: DMS Data Retrieval*	A set of common queries shall be agreed upon by the team and made available to the project team via the web UI.	Shall	Test
UC04-FN-005	Functional	*UC04: DMS Data Retrieval*	The project team shall review and approve the data {schema, architecture} prior to DMS go-live.	Shall	Test
UC04-FN-006	Functional	*UC04: DMS Data Retrieval*	Data for researchers shall be made available to the USDOT within ten (10) days of source generation.	Shall	Inspection
UC04-FN-007	Functional	*UC04: DMS Data Retrieval*	DMS orchestration services shall push approved data to a designated WebApp in a segmented portion of the DMS for sharing with the general public.	Shall	Test
UC04-FN-008	Functional	*UC04: DMS Data Retrieval*	The DMS shall provision and enable a secure connection via API for the USDOT to connect and extract processed data.	Shall	Test
UC04-FN-009	Functional	*UC04: DMS Data Retrieval*	The DMS shall receive requests for raw sensor data, curated without PII and PHI, and provide that data set within three (3) business days.	Shall	Test
UC04-PF-001	Performance	*UC04: DMS Data Retrieval*	Data queries shall be efficient and data results shall be optimized.	Shall	Test
UC04-SR-001	Security	*UC04: DMS Data Retrieval*	The DMS shall provision an HTTPS/TLS 1.2 encrypted tunnel for the PSU-RMC to send data securely to the DMS.	Shall	Test

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UC04-SR-002	Security	*UC04: DMS Data Retrieval*	The DMS shall provision an HTTPS/TLS 1.2 encrypted tunnel for the CMU-RMC to send data securely to the DMS.	Shall	Test
UC04-FN-010	Functional	*UC04: DMS Data Retrieval*	A web-based user interface (web UI) shall be made available for the anonymous access to project approved data sets.	Shall	Test
TESTMS-NF-001	Non-Functional	*Test Phase 01: Modeling & Simulation*	The Penn State test track shall be used to establish the ground truth characteristics for calibrating simulations for closed-track testing.	Shall	Test
TESTMS-SFTY-001	Safety	*Test Phase 01: Modeling & Simulation*	ISO/PAS 21448 Safety of The Intended Function (SOTIF) must be demonstrated.	Shall	Test
TESTMS-SFTY-001	Safety	*Test Phase 01: Modeling & Simulation*	For all simulated test runs, SIM outcomes must demonstrate the ego vehicle's behavior and capability to make safe driving decisions on the road.	Shall	Demonstration
TESTMS-SFTY-002	Safety	*Test Phase 01: Modeling & Simulation*	The CMU ADS behavioral safety features must be modeled.	Shall	Demonstration
TESTMS-SFTY-003	Safety	*Test Phase 01: Modeling & Simulation*	Models must provide, and simulation must demonstrate, an assessment of failure modes and failure mitigation strategies.	Shall	Demonstration
TESTMS-SFTY-004	Safety	*Test Phase 01: Modeling & Simulation*	The CMU ADS must demonstrate redundancy capacity to operate safely when there is a system fault or failure.	Shall	Demonstration
TESTMS-NF-001	Non-Functional	*Test Phase 01: Modeling & Simulation*	For each simulated test run that is documented, the ADS features, ODD, OEDR, failure mode behaviors, and ego vehicle maneuvers must show how the simulated environment is setup and the results of the test run executed.	Shall	Demonstration
TESTMS-NF-002	Non-Functional	*Test Phase 01: Modeling & Simulation*	Results of simulation shall be comprehensively analyzed, evaluated and approved by the project team authorities (PM, Leads, Chief SE) in a final review workshop. The workshop is a collaborative meeting aimed to satisfy decision gate requirements through demonstration.	Shall	Demonstration
TESTMS-IM-001	Information/Document Mgt	*Test Phase 01: Modeling & Simulation*	A model for testing must include all attributes that define the operational design domain (ODD) within the scope of the factors being tested.	Shall	Demonstration
TESTMS-IM-001.A	Information/Document Mgt	*Test Phase 01: Modeling & Simulation*	The ODD shall include all attributes that define physical infrastructure.	Shall	Demonstration

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REQ ID	REQ TYPE	*TITLE*	DESCRIPTION	IMPORTANCE	VERIFICATION METHOD
TESTMS-IM-001.A.1	Information/Document Mgt	*Test Phase 01: Modeling & Simulation*	Physical infrastructure shall include roadway geometry.	Shall	Demonstration
TESTMS-IM-001.B	Information/Document Mgt	*Test Phase 01: Modeling & Simulation*	The ODD shall include all attributes that define operational constraints.	Shall	Demonstration
TESTMS-IM-001.C	Information/Document Mgt	*Test Phase 01: Modeling & Simulation*	The ODD shall include all attributes that define objects.	Shall	Demonstration
TESTMS-IM-001.C.1	Information/Document Mgt	*Test Phase 01: Modeling & Simulation*	Objects shall include classification of work zone safety devices.	Shall	Demonstration
TESTMS-IM-001.C.2	Information/Document Mgt	*Test Phase 01: Modeling & Simulation*	Objects shall include classification of construction workers.	Shall	Demonstration
TESTMS-IM-001.C.3	Information/Document Mgt	*Test Phase 01: Modeling & Simulation*	Objects shall include coating property.	Shall	Demonstration
TESTMS-IM-001.D	Information/Document Mgt	*Test Phase 01: Modeling & Simulation*	The ODD shall include all attributes that define connectivity.	Shall	Demonstration
TESTMS-IM-001.D.1	Information/Document Mgt	*Test Phase 01: Modeling & Simulation*	Connectivity shall include radio and associated properties.	Shall	Demonstration
TESTMS-IM-001.E	Information/Document Mgt	*Test Phase 01: Modeling & Simulation*	The ODD shall include all attributes that define environmental conditions.	Shall	Demonstration
TESTMS-IM-001.F	Information/Document Mgt	*Test Phase 01: Modeling & Simulation*	The ODD shall include all attributes that define zones.	Shall	Demonstration
TESTMS-IM-001.F.1	Information/Document Mgt	*Test Phase 01: Modeling & Simulation*	Zones shall include a work zone geofence and associated properties.	Shall	Demonstration
TESTMS-IM-002	Information/Document Mgt	*Test Phase 01: Modeling & Simulation*	A model {for testing} must be simulated and include the object and event detection and response (OEDR) capabilities of the CMU ADS.	Shall	Demonstration
TESTMS-IM-003	Information/Document Mgt	*Test Phase 01: Modeling & Simulation*	For each test run, the simulator must log data from the dynamic driving task of the CMU ADS to the DMS (i.e., monitoring the drive environment for road, traffic, and visibility). This includes detection,	Shall	Demonstration

REQ ID	REQ TYPE	*TITLE*	DESCRIPTION	IMPORTANCE	VERIFICATION METHOD
			recognition, classification of objects, classification of events, and the behavioral response of the vehicle.		
TESTMS-IM-004	Information/Document Mgt	*Test Phase 01: Modeling & Simulation*	Output from simulated test runs must include the features and values of the ODD.	Shall	Demonstration
TESTMS-IM-005	Information/Document Mgt	*Test Phase 01: Modeling & Simulation*	All scenarios considered for closed-track testing must be qualified with a “scenario test artifact” certified by the project team, which describes the ADS feature, the ODD, expected OEDRs, expected failure mode behaviors (if any) of the environment setup and the expected execution results.	Shall	Demonstration
TESTCT-RG-001	Policy and Regulation	*Test Phase 02: Closed Track*	Approval shall be obtained from PennDOT and proper staffing arrangements made prior to beginning closed-track testing as per work zone testing application form requirements and AV testing regulations in the state of Pennsylvania (ref. SRD section 2.2 RG-014)	Shall	Inspection
TESTCT-NF-001	Non-Functional	*Test Phase 02: Closed Track*	The Penn State test track shall be used to establish the ground truth characteristics of the roadway and quantitative hazard models that can be calibrated and measured during testing.	Shall	Demonstration
TESTCT-NF-002	Non-Functional	*Test Phase 02: Closed Track*	All scenarios being tested at the Penn State test track shall have been previously simulated in a traffic simulator, drive simulator, and vehicle actuation simulator (i.e., CADRE) and approved/cleared by the project team for closed-track testing.	Shall	Demonstration
TESTCT-IM-001	Information/Document Mgt	*Test Phase 02: Closed Track*	All scenarios approved/cleared for closed-track testing must be qualified by a unique “scenario test artifact” certified by the project team for testing, which describes the ADS feature, the ODD, expected OEDRs, expected failure mode behaviors (if any) of the environment setup and the expected execution results.	Shall	Inspection
TESTCT-IM-002	Information/Document Mgt	*Test Phase 02: Closed Track*	For each test run, the test team shall measure and qualify performance results of the test run against the “scenario test artifact”, which must be on-hand during testing.	Shall	Inspection
TESTCT-IM-003	Information/Document Mgt	*Test Phase 02: Closed Track*	All variances in the expected results, outlined in the scenario test artifact, must be logged by the tester.	Shall	Inspection

REQ ID	REQ TYPE	*TITLE*	DESCRIPTION	IMPORTANCE	VERIFICATION METHOD
TESTCT-IM-004	Information/Document Mgt	*Test Phase 02: Closed Track*	CMU ADS event recorded data for each test run shall be reviewed and used to inform on the pass/fail/repeat success criteria for the scenario.	Shall	Analysis
TESTCT-IM-005	Information/Document Mgt	*Test Phase 02: Closed Track*	Closed-track test runs shall be recorded using camera video and sent to the DMS.	Shall	Inspection
TESTCT-PF-001	Performance	*Test Phase 02: Closed Track*	Results from a closed-track test run must include performance data from the CMU ADS CADRE stack on the CMU ADS's OEDR and failure mode behaviors (FS, FO).	Shall	Inspection
TESTCT-PF-002	Performance	*Test Phase 02: Closed Track*	Results from a closed-track test run must include the CMU ADS features, the ODD measured (i.e., communication types, HD map domain, work zone objects and coatings).	Shall	Inspection
TESTCT-PF-003	Performance	*Test Phase 02: Closed Track*	Unexpected FS behaviors shall be logged, evaluated and used to inform on changes to the use-case pipeline (architecture, function, process, etc.) in order to achieve the expected outcome as determined by vehicle simulator.	Shall	Analysis
TESTCT-PF-004	Performance	*Test Phase 02: Closed Track*	Unexpected FO behaviors shall be logged and evaluated. The project team shall determine if the FO behavior is either acceptable or needs correcting and is correctable. For further information on handing FO behaviors, the project test plan shall be referenced.	Shall	Analysis
TESTOR-RG-001	Policy and Regulation	*Test Phase 03: Open Road*	Approval shall be obtained and proper arrangements made from PennDOT prior to beginning open-road testing as per work zone testing application form and AV testing regulations (ref. SRD section 2.2 RG-014)	Shall	Inspection
TESTOR-NF-001	Non-Functional	*Test Phase 03: Open Road*	Prior to go-live, the roadway where open-road testing will be conducted shall be used to establish the ground truth characteristics of the roadway and quantitative hazard models that can be calibrated and measured during testing.	Shall	Inspection
TESTOR-NF-002	Non-Functional	*Test Phase 03: Open Road*	All scenarios being tested on the open-road shall have been previously simulated in a traffic simulator, drive simulator, and vehicle actuation simulator (i.e., CADRE) and approved/cleared by the project team for closed-track testing.	Shall	Demonstration

REQ ID	REQ TYPE	*TITLE*	DESCRIPTION	IMPORTANCE	VERIFICATION METHOD
TESTOR-NF-003	Non-Functional	*Test Phase 03: Open Road*	All scenarios being tested on the open-road shall have been previously tested at the Penn State closed-track and approved/cleared by the project team for open-road testing.	Shall	Demonstration
TESTOR-IM-001	Information/Document Mgt	*Test Phase 03: Open Road*	All scenarios approved/cleared for open-road testing must be qualified by a unique “scenario test artifact” certified by the project team for testing on the open-road, which describes the ADS feature, the ODD, expected OEDRs, expected failure mode behaviors (if any) of the environment setup, results from closed-track tests and the expected execution for open-road.	Shall	Inspection
TESTOR-IM-002	Information/Document Mgt	*Test Phase 03: Open Road*	For each test run, the test team shall measure and qualify performance results of the test run against the “scenario test artifact”, which must be on-hand during testing.	Shall	Inspection
TESTOR-IM-003	Information/Document Mgt	*Test Phase 03: Open Road*	All variances in the expected results, outlined in the scenario test artifact, must be logged by the tester.	Shall	Inspection
TESTOR-IM-004	Information/Document Mgt	*Test Phase 03: Open Road*	CMU ADS event recorded data for each test run shall be reviewed and used to inform on the pass/fail/repeat success criteria for the scenario.	Shall	Analysis
TESTOR-IM-005	Information/Document Mgt	*Test Phase 03: Open Road*	Open-road test runs shall be recorded using camera video and sent to the DMS.	Shall	Inspection
TESTOR-PF-001	Performance	*Test Phase 03: Open Road*	Results from an open-road test run must include performance data from the CMU ADS CADRE stack on the CMU ADS’s OEDR and failure mode behaviors (FS, FO).	Shall	Inspection
TESTOR-PF-002	Performance	*Test Phase 03: Open Road*	Results from an open-road test run must include the CMU ADS features, the ODD measured (i.e., communication types, HD map domain, work zone objects and coatings).	Shall	Inspection
TESTOR-PF-003	Performance	*Test Phase 03: Open Road*	Unexpected FS behaviors shall be logged, evaluated and used to inform on changes to the use-case pipeline (architecture, function, process, etc.) in order to achieve the expected outcome as determined by vehicle simulator and closed-track testing.	Shall	Analysis
TESTOR-PF-004	Performance	*Test Phase 03: Open Road*	Unexpected FO behaviors shall be logged and evaluated. The project team shall determine if the FO behavior is either acceptable	Shall	Analysis

REQ ID	REQ TYPE	*TITLE*	DESCRIPTION	IMPORTANCE	VERIFICATION METHOD
			or needs correcting and is correctable. For further information on handing FO behaviors, the project test plan shall be referenced.		
EXPRM-IM-001	Information/Document Mgt	*Planned Experimentation*	A summary of the baseline HD map generation, commensurate with the level of effort required for experimentation, shall be documented. The summary may include challenge(s), hypothesis, methods, HD map features, final outcome, etc.	Shall	Analysis
EXPRM-IM-002	Information/Document Mgt	*Planned Experimentation*	A summary of the methods for detection and classification of PPG coatings, commensurate with the level of effort required for experimentation, shall be documented. The summary may include challenge(s), hypothesis, methods, coating features, final outcome, etc.	Shall	Analysis
EXPRM-IM-003	Information/Document Mgt	*Planned Experimentation*	A summary of the methods for detection and classification of objects and events related to the work zone and/or navigation, commensurate with the level of effort required for experimentation, shall be documented. The summary may include challenge(s), hypothesis, methods, object features, event details, outcomes, etc.	Shall	Analysis
EXPRM-IM-004	Information/Document Mgt	*Planned Experimentation*	A summary of the methods for embedding centerline data and obstacle definitions as data flows-in directly, commensurate with the level of effort required for experimentation, shall be documented. The summary may include targeted process flows, challenge(s), hypothesis, methods, features, final outcome, etc.	Shall	Analysis
EXPRM-IM-005	Information/Document Mgt	*Planned Experimentation*	A summary of the methods employed to improve map generation process, commensurate with the level of effort required for experimentation, shall be documented. The summary may include challenge(s), hypothesis, methods, design, algorithms, final outcome, etc.	Shall	Analysis
EXPRM-IM-006	Information/Document Mgt	*Planned Experimentation*	A summary of the methods for conforming to SAE J2735 encodings, HD map file formats and transmittal mediums, commensurate with the level of effort required for experimentation, shall be documented. The summary may include challenge(s), hypothesis, methods, encodings, formats, protocol stack details, final outcome, etc.	Shall	Analysis

REQ ID	REQ TYPE	*TITLE*	DESCRIPTION	IMPORTANCE	VERIFICATION METHOD
EXPRM-IM-007	Information/Document Mgt	*Planned Experimentation*	A summary of the methods and results of preserving data privacy, commensurate with the level of effort required for experimentation, shall be documented. The summary may include challenge(s), tools used, integration details, final methods and outcome, etc.	Shall	Analysis

Source: PennDOT

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Appendix C: Acronyms and Key Terms/Definitions

Abbreviation/Acronym	Definition
ACL	Access Control List
ADS	Autonomous Driving System
API	Application Programming Interface
ASD	Automatic Shutdown Relay
AV	Autonomous Vehicle
AVIRP	Automated Vehicle Incident Response Plan
BSM	Basic Safety Message
CADRE	Connected and Autonomous Driving Research and Engineering
CMU	Carnegie Mellon University
CMU-RMC	CMU Research Management Center (Back-Office Research Lab Computer)
CORS	Continuously Operating Reference Station
CV	Connected Vehicle
C-V2X or V2X	Cellular Vehicle to Everything
DMS	Data Management System
DSRC	Dedicated Short Range Communications
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HD	High-Definition
HPC	High Performance Computer
INS	Inertial Navigation System
LiDAR	Light Detection and Ranging
LTI	Larson Transportation Institute
MAPVAN	PSU Mapping Van
OBU	Onboard Unit
OEDR	Object and Event Detection and Response
PATA	Pennsylvania Typical Application
PCMS	Portable Changeable Message Sign
PennDOT	Pennsylvania Department of Transportation
PPG	PPG Industries, Inc.
PPS	Pulse Per Second
PSU	Penn State University
PSU-RMC	PSU Research Management Center (Back-Office Research Lab Computer)
PTC	Pennsylvania Turnpike Commission
PTS	Pennsylvania Turnpike Commission Maintenance and Protection of Traffic Standards
RF	Radio Frequency
ROS	Robot Operating System
RSU	Roadside Unit
SAE	SAE International
SPaT	Signal Phase and Timing

Abbreviation/Acronym	Definition
SUMO	Simulation of Urban MObility
SV	Shadow Vehicle
TMA	Truck Mounted Attenuator
USDOT	United States Department of Transportation
WZDx	Work Zone Data Exchange

Key Terms	Definition
Azure Platform	Deloitte's cloud based DMS
CADRE TROCS	CMU's simulation system
CARLA	An open-source autonomous driving simulator
Ego Vehicle	Ego vehicle refers to the simulated CMU-AV
SUMO	An open-source, portable, microscopic, and continuous multi-modal traffic simulation package designed to handle large networks.
Work Zone Scenario	The work zone layout relating to the PATA setup arrangement given in PennDOT's Publication 213 and the layout relating to the PTS setup arrangement specified in PTC PTS 900 series standards.
SnLIB	**Scenario library** Represents the array of unique permutations planned for simulation testing that result from the six use cases and the variances within the ODD, for each ADS feature, when its intended and able to operate, with respect to roadway types, speed range, lighting conditions, weather conditions, and other operational constraints.
ODD	**Operational design domain** The conditions in which an ADS is designed to handle, including physical infrastructure, operational constraints, objects, connectivity, environmental conditions, and zones.
DDT	**Dynamic driving task** The act of driving a vehicle on a road, which includes two important sub-tasks: vehicle movement [consists of lateral (acceleration, braking) and longitudinal (steering)] and object and event detection and response.
ADS	**Automated driving system** A vehicle developed to perform the primary functions of the dynamic driving task.
OEDR	**Object and event detection and response** Subtasks of the dynamic driving task that include monitoring the driving environment (detecting, recognizing, and classifying objects and events and preparing to respond as needed) and executing an appropriate response to such objects and events (i.e., as needed to complete the DDT and/or DDT fallback; (SAE International, 2016).
DSRC	Dedicated short range communications
C-V2X	Cellular vehicle to everything communications

Key Terms	Definition
fallback	**Fallback** A response to operate the vehicle when something goes wrong, such as bringing it to an MRC. By definition, Fallback is outside the DDT.
MRC	**Minimal risk condition** A condition to which a user or an ADS may bring a vehicle after performing the DDT fallback in order to reduce the risk of a crash when a given trip cannot or should not be completed.
FS	**Fail-Safe** A fail mode behavior technique used when an ADS cannot continue to function (e.g., transitioning control to the fallback-ready operator, moving out of a lane, stopping safely in a lane, etc.).
FO	**Fail-Operational** A fail mode behavior technique used to allow an ADS to function at a reduced capacity, potentially for a brief period of time or with reduced capabilities (e.g., degraded mode of operation such as reduced speed, reduced maneuvers, reduced ODD, etc.)

Source: PennDOT