Automated Driving System Demonstration (ADS) Grant Application | NOFO693JJ319NF00001

Safe Integration of Automated Vehicles into Work Zones | PKG 00247169

SYSTEM REQUIREMENTS
for the
Safe Integration of Automated Vehicles into Work Zones Project

FEBRUARY 25, 2022

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Acknowledgement of Support
This material is based upon work supported by the U.S. Department of Transportation under Grant Award No. NOFO693JJ319NF00001.

This material is being produced with the support of HNTB Corporation under Contract for the Automated Driving System Demonstration Grant.

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Technical Report Documentation

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA-JPO-XX-XXX		
4. Title and Subtitle System Requirements for Safe Integration of Automated Vehicles into Work Zones		**5. Report Date** **6. Performing Organization Code**
7. Author(s) Mark Kopko (PennDOT), Gunnar Rhone (PennDOT), Jess Baker, SEP (HNTB)		**8. Performing Organization Report No.**
9. Performing Organization Name And Address Pennsylvania Department of Transportation Keystone Building 400 North St., Fifth Floor Harrisburg, PA 17120		**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.** NOFO693JJ319NF00001
12. Sponsoring Agency Name and Address ITS Joint Program Office 1200 New Jersey Avenue, S.E., Washington, DC 20590		**13. Type of Report and Period Covered** Systems Requirements **14. Sponsoring Agency Code**

15. Supplementary Notes
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16. Abstract

The Automated Driving System Demonstration will evaluate the impact that three configurable factors have on an autonomous vehicle's ability to navigate safely in a work zone. Factors include improved connectivity, visibility, and mapping between automated vehicles and work zone objects in an effort to advance PENNDOT and USDOT research to enable safe integration of automated driving systems in a work zone.

This document presents high-level system requirements in six categories, which include (1) general requirements for the project, (2) tailoring functions for existing systems, (3) the data management system, (4) requirements for the six use cases outlined in the concept of operations, (5) the three test phases, and lastly (6) preliminary requirements for research and experimentation activities.

For existing systems, requirements focus on identifying functional, non-functional, and constraints. For the six use cases, requirements are expanded and include any requirement type needed to meet the defined use case including interface requirements, data, security, performance and knowledge management. Lastly, requirements for the three test phases and research activities center around maintaining the safety of the system and preserving (i.e., documenting) the knowledge gained through each phase of the project.

17. Key Words	18. Distribution Statement
Automated Driving System, Automated Vehicle, Work Zone, Data, Mapping, Safety, Demonstration	

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified		

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Table of Contents

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LIST OF FIGURES

LIST OF TABLES

Chapter 1: Introduction

1.1 Project Background

The Pennsylvania Department of Transportation (PennDOT) was awarded $8.4 million by the U.S. Department of Transportation (USDOT) for the research and development of Automated Driving Systems (ADS) in work zones. With the funding, PennDOT intends to research the impact of leveraging three factors to improve the safe navigation of an ADS when it enters a designated work zone. These factors include the use of a high-definition (HD) map of a construction area (i.e., work zone), an ADS ability to perceive new innovative coatings on work zone objects, and various connectivity methods including C-V2X, 4G/5G, Wi-Fi, and DSRC.

To demonstrate the viability of the solutions being researched, the project will develop models and conduct simulations with varying scale, complexity, and duration. The project's performance measures will drive the objectives for virtual testing. Upon establishing a set of criteria and configurations during the simulation period, the project team will demonstrate real-world performance by implementing the successfully simulated environment (criteria, configurations) at the Penn State closed-track facility. Outcomes of close-track testing will be used to inform changes and refine engineering configurations where necessary. Once the refined system has been modeled, simulated, and successfully tested at the closed-track, those operational design domain configurations will be integrated and demonstrated within a limited and controlled open-road network.

1.2 Purpose and Scope

This System Requirements Document (SRD) is one artifact in a series of engineering document deliverables in the planning phase of the ADS project (hereon referred to as "the project"). Requirements developed at this stage are high-level and generally focus on providing a comprehensive context for research to be conducted to meet project objectives.

This document presents requirements in six different categories:

- General requirements for the development of the project,
- Requirements for tailoring the functions of existing systems,
- Requirements for the new data management system (DMS) being developed for this project,
- Requirements for the six use cases outlined in the concept of operations (ConOps),
- Requirements for the three test phases, and
- Preliminary requirements are presented for research activities.

For existing systems, requirements focus on functional, non-functional, and constraints. For the six use cases, however, requirements are expanded to include interface, data, security, performance, and knowledge management. Requirements for the three test phases as well as for the research activities center around maintaining the safety of the system and preserving (i.e., documenting) the knowledge gained through each phase of the project.

Figure 1 provides the meta model for the requirements contained within this SRD.

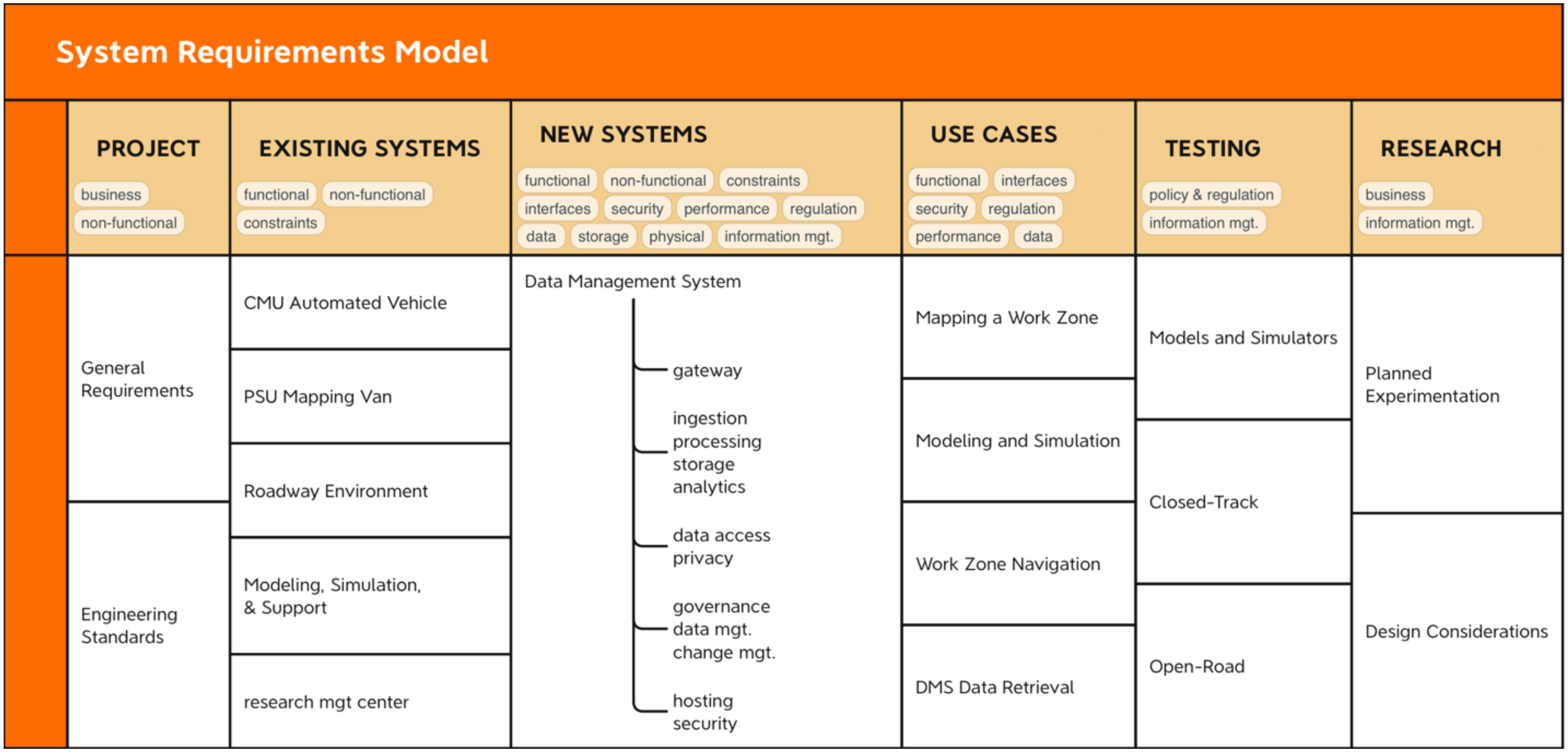

Figure 1: ADS System Requirements Model

Source: Pennsylvania Department of Transportation

1.3 Key Terms

Table 1 presents key terms used in this SRD to provides a baseline definition for how these terms are used for the project moving forward.

Table 1: Key Terms

Name	Description
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
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

Chapter 2: System Definition

2.1 System Context

The ADS project intends to measure the behavioral response of a highly automated driving system when it is provided with a HD map of a work zone having workers present, work trucks, and construction safety devices (cones, barrels, etc.) with stripping and markings that have a coating with a high light-reflectance value (LHR) property. The work zone environment will be instrumented with 4G/5G, Wi-Fi, C-V2X, and DSRC communication capabilities for message and data exchanges.

The system concept described in the project's ConOps brings together five (5) pre-existing functional systems, enhanced and tailored by the project to meet research objectives. This system of systems includes

- A system that maps the construction area,
- An instrumented roadway network,
- An automated driving system capable of level 4 automation,
- The back-office processing center(s) at PSU and CMU having modeling and simulation and other support tools, and
- A cloud-based DMS.

Testing of these systems will be conducted by simulating the drive behavior of the vehicle in a digital environment at Penn State and CMU during the second year of the project. Testing will then be conducted in a closed-track environment at Penn State during year three. Finally, the system developed will be demonstrated in a controlled, limited open-road environment the fourth year. below provides a contextual representation of the ADS project as outlined in the ConOps.

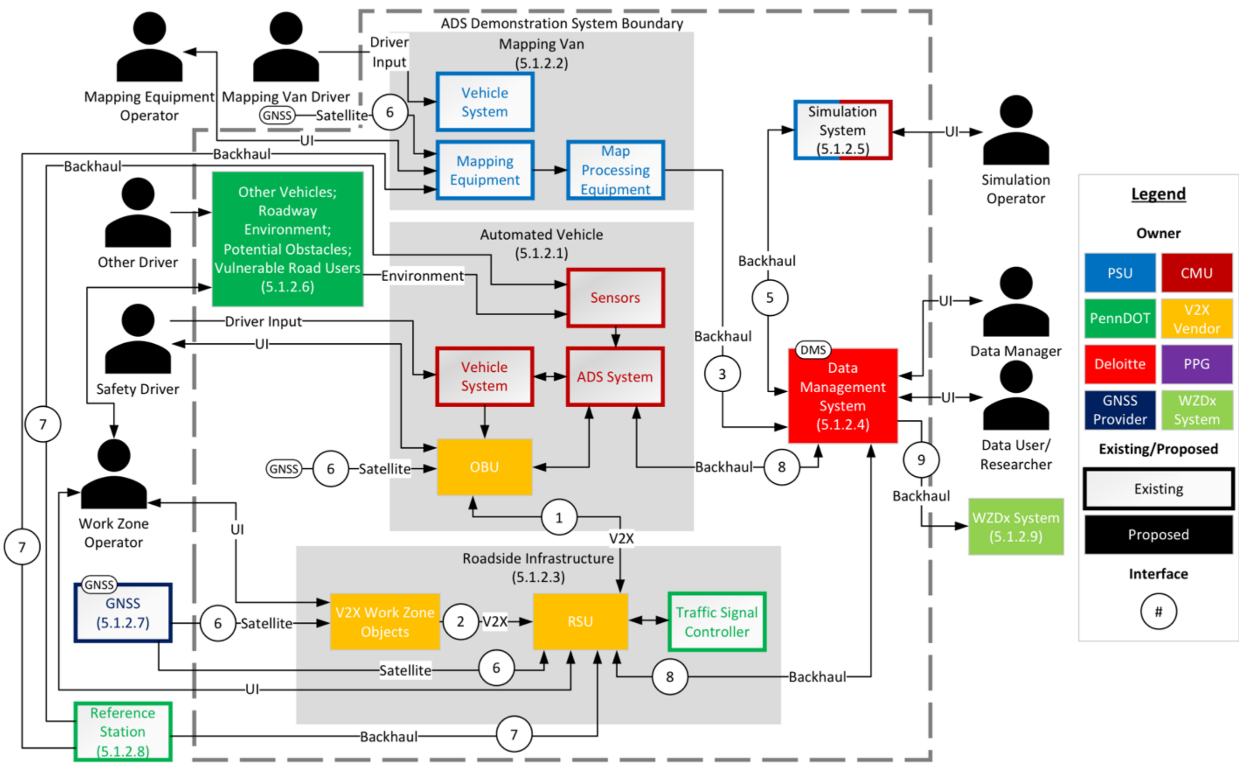

Figure 2: ADS Project, System of Systems Context Design

Source: Pennsylvania Department of Transportation

2.2 Project Description and Goals

To guide the vision presented in **Figure 2**, the project will need to align industry practices and standards for connected and automated vehicle communication, system configuration, data transmissions, and regulatory requirements as outlined in the table below. In general, the requirements herein are high-level to aid in meeting the project's performance objectives and include requirements for non-functional (NF), information management (IM), policy and regulation (RG), and security (SR). **Appendix C. Requirements Matrix** provides additional definitions for the requirement types included in this SRD.

Table 2: General Requirements for ADS Project & Research Activities

Requirement ID	Requirement
GEN-IM-001	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 tradeoffs, 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.

Requirement ID	Requirement
GEN-NF-001	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.
GEN-RG-001	SAE J3016_202104 Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems shall be used.
GEN-RG-002	SAE SS_V2X_001 Security Specification through the Systems Engineering Process for SAE V2X Standards shall be considered.
GEN-RG-003	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.
GEN-RG-003.A	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.
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 parameters conform to LTE-V2X vehicle-level requirements specified in SAE J3161/1 Standard WIP.
GEN-RG-004	SAE J2735_201603 Dedicated Short Range Communications (DSRC) Message Set Dictionary shall be used to assure applications using DSRC are interoperable.
GEN-RG-005	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.
GEN-RG-006	SAE J2945/2_201810 DSRC Performance Requirements for V2V Safety Awareness shall be used to specify interface requirements for V2V Safety applications.
GEN-RG-007	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.
GEN-RG-008	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.
GEN-RG-009	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

Requirement ID	Requirement
	Internet Protocol version 6 that can be directly supported by applications, and the Management Information Base for the WAVE protocol stack.
GEN-RG-0100	IEEE 1609.4-2016 Standard for WAVE Multi-Channel Operations standard shall be used to provide enhancements of the IEEE 802.11 Media Access Control to support WAVE operations and describes various standard message formats for DSRC applications.
GEN-RG-011	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.
GEN-RG-012	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.
GEN-RG-013	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.
GEN-RG-014	The ATC family of standards shall be supported: • ATC 5201 ATC Standard • ATC 5401 Application Programming Interface (API) Standard • ATC 5301 ATC Cabinet Standard
GEN-RG-015	A Notice of Testing application shall be submitted through the PennDOT website www.penndot.gov/av[1] prior to testing.
GEN-RG-015.A	The Safety and Risk Mitigation Plan shall be submitted with Notice of Testing.
GEN-RG-015.B	Testing activities shall meet PennDOT's operational requirements for automated vehicle testing as per the *AUTOMATED VEHICLE TESTING GUIDANCE*[2] (July 23, 2018).
GEN-SR-001	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 requirements specific to systems, processes, and data are detailed in their respective section.

Source: PennDOT

1 *www.penndot.gov/av*

2 *https://www.penndot.gov/ProjectAndPrograms/ResearchandTesting/Autonomous%20_Vehicles/Documents/PUB_950_9-20.pdf*

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2.3 Stakeholder Requirements

Table 3 describes the requirements for the individual roles of the stakeholders participating in testing and associated responsibility.

Table 3: ADS Stakeholder Requirements

User	User Need	Requirement
Safety Driver	Operation of AVs when human intervention is required	Valid driver's license Enhanced AV operations training and experience Ability to intervene in system interruption conditions Ability to safely maneuver the vehicle under all system modes of operation as defined in ConOps section 5.2
Safety Associate	Backup safety operator	Enhanced training of AV operations Knowledge of AV backend operations
Data Manager	Manage, operate and maintain data	Data Management training and analysis of CAV data. Possess knowledge of data collection, integrity and flow Ability to monitor data and any malfunctions
Simulation Operator	Manage, operate, and maintains simulation systems	Conduct both AV and Traffic Simulation Develop and configure scenarios for testing an AV using drive and traffic simulation software
Data User/Researcher	Use data for research	DMS operation Data interpretation and reporting
Mapping Equipment Operator	Operation of Mapping Van	Trained on the installation, calibration, and/or operation of the mapping equipment Enhanced Mapping Van operations training and experience Communicate with mapping van driver for safe operations
Mapping Van Driver	Operate and drive the Mapping Van	Valid driver's license Enhanced Mapping Van operations training and experience Safe operating vehicle conditions for data collection
Work Zone Operator	Operate any activities of the work zone	Safe work zone conditions Safety vest Safety hard hat and boots Safe environment for various work zone scenario testing with static and dynamic work zone devices
Core Project Team	Maintain a safe and working environment	CMU must maintain the automated vehicle in safe operable condition Penn State must maintain the mapping van in safe operable condition PennDOT must maintain all field devices and support systems in operable condition

Source: PennDOT

Chapter 3: High-Level System Requirements (HLR)

This section presents high-level functional, non-functional, and constraint requirements for the systems participating in the ADS project, including the AV, mapping van, simulation software, the roadside environment, and DMS.

For each system presented in this section, the ITS perspective is described, the project's implementation-specific description is provided, and any assumptions considered are made known.

3.1 CMU's Automated Driving System (ADS)

3.1.1 ITS PERSPECTIVE

The ADS generically represents SAE level 3 and SAE level 4 highly automated driving system. The vehicle is capable of driving autonomously and requires minimal operator interaction.

3.1.2 INDUSTRY PERSPECTIVE

SAE J3016 defines an ADS feature as "a driving automation system's design-specific functionality at a specific level of driving automation within a particular Operational Design Domain." Referring to this definition, each feature can be described in terms of the following.

3.1.3 PROJECT DETAIL

The CMU ADS is a level 4 automated vehicle capable of operating in a virtual world and limited real-world environment. Given a HD map, the CMU ADS 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.

To accomplish its task, the vehicle is equipped with sensing, computing, communicating, and actuating capabilities. The on-vehicle subsystems of the CMU ADS are:

- Sensors: LiDARs, radars, cameras, an inertial measurement unit (IMU), GPS pulse per second (PPS) receivers.
- Compute: 5 embedded PCs and a dSpace microAutoBox II ("box"). The box takes serves as the interface between the ADS software stack & the vehicle's by-wire (actuation) subsystem. It is capable of receiving digital inputs to produce digital outputs as well as accepting analog inputs to produce analog outputs.
- Communications: 100Mbps ethernet backbone, multiple CAN buses, DSRC & C-V2X transceivers, and 4G/5G radio.

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- Actuation: primary controls: steering, braking, throttling, and secondary controls: turn signals, flashers, horns, etc.
  - Additional off-vehicle subsystems reside at the CMU research management center RMC and includes the following components:
    - Code repository for the CADRE software stack, map databases and servers, cloud services.

The CMU ADS is equipped with, and operated by, the connected autonomous driving research engineering (CADRE) software stack. **Figure 3** provides an illustration of the modules that make up CADRE.

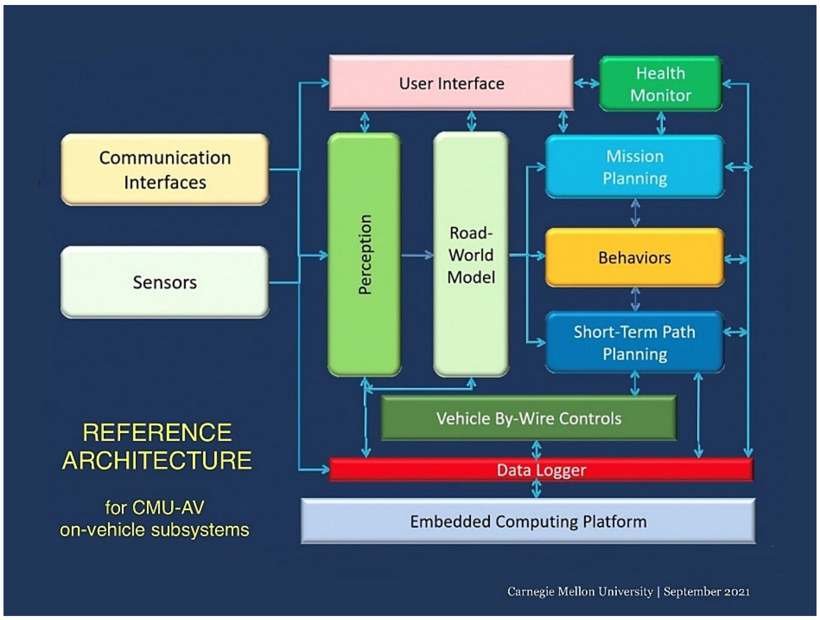

Figure 3: CMU ADS CADRE Reference Architecture

Source: Carnegie Mellon University

The CADRE stack that runs the CMU ADS consists of the following software modules:

- **Perception**: This module receives sensory input and inputs from the communications module (i.e., SAE messages) and "perceives" objects, classifying where necessary. Outputs from perception are used to create a relative road-world model of where the vehicle is at any given time and space.
- **Road-world model** (RWM): This module positions the vehicle in reference to a global coordinate system. It is how location will map to incoming HD maps. While perception is a relative frame, the RMS is absolute to the global coordinate system. Given the RWM, the CMU ADS knows when it's approaching an intersection, stop sign, traffic light, about to merge, take an exit, etc. This is what the RWM contains, which is then fed into the behaviors module.

- **Behaviors**: Will apply rules of the road based on the current operating context of the vehicle. It decides what to do (proceed, at what speed (roughly), come to stop, etc.). Behavioral decisions at this layer issue commands to the short-term path planner to go or not.
- **Short-term path planner** (STPP): Based on the vehicle's speed, the STPP decides on the upcoming 15-30m look-ahead how to navigate safely around obstacles and come to stop if necessary. It also modulates speed around turns. Based on what the STPP decides in terms of orientation and speed of the vehicle, the STPP sends commands to the by-wire (actuation) to steer, actuate, or brake, etc.
- **Data logger**: All subsystems are logging event and other data as necessary, but not ALL data is logged during autonomous drive mode due to intense workload and data processing that occurs while driving and the vehicle's current on-board computing limitations.
- **Mission planner**: Given the map and where a user wants to go, the module plans the vehicle route from source to destination. The behaviors module receives route information and considers its position at a current point in time and given data input from the RWM the CMU ADS will know which direction (straight, right, left, etc.) it needs to proceed. This information is sent to the STPP for generating actuation commands, i.e., turn the vehicle, go straight, etc.
- **User interface**: Allows in-vehicle users to interact with the CADRE SW stack.
- **Health monitor**: Monitors the hardware and software subsystems for errors, bugs, issues, conflicts, etc., and generates different kinds of (video imagery and audible) alerts.
- **Embedded computing** platform runs all the tasks in the CADRE software stack.

3.1.4 ASSUMPTIONS

The CMU ADS is an existing system owned and operated by Carnegie Mellon University. It is assumed on-vehicle sensors, computing hardware and storage, communication and actuation equipment, as well as the CADRE system are fully operational and function as designed.

Table 4: HLR for CMU's ADS System

Requirement ID	Requirement
ADS-CN-001	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).
ADS-CN-002	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.
ADS-CN-003	Due to the highly complex computing load, the CMU ADS data logger captures operational data only and does not record all streaming sensory data.

Requirement ID	Requirement
ADS-SFTY-001	The CMU ADS shall be capable of independent object detection and collision avoidance.
ADS-SFTY-002	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.
ADS-SFTY-003	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).
ADS-SFTY-004	The CMU ADS shall be capable of mitigating failures when data affects safe driving within its operational design domain and minimal risk condition triggered.
ADS-FN-001	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.
ADS-FN-002	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 Electrical and Electronics Engineers (IEEE) 1609 suite and IEEE 802.11 standards [2] to [6].
ADS-FN-003	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.
ADS-FN-004	The CMU ADS shall provide a mechanism that allows the safety driver to manage and terminate the automatic control and operation of the vehicle.
ADS-FN-005	The CMU ADS shall detect, analyze, classify, and monitor objects greater than {QxRxS} within {sensor range} proximity to the vehicle.
ADS-FN-006	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.
ADS-FN-007	The CMU ADS shall monitor its subsystems and inform the safety driver of errors, power or communication failures with any of its subsystem elements.
ADS-FN-008	The CMU ADS shall not respond to incoming TCP-IP requests.
ADS-FN-009	The CMU ADS may be capable of receiving RTK correctional signals using PennDOT CORS base station.
ADS-FN-010	Transmitting over DSRC, the CMU ADS must be capable of receiving a high-definition map file from the roadway environment in {SAE encoded} format.
ADS-FN-011	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.
ADS-FN-012	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 {XML, JSON, GEOJSON, GML, KML, KMZ, SHP, SHX, DBF, GPX, etc.} format.
ADS-FN-013	The CMU-RMS must document the method for the CMU ADS to ingest, process, read, and use HD map file(s).
ADS-FN-014	The CMU-RMS shall document the processing steps required for the CMU ADS 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

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Requirement ID	Requirement
	• 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 ADS can use the map to navigate along path • Validate the CMU ADS knows when it is approaching (a) geofenced work zone, (b) work zone objects
ADS-FN-015	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.

Source: PennDOT

3.2 PSU Mapping Van (MAPVAN)

3.2.1 ITS PERSPECTIVE

The MAPVAN represents an infrastructure owned and operated maintenance and construction vehicle managed by traffic operations and/or maintenance and construction center(s). The vehicle drives around a designated construction area multiple times to generate a high-definition map used to geofence a work zone and identify regulatory safety objects (e.g., cone, barrel, channelizer, sign, signal, etc.) and construction workers.

3.2.2 PROJECT DETAIL

The PSU MAPVAN is instrumented with sensors (LiDAR, radar, camera, encoders, GPS, INS, steering ASD), an onboard unit, one computational system, two hard disk drives, supported by back-office processing computers at PSU. Onboard sensors are managed by the vehicle’s robot operating system (ROS) and are triggered via embedded trigger processes which use GPS/PPS for synchronization. Data is first offloaded to a hard disk drive (HDD) for processing, another HDD for backup, then sent to PSU’s back-office computer for further processing.

The primary function of the MAPVAN is mapping data acquisition to create a digital representation of the construction zone in a high-definition map.

- **MAPVAN data collection:** The onboard computer collects data (LiDAR, radar, camera, encoders, GPS, INS data) and records that data. Generally, one hour of data collection translates into one hour of data transfer, and roughly 10 hours of data processing per hour of data collection. Although the MAPVAN has double alternator capability, it is not equipped with sufficient power to sustain the 10-hour data processing workload and, therefore, only the data collection step is performed onboard the MAPVAN. The data processing step is offloaded and later run from the Penn State project research laboratory.

- **Data processing for HD map creation:** A substantial burden for on-vehicle data collection is processing camera data, which makes up 98% of the data volume. To circumvent this issue, the MAPVAN pushes camera data into a separate repository and uses a hash table to associate the images to prevent the primary database from becoming overly bloated with camera data. The splitting-out of time-synchronized camera data from all other data requires another careful processing step that will add overhead to the processing time, which should be considered.

MAPVAN camera data does not need to be placed in the CMU ADS pipeline. However, it is useful for redundancy checks. Clean data can catch glitches—particularly when there are GPS dropouts. Therefore, to develop ground truth calibration of relative position to obstacles, the cleaning process includes Bayesian data fusion with the RMS system as well as collocation of obstacles—not just position as located by the DGPS system. There are steps baked-in to the MAPVAN processing as truth checks over the data flow, which may take longer but if skipped could introduce positional inaccuracies of detected objects. This is something the project must consider as it tries to find opportunities to reduce the amount of time it takes to generate a HD map from raw data input to a consumable, formatted output.

To make map data useful for the CMU ADS, the system will need to focus on centerline data and obstacle definitions. Currently, PSU is exploring concepts for processing these metrics as the data flows-in directly.

Year-one efforts for map generation focus on coordinating data definitions between systems.

Table 5: HLR for PSU's MAPVAN System

Requirement ID	Requirement
MAPVAN-FN-001	A baseline HD map will need to be established for the project and defined in terms of scale, data accuracy, resolution, and density.
MAPVAN-FN-002	A baseline HD map shall be used for the closed-track roadway network.
MAPVAN-FN-003	A baseline HD map shall be used for the open-road roadway network.
MAPVAN-FN-004	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.
MAPVAN-FN-005	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.
MAPVAN-FN-006	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.
MAPVAN-FN-007	MAPVAN camera data may be used for redundancy verification of data collected by the ego vehicle.

Requirement ID	Requirement
MAPVAN-FN-008	The mapping task may explore methods for identifying, processing, and defining obstacles and centerline data during data capture.

Source: PennDOT

3.3 Modeling & Simulation Support Systems

3.3.1 Vehicle Simulators (CARLA & CADRE)

3.3.1.1 ITS PERSPECTIVE

The vehicle simulation tools represent open-source or third-party software that supports development, training, and validation of ADS and AV research. In addition to open-source code and protocols, modeling and simulation tools can digitalize real-world assets (urban layouts, buildings, vehicles) that can be used freely and supports flexible specification of sensor suites and environmental conditions.

3.3.1.2 PROJECT DETAIL

Modeling and simulation tasks will be carried out by both the CMU and PSU. The CMU-RMC will be conducting microsimulations while the PSU-RMC conducts macrosimulation. Macroscopic simulations are described in more detail in the next section.

As illustrated in **Figure 3**, the micro simulator tool for the connected and autonomous driving research and engineering (CADRE) stack is responsible for operating the CMU ADS in a limited virtual world. Given a map, the simulated CMU ADS (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. The CADRE simulator is connected to the CARLA simulator, which is responsible for issuing driving commands for the ego vehicle and returns (i.e., outputs) simulated sensor readings which is fed into the CADRE simulator, engaging and invoking the subsystems within CADRE to operate the vehicle in the virtual world. This synchronous co-simulation process happens in real-time.

Table 6: HLR for Drive Simulation System

Requirement ID	Requirement
SIMDRIVE-CN-001	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.
SIMDRIVE-CN-002	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.

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DEPARTMENT OF TRANSPORTATION

Requirement ID	Requirement
SIMDRIVE-CN-003	Simulation requires real-time data and shall receive HD map files from the DMS, which is not a real-time data system.
SIMDRIVE-FN-001	A basic configuration for the CADRE stack shall be established using the generated HD map provided by the DMS.
SIMDRIVE-FN-001.A	The system shall verify the HD map can be loaded correctly.
SIMDRIVE-FN-001.B	The system shall verify the ego vehicle can read the map correctly.
SIMDRIVE-FN-001.C	The system shall verify the ego vehicle can follow the rules of the road (i.e., stop at stop lights, react to traffic, etc.).
SIMDRIVE-FN-002	The system shall verify the ego vehicle can drive along the given path navigating {X m/ft.} from the mapped construction zone boundary.

Source: PennDOT

3.3.2 Traffic Simulation (SUMO & CARLA)

3.3.2.1 ITS PERSPECTIVE

The traffic simulation tool provides a realistic view of the real word, traffic flow, impacts and maps the network in detail, modeling different geometries.

3.3.2.2 PROJECT DETAIL

For the project, SUMO will be used to generate a simplified representation of the AV behavior as simulated by the CARLA tool, testing how it interacts with traffic via simulation.

The purpose of simulating traffic is to understand how the construction zone and the CMU ADS navigating that work zone would affect traffic flow, both before and after. The challenge with before-after comparisons with closed-track and open-road testing is that there will either be no traffic present, or the traffic permitted will not be fully representative of all scenarios simulated. To mitigate this challenge, the project can initialize simulation at the exact same conditions to get repeatable outputs, and thereby do comparisons of behavior using this alternate approach—which integrates the traffic simulator with a drive simulator (i.e., CARLA) for processing high-resolution, high-accuracy, low vehicle density test runs.

Table 7: HLR for Traffic Simulation System

Requirement ID	Requirement
SIMTRAFFIC-CN-001	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.

Requirement ID	Requirement
SIMTRAFFIC-FN-001	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.
SIMTRAFFIC-NF-001	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.
SIMTRAFFIC-NF-002	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.
SIMTRAFFIC-NF-003	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.

Source: PennDOT

3.3.3 PSU and CMU Research Management Centers (PSU-RMC, CMU-RMC)

3.3.3.1 ITS PERSPECTIVE

The research management centers represent the ITS back-office support system(s) that remotely monitor and manage ITS capabilities in work zones—gathering, storing, and disseminating work zone information to other systems. It manages traffic in the vicinity of the work zone and advises drivers of work zone status. This management could happen as part of the ITS-CV traffic management center, construction and maintenance management center, or a third-party, cloud-hosted management center.

3.3.3.2 PROJECT DETAIL

For this project, both PSU and CMU have a dedicated workbench in a laboratory environment. The PSU-RMC is responsible for processing the data collected during mapping of the work zone and conducting traffic simulation. The CMU-RMC is responsible for conducting vehicle simulation and other activities carried out for the project.

Table 8: HLR for Research Centers

Requirement ID	Requirement
PSURMC-SR-001	The PSU-RMC shall establish a secure tunnel via virtual private network to send data to the DMS.
CMURMC-SR-001	The CMU-RMC shall establish a secure tunnel via virtual private network to send data to the DMS.

Source: PennDOT

3.4 Roadway Environment (RWE)

The RWE represents a smart, connected roadside infrastructure which includes the instrumentation used to communicate and exchange information with vehicles, pedestrians, and other connected devices, as well as the roadway and its general characteristics. For this project, the RWE consists of roadside units, edge hardware to support high performance computing, work zone safety devices, and digital worker vests.

3.4.1 Roadside Units (RSU)

3.4.1.1 ITS PERSPECTIVE

The RSU represents the ITS equipment distributed on and along the roadway which monitors and controls traffic and monitors and manages the roadway used in combination with other field equipment. Detectors, environmental sensors, traffic signals, highway advisory radios, dynamic message signs, CCTV cameras with video image processing systems, and warning systems are all represented as equipment on the roadways. Lane management systems and barrier systems that control access to transportation infrastructure such as roadways, bridges, and tunnels are also included.

3.4.1.2 PROJECT DETAILS

Tor this project, 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 connected high-performance computing system.

Table 9: HLR for Roadside Units

Requirement ID	Requirement
RSU-DR-001	An RSU shall receive basic safety messages (BSM) broadcast from vehicles in its vicinity.
RSU-DR-002	An RSU shall broadcast SAE J2735 compliant MAP messages.
RSU-FN-001	An RSU shall be capable of providing channel assignments and operating instructions to OBUs in its communications zone.
RSU-FN-002	An RSU shall broadcast SAE J2735 compliant messages using DSRC and C-V2X communication standards.
RSU-FN-003	The RSU shall off load messages received to the HPC for transmission to the DMS.
RSU-FN-004	The RSU shall be capable of transmitting messages over DSRC to the CMU ADS within the roadway environment in SAE encoded format.
RSU-FN-005	The RSU shall be capable of transmitting messages over C-V2X to the CMU ADS within the roadway environment in SAE encoded format.
RSU-FN-006	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

Requirement ID	Requirement
	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.

Source: PennDOT

3.4.2 High Performance Computer (HPC)

3.4.2.1 ITS PERSPECTIVE

The HPC represents the roadside hardware used for processing, aggregating, and logging data broadcasting among connected devices along the roadway network (e.g., vehicles, RSU, PID, VRUs, microtransit, etc.). The HPC is an edge device often installed in an ITS cabinet and serves many purposes—such as data broker, a hub for V2X applications, work zone surveillance, traffic control, driver warning, work crew safety systems, etc.

3.4.2.2 PROJECT DETAIL

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

At the time of this writing, the project is evaluating BSM, TIM, and SPaT/MAP applications in support of data transmits for meeting use case objectives. If these (or other) CV apps are deemed necessary during research and testing, the HPC shall be capable of deploying off-the-shelf CV applications that read, write, create, and transmit the necessary SAE formatted data messages that enable the desired functionality. Additional information on connected vehicle applications can be found on the USDOT ITS Joint Program Office for connected vehicle deployments at https://www.its.dot.gov/pilots/cv_pilot_apps.htm.

Table 10: HLR for Edge HPC

Requirement ID	Requirement
HPC-DR-002	The HPC shall be capable of transmitting HD maps files from the DMS to the CMU-ADS OBU.

Requirement ID	Requirement
HPC-NF-001	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.
HPC-IF-001.A	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.
HPC-IF-001.B	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.
HPC-IF-001.C	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.
HPC-IF-001.D	The HPC shall be capable of facilitating data exchanges to and from an LTE C-V2X configured RSU.
HPC-IF-001.E	The HPC shall be capable of facilitating data exchanges to and from a DSRC configured RSU.
HPC-IF-001.F	The HPC should be capable of facilitating data exchanges to and from a configurable GPS device.
HPC-IF-001.G	The HPC should be capable of facilitating data exchanges to and from a configurable Zigbee mesh network.
HPC-FN-002	The HPC shall collect, aggregate, store and send SAE formatted messages, as defined in the SAE V2X Communication Message Set Dictionary[3], from the RSU to the DMS.
HPC-DR-003	The HPC shall aggregate precise location and time information from GPS equipped V2X work zone objects and transmit securely {SSL,TLS,IPSec} to the DMS for archival.
HPC-SR-001	All communications to and from the edge HPC must be authorized, authenticated, and the payload secured.
HPC-FN-001	The HPC shall provide administrative access to authenticated users from the local network and remotely through a virtual private network interface.

Source: PennDOT

3.4.3 V2X Work Zone Objects (mounted GPS) Cones, Barrels, DMS

3.4.3.1 ITS PERSPECTIVE

Represents deployed field devices used for work zone surveillance, traffic control, providing driver warnings, and safety warnings to work crews.

3 https://www.sae.org/standards/content/j2735set_202007/

3.4.3.2 PROJECT DETAIL

For this project, V2X work zone objects include cones and barrels instrumented with GPS radios for establishing a connected environment. The objects serve as beacons to provide precise position and time data. If the devices procured support position correction, the GPS receiver may use PennDOT's reference stations to receive position correction data to improve its accuracy.

Table 11: HLR for V2X Work Zone Objects

Requirement ID	Requirement
WZO-FN-001	V2X work zone objects shall be instrumented with global positioning system (GPS) communication devices.
WZO-FN-002	V2X work zone objects shall be capable of securely transmitting data over the air via 4G, 5G, or Wi-Fi radio.
WZO-FN-003	V2X work zone objects should be capable of being configured as end devices (no routing) within PennDOT's ZigBee mesh network.
WZO-FN-004	V2X work zone objects may use PennDOT's reference station to receive position correction.
WZO-DR-001	V2X work zone objects shall provide precise position and time information from its GPS device.

Source: PennDOT

3.4.4 Digital Worker Vests (mounted GPS)

3.4.4.1 ITS PERSPECTIVE

The 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.

3.4.4.2 PROJECT DETAIL

Information flowing from the digital worker vests will broadcast precise position and time information used to form a digital representation of the dynamic movement of Maintenance and Construction Field Personnel. The CMU-AV will be responsible for worker detection through its on-board sensory inputs for line-of-sight positions, while the roadside environment will be responsible broadcasting work zone safety warnings.

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DEPARTMENT OF TRANSPORTATION

Table 12: HLR for Digital Worker Vests

Requirement ID	Requirement
DWV-FN-001	Digital worker vests shall be instrumented with global positioning system (GPS) communication devices.
DWV-FN-002	Digital worker vests shall be capable of securely transmitting data over the air via 4G, 5G, or Wi-Fi radio
DWV-FN-003	Digital worker vests should be capable of being configured as end devices (no routing) within PennDOT's ZigBee mesh network.
DWV-FN-004	Digital worker vests may use PennDOT's reference station to receive position correction.
DWV-DR-001	Digital worker vests shall provide precise position and time information from its GPS device.

Source: PennDOT

3.5 Data Management System (DMS)

3.5.1.1 ITS PERSPECTIVE

The role of 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 monitoring, program assessment, operations, and supports research applications. The data received is formatted and tagged with attributes that define the data source, conditions under which it was collected, data transformations, and other information (i.e., meta data) necessary to interpret and understand the data in context. The archive prepares data (as an asset) to serve as inputs to other federal, state, and local data reporting systems. Alternatively, the archive system may operate as a distinct center that collects data from multiple agencies, sources and provides a general data warehouse service.

3.5.1.2 PROJECT DETAIL

The DMS shall be developed as a cloud-based system for the ADS project and will be responsible for data archiving, data versioning, managing application programming interfaces (API), and securing data exchanges to, from, and at rest within storage container(s).

The DMS is built upon Microsoft Azure, protected by an Azure Firewall and provides a secure mechanism (VPN, SSL, etc.) for sources to connect and exchange data securely. An Azure Virtual Network (VNet) will be used to secure the Azure resources, which contain the data within the ADS project. The Azure VNet is essential for a private network in Azure. The VNet enables many types of Azure resources to securely communicate with each other, the internet, and on-premises networks. Other additional benefits of the Azure VNet include filtering network traffic, routing network traffic, and integration with Azure services. To filter network traffic to and from Azure resources in a VNet, Azure Network Security Groups (NSGs) will be implemented. An NSG contains security rules that allow or deny inbound network traffic to, or outbound network traffic from, Azure resources. For each rule, the source and destination, port, and protocol must be specified. Additional security services that will be implemented include TLS 1.2 encryption during data-in-transit, which aims to secure data actively being transferred from one location to another, as well as 256-bit AES encryption for data-at-rest, which aims to secure inactive data stored within the DMS.

The DMS will leverage Azure Active Directory (Azure AD) for access management. Azure AD is Microsoft's cloud-based identity and access management service. Azure role-based access control (RBAC) will be used as the authorization mechanism, which determines what data each stakeholder group will have access. Using Azure RBAC, each stakeholder group will be granted their respective access (e.g., read, read/write). Azure Key Vault, Microsoft's cloud service for securely storing and accessing secrets, will be used to control access to any passwords, certificates or API key that will be used within the DMS.

A graphical user interface (GUI) will be provided for project members to view, query, and pull data from the DMS. An API will be supplied to enable USDOT and other researchers to connect and extract data for analysis and research purposes. The API will also be used to push data to a separate repository for sharing with the general public via a publicly accessible WebApp. The APIs in use will be properly documented with sample code and information to make the API interaction seamless. The various APIs enable specific components of the ADS environment to interact with various types of data correlated to matching parameters based on requests and returns a list of all data activities matching filter designations from the requests made to the DMS.

Data will be uploaded by the project team—namely, PSU and CMU—using Azure Storage Explorer. This is a free GUI tool from Microsoft made available on Windows, Mac, and Linux. With this tool, the team can access and manage Azure Blob Storage as well as move data to and from Azure Data Lake Storage. An alternative option to uploading data can be achieved using AzCopy, a command-line utility for automation purposes. AzCopy is Microsoft Azure's command-line utility for copying data to or from Azure Blob Storage using simple commands that are designed for optimal performance, which will also be made available to the project team. **Figure 4** provides a diagram of the system architecture for the project's data management system built within the Azure cloud platform.

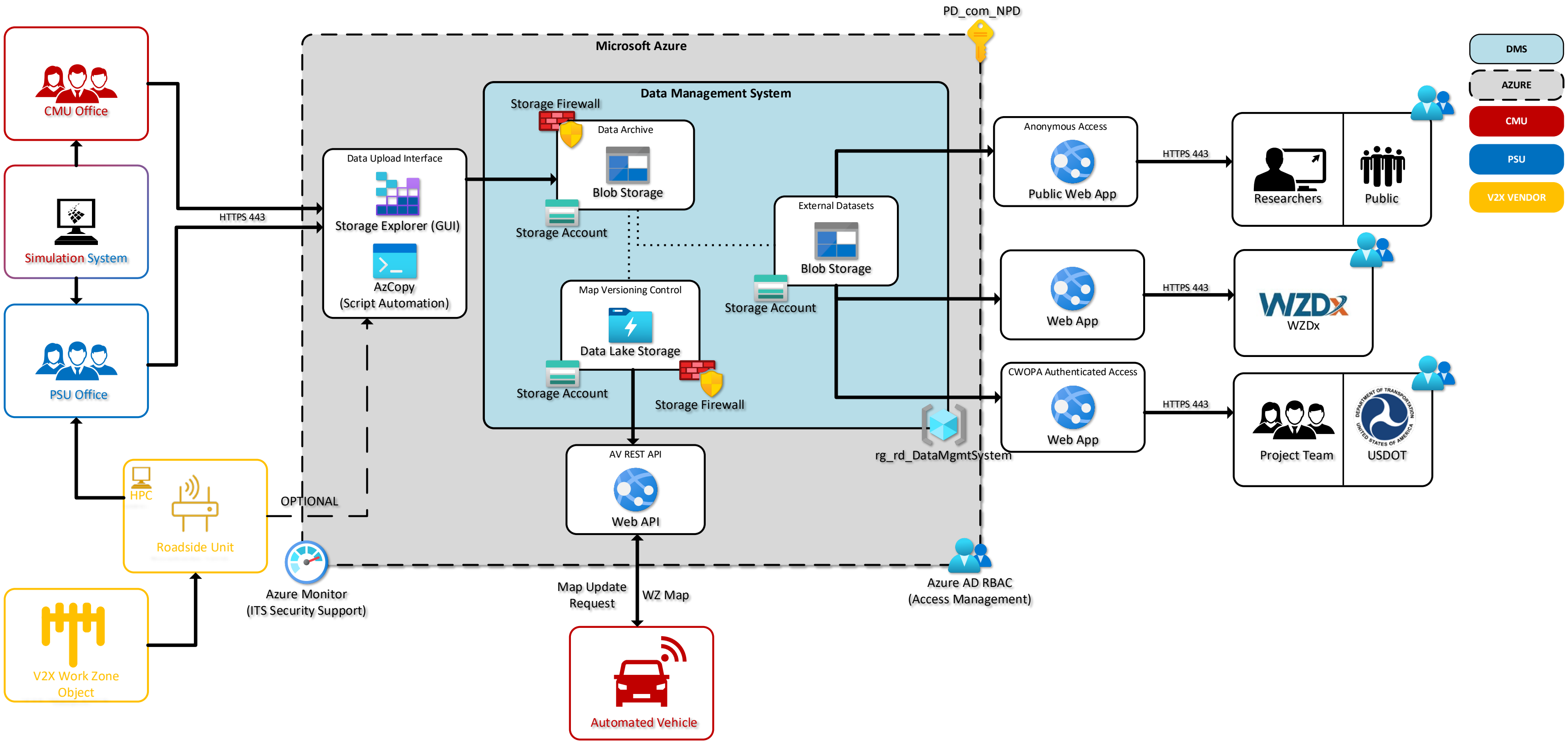

Figure 4: Data Management System Reference Architecture

Source: Pennsylvania Department of Transportation

Table 13 below provides the high-level requirements for the DMS.

Table 13: HLR for Data Management System

Requirement ID	Requirement
DMS-FN-001	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.
DMS-FN-002	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.
DMS-FN-003	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.
DMS-FN-004	For the USDOT, the DMS shall provide a secure API for accessing and exporting project data and computed data.
DMS-FN-005	For anonymous researchers and the general public, the DMS shall provide a WebApp to access data that is predefined and flagged as publicly accessible.
DMS-SR-001	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.
DMS-SR-002	Azure cloud environment shall implement and configure a firewall protective measure to ensure the DMS system is secured.
DMS-NF-001	Access violations shall be investigated and reported to the project within one (1) day of discovery.
DMS-NF-002	The DMS shall minimize the cost of ownership where possible. For instance, researchers may extract data and conduct analysis on the client-side.
DMS-FN-006	The DMS shall maintain separate containers for each system (CMU ADS, MAPVAN, HPC) to store data.
DMS-FN-007	The DMS shall optimize storage for fast access for data that is accessed frequently.
DMS-FN-008	The DMS shall optimize archive storage access for raw sensor data.
DMS-SR-009	The DMS shall optimize archive storage costs for data sets that have not been accessed within 180 days or more.

Source: PennDOT

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Chapter 4: Use Case Requirements

This section presents the six use cases for the project. Requirements from the previous section are expanded to include use case specific functional, non-functional, and constraints as well as interface, data, knowledge management, security, and performance requirements, specific to that use case.

For each subsequent section, a description of the use case is given, which identifies all systems participating and provides details about the characteristics unique to that case.

4.1 Use Case 01: Work Zone Mapping

DESCRIPTION: Generates a high-definition map of a work zone and sends the map file to the DMS.

ACTIVE SYSTEMS: MAPVAN, PSU-RMC, DMS

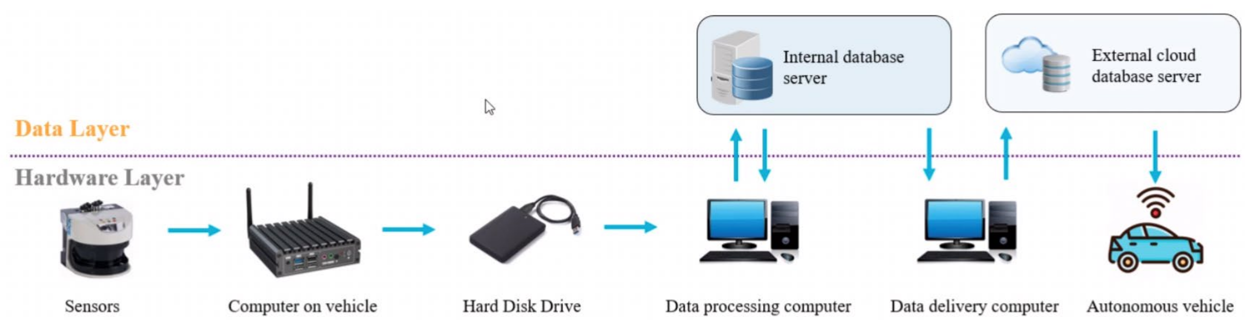

Figure 5: UC01: Work Zone Mapping Work Flow

Source: Penn State University, 2021

4.1.1 Map Generation

The PSU mapping van uses data from onboard sensors to create a digital representation of a real-world map. Activated sensors record data onto the primary data hard disk along with an archive disk. The primary data disk is offloaded to a PC on a workbench at Penn State laboratory environment for fusion, transformation, and eventual output into consumable format(s) for the DMS, CARLA, and SUMO subsystems.

<u>Limitations:</u> fusing, transforming, and outputting map sensor data into ingestible formats is a lengthy, compute intensive, algorithmic process. Although the demonstration vehicle has double alternator capability compared to a typical OEM vehicle, its power is still insufficient for onboard map generation. To mitigate, data is written to a disk drive, then transferred to the PSU-LAB for processing.

Table 14: UC01: Map Generation Interfaces

Source	Destination	Data	Notes
Mapping Van (MAPVAN)	Workbench (PSU-RMC)	Raw sensor data (camera, LiDAR, radar, other) Static data (e.g., vehicle type)	Manual data transfer from HDD to data processing computer via device port.
Workbench (PSU-RMC)	Mapping Van (MAPVAN)	Configuration files Work zone information	This data could be handwritten instructions.

Source: PennDOT

Table 15: UC01: Map Generation Requirements

Requirement ID	Requirement
UC01-CN-001	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 systems (i.e., the DMS and CMU ADS drive simulator) the day after the mapping took place.
UC01-CN-002	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.
UC01-CN-003	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.
UC01-PF-001	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.
UC01-FN-001	A geofence work zone shall be established from a base set of criteria, which must be documented.
UC01-FN-002	Geofenced zone boundaries shall use edge objects/artifacts with a configurable buffer cushion from detected objects.
UC01-FN-003	The zone mapped must be accurate to 5 (cm), accounting for inaccuracies, standard and anomalous deviations in processing (time, space).
UC01-FN-004	The processed HD map file must be generated and made available in the format(s) determined during experimentation (see section 6.1).
UC01-PF-002	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.

Source: PennDOT

4.1.2 HD Map Storage

The raw sensor data collected during the mapping process along with the HD map files generated at the Penn State laboratory workbench will be transmitted to the DMS. The PSU-

RMC (i.e., the computer at PSU that generates maps) establishes a connection to the DMS over a virtual private network to exchange data.

Table 16: UC01: Map Storage Interfaces

Source	Destination	Data	Notes
Workbench (PSU-RMC)	DMS	Raw sensor data (camera, LiDAR, radar, other) Processed sensor data (i.e., work zone map, baseline map)	VPN tunnel over an ISP connection.

Source: PennDOT

Table 17: UC01: Map Storage Requirements

Requirement ID	Requirement
UC01-CN-004	Processing and transforming sensor data into exportable formats should be completed within a 24-hour turnaround 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.
UC01-CN-005	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.
UC01-NF-001	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.
UC01-FN-005	The DMS shall maintain a copy of all raw data as ingested.

Source: PennDOT

4.2 Use Case 02: Simulation

DESCRIPTION: Using the HD-MAP generated from UC01, conduct simulations of the predefined scenarios as outlined in the scenario library. To accomplish this, the HD map produced by UC01 will need to be linked to the road network. The traffic simulator will inject vehicle densities, conduct drive simulations, and measure the drive performance. This process flow will be conducted by PSU. In parallel with the traffic simulator, CMU will retrieve the HD-MAP data stored in the DMS from UC01 and set up a digital map. The simulation operator configures a digital twin of the work zone in the simulator and conducts drive simulation, integrating CADRE sensor readings and measures the ego vehicle's ability to navigate the virtual work zone environment. Performance data generated by simulation systems will be sent to the DMS.

ACTIVE SYSTEMS: PSU-RMC, SIMTRAFFIC, SIMDRIVE, SIMCADRE, CMU-RMC, DMS

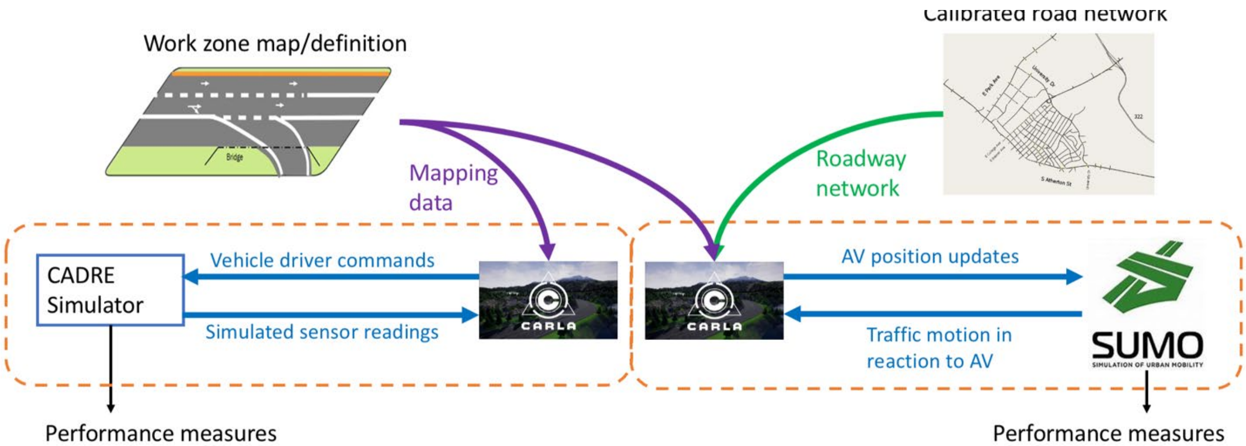

Figure 6: UC02: Simulating the Work Zone Environment

Source: Penn State University, Carnegie Mellon University.

4.2.1 Road Network Linking

To use a processed HD map outputted from the map generation function, the map will need to be calibrated to the connections of roads in the environment. The road network includes the highway segment around the State College, PA, on I-99 and Route 322.

The calibration includes three steps. First, the model is calibrated for capacity at the key bottlenecks in the system (the capacity calibration step). Second, the model is calibrated for traffic flows at non-bottleneck locations in the system (the route choice calibration step). Finally, the overall model performance is calibrated against field-measured system performance measures. In a recent process, PSU matched the signal timings and traffic volumes/turning movement counts where available to match the simulation with empirical data. The turning movement count data were obtained from an older study by the State College Borough for signal timing (2013), traffic volumes obtained from PennDOT Annual Average Daily Traffic (AADT) data, and the k (the proportion of annual average daily traffic occurring in an hour) and d (proportion of traffic traveling in the peak direction during a hour) factors were applied.

Table 18: UC02: Road Network Linking Interfaces

Source	Destination	Data	Notes
Workbench (PSU-RMC)	SIM-TRAFFIC (SUMO)	HD map file of work zone (i.e., processed sensor data)	

Source: PennDOT

Table 19: UC02: Road Network Linking Requirements

Requirement ID	Requirement
UC02-FN-001	The HD map shall be linked to the physical road network architecture.
UC02-FN-002	Traffic data shall be calibrated to the network map, ensuring simulated traffic matches realistic traffic volumes and turning counts.

Source: PennDOT

4.2.2 Traffic Simulation

To simulate a work zone, the roadway network (highway, arterial, etc.) will need to be selected and flow rates of vehicles in-out of the CARLA simulation boundaries will need to be defined. 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.

Since the human eye is sensitive to seeing jumps in data visualizations due to uncoordinated data exchanges, the co-simulation task will need to consider a time synchronization and data synchronization process for mitigation.

Table 20: UC02: Traffic Simulator Interfaces

Source	Destination	Data	Notes
SIM-TRAFFIC (SUMO)	SIM-DRIVE (CARLA)	Traffic conditions and motion in response to ego vehicle position	
SIM-DRIVE (CARLA)	SIM-TRAFFIC (SUMO)	Ego vehicle position updates	

Source: PennDOT

Table 21: UC02: Traffic Simulator Requirements

Requirement ID	Requirement
UC02-CN-001	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.
UC02-FN-003	A roadway network shall be selected and flow rates of vehicles in-out of the CARLA simulation boundaries shall be defined.
UC02-FN-004	A co-simulation task shall create a process for time synchronization and data synchronization in order to generate smooth transitions in simulations.
UC02-IM-001	The output from simulation runs shall be archived in the DMS.

Source: PennDOT

4.2.3 Simulated ADS Work Zone Navigation

The simulation uses retrieved mapping data from the DMS to set up a digital map. The Simulation Operator then sets up a work zone configuration in the simulation and conducts the simulation. The simulated ADS performance data is then sent to the DMS to be used by other actors and subsystems. The Data Manager will ensure the integrity of the data used by the DMS.

Table 22: UC02: Simulator Work Zone Navigation Interfaces

Source	Destination	Data	Notes
SIM-DRIVE (CARLA)	SIM-CADRE	Ego vehicle drive commands.	
SIM-CADRE	SIM-DRIVE (CARLA)	Ego vehicle simulated sensor reading data.	

Source: PennDOT

Table 23: Simulator ADS Work Zone Navigation Requirements

Requirement ID	Requirement
UC02-CN-002	Processing and transforming sensor data into exportable formats should be completed within a 24-hour turnaround 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.
UC02-CN-003	Due to power limitations in the van, the function of generating maps must be offloaded as a back-office task.
UC02-CN-004	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.

Source: PennDOT

4.3 Use Case 03: Work Zone Navigation

DESCRIPTION: Demonstrate the CMU ADS ability to navigate through a basic work zone under the conditions established for each scenario. For all permutations of this use case, when the CMU ADS encounters a work zone and navigates through that zone, performance data is recorded for evaluation.

Using V2X communications (various types as outlined in the requirements below), the CMU ADS receives processed HD-MAP data from the roadway network from the DMS. The CMU ADS will read, validate, load, and navigate through a work zone as set up by the Work Zone Operators, in accordance with the scenario being tested.

ACTIVE SYSTEMS: CMU ADS, RWE (includes RSU, HPC, WZO, DSV), and DMS

Table 24: UC03: Work Zone Navigation Interfaces

Source	Destination	Data	Notes
RSU	HPC	Basic safety messages Admin data (RSU configs, active radio, other)	Design alternative 2: aggregate telemetry data from CMU ADS.
HPC	RSU	SAE J2735 messages (other, TIM for work zone)	
HPC	CMU ADS	Map files received from DMS SAE J2735 messages (other, TIM for work zone)	Design alternative 1: primary data broker (logger & aggregator)
HPC	DMS	Basic safety messages Aggregated roadside data	
DMS	HPC	Map files (various formats)	
CMU ADS	HPC	Basic safety messages	Data collected will depend on testing scenarios

Source: PennDOT

Table 25: UC03: Work Zone Navigation Requirements

Requirement ID	Requirement
UC03-SFTY-001	The project team shall attempt to identify, correct or address potential failures of in the "work zone navigation" pipeline before and during testing.
UC03-SFTY-001.A	Identify potential failure modes for CMU ADS communications, sensing, perception, navigation and control, and HMI.
UC03-SFTY-001.B	Identify potential causes and effects of those failure modes.
UC03-SFTY-001.C	Prioritize failure modes based on risk.
UC03-SFTY-001.D	Identify and demonstrate an appropriate corrective action or a mitigation strategy for each failure mode.
UC03-NF-001	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.).
UC03-NF-002	A work zone shall be tested measuring regulatory and warning signs and pavement markings.
UC03-NF-003	A work zone shall be tested given an HD map from the DMS to the CMU ADS

Requirement ID	Requirement
UC03-NF-004	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.
UC03-NF-005	A work zone shall be tested using temporary signal navigation.
UC03-NF-006	A work zone shall be tested measuring object detection while operating in normal mode.
UC03-NF-007	A work zone shall be tested with induced failure modes.
UC03-NF-007.A	A work zone shall be tested under degraded conditions with predefined course of action of uncertainty.
UC03-NF-007.B	A work zone shall be tested with equipment failure.
UC03-NF-007.C	A work zone may be tested with object misdetection.
UC03-NF-008	The project may review and update the scenarios considered for testing based on modeling and simulation test results.
UC03-SR-001	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.
UC03-DATA-001	The DMS should collect, store, and process CMU ADS BSM messages from the HPC on the roadway network.
UC03-DATA-002	The DMS should collect, store, and process incoming aggregated data from the HPC on the roadway network.
UC03-DATA-003	The DMS should collect, store, and process log data from the HPC on the roadway network.
UC03-DATA-004	The DMS should receive incoming data requests from the HPC on the roadway network.
UC03-DATA-005	The DMS shall send map data to the CMU-RMC.
UC03-DATA-006	The DMS shall send map data to the HPC on the roadway network.

Source: PennDOT

4.4 Use Case 04: DMS Data Retrieval

DESCRIPTION: Demonstrate the ability for the DMS to receive an incoming request and return data to the user based on the request type, user authorization, and interface. Test cases for this include sending/receiving data from the CMU-RMS, PSU-RMC, CMU ADS, HPC (and roadside environment), the project team, and general public.

Figure 7 provides a basic view of the send/receive transaction for all users of the DMS.

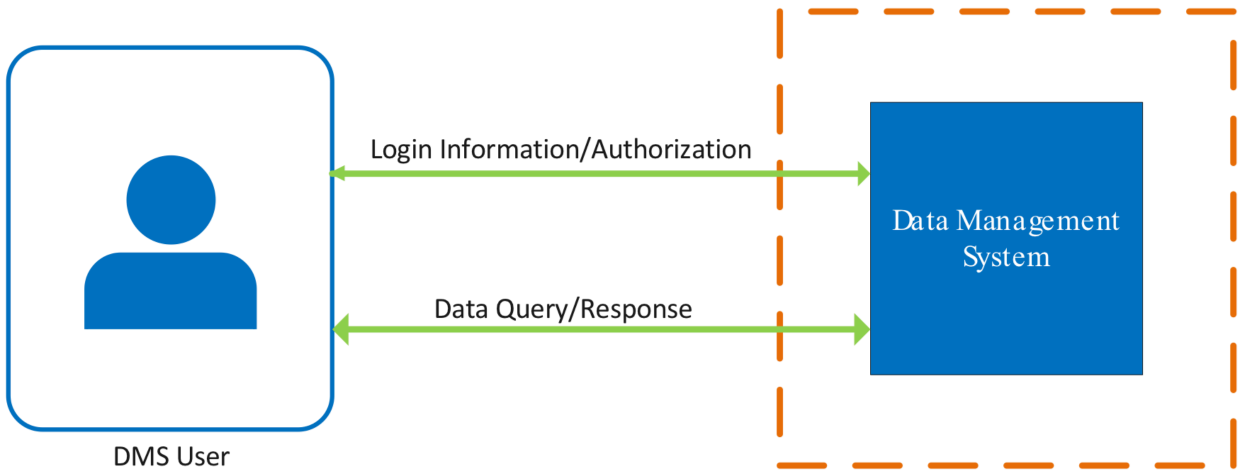

Figure 7: UC04: DMS Data Retrieval Transaction

Source: Pennsylvania Department of Transportation

4.4.1 CMU-RMC and PSU-RMC Data Retrieval During Simulation

During phase two of the project, both CMU-RMC and PSU-RMC will need to access the DMS to store and retrieve simulation and experimentation data from the DMS. To perform data retrieval data user must (1) open the Microsoft Azure Storage Explorer application on their respective back-office computer. Once the application is open the user must (2) log into Azure AD with their Commonwealth of PA (CoPA) account and (3) authenticate their Azure AD login. After the user has successfully signed in the user can (4) perform data retrieval.

<u>Limitations:</u> Data can only be retrieved by using the CoPA account (username@pa.gov) with required roll-based access control (Azure RBAC). **Figure 8** provides a basic view of the authorization sequence for CMU and PSU to retrieve data from the DMS from each respective RMC.

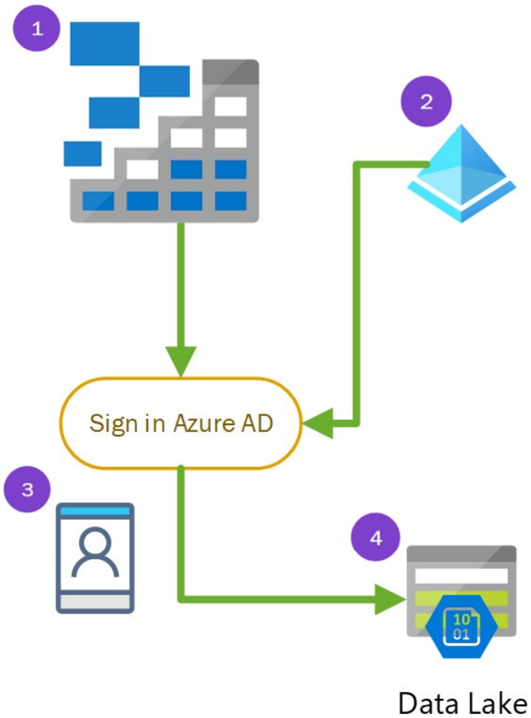

Figure 8: UC04: DMS Data Retrieval from the CMU-RMC and PSU-RMC

Source: Pennsylvania Department, Deloitte

Table 26: UC04: DMS Interfaces for CMU-RMC and PSU-RMC

Source	Destination	Data	Notes
DMS	Workbench (PSU-RMC)	Camera image data LiDAR data Radar data GPS/INS Processed map files	
DMS	Workbench (CMU-RMC)	Map data	

Source: PennDOT

Table 27: UC04: DMS Requirements

Requirement ID	Requirement
UC04-SR-001	The DMS shall provision an HTTPS/TLS 1.2 encrypted tunnel for the PSU-RMC to send data securely to the DMS.

Requirement ID	Requirement
UC04-SR-002	The DMS shall provision an HTTPS/TLS 1.2 encrypted tunnel for the CMU-RMC to send data securely to the DMS.
UC04-DATA-001	The DMS shall receive incoming data requests from the CMU-RMC.
UC04-DATA-002	The DMS shall send map data to the CMU-RMC.
UC04-DATA-003	The DMS shall collect, store, and process camera image data from the MAPVAN.
UC04-DATA-004	The DMS shall collect, store, and process LiDAR data from the MAPVAN.
UC04-DATA-005	The DMS shall collect, store, and process radar data from the MAPVAN.
UC04-DATA-006	The DMS shall collect, store, and process GPS/INS data from the MAPVAN.
UC04-DATA-007	The DMS shall collect, store, and process processed map files from the PSU-RMC.
UC04-DATA-013	The DMS shall collect, store, and process simulated data from the traffic simulation process.
UC04-FN-005	Data queries shall be efficient and data results shall be optimized.
UC04-FN-007	The project team shall review and approve the data {schema, architecture} prior to DMS go-live.
UC04-SR-003	The DMS shall receive requests for raw sensor data, curated without PII and PHI, and provide that data set within three (3) business days.

Source: PennDOT

4.4.2 CMU-ADS Data Retrieval From DMS During Closed-Loop and Open-Road Testing

During phases three and four of the project, the CMU ADS is designed to access the DMS to retrieve HD map data from the DMS for navigating a work zone. **Figure 9** below illustrates the steps for the CMU-ADS to perform a data retrieval from the DMS.

(1) Shared access signature (SAS) token provides secure delegated access to resources in the storage account with read-only permissions generated. Then that SAS token will be placed securely in (2) the key vault with get permissions. An Azure Policy is attached to the (3) service principal object in key vault to retrieve the secret. From there the CMU-ADS is given the client identifier (ID) and the secret to retrieve the SAS token and (4) connect to perform a data retrieval.

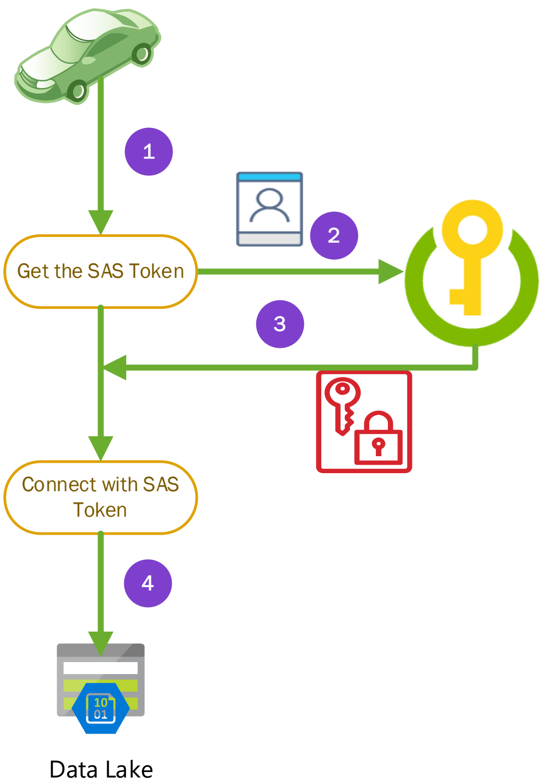

Figure 9: UC04: DMS Data Retrieval for CMU

Source: Pennsylvania Department, Deloitte

Table 28: UC04: DMS Interfaces for the CMU-ADS

Source	Destination	Data	Notes
DMS	CMU-ADS	HD map file of work zone	OTA communications

Source: PennDOT

Table 29: UC04: DMS Requirements for the CMU-ADS

Requirement ID	Requirement
UC04-DATA-007	The DMS shall collect, store, and process camera image data from the CMU ADS.
UC04-DATA-012	The DMS shall collect, store, and process GPS/PPS data from the CMU ADS.

Source: PennDOT

4.4.3 RSE Data Retrieval During Closed-Loop and Open-Road Testing

During phases three and four of the project, the roadside infrastructure by way of the HPC is designed to access the DMS to retrieve data from the DMS for facilitating data exchanges from work zone objects, the RSU, and CMU ADS. **Figure 10** illustrates the steps for the CMU-ADS to perform a data retrieval from the DMS.

(1) SAS token with Read-Write permissions is generated. That SAS token will be placed securely in (2) Key Vault with Get permissions. An Azure Policy is attached to the (3) service principal object in Key Vault to retrieve the secret. From there the CMU-ADS is given the client id and secret to retrieve the SAS token and (4) connect to perform a data retrieval.

Figure 10 below provides a basic view of the authorization sequence for the RSE to retrieve data from the DMS.

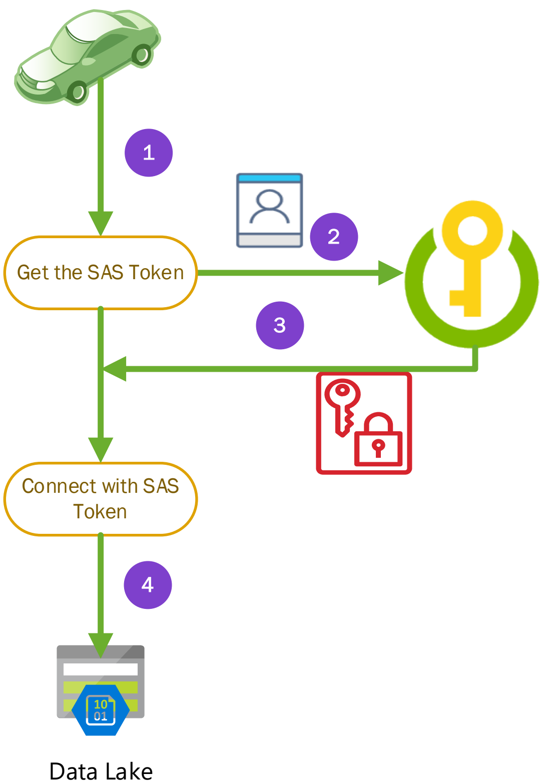

Figure 10: UC04: DMS Data Retrieval for RSE

Source: Pennsylvania Department, Deloitte

Table 30: UC04: DMS Interfaces for the RSE

Source	Destination	Data	Notes
HPC	DMS	Aggregated roadway data (BSM, SPaT/MAP, SRM, etc.)	TLS 1.2 encrypted tunnel over an ISP connection.
DMS	HPC	HD-MAP file	

Source: PennDOT

Table 31: UC04: DMS Requirements for the RSE

Requirement ID	Requirement
UC04-DATA-001	The DMS shall receive incoming data requests from the HPC.
UC04-DATA-002	The DMS shall send map data to the HPC.

Source: PennDOT

4.4.4 Project Team and USDOT Project Data Retrieval

Throughout the life of the project, the project team and USDOT will need to access the DMS to retrieve data. For these user types to perform data retrieval they will use a web-based UI using their respective CoPA account (username@pa.gov) with the required RBAC permissions. Additionally, the USDOT will be provided an API to the same application that will enable them to perform data retrieval.

Limitations: For the project team data can only be retrieved by using a CoPA account (username@pa.gov) with the required RBAC permissions.

Figure 11 below provides a basic view of the authorization sequence for the project team and USDOT to retrieve data from the DMS.

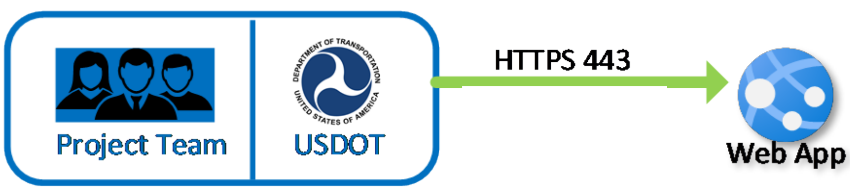

Figure 11: UC04: DMA Data Retrieval for the Project Team and USDOT

Source: Pennsylvania Department, Deloitte

Table 32: UC04: DMS Interfaces for the Project Team and USDOT

Source	Destination	Data	Notes
DMS	Web UI	All project data	Project team will require Azure AD authentication.
DMS	Web API	Approved project data for research (i.e., processed data without no PII)	USDOT will require Azure AD authentication.

Source: PennDOT

Table 33: UC04: DMS Requirements for the Project Team and USDOT

Requirement ID	Requirement
UC04-PF-001	A web-based user interface (web UI) shall be made available for data access.
UC04-FN-003	API will be provided for the USDOT and other researchers to extract research data.
UC04-FN-006	A set of common queries shall be agreed upon by the team and made available to the project team via the web UI.
UC04-SR-001	The DMS shall provision and enable a secure connection via API for the USDOT to connect and extract processed data.
UC04-FN-006	Data for researchers shall be made available to the USDOT within ten (10) days of source generation.

Source: PennDOT

4.4.5 General Public Data Retrieval to Open-Sourced Data Sets

Throughout the life of the project, PennDOT will ensure specific project data is made available for public consumption via open-source access to the web UI. For the general public to perform data retrieval, they will use a web-based UI and access data that is approved the project team.

Limitations: The project team will review and determine which data sets can and should be made available for public use after the testing phases.

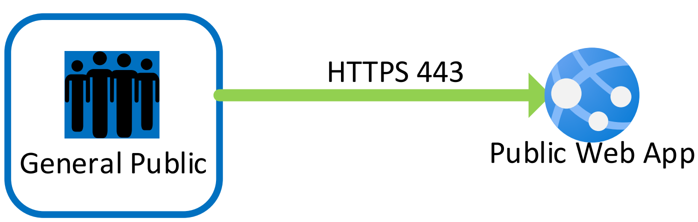

Figure 12: UC04: DMS Data Retrieval for the General Public

Source: Pennsylvania Department, Deloitte

Table 34: UC04: DMS Interfaces for the General Public

Source	Destination	Data	Notes
DMS	Web UI	Approved project data for public use	no authentication required

Source: PennDOT

Table 35: UC04: DMS Requirements for the General Public

Requirement ID	Requirement
UC04-FN-001	A web-based user interface (web UI) shall be made available for the anonymous access to project approved data sets.
UC04-FN-009	DMS orchestration services shall push approved data to a designated WebApp in a segmented portion of the DMS for sharing with the general public.

Source: PennDOT

Chapter 5: Testing Requirements

This section presents preliminary requirements for the three phases of testing—model and simulation, closed-track, and open-road. Requirements for these test phases center around maintaining the safety of the system and knowledge management.

5.1 Modeling & Simulation Testing

Table 36 below provides the preliminary requirements for the outcome of modeling and simulation testing.

Table 36: Preliminary Testing Requirements for Modeling & Simulation

Requirement ID	Requirement
TESTMS-NF-001	The Penn State test track shall be used to establish the ground truth characteristics for calibrating simulations for closed-track testing.
TESTMS-SFTY-001	ISO/PAS 21448 Safety of The Intended Function (SOTIF) must be demonstrated.
TESTMS-SFTY-002	For all simulated test runs, SIM outcomes must demonstrate the ego vehicle's behavior and capability to make safe driving decisions on the road.
TESTMS-SFTY-003	The CMU ADS behavioral safety features must be modeled.
TESTMS-SFTY-004	Models must provide, and simulation must demonstrate, an assessment of failure modes and failure mitigation strategies.
TESTMS-SFTY-005	The CMU ADS must demonstrate redundancy capacity to operate safely when there is a system fault or failure.
TESTMS-NF-001	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.
TESTMS-NF-002	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.
TESTMS-IM-001	A model {for testing} must include all attributes that define the operational design domain (ODD) within the scope of the factors being tested.
TESTMS-IM-001.A	The ODD shall include all attributes that define physical infrastructure.
TESTMS-IM-001.A.1	Physical infrastructure shall include roadway geometry.
TESTMS-IM-001.B	The ODD shall include all attributes that define operational constraints.
TESTMS-IM-001.C	The ODD shall include all attributes that define objects.
TESTMS-IM-001.C.1	Objects shall include classification of work zone safety devices.
TESTMS-IM-001.C.2	Objects shall include classification of construction workers.
TESTMS-IM-001.C.3	Objects shall include coating property.

Requirement ID	Requirement
TESTMS-IM-001.D	The ODD shall include all attributes that define connectivity.
TESTMS-IM-001.D.1	Connectivity shall include radio and associated properties.
TESTMS-IM-001.E	The ODD shall include all attributes that define environmental conditions.
TESTMS-IM-001.F	The ODD shall include all attributes that define zones.
TESTMS-IM-001.F.1	Zones shall include a work zone geofence and associated properties.
TESTMS-IM-002	A model {for testing} must be simulated and include the object and event detection and response (OEDR) capabilities of the CMU ADS.
TESTMS-IM-003	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, recognition, classification of objects, classification of events, and the behavioral response of the vehicle.
TESTMS-IM-004	Output from simulated test runs must include the features and values of the ODD.
TESTMS-IM-005	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.

Source: PennDOT

5.2 Closed-Track Testing

The following preliminary requirements have been established for closed-track testing. Requirements specific to the operation of safety drivers are listed in **2.3 Stakeholder Requirements**.

Table 37: Closed-Track Testing Preliminary Requirements

Requirement ID	Requirement
TESTCT-RG-001	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)
TESTCT-NF-001	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.
TESTCT-NF-002	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.
TESTCT-IM-001	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

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DEPARTMENT OF TRANSPORTATION

Requirement ID	Requirement
	feature, the ODD, expected OEDRs, expected failure mode behaviors (if any) of the environment setup and the expected execution results.
TESTCT-IM-002	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.
TESTCT-IM-003	All variances in the expected results, outlined in the scenario test artifact, must be logged by the tester.
TESTCT-IM-004	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.
TESTCT-IM-005	Closed-track test runs shall be recorded using camera video and sent to the DMS.
TESTCT-PF-001	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).
TESTCT-PF-002	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).
TESTCT-PF-003	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.
TESTCT-PF-004	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.

Source: PennDOT

5.3 Open-Road Controlled Testing

The following preliminary requirements have been established for open-road controlled testing.

Table 38: Open-Road Testing Preliminary Requirements

Requirement ID	Requirement
TESTOR-RG-001	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)
TESTOR-NF-001	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.
TESTOR-NF-002	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.
TESTOR-NF-003	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.
TESTOR-IM-001	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

Requirement ID	Requirement
	any) of the environment setup, results from closed-track tests and the expected execution for open-road.
TESTOR-IM-002	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.
TESTOR-IM-003	All variances in the expected results, outlined in the scenario test artifact, must be logged by the tester.
TESTOR-IM-004	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.
TESTOR-IM-005	Open-road test runs shall be recorded using camera video and sent to the DMS.
TESTOR-PF-001	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).
TESTOR-PF-002	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).
TESTOR-PF-003	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.
TESTOR-PF-004	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.

Source: PennDOT

Chapter 6: Research Requirements

6.1 Experimentation

The ADS project is faces many challenges unresolved within the industry. For these concepts, the team is planning on conducting some experimentation. For such cases, the project is planning to explore and conduct experimentation over the following topics:

- **Base Map Generation:** The project will conduct an experimentation to establish a baseline map for the project, evaluating fusion of data from GNSS, INS, CORS subsystems.
- **PPG Coating Detection and Classification:** The project team will need to evaluate and model how the CMU ADS will detect and classify PPG's new-to-market coatings aimed to increase visibility to radar and LiDAR sensors. The team will need to determine what features need to be analyzed, measured, and how the CMU ADS will respond (e.g., tactical maneuvers) to detected PPG events.
- **Work Zone Object Detection and Classification:** Given an HD map, the CMU ADS system will need to focus on centerline data and obstacle definitions.
- **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 mapping van data, the project may explore algorithms to reduce the time it takes to generate a HD map.
- **Message Formats and Transmittal Medium:** There will be some loss of mapping data that occurs as raw data are 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 DSRC and 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 USDOT developed to identify and remove secure data through techniques such as masking, obfuscating, etc.

Table 39: Preliminary Requirements for Planned Experiments

Requirement ID	Requirement
EXPRM-IM-001	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.
EXPRM-IM-002	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.
EXPRM-IM-003	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.
EXPRM-IM-004	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.
EXPRM-IM-005	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.
EXPRM-IM-006	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.
EXPRM-IM-007	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.

Source: PennDOT

6.2 Design Considerations

In addition to scientific experimentation, there are a number of design decisions and approaches the project must consider—each with its own benefit and drawbacks. Decisions surrounding certain design concepts may require testing to gain further perspective and understanding of impacts before final decisions are made. The project will need to be nimble enough to accommodate and test more than one design. For this reason, the project is not delivering a system design document, rather the requirements serve as guide rails over future phases of the project.

The following design considerations are being discussed and concepts evolved among the project team.

6.2.1 Architecting the System of Interest (SOI)

In addition to tailoring existing systems and subsystems to meet project objectives, the way the project's SOI is designed (i.e., the roadway environment, geofenced construction area, the AV, and the back-office management centers) is equally important. Design decisions impact how the system functions and operates, which has direct impact on project objectives.

One example of this is how to define the DMS. As a point of reference, the City of Columbus has defined the DMS as a live Operating System while the FDOT District 5 defined their SunStore as a centralized repository and source for truth data and decision making.

6.2.2 Latency

High latency has been and continues to be a common industry challenge today. Data exchanges between a cloud system (DMS) and the roadside environment (HPC and RSU) may encounter high latency when an ADS is moving at a given speed. The project will need to test the spatial context, storing HD map files in cloud verses right at the edge of the roadside without significant impact to the project

6.2.3 Data Exchanges

The project will need to review and consider the formats of the generated HD map files. Currently, the map generation function outputs data in XML format—albeit it is capable of outputting other formats as well. The challenge is collaborating with prior USDOT efforts and technical working groups on the work zone data specification (v.3.1) format, given most CV/AV deployments conform to the SAE J2735 message set, as described in the planned experimentation section above. Where relevant ideas or discoveries are made, the project anticipates collaborating with SAE for future standards consideration.

6.2.4 Data Accessibility

The DMS is the primary repository and source for truth data on this project. There are, however, hard costs associated with importing, exporting, and querying data. The project will therefore explore the possibility of pushing data in parallel workflows to both the DMS and the USDOT {secure data commons} repository from the CMU and PSU research management centers, where the data originates.

Table 40: Preliminary Requirements for Design Considerations

Requirement ID	Requirement
NF-001	The system shall be designed with flexibility in to support more than one method or approach for data storage, file formats, transmission mediums, etc.

Requirement ID	Requirement
NF-002	To the extent possible, system implementation shall be generically deployable and compatible with common government roadside implementations.
NF-003	Latency in data exchanges shall be minimized.
NF-004	The HD map generation process shall explore ways to conform to the SAE data format standard for transmitting messages over C-V2X and DSRC.

Source: PennDOT

Appendix A. Acronyms

The list of acronyms and initialisms is provided in **Table 41** below.

Table 41: Acronyms

Acronym	Definition
AADT	Annual Average Daily Traffic
ACL	Access Control List
ACS	Actuated Signal Controllers
AD	Azure Active Directory
ADS	Automated Driving System
API	Application Programming Interface
AV	Automated Vehicle
BSM	Basic Safety Message
CADRE	Connected Autonomous Driving Research Engineering
CMU	Carnegie Mellon University
CMU-RMC	Carnegie Mellon University Research Management Center
ConOps	Concept of Operations
CoPA	Commonwealth of Pennsylvania
CORS	Continuous Operating Reference Station
C-V2X	Cellular Vehicle to Everything
DDT	Dynamic Driving Task
DMS	Data Management System
DSRC	Dedicated Short-Range Communications
FO	Fail-Operational
FS	Fail-Safe
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GUI	Graphical User Interface
HD	High-Definition
HDD	Hard Disk Drive
HLR	High-Level Requirements
HPC	Hight Performance Computer

Acronym	Definition
IEEE	Institute of Electrical and Electronics Engineers
INS	Inertial Navigation System
ISO	International Standards Organization
ITS	Intelligent Transportation Systems
IVV	Integration, Verification, and Validation
LIDAR	Light Detection and Ranging
LRV	Light Reflectance Value
LTI	Larson Transportation Institute
MAPVAN	Penn State Mapping Van
MBI	Michael Baker International
MBSE	Model-Based Systems Engineering
MRC	Minimal Risk Condition
MS	Microsoft
MTP	Master Testing and Validation Plan
NHTSA	National Highway Traffic Safety Administration
NSG	Azure Network Security Group
ODD	Operational Design Domain
OEDR	Object and Event Detection and Response
OST-R	Office of the Assistant Secretary for Research and Technology
PennDOT	Pennsylvania Department of Transportation
PfMP	Performance Management Plan
PM	Project Manager
PMBoK	Project Management Body of Knowledge
PMP	Project Management Plan
PPS	Pulse per Second
PSU	The Pennsylvania State University
PSU-RMC	Penn State University Research Management Center
PTC	Pennsylvania Turnpike Commission
QCOMM	Qualcomm
QMP	Quality Management Plan
RADAR	Radio Detection and Ranging
RBAC	Azure Role-Based Access Control
RFP	Request for Proposal

Acronym	Definition
RM	Risk Management
RMP	Risk Management Plan
ROS	Robot Operating System
RSU	Roadside Unit
RTVM	Requirements Traceability and Verification Matrix
RWE	Roadway Environment
RWM	Real-World Model
PiB	Pebibyte
SAE	Society of Automotive Engineers
SAS	Shared Access Signature
SASP	System Architecture and Standard Plans
SE	Systems Engineering
SEBoK	Systems Engineering Body of Knowledge
SEMP	Systems Engineering Management Plan
SME	Subject Matter Expertise
SMP	Safety Management Plan
SnLIB	Scenario Library
SOFIT	Safety of the Intended Function
SOI	System of Interest
SPC	Statistical Process Control
SRD	System Requirements Document
SSL	Secure Socket Layer
STPP	Short-Term Path Planner
SUMO	Sumo Traffic Simulation Software
TLS	Transport Layer Security
U.S. DOT	United States Department of Transportation
V2X	Vehicle to Everything
VNet	Azure Virtual Network
WAVE	Wireless Access in Vehicular Environments
WebUI	Web-Based User Interface
WZO	Work Zone Object
WZTC	Work Zone Traffic Control

Source: PennDOT

Appendix B. Interface Matrix

Table 42 provides a matrix of the interfaces to be established for the ADS project based on the concept and requirements established through the systems engineering process.

Table 42: Interface Matrix

Reference	Source	Destination	Data	Notes
Interface 01	Mapping Van (MAPVAN)	PSU Workbench (PSURMC)	Raw sensor data (camera, LiDAR, radar, other) Static data (e.g., vehicle type)	UC01: Work Zone Mapping Manual data transfer from HDD to data processing computer via device port
Interface 02	PSU Workbench (PSURMC)	Mapping Van (MAPVAN)	Configuration files Work zone information	UC01: Work Zone Mapping This data could be handwritten instructions
Interface 03	PSU Workbench (PSURMC)	DMS	Raw sensor data (camera, LiDAR, radar, other) Processed sensor data (i.e., work zone map, baseline map)	UC01: Work Zone Mapping VPN tunnel over an ISP connection.
Interface 04	PSU Workbench (PSURMC)	SIM-TRAFFIC (SUMO)	HD map file of work zone (i.e., processed sensor data)	UC02: Simulation
Interface 05	SIM-TRAFFIC (SUMO)	SIM-DRIVE (CARLA)	Traffic conditions and motion in response to ego vehicle position Ego vehicle position updates	UC02: Simulation Software interface.
Interface 06	SIM-DRIVE (CARLA)	SIM-CADRE	Ego vehicle drive commands	UC02: Simulation Software interface.
Interface 07	SIM-CADRE	SIM-DRIVE (CARLA)	Ego vehicle simulated sensor reading data	UC02: Simulation Software interface.

Reference	Source	Destination	Data	Notes
Interface 08	RSU	HPC	Basic safety messages Admin data (RSU configs, active radio, other)	UC03: Work Zone Navigation Design alternative 2: aggregate telemetry data from CMU ADS.
Interface 09	HPC	RSU	SAE J2735 messages (other, TIM for work zone)	UC03: Work Zone Navigation
Interface 10	HPC	CMU ADS (ADS)	Map files received from DMS SAE J2735 messages (other, TIM for work zone)	UC03: Work Zone Navigation Design alternative 1: primary data broker (logger & aggregator)
Interface 11	HPC	DMS	Basic safety messages Aggregated roadside data	UC03: Work Zone Navigation
Interface 12	DMS	HPC	Map files (various formats)	UC03: Work Zone Navigation
Interface 13	CMU ADS (ADS)	HPC	Basic safety messages	UC03: Work Zone Navigation Data collected will depend on testing scenarios
Interface 14	HPC	DMS	Aggregated roadway data (BSM, SPaT/MAP, SRM, etc.)	UC04: DMS Data Retrieval SSL tunnel over an ISP connection.
Interface 15	DMS	HPC	HD-MAP file	UC04: DMS Data Retrieval For LTE C-V2X, DSRC, and 4G/5G communication use cases
Interface 16	DMS	CMU ADS (ADS)	HD-MAP file	UC04: DMS Data Retrieval OTA communications
Interface 17	DMS	Web UI	All project data Restricted open data for general public	Project team will require Azure AD authentication
Interface 18	DMS	Web API	Approved project data for research (i.e., processed data without no PII)	USDOT will require Azure AD authentication

Source: PennDOT

Appendix C. Requirements Matrix

This appendix provides definitions for the terminology, requirement types, and methods of verification employed for each requirement during system testing to ensure the system conforms to the requirements established through this SRD.

C.1. REQUIREMENT TYPE DEFINITIONS

Table 43 provides definitions for the requirement types that have been included in the project.

Table 43: Preliminary Requirements for Design Considerations

Requirement Code	Requirement Name
CN	Constraints
DR	Data
FN	Functional
IF	Interface
IM	Information/Document Mgt
NF	Non-Functional
PF	Performance
PY	Physical
RG	Policy and Regulation
SFTY	Safety
SR	Security
ST	Storage and Transport

Source: PennDOT

C.2. VERIFICATION METHODS

Table 44 provides definitions for the systems engineering verification methods for testing system functionality against the requirements established in this document.

Table 44: Verification Methods

Method	Description
Inspection	Verification through a visual, auditory, olfactory, or tactile comparison.

Method	Description
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

C.3. TERMINOLOGY CONFORMANCE

Table 45 provides definitions for the importance characteristics of the terminology used to establish requirements.

Table 45: Terminology Conformance

Declarative	Description
Shall	Indicates the definition is an absolute, non-negotiable requirement for the specification and must pass testing to receive system validation.
Shall-Not	Indicates the definition is an absolute, non-negotiable prohibition of the specification and must pass testing to receive system validation.
Must	A mandatory requirement that addresses an essential stakeholder need. Testing can pass, fail, or be deferred and the system still receive validation by stakeholder consensus, agreement or design change request.
Should	Indicates there may exist valid reasons or circumstances to omit a particular item, but the full implications must be understood and carefully weighed before choosing a different course.
Should-Not	Indicates there may exist valid reasons or circumstances when a particular function or condition is acceptable or even useful, but the full implications should be understood, and the case carefully weighed before implementing any function or condition described with this label.
May	Indicates an item is optional. Some vendors may choose to include or implement optional requirements to add value or enhance their overall product while other vendors may omit the same optional requirement to reduce cost, increase time to market, etc. An implementation which does not include an optional requirement SHALL be interoperable with implementations that do include optional requirements; albeit with reduced functionality, and vice versa (with exception for the feature the option provides).

Source: PennDOT

C.4. REQUIREMENTS MATRIX

Table 46 provides a centralized matrix for the high-level requirements established for each of the systems in the ADS project, combined with general requirements for the project, for each use case, the three phases of testing, and requirements for the planned experimentation.

Table 46: Requirements Matrix

Requirement ID	Requirement 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 tradeoffs, 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,	Shall	Test

Requirement ID	Requirement Type	Title	Description	Importance	Verification Method
			require this standard to be effective. Provides reference system architecture based on CV2X technology, using 3GPP Release 14 & Release 15 PC5.		
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 parameters conform to LTE-V2X vehicle-level requirements specified in SAE J3161/1 Standard WIP.	Shall	Test
GEN-RG-004			SAE J2735_201603 Dedicated Short RangeShort-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	May	Test

Requirement ID	Requirement Type	Title	Description	Importance	Verification Method
			Management Messages may be used to defines secure message formats and processing within DSRC/WAVE.		
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 Media Access Control to support WAVE operations and describes various standard message formats for DSRC applications.	Shall	Test
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	Shall	Test

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DEPARTMENT OF TRANSPORTATION

Requirement ID	Requirement Type	Title	Description	Importance	Verification Method
			• ATC 5301 ATC Cabinet Standard		
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 requirements specific to systems, processes, and data are detailed in their respective section.	Shall	Demonstration
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

Requirement ID	Requirement Type	Title	Description	Importance	Verification Method
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
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

Requirement ID	Requirement Type	Title	Description	Importance	Verification Method
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
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

Requirement ID	Requirement Type	Title	Description	Importance	Verification Method
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 Electrical and Electronics Engineers (IEEE) 1609 suite and IEEE 802.11 standards [2] to [6].	Shall	Test
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

pennsylvania
DEPARTMENT OF TRANSPORTATION

Requirement ID	Requirement Type	Title	Description	Importance	Verification Method
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
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	Shall	Test

Requirement ID	Requirement Type	Title	Description	Importance	Verification Method
			safely among other drivers. Specific scenarios will be documented and measured by the project.		
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
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	Shall	Demonstration

pennsylvania
DEPARTMENT OF TRANSPORTATION

Requirement ID	Requirement Type	Title	Description	Importance	Verification Method
			is existing, integrated, and fully functional prior to the start of this project.		
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
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

pennsylvania
DEPARTMENT OF TRANSPORTATION

Requirement ID	Requirement Type	Title	Description	Importance	Verification Method
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
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

Requirement ID	Requirement Type	Title	Description	Importance	Verification Method
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
HPC-IF-001.C	Interface	Smart Infrastructure: High	The HPC should be capable of facilitating data exchanges to and from a configurable 4G or 5G, over-the-air network device to	Should	Test

pennsylvania
DEPARTMENT OF TRANSPORTATION

Requirement ID	Requirement Type	Title	Description	Importance	Verification Method
		Performing Computer	facilitate data exchanges to and from the cloud-based, DMS system using cellular.		
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

Requirement ID	Requirement Type	Title	Description	Importance	Verification Method
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
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

Requirement ID	Requirement Type	Title	Description	Importance	Verification Method
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
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

Requirement ID	Requirement Type	Title	Description	Importance	Verification Method
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 systems (i.e., the DMS and CMU ADS drive simulator) the day after the mapping took place.		Analysis
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 **6.1**).	Shall	Inspection

Requirement ID	Requirement Type	Title	Description	Importance	Verification Method
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
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

pennsylvania
DEPARTMENT OF TRANSPORTATION

Requirement ID	Requirement Type	Title	Description	Importance	Verification Method
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 turnaround 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
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

Requirement ID	Requirement Type	Title	Description	Importance	Verification Method
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
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	Shall	Test

pennsylvania
DEPARTMENT OF TRANSPORTATION

Requirement ID	Requirement Type	Title	Description	Importance	Verification Method
			data files and messages securely to and from the roadside and DMS.		
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
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

Requirement ID	Requirement Type	Title	Description	Importance	Verification Method
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
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

pennsylvania
DEPARTMENT OF TRANSPORTATION

Requirement ID	Requirement Type	Title	Description	Importance	Verification Method
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
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

pennsylvania
DEPARTMENT OF TRANSPORTATION

Requirement ID	Requirement Type	Title	Description	Importance	Verification Method
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
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

Requirement ID	Requirement Type	Title	Description	Importance	Verification Method
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, recognition, classification of objects, classification of events, and the behavioral response of the vehicle.	Shall	Demonstration

Requirement ID	Requirement Type	Title	Description	Importance	Verification Method
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

Requirement ID	Requirement 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

Requirement ID	Requirement 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

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Requirement ID	Requirement Type	Title	Description	Importance	Verification Method
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 or needs correcting and is correctable. For further information on handing FO behaviors, the project test plan shall be referenced.	Shall	Analysis
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	Shall	Analysis

Requirement ID	Requirement Type	Title	Description	Importance	Verification Method
			documented. The summary may include challenge(s), hypothesis, methods, encodings, formats, protocol stack details, final outcome, etc.		
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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